

Challenge Journal of **CONCRETE RESEARCH LETTERS**

Vol.17 No.3 (2026)

acoustic emission aerated concrete artificial neural
network compressive strength corrosion
cracking ductility durability energy
absorption ferrocement flexural strength
fly ash fracture mechanics mechanical properties
mortar optimization nanoparticle palm oil
fuel ash polymer concrete reinforced concrete
self-compacting concrete steam curing
strengthening superplasticizer tensile strength
workability waste disposal water absorption



TULPAR
ACADEMIC PUBLISHING

ISSN 2548-0928



Challenge Journal of CONCRETE RESEARCH LETTERS

EDITOR-IN-CHIEF

Prof. Dr. Gebrail BEKDAŞ
İstanbul University-Cerrahpaşa, Türkiye

CO-EDITORS-IN-CHIEF

Prof. Dr. Sinan Melih NİGDELİ
İstanbul University-Cerrahpaşa, Türkiye

Prof. Dr. Ümit IŞIKDAĞ
Mimar Sinan Fine Arts University, Türkiye

ASSOCIATE EDITORS

Assoc. Prof. Dr. Serdar ULUSOY
Assoc. Prof. Dr. Aylin Ece KAYABEKİR
Dr. Ayla OCAK

Turkish-German University, Türkiye
İstanbul Gelişim University, Türkiye
İstanbul Gelişim University, Türkiye

ASSISTANT EDITOR

Research Assistant Yaren AYDIN

İstanbul University-Cerrahpaşa, Türkiye

EDITORIAL BOARD

Prof. Dr. Gamal Elsayed ABDELAZIZ	<i>Benha University, Egypt</i>
Prof. Dr. Zubair AHMED	<i>Keyano College, Canada</i>
Prof. Dr. Ahmet Ferhat BİNGÖL	<i>Atatürk University, Türkiye</i>
Prof. Dr. Jiwei CAI	<i>Henan University, China</i>
Prof. Dr. Ferit ÇAKIR	<i>Gebze Technical University, Türkiye</i>
Prof. Dr. Mohamed GHRICI	<i>Hassiba Benbouali University of Chlef, Algeria</i>
Prof. Dr. Khandaker M. Anwar HOSSAIN	<i>Toronto Metropolitan University, Canada</i>
Prof. Dr. Jamal KHATIB	<i>Beirut Arab University, Lebanon</i>
Prof. Dr. Han Seung LEE	<i>Hanyang University, Republic of Korea</i>
Prof. Dr. Jahangir MIRZA	<i>Hydro-Québec Research Institute, Canada</i>
Prof. Dr. Ashraf Ragab MOHAMED	<i>Alexandria University, Egypt</i>

Prof. Dr. Meral OLTULU	<i>Atatürk University, Türkiye</i>
Prof. Dr. Hamidah Mohd SAMAN	<i>Universiti Teknologi Mara, Malaysia</i>
Prof. Dr. Xiao-Yong WANG	<i>Kangwon National University, Republic of Korea</i>
Prof. Dr. Chunjiang ZOU	<i>Wuhan University, China</i>
Assoc. Prof. Dr. Saleh Omar BAMAGA	<i>University of Bisha, Saudi Arabia</i>
Assoc. Prof. Dr. Zinnur ÇELİK	<i>Atatürk University, Türkiye</i>
Assoc. Prof. Dr. Türkay KOTAN	<i>Erzurum Technical University, Türkiye</i>
Assoc. Prof. Dr. Mohammed Seddik MEDDAH	<i>Sultan Qaboos University, Oman</i>
Assoc. Prof. Dr. Brabha NAGARATNAM	<i>Northumbria University, United Kingdom</i>
Assoc. Prof. Dr. Ayman Youssef NASSIF	<i>University of Technology and Education HCMC, Vietnam</i>
Dr. Mahmoud SAYED AHMED	<i>Toronto Metropolitan University, Canada</i>
Dr. Ibrahim ALAMERI	<i>Sana'a University, Yemen</i>
Dr. Salam Rafea ARMOOSH	<i>University of Anbar, Iraq</i>
Dr. Aamer Rafique BHUTTA	<i>Aramco, Saudi Arabia</i>
Dr. Ali KEYVANFAR	<i>Kennesaw State University, United States</i>
Dr. Khairunisa MUTHUSAMY	<i>Universiti Malaysia Pahang, Malaysia</i>
Dr. Arezou SHAFAGHAT	<i>Georgia Institute of Technology, United States</i>
Dr. Jitendra Kumar SINGH	<i>Jindal Steel and Power, India</i>

E-mail: cjcr1@challengejournal.com

Web page: cjcr1.challengejournal.com

Tulpar Academic Publishing
www.tulparpublishing.com





Challenge Journal of CONCRETE RESEARCH LETTERS

CONTENTS

Research Articles

Comparative study on the use of quarry waste and river sand as fine aggregates in pervious concrete performance	222–239
<i>Mathuranayagam Arunan, Daniel Niruban Subramaniam, Navaratnarajah Sathiparan</i>	
Mechanical and durability characteristics of SCC incorporating recycled aggregate and steel slag	240–249
<i>Pottur Ramachandra, Periyapatna Shanthaguptha Niranjana</i>	
Effectiveness of TiO₂ coating on concrete surfaces for photocatalytic degradation of solutions	250–261
<i>Fatih Şamdan, Canan Şamdan, Emir Günaltı, Serdal Ünal, Mehmet Canbaz</i>	
Potential and production of pervious concrete incorporating rice husk as a partial aggregate replacement	262–277
<i>Mohd Syahrul Hisyam Mohd Sani, Nurul Huda Abdullah, Fadhluhartini Muftah</i>	
Effect of crushed brick chips as coarse aggregate on the mechanical properties, water absorption and cost of concrete	278–292
<i>Md. Rashedul Haque, Md. Saied Sakib, Abu Saeed, Md. Abu Sufian</i>	
Effect of different activations of supplementary cementitious materials on the early-age compressive strength of mortars based on quaternary binders	293–304
<i>Ali Abbache, Zoubir Makhoulfi, Hichem Berkak, Rachid Rabehi, Mohammed Seghir Ammari</i>	
Mechanical performance evaluation of conventional and pervious concrete reinforced with steel and nylon fibers	305–318
<i>Md. Izharul Haque Azad, Md. Abu Helal, Md. Abdul Malek, Rahat Ali, Md. Ahmadullah Hossain Raihan, Md. Washim Akram</i>	
Evaluation of the effectiveness of glass waste powder in improving the durability of sand concretes	319–340
<i>Mohammed Seghir Ammari, Madani Bederina, Issam Zaiz, Boubaker Fethiza Ali, Ahmed Merrah, Hichem Berkak, Hiyam Khezzane, Reguia Zellouma</i>	
A field-exposure study on the effects of seasonal temperature variations and curing conditions on concrete strength and density	341–351
<i>Rukiye Koçkar Tuğla</i>	

Mechanical performance of concrete using rice husk ash-plastic artificial aggregates with varying particle sizes	352–363
---	----------------

*Dwi Nurtanto, Ketut Aswatama Wiswamitra,
Mohamad Fikri Nurhidayat, Bagas Rahmandita Subchan, Imam Junaidi*

Evaluation of shear strength prediction models for polypropylene fiber-reinforced concrete beams without stirrups: Influence of residual tensile strength estimation on fib-MC2010 code predictions	364–386
--	----------------

Kadir Sengun, Hasan Cem Akkaya

Review Articles

Sugarcane bagasse ash in cementitious systems: A review of fresh, mechanical, and durability properties	387–404
--	----------------

Sachin Kumar Verma, Anil Kumar Sachan, Rama Shanker





Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Comparative study on the use of quarry waste and river sand as fine aggregates in pervious concrete performance

Mathuranayagam Arunan ^a , Daniel Niruban Subramaniam ^a , Navaratnarajah Sathiparan ^{a,*}

^a Department of Civil Engineering, University of Jaffna, Ariviyal Nagar, Kilinochchi 44000, Sri Lanka

ABSTRACT

This study examines the use of quarry waste as a partial replacement for coarse aggregate in pervious concrete, aiming to enhance its mechanical strength, permeability, and durability while promoting sustainability in construction. Various pervious concrete mixes were prepared with different levels of river sand and quarry waste replacements (4%, 8%, and 12%) and tested for compressive strength, flexural strength, impact strength, permeability, porosity, and abrasion resistance. The results indicate that quarry waste significantly enhances mechanical properties, with the 12% replacement mix showing a 49.1% increase in compressive strength (8.04 MPa) compared to the 5.39 MPa of the control mix. Additionally, quarry waste led to a notable reduction in porosity, reaching 0.318 at the 12% level compared to 0.343 for the control. While both materials reduced permeability, quarry waste maintained higher values than river sand, with the optimal 8% replacement (Q8) providing a permeability of 4.77 cm/s, which is 25% higher than the 3.79 cm/s observed for the R12 river sand mix. Furthermore, quarry waste-based mixes exhibited improved abrasion resistance, with weight loss as low as 36.7% at 200 revolutions. This study shows that using 8% quarry waste in concrete results in a 31% strength increase while keeping its hydrological performance high. It highlights that quarry waste is an environmentally friendly and cost-effective alternative to river sand, improving both strength and durability. The findings offer valuable insights into the use of quarry waste in sustainable construction and lay the groundwork for future research into optimizing pervious concrete mixes for specific applications.

ARTICLE INFO

Article history:

Received – February 13, 2026
Revision requested – April 4, 2026
Revision received – April 13, 2026
Accepted – April 24, 2026

Keywords:

Pervious concrete
Quarry waste
River sand
Mechanical properties
Durability



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

Citation: Arunan M, Subramaniam DN, Sathiparan N (2026). Comparative study on the use of quarry waste and river sand as fine aggregates in pervious concrete performance. *Challenge Journal of Concrete Research Letters*, 17(3), 222–239.

1. Introduction

Pervious concrete, also known as porous or permeable concrete, is a sustainable construction material designed to allow water to pass through its interconnected voids, thus reducing surface runoff and promoting groundwater recharge (Tie et al. 2020). Traditionally, pervious concrete is composed mainly of coarse aggregates, cement, and limited or no fine aggregates to maintain high permeability. However, the incorporation of fine aggregates in pervious concrete has gained attention for its potential to enhance me-

chanical strength while maintaining balanced hydraulic properties (He et al. 2023). Fine aggregates help fill voids between coarse particles, leading to a denser matrix that enhances the load-bearing capacity without significantly compromising permeability (Khankhaje et al. 2025). Several studies have investigated the effect of fine aggregate content on the mechanical and hydraulic properties of pervious concrete (Lori et al. 2019). Research has demonstrated that incorporating controlled amounts of fine aggregate can improve compressive strength and durability, while excessive fines may reduce permeability (Elango et al. 2021).

* Corresponding author. E-mail address: sakthi@eng.jfn.ac.lk (N. Sathiparan)
ISSN: 2548-0928 / DOI: <https://doi.org/10.20528/cjrl.2026.1121>

River sand has been the conventional fine aggregate used in concrete production worldwide, including pervious concrete (Miah et al. 2023). However, the increasing environmental concerns related to the excessive extraction of natural river sand have driven researchers and industry professionals to explore alternative materials (Rentier and Cammeraat 2022). Quarry waste, a byproduct of aggregate production, is emerging as a promising substitute for natural fine aggregates (Altheeb 2022). Comparable studies using waste-derived fine aggregates as partial sand substitutes have also shown that appropriate replacement levels can improve mechanical performance while reducing reliance on natural river sand (Wee Chit et al. 2025). Utilizing quarry waste not only reduces the environmental footprint associated with sand mining but also provides a sustainable way to manage industrial byproducts that would otherwise contribute to landfill waste (Gunasekaran and Sathiparan 2024; Pakkiyachandran and Sathiparan 2025). Quarry waste possesses several advantages as a fine aggregate in pervious concrete. Its angular shape and rough texture improve the interlocking between particles, potentially enhancing the mechanical strength of the concrete (Sathiparan et al. 2022). Furthermore, quarry waste typically exhibits lower silt and clay content than river sand, which can positively influence the hydraulic conductivity of pervious concrete by minimizing pore clogging (Coughlin et al. 2012). Additionally, the availability and low cost of quarry waste make it an economically viable alternative, especially in regions where natural sand resources are becoming scarce (Sundaralingam et al. 2022).

Several studies have investigated the impact of quarry waste on the mechanical properties of pervious concrete. For instance, Sundaralingam et al. (2022) found that replacing river sand with quarry dust up to 30% by weight improved the compressive strength of concrete. Similarly, Sruthi Reddy and Sumetha (2024) observed an enhancement in flexural strength in pervious concrete mixes incorporating quarry fines. These findings suggest that quarry waste can contribute positively to the structural integrity of pervious concrete. However, the performance of waste-derived aggregates remains strongly dependent on their material characteristics and replacement level (Samdan et al. 2024; Niroula and Bhatt 2026). The primary function of pervious concrete is to allow water infiltration. Research indicates that the inclusion of quarry waste can influence the permeability of pervious concrete. Nune and Dakshina Murthy (2021) reported that replacing river sand with quarry dust did not significantly affect the permeability of pervious concrete, maintaining its hydrological performance. However, Febin et al. (2019) noted that excessive replacement levels might reduce permeability due to the finer particle size of quarry dust, which could lead to pore clogging. Durability is a critical factor for pervious concrete exposed to various environmental conditions. Studies have shown that quarry waste can enhance the durability of pervious concrete. Meisuh et al. (2018) demonstrated that concrete containing quarry dust exhibited improved resistance to chemical attacks,

such as exposure to sulfate and acid. Additionally, Al-Kharabsheh et al. (2022) found that incorporating quarry fines enhanced the freeze-thaw durability of pervious concrete, making it suitable for regions with harsh climatic conditions.

Utilizing quarry waste as a replacement for river sand in pervious concrete offers significant environmental and economic advantages, consistent with broader waste-valorization strategies aimed at reducing natural-resource consumption and supporting more sustainable construction practices (Ünal and Canbaz 2025, 2026). The use of quarry waste as an alternative aggregate has emerged as a promising strategy for developing sustainable, low-cost concrete that maintains rigorous performance standards (Hamada et al. 2023). However, a significant gap remains in the current body of knowledge regarding the holistic performance of pervious concrete where river sand is replaced by quarry waste. Most existing studies focus on isolated parameters, such as compressive strength or basic permeability, without systematically evaluating how these properties interact with durability factors like impact toughness and abrasion resistance in tandem. Furthermore, the specific influence of quarry waste's angular geometry on the trade-off between pore tortuosity and mechanical interlocking in pervious systems is not fully understood. The study evaluates the mechanical properties (compressive, flexural, and impact strength), hydraulic performance (permeability), and durability aspects (abrasion resistance) of pervious concrete mixtures with varying quarry waste content as a replacement for a portion of the coarse aggregate. The objective is to determine the optimal replacement level of quarry waste that can enhance the strength and durability of pervious concrete without compromising its essential hydraulic functionality, consistent with broader sustainable-concrete approaches that seek to balance environmental benefits with strength and permeability performance (Mahmud et al. 2025).

2. Methodology

2.1. Materials

In the present study, the materials selected for the investigation include Ordinary Portland Cement (OPC), river sand, quarry waste, and coarse aggregates. Ordinary Portland Cement (OPC) was used as the primary binding material. It has a bulk density of 1360 kg/m³ and a specific gravity of 3.15. The chemical composition of the OPC mainly consists of SiO₂ (20.60%), Al₂O₃ (4.51%), Fe₂O₃ (3.62%), and CaO (66.55%). For the fine aggregates, both river sand and quarry waste were used. The river sand was sourced from the Muthayankattu riverbed in the Northern Province of Sri Lanka, while quarry waste was obtained from a manufacturing plant in Divulapitiya, Western Province, Sri Lanka. The particle size distribution of the river sand and quarry waste is given in Fig. 1, and the physical properties are given in Table 1. The river sand had a bulk density of 1720 kg/m³ and a

specific gravity of 2.57, with 95.6% sand content and 0.6% fine content. The quarry waste, on the other hand, had a bulk density of 1750 kg/m³ and a specific gravity of 2.63, with 85.6% sand content and 7.2% fine content. Both materials were sieved and sun-dried to remove impurities, ensuring their suitability for use in concrete production.

The coarse aggregates used in the study were natural granite-gneiss rocks, sourced from the Western

Province of Sri Lanka. These aggregates were sieved to achieve sizes between 5 mm and 12 mm, making them suitable for use as coarse aggregates in pervious concrete. The coarse aggregates had a bulk density of 1491 kg/m³, a specific gravity of 2.72, and an absorption rate of 0.20%. Additional tests on these aggregates revealed an aggregate crushing value of 30.5%, which indicated that they were of adequate quality for use in concrete production.

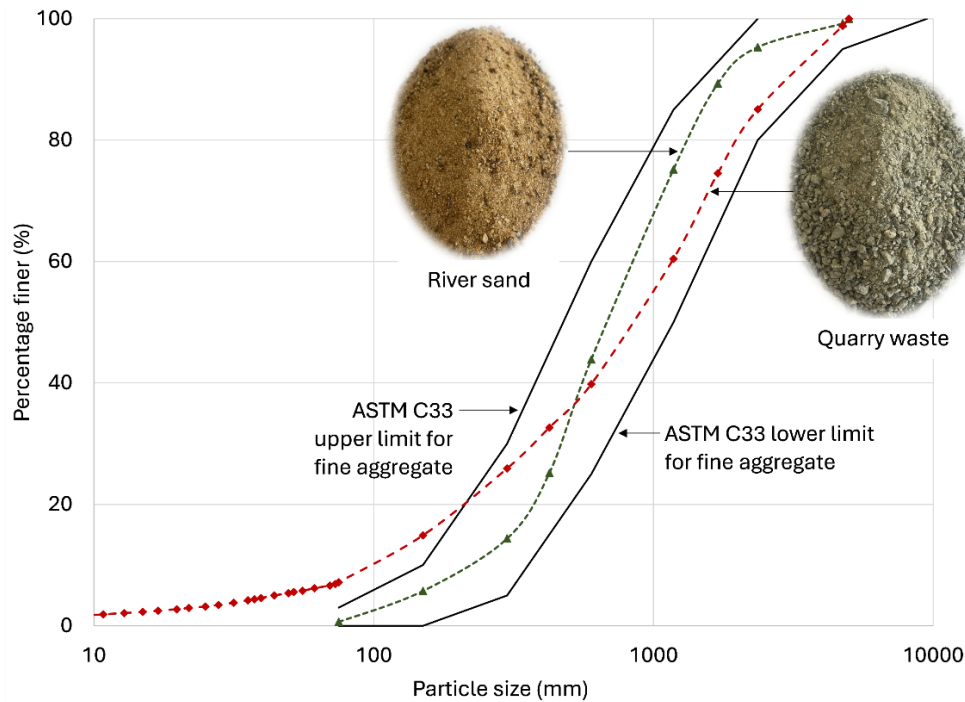


Fig. 1. Particle size distribution of the river sand and quarry waste.

Table 1. Physical properties of river sand and quarry waste.

Properties	River sand	Quarry waste
Bulk density (kg/m ³)	1720	1750
Specific gravity	2.57	2.63
Fineness modulus	2.72	2.96
Gravel (%)	0.8	1.2
Sand (%)	98.6	91.6
Fine (%)	0.6	7.2
Uniformity coefficient (Cu)	4.0	11.4
Coefficient of gradation (Cc)	1.1	1.18

2.2. Mix design

The mix design for the pervious concrete used in this study is based on a series of pre-determined mix proportions, and the details of the mix design are summarized in Table 2. The replacement of coarse aggregate with fine aggregates (river sand or quarry waste) was conducted on a weight-based basis to maintain a constant total aggregate-to-cement ratio of 4.0 for all mixtures. As the replacement level of fine aggregate in-

creased (4%, 8%, and 12%), the mass of the coarse aggregate was proportionally reduced. This mix design ensures that the different proportions of aggregates contribute to both the structural strength and permeability properties of the concrete. The aggregates, river sand, and quarry waste used in the mixtures were thoroughly tested for their physical properties, ensuring compliance with industry standards for durability and performance.

For the preparation of PC samples, aggregates of the specified mix were first weighed according to the designed mix proportions. The cement was added to the aggregate mixture, followed by the addition of water based on the water-to-cement ratio of 0.3. While the w/c ratio was held constant at 0.3, the inclusion of higher fine aggregate content, particularly with quarry waste, increases the total specific surface area of the mix. This can lead to a reduction in workability, as evidenced by the zero-slump measured for all pervious concrete samples. A mixing duration of 20 minutes in a 120-liter concrete mixer was employed to achieve a homogeneous mixture and ensure the higher fine content did not compromise cement paste hydration. The fresh mix was then measured for slump, which was found to be zero, adhering to the specifications for PC. After mixing, the mixture was placed into moulds. Once the mixture was placed

entirely, the excess was leveled using an iron rod, as shown in Fig. 2, and the molds were left undisturbed for 24 hours. After this initial curing period, the sam-

ples were demoulded and placed into a water bath to cure for 28 days, ensuring proper hydration of the cement.

Table 2. Quantity of constituents for control and modified pervious concrete mixes (fine aggregate percentages of 4, 8, and 12% represent the weight-based replacement of the coarse aggregate fraction).

Mix ID	Cement (kg/m ³)	Coarse aggregate (kg/m ³)	River sand (kg/m ³)	Quarry waste (kg/m ³)	Water (kg/m ³)
Control	389.1	1556.4	–	–	116.7
R04	389.1	1494.1	62.3	–	116.7
R08	389.1	1431.9	124.5	–	116.7
R12	389.1	1369.6	186.8	–	116.7
Q04	389.1	1494.1	–	62.3	116.7
Q08	389.1	1431.9	–	124.5	116.7
Q12	389.1	1369.6	–	186.8	116.7



Fig. 2. Casting procedure of pervious concrete mix.

To determine the density, porosity, and compressive strength, cubes with dimensions of 100 mm were used. Flexural bending tests were conducted on beams with dimensions of 200 mm × 100 mm × 65 mm, and impact tests were performed on blocks with dimensions of 100 mm × 100 mm × 60 mm. Permeability tests were conducted using cylindrical specimens measuring 100 mm in diameter and 150 mm in height.

2.3. Testing

2.3.1. Compressive strength

In accordance with BS EN 12390-3 (2019), the compressive strength of the pervious concrete was evaluated using a universal testing machine (UTM), as illustrated in Fig. 3(a). The specimens, cast in 100 mm cube molds and cured under standard conditions, were subjected to a constant loading rate of 1 mm/min until failure. This controlled loading rate ensures uniform force application, allowing for an accurate measurement of the material's compressive strength without introducing shock loads that could affect the results. The test was continued until the specimen fractured, and the maximum load reached at the point of failure was recorded. The compressive strength was then calculated by dividing the maximum load by the specimen's cross-sectional area.

2.3.2. Flexural tensile strength

The flexural bending strength of pervious concrete specimens was evaluated following ASTM C78/C78M (2021) as shown in Fig. 3(b). The specimens used for this test were rectangular beams with dimensions of 200 mm × 100 mm × 65 mm. This test measures the ability of pervious concrete to resist bending stresses, a crucial property for applications where the material is subjected to flexural forces, such as pavements and sidewalks. The flexural bending test was conducted by placing the specimen on two supports, ensuring the beam was centered and properly aligned, and applying the load at the middle of the span at a constant loading rate of 1 mm/min. As the load was gradually increased, the test continued until the specimen fractured or failed. The flexural strength was calculated using Eq. (1):

$$f_r = \frac{3PL}{2bd^2} \quad (1)$$

where

- f_r is the flexural strength (MPa);
- P is the maximum load applied (N);
- L is the length of the span (mm);
- b is the width of the beam (mm).

2.3.3. Porosity

To measure the porosity of pervious concrete, the immersion method, as outlined in ASTM C642 (2021), was followed, as shown in Fig. 3(c). First, the dry weight of the pervious concrete (W_{dry}) sample was measured using a balance. This was the weight of the

sample before it was immersed in water. The pervious concrete sample was then fully submerged in a container of water, ensuring that no air was trapped in the pores. While the sample was fully submerged, it was weighed again, which was referred to as the apparent weight (W_{sub}). The porosity was calculated by Eq. (2).

$$\text{Porosity} = \left(1 - \frac{W_{dry} - W_{sub}}{\rho_w \cdot V_{total}}\right) \times 100 \quad (2)$$

where

- W_{dry} is the mass of the oven-dried sample (kg);
- W_{sub} is the mass of the sample submerged in water (kg);
- V_{total} is the total volume of the specimen (m^3), calculated from the dimensions of the 100 mm cube;
- ρ_w is the density of water (approximately 1000 kg/m^3).

2.3.4. Permeability

The permeability of the pervious concrete was determined using the falling head method, as outlined in ASTM D2434 (2022), as shown in Fig. 3(d). This method is a standard approach for measuring the hydraulic conductivity of porous materials. A cylindrical sample of pervious concrete, with a diameter of 100 mm and a height of 150 mm, was used for testing. The sample was placed in a permeameter, and its initial water height was recorded. To ensure the sample was fully saturated, the concrete was submerged in water, eliminating any air voids within its pores. The test involved allowing water to flow through the sample and recording the time taken for the water level to drop over a known distance. The permeability of the sample was determined using the falling head formula, given by Eq. (3).

$$K = \frac{\alpha \cdot L}{A \cdot t} \ln \left(\frac{h_1}{h_2} \right) \quad (3)$$

where:

- K is the hydraulic conductivity (permeability) of the sample;
- α is the cross-sectional area of the standpipe (water column);
- L is the length of the specimen (150 mm);
- A is the cross-sectional area of the pervious concrete specimen (calculated using its diameter of 100 mm);
- t is the time taken for the water level to drop;
- h_1 and h_2 are the initial and final water heights, respectively.

2.3.5. Impact strength

The impact strength of pervious concrete specimens was assessed using a modified protector hammer dropping test. This test was adapted from Azevedo et al. (2019) as shown in Fig. 3(e). The test measures the material's toughness and its ability to absorb impact energy without failure. For the impact strength test, the specimen was placed on a flat, stable surface to receive the impact load. The test utilized a

protector hammer dropped from an initial height of 100 mm, with the height gradually increased in 20 mm increments until failure occurred. The hammer was released from a fixed height, and the specimen was monitored for visible signs of cracking, fracture, or complete failure upon each drop. The number of drops and the corresponding height at which failure occurred

were recorded during the test. The impact energy (IE) was computed by Eq. (4) (Ismail et al. 2019).

$$IE = \sum mgh \quad (4)$$

where $m = 4.5$ kg (protector hammer weight); $g = 9.81$ m/s²; and h = drop height in m.



(a) Compression test



(b) Flexural bending test



(d) Permeability test



(c) Porosity test



(e) Impact resistance test

Fig. 3. Testing setup for different tests conducted on pervious concrete specimens.

2.3.6. Abrasion resistance

The abrasion resistance of the pervious concrete specimens was evaluated using the Los Angeles Abrasion Value (LAHV) method, as outlined in ASTM C1747

(2013). For this test, the specimens were prepared in the form of 100 mm cubes. The samples were subjected to the abrasion test by rotating them in the LAHV, with the number of revolutions set at 50, 100, 150, and 200 revolutions. After each set of revolutions,

the weight of the specimens was measured. The weight loss was then calculated to determine the abrasion resistance. The weight loss percentage was calculated using Eq. (5):

$$\text{Weight loss} = \frac{(\text{Initial weight} - \text{Final weight})}{\text{Initial weight}} \times 100 \quad (5)$$

This test simulates the wear and tear that pervious concrete may undergo in real-world conditions, such as high-traffic areas or exposure to abrasive forces. The results help assess the material's durability and suitability for applications where resistance to degradation is essential.

2.4. Statistical Analysis

Data are presented as mean $\pm$ standard deviation (SD). The normality of distribution and equality of variances were confirmed using Shapiro-Wilk and Levene's tests, respectively. Differences between groups (3 per group) were analyzed using a one-way analysis of variance (ANOVA) followed by Tukey's HSD post-hoc test for multiple comparisons. The relationship between two variables was evaluated using Pearson's correlation coefficient. All statistical calculations

were performed using IBM SPSS Statistics (Version 26.0). A p-value of less than 0.05 was considered statistically significant.

3. Results and Discussion

3.1. Density

Fig. 4 illustrates the density variation of various pervious concrete mixes. The control mix had a density of 1612 kg/m³. When river sand was used as a replacement for coarse aggregate, the density increased with the percentage of river sand replacement. The R4 mix exhibited a slight increase in density to 1620 kg/m³, and the R8 mix had a density of 1632 kg/m³. As the river sand replacement reached 12% (R12), the density increased further to 1649 kg/m³. These increases in density suggest that river sand, being finer than coarse aggregate, contributes to a more compact packing of the concrete particles, reducing the voids and leading to a denser structure. The finer texture of river sand fills the gaps between the larger aggregates, improving the overall packing efficiency of the concrete mix.

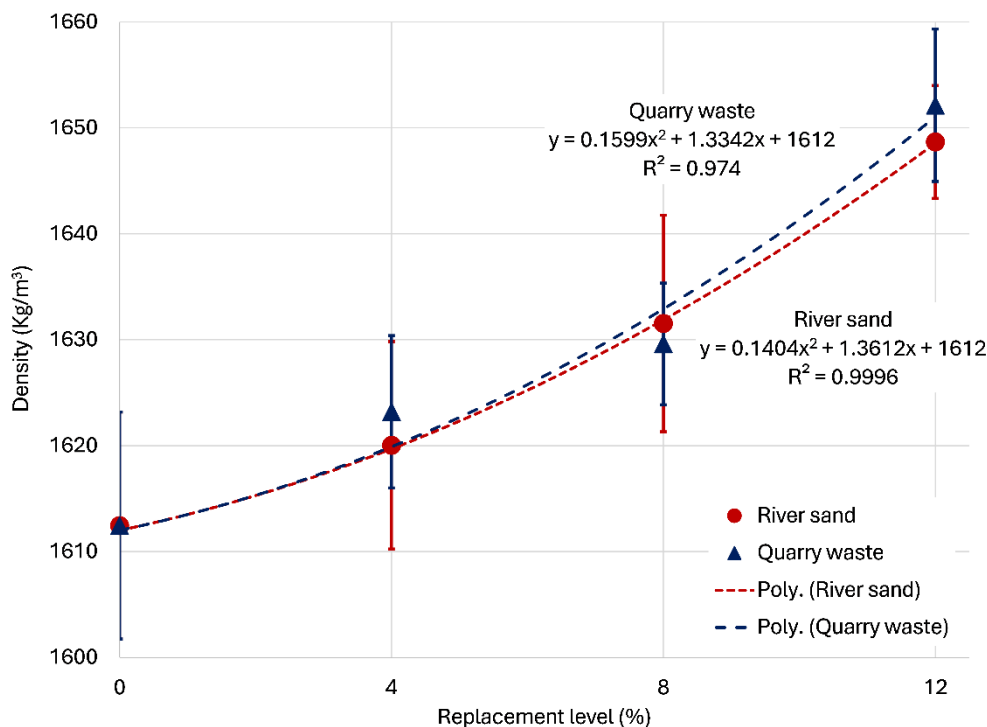


Fig. 4. Density variation for different pervious concrete mixes.

Similarly, the mixes with quarry waste replacement showed a progressive increase in density as the percentage of quarry waste increased. The Q4 mix had a density of 1622 kg/m³, which was slightly higher than the control mix. At 8% quarry waste replacement (Q8), the density rose to 1630 kg/m³, and at 12% quarry waste replacement (Q12), the density increased to 1652 kg/m³, the highest among all mixes. The angular and irregular shape of quarry waste particles leads to better interlocking and a denser packing structure,

which results in a significant increase in the overall density of the concrete mix (Pakkiyachandran and Sathiparan 2025). The higher density observed with quarry waste replacement suggests that the material's angular particles fit together more efficiently, reducing void spaces and improving the compactness of the concrete (Sukkarak et al. 2025). When comparing river sand and quarry waste replacements, it is evident that quarry waste results in a slightly higher density than river sand, particularly at higher replacement levels.

3.2. Porosity

Fig. 5 illustrates the porosity variation of several pervious concrete mixes. The control mix had a porosity of 0.343, which serves as the baseline for conventional pervious concrete. For the mixes with river sand replacement, the porosity decreased slightly as the percentage of river sand increased. The R4 mix had a porosity of 0.336, while the R8 and R12 mixes had po-

rosities of 0.332 and 0.328, respectively. These decreases in porosity suggest that the finer particles of river sand fill voids more efficiently than coarse aggregates, resulting in a denser packing of the particles and a reduction in the overall porosity.

The finer nature of river sand helps to create a more compact structure, reducing the amount of void space between particles and making the concrete less porous.

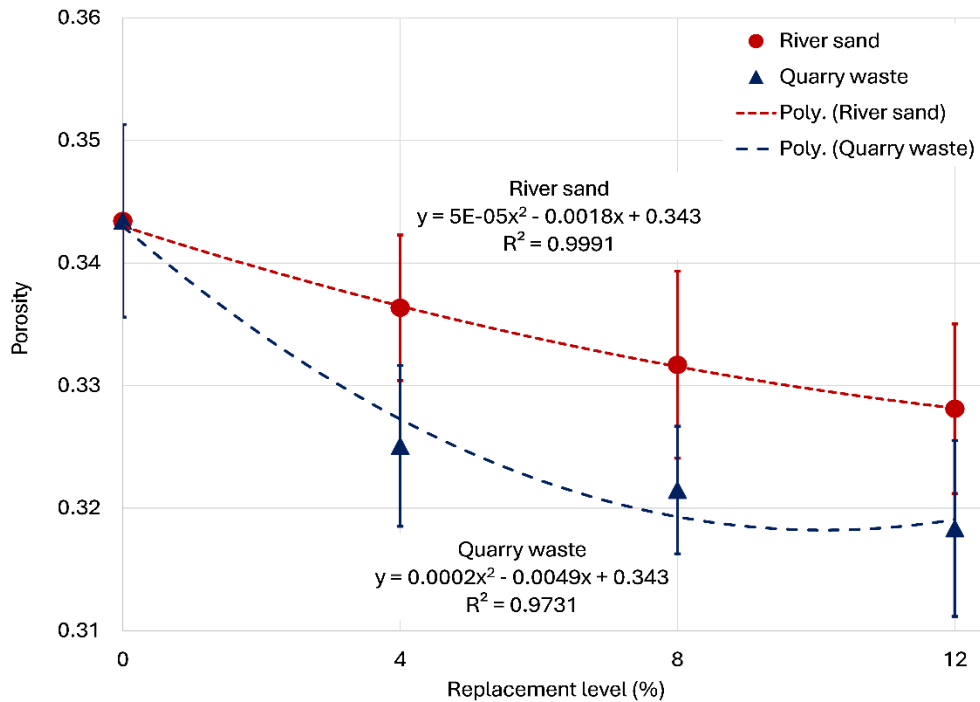


Fig. 5. Porosity variation for different pervious concrete mixes.

In contrast, the mixes with quarry waste replacement showed a more significant reduction in porosity. The Q4 mix had a porosity of 0.325. As the proportion of quarry waste increased to 8% (Q8) and 12% (Q12), the porosity continued to decrease to 0.321 and 0.318, respectively. Quarry waste, due to its angular shape, contributes to a denser packing of particles compared to rounded aggregates. The angular particles interlock more effectively, resulting in fewer voids and a denser concrete structure, which leads to a reduction in porosity (Gunasekaran and Sathiparan 2024). This pattern demonstrates that quarry waste is more effective than river sand in reducing porosity.

When comparing the effects of river sand and quarry waste replacements, it is clear that both materials reduce porosity, but quarry waste replacement leads to a more substantial decrease. The angular nature of quarry waste particles creates a more compact packing structure, which significantly reduces the void spaces in the concrete (Islam 2023). On the other hand, river sand, while it reduces porosity, does so to a lesser extent due to its finer, yet less angular, nature. This reduction in porosity can enhance the mechanical properties of the concrete, such as strength, but may also decrease its permeability, which is a crucial characteristic for stormwater management. Thus, a balance between strength and permeability must be care-

fully considered when designing pervious concrete mixes for specific applications.

3.3. Compressive strength

Fig. 6 illustrates the variation in compressive strength with different levels of replacement of river sand and quarry waste. The control specimen exhibited the lowest compressive strength at 5.39 MPa, while specimens with sand additions showed progressive increases in strength corresponding to the percentage of sand replacement. Both river sand and quarry waste improved the compressive strength of the pervious concrete. For river sand, the compressive strength increased from 5.84 MPa (for 4%) to 7.27 MPa (for 12%), representing approximately a 35% increase over the control specimen. Quarry waste specimens exhibited a similar trend, with compressive strength increasing from 6.75 MPa (for 4%) to 8.04 MPa (for 12%), representing a nearly 19% increase compared to the control.

The strength improvement can be attributed to the partial filling of voids between the coarse aggregates by fine particles from the sand. This reduces the overall porosity and enhances the particle packing density within the matrix. The finer particles also contribute to better interlocking between cement paste

and aggregates, leading to improved load transfer and resistance under compression (Hong et al. 2023). At each corresponding replacement percentage, quarry waste specimens consistently exhibited higher compressive strength than those with river sand. For example, at a 12% replacement rate, Q12 showed 8.04 MPa compared to 7.27 MPa for R12. This

difference is likely due to the angularity and surface texture of quarry waste particles, which provide improved mechanical interlock and bonding with the cement paste compared to the smoother and more rounded river sand particles. Additionally, quarry waste may have fewer impurities, resulting in a stronger cement matrix.

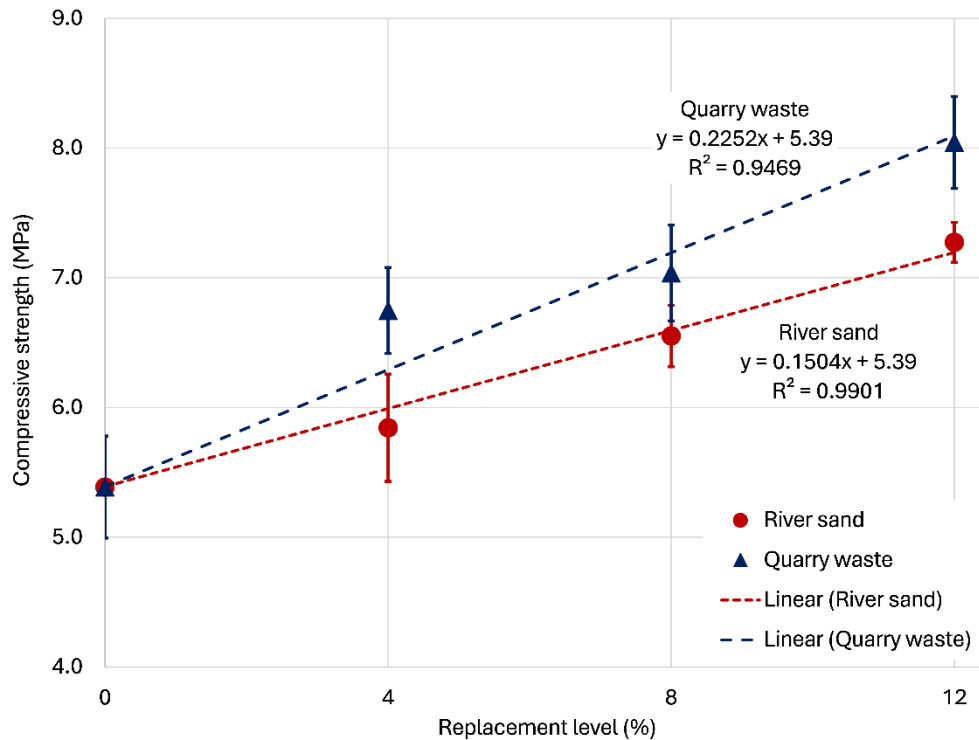


Fig. 6. Compressive strength variation for different pervious concrete mixes.

3.4. Flexural strength

The flexural strength test results shown in Fig. 7 indicate an increase in the flexural performance of pervious concrete specimens when river sand and quarry waste are incorporated into the mix compared to the control specimen containing only cement and coarse aggregate. The control specimen exhibited the lowest flexural strength of 1.17 MPa. With the addition of river sand, flexural strength improved progressively from 1.20 MPa at 4% replacement to 1.40 MPa at 12% replacement, representing an approximate 20% increase over the control. Similarly, specimens with quarry waste exhibited increased flexural strength, albeit with less pronounced variation, ranging from 1.29 MPa (for 4%) to 1.33 MPa (for 12%). The enhancement in flexural strength can be attributed to the fine particles' role in filling the voids between coarse aggregates, resulting in a denser and more homogeneous matrix. This improved packing reduces stress concentrations and microcracking under bending loads, thereby increasing resistance to flexural failure.

At lower sand replacement levels (4% and 8%), quarry waste specimens exhibited higher flexural strength than river sand specimens, likely due to the angular shape and rough texture of quarry waste, which enhances mechanical interlock and bond strength within the cement matrix. However, at the

highest replacement level (12%), the river sand specimen surpassed the quarry waste specimen in flexural strength. The observed behavior stems from variations in particle size distribution and packing density at elevated fines contents. Specifically, the spherical geometry of river sand likely optimized workability and stress distribution under flexure. While increased sand content generally improved flexural strength by reducing porosity and enhancing matrix cohesion, this trend was most pronounced in river sand specimens. Conversely, the marginal gains in quarry waste samples suggest a threshold beyond which additional fines provide diminishing returns for flexural performance, a trend also observed in other waste-modified cementitious systems, where performance may peak at an optimum replacement level and decline beyond it (Turan et al. 2025).

3.5. Impact strength

The impact strength test results for the pervious concrete specimens, shown in Fig. 8, demonstrate minor variations with the addition of river sand and quarry waste compared to the control specimen, which consists only of cement and coarse aggregate. The control specimen showed an impact strength of 117.99 J. The addition of river sand at 4% and 8% lev-

els slightly increased the impact strength to 119.48 J and 118.49 J, respectively. In contrast, a 12% replacement showed a marginal decrease to 116.49 J, which is slightly below the control. Quarry waste specimens exhibited a maximum impact strength of 124.46 J at

4% replacement, followed by a decrease at higher percentages. Overall, the impact strength values remained relatively stable across all mixes, with only minor differences within a narrow range (approximately ± 6 J).

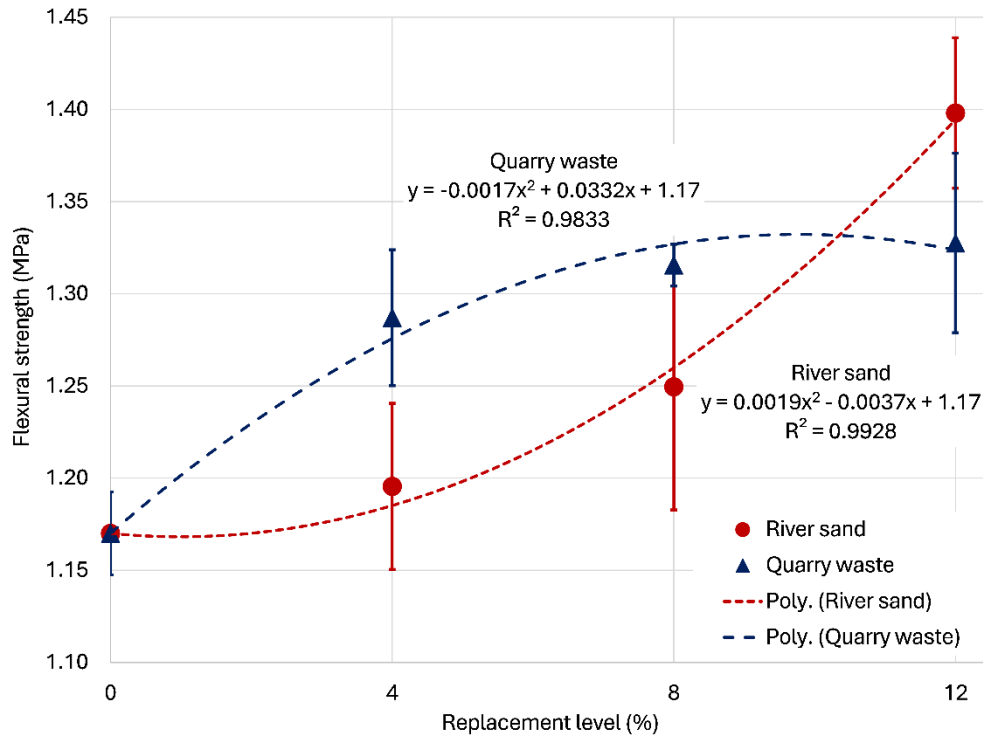


Fig. 7. Flexural strength variation for different pervious concrete mixes.

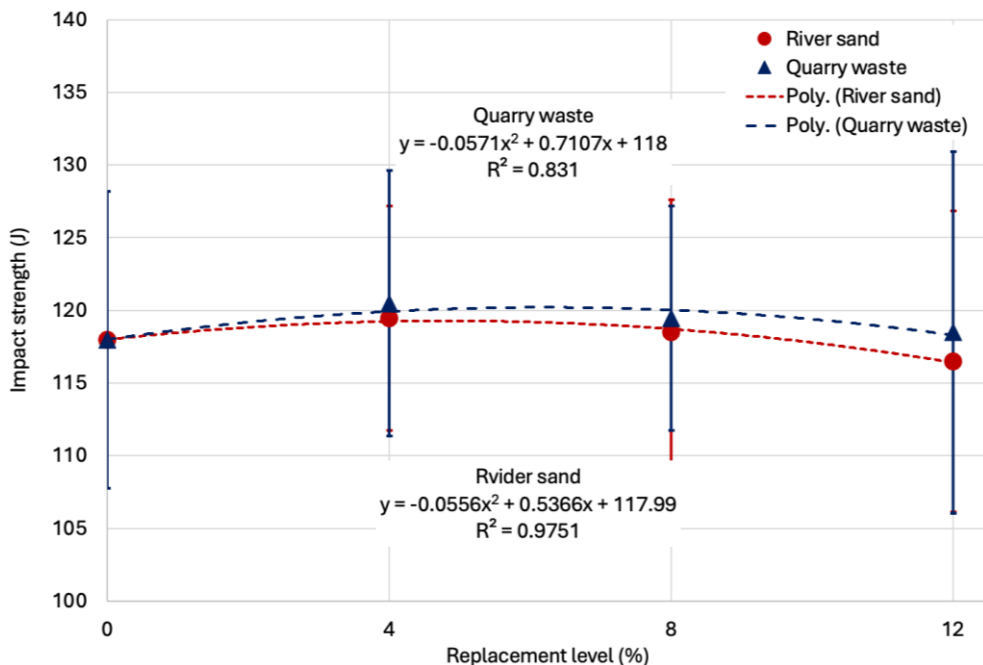


Fig. 8. Impact strength variation for different pervious concrete mixes.

Impact strength reflects a material's ability to absorb energy under sudden loading or shock (Nurul Fazita et al. 2019). The slight impact strength changes with sand addition suggest that fine particles do not significantly change the toughness or energy absorp-

tion capacity of the pervious concrete matrix. Quarry waste's angular and rough particle texture may improve particle interlock and energy dissipation under impact at low sand contents, explaining the slightly higher Q4 value. As sand content in-creases, matrix

brittleness or the reduction of large, interconnected pores that dissipate impact energy may reduce impact strength. The smoother particle surface of river sand specimens may result in less mechanical interlock than quarry waste, resulting in only slight impact resistance improvements (Ji et al. 2013). Given the aggregate-to-cement ratio (4.0) and low water-to-cement ratio (0.3), the cement paste is expected to be relatively dense. However, the inherent porosity of pervious concrete plays a significant role in impact resistance. Fine sand addition partially fills voids, which can increase density but may also reduce the concrete's ability to deform plastically under impact, thereby balancing the overall impact strength.

The absence of notable enhancement in impact resistance, despite the rise in density, can be ascribed to the opposing effects of fine aggregate incorporation. The incorporation of fillers improves the load-bearing capacity of the matrix, yet concurrently elevates the brittleness of the concrete structure. In traditional pervious concrete, the elevated porosity facilitates energy dissipation via internal voids during abrupt loading events. The infusion of fine particles into these voids enhances the rigidity of the matrix, thereby constraining its plastic deformation and energy absorption capabilities. Thus, the structural advantages of heightened density are counterbalanced by a decrease in the material's intrinsic toughness, resulting in consistent impact values across all mix varieties.

3.6. Permeability

Increasing the sand content from 4% to 12% progressively enhanced the compressive strength in both types of sand. The higher fine content reduces the size and connectivity of large voids typical in pervious concrete, thus increasing strength. However, it is essential to maintain a balance, as excessive fines can reduce

permeability, a key performance criterion for pervious concrete. The permeability test results for pervious concrete specimens incorporating river sand and quarry waste are shown in Fig. 9. The control specimen exhibited the highest permeability at 6.12 cm/s. However, as river sand and quarry waste replaced the coarse aggregate at varying percentages, permeability decreased in both cases. For river sand replacement (R4, R8, and R12), the permeability values were 5.63 cm/s, 4.69 cm/s, and 3.79 cm/s, respectively. Similarly, for quarry waste replacement (Q4, Q8, and Q12), the permeability values were 5.76 cm/s, 4.77 cm/s, and 3.98 cm/s, respectively.

The observed reduction in permeability with increasing replacement percentages can be attributed to the finer particle size and smoother texture of river sand compared to coarse aggregate (Santhosh et al. 2021). River sand tends to fill the voids between larger particles, leading to a denser concrete structure with reduced porosity. This results in a significant reduction in the flow of water through the concrete (Zhou et al. 2024). Additionally, river sand has a larger surface area, which enhances the bond with the cement paste, contributing further to the reduction in permeability. In contrast, the use of quarry waste, although effective in reducing permeability, exhibited slightly higher permeability values at equivalent replacement levels when compared to river sand. Quarry waste consists of angular, irregularly shaped particles that, while increasing the surface area and enhancing packing density, do not fill the voids as effectively as river sand (Dinh et al. 2022). As a result, the water flow paths in concrete containing quarry waste tend to be more interconnected, allowing for higher permeability than in river sand replacements. However, as the percentage of quarry waste increased, permeability decreased, indicating that higher replacement levels still lead to improved water resistance, albeit at a slower rate than river sand.

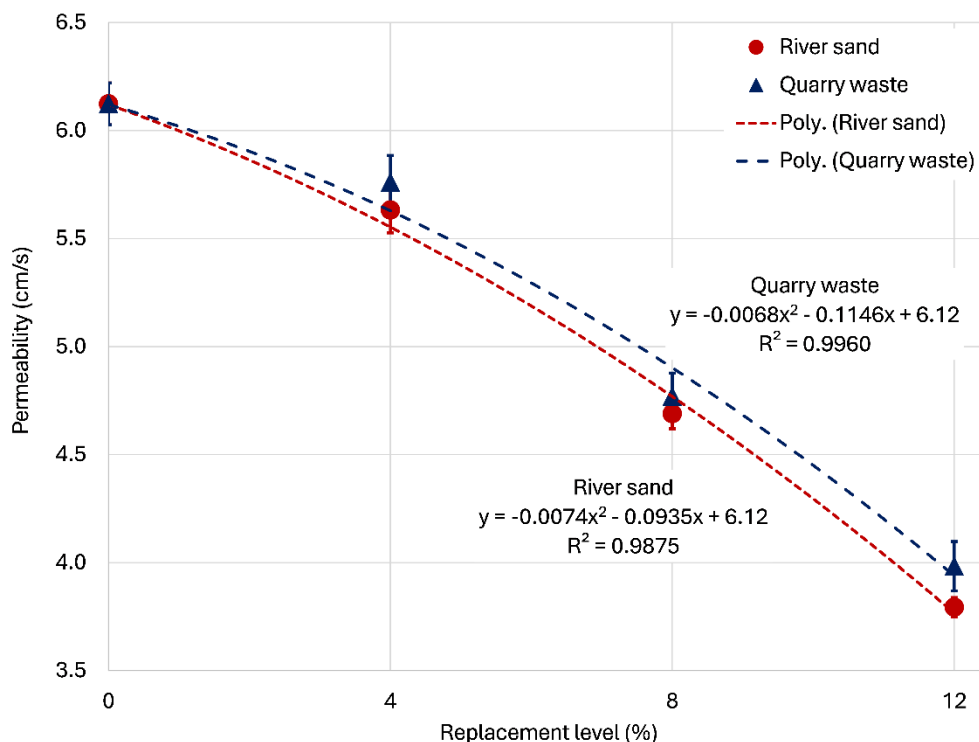


Fig. 9. Permeability variation for different pervious concrete mixes.

Pore tortuosity and connectivity explain why quarry waste mixes have lower porosity but higher permeability than river sand. Pervious concrete permeability depends on void volume and flow path efficiency. The angular and irregular geometry of quarry waste particles creates a highly interconnected 'skeleton'. These particles interlock to reduce porosity but prevent a tortuous path. River sand's rounded shape allows particles to sit closer in the pores' throat, increasing water channel tortuosity and decreasing connectivity. Even with fewer total voids, the quarry

waste matrix allows water to infiltrate more directly and easily.

3.7. Abrasion resistance

Fig. 10 illustrates the pervious concrete specimens after a specific number of revolutions. The abrasion resistance test results, presented in Fig. 11, indicate the durability of pervious concrete specimens when subjected to varying percentages of river sand and quarry waste, as shown by the weight loss percentage.

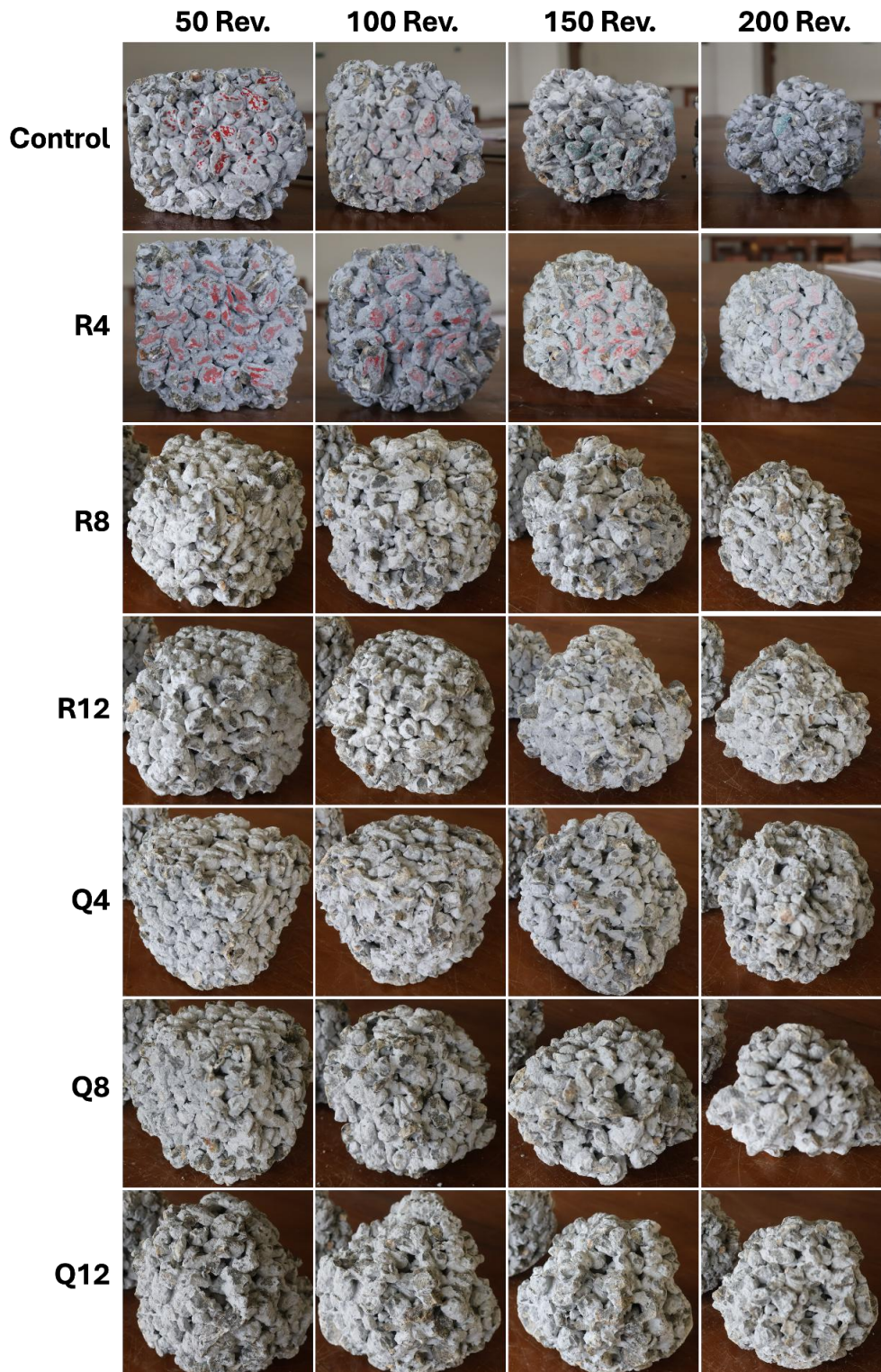


Fig. 10. Pervious concrete specimens after a specific number of revolutions.

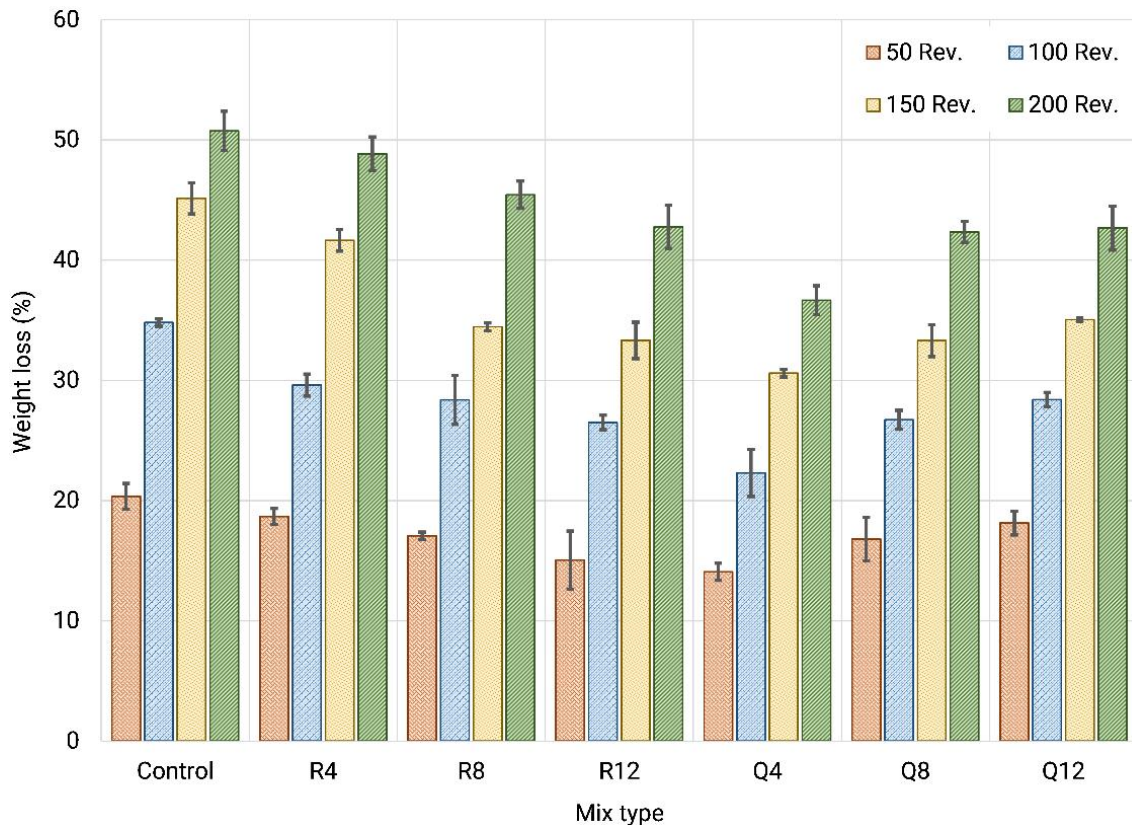


Fig. 11. Weight loss due to abrasion for different pervious concrete mixes.

The control specimen showed the highest weight loss percentage at each revolution stage. The weight loss increased from 20.4% at 50 revolutions to 50.7% at 200 revolutions. The addition of river sand and quarry waste to the mix resulted in a decrease in abrasion loss, demonstrating improved abrasion resistance with the incorporation of fine aggregates. For river sand specimens, the weight loss percentages decreased from 18.7% (for 4%) at 50 revolutions to 42.8% (for 12%) at 200 revolutions. Quarry waste specimens also showed lower abrasion losses compared to the control, with Q4 exhibiting the best performance at 14.1% at 50 revolutions and 36.7% at 200 revolutions. The reduction in abrasion loss with increasing river sand content can be attributed to the finer, well-rounded particles that help achieve a denser matrix. This enhances particle interlock and improves the cohesion of the cement paste with the aggregates, providing better resistance to wear and tear. At higher river sand contents, the reduction in weight loss is most notable, suggesting that higher fine aggregate content contributes to better packing and improves the overall abrasion resistance of the pervious concrete.

The effects of sand addition become more evident as the number of revolutions increases. At 50 revolutions, the weight loss for both river sand and quarry waste specimens is slightly lower than the control, but this reduction becomes more pronounced with higher revolutions. At 200 revolutions, river sand specimens (R12) show significant reductions in abrasion loss, which suggests that sand addition enhances the concrete's long-term durability and resistance to mechan-

ical wear. Quarry waste specimens also show a reduction in abrasion loss, but the improvement is not as significant as that in the river sand specimens. Quarry waste particles tend to be angular and rough, which enhances the bond between the aggregates and the cement paste (Nedeljković et al. 2021); however, this may also increase internal friction and surface wear. Despite this, even a 4% replacement with quarry waste significantly improves abrasion resistance compared to the control specimen. Quarry waste specimens, while performing better than the control at all stages, do not show as significant a reduction in abrasion loss as the river sand specimens, especially at higher sand contents. This can be attributed to the angular nature of the quarry waste particles, which, while providing strong bonding, may not contribute as effectively to reducing internal voids or achieving optimal cohesion at higher percentages.

3.8. Statistical analysis

The correlation analysis of various properties of pervious concrete is shown in Fig. 12. The results reveal significant trends in how changes in one property influence the others, which can guide the optimization of pervious concrete mixes for various applications. The density of pervious concrete plays a crucial role in determining several of its properties. A strong negative correlation between density and permeability (-0.97) indicates that denser concrete tends to have lower permeability, likely due to reduced pore space and better particle packing. Additionally, density is positively correlated with both compressive strength ($r = 0.90$)

and flexural strength ($r = 0.84$), suggesting that denser concrete mixtures exhibit superior load-bearing and bending capabilities. However, the negative correlation between density and impact strength (-0.50) indicates that denser concrete might be less able to absorb impact energy, likely due to its brittleness.

Porosity, which measures the void spaces within the concrete, is another critical factor affecting permeability and strength. The positive correlation between porosity and permeability ($r = 0.65$) suggests that as porosity increases, the material's ability to allow water to flow through it also increases. In contrast, porosity is strongly negatively correlated with compressive strength (-0.93) and flexural strength (-0.77), which is consistent with the idea that more voids in the concrete lead to a weaker structure. The relationship between porosity and impact strength is weak (-0.20), suggesting that porosity has little effect on the material's ability to resist impacts. However, porosity and weight loss due to abrasion resistance show a positive

correlation (0.79), indicating that higher porosity could reduce resistance to surface wear, potentially due to a rougher texture that resists abrasion.

The permeability of pervious concrete is another critical property, with a strong negative correlation with compressive strength (-0.85) and flexural strength (-0.84). This suggests that higher permeability, which typically indicates lower density and more voids, results in reduced mechanical strength. Interestingly, permeability is positively correlated with impact strength (0.55), possibly because concrete with higher permeability can better absorb and dissipate impact energy. The correlation analysis reveals the intricate relationships between the physical and mechanical properties of pervious concrete. The findings highlight the importance of carefully balancing density, porosity, and permeability to optimize the performance of pervious concrete, particularly in applications that require both high water permeability and structural strength.

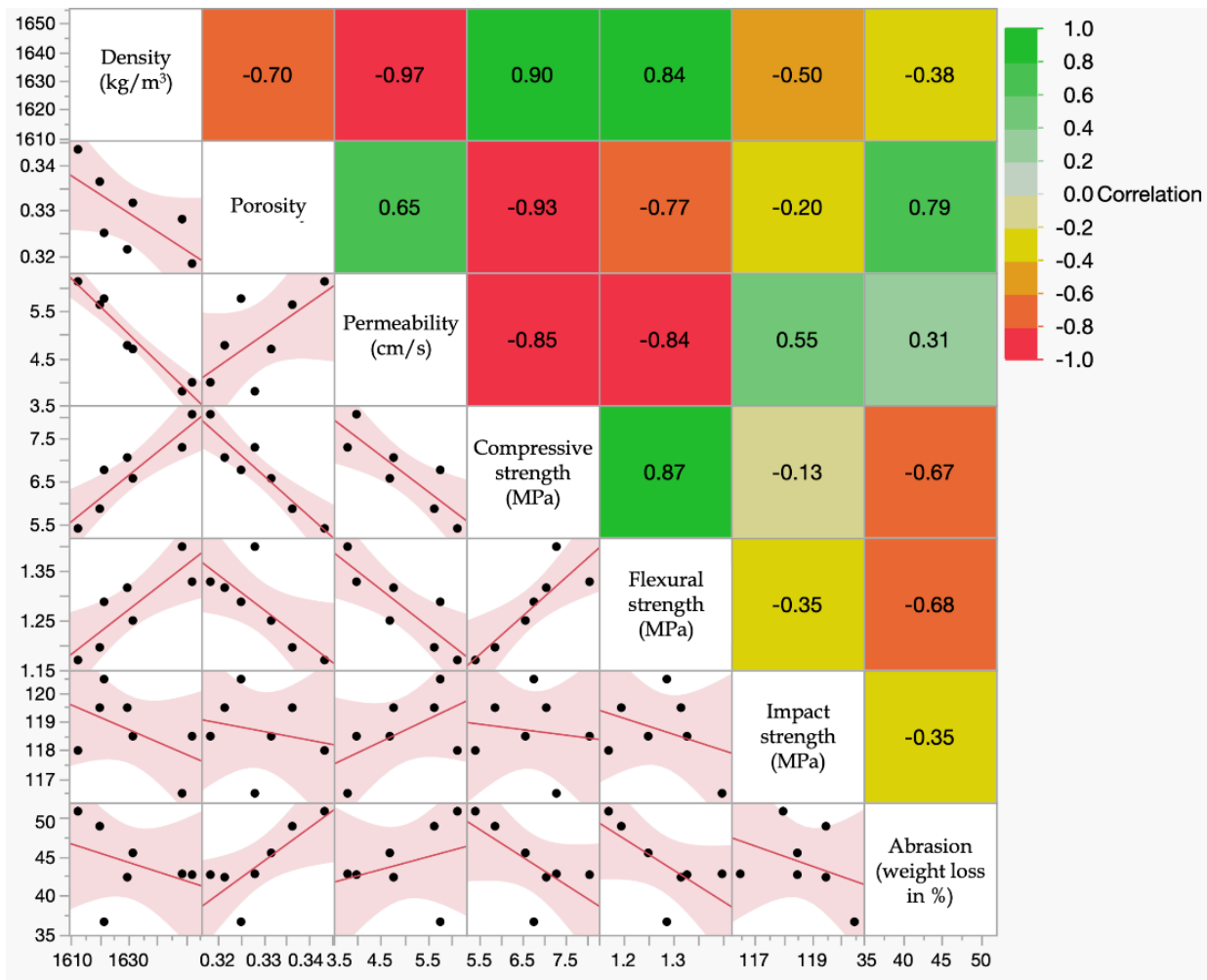


Fig. 12. The correlation analysis of various properties of pervious concrete.

The ANOVA results from Tables 3 and 4 of the study, which examine the effects of river sand and quarry waste on pervious concrete, provide critical insights into the relationship between aggregate type and replacement levels, as well as various concrete properties. Table 3 analyzes the statistical significance of re-

placement levels of different aggregates, with p-values indicating the strength of their effects on properties. For river sand, significant effects are observed on compressive strength and flexural strength at higher replacement levels, with p-values as low as $4.5E-04$ and $3.8E-07$, suggesting that increased river sand content

leads to enhanced strength properties. However, properties such as density and porosity are less significantly affected, with p-values higher than the conventional threshold for statistical significance (0.05). Furthermore, impact resistance and abrasion show no significant variation with changes in the river sand replacement level, as evidenced by consistently high p-values. In contrast, quarry waste exhibits a more pro-

nounced impact on compressive and flexural strengths, with p-values as low as 3.5E-04, particularly at higher replacement levels. QS also significantly influences porosity at the lower replacement levels, with p-values as low as 0.001. However, similar to river sand, the effect of QS on impact resistance and abrasion is minimal, with p-values indicating no significant impact on these properties.

Table 3. Summary of statistical analysis of results for aggregate replacement level.

		Dispersion of values between 0 & 4%		Dispersion of values between 4 & 8%		Dispersion of values between 8 & 12%		Dispersion of values between 0, 4, 8 & 12%	
		p-value	Sign.	p-value	Sign.	p-value	Sign.	p-value	Sign.
River sand	Density	0.229	X	0.075	X	0.005	✓	8.7E-06	✓
	Porosity	0.108	X	0.266	X	0.414	X	0.008	✓
	Compressive strength	0.111	X	0.011	✓	4.5E-04	✓	3.8E-07	✓
	Flexural strength	0.430	X	0.310	X	0.030	✓	0.001	✓
	Impact strength	0.823	X	0.881	X	0.815	X	0.980	X
	Permeability	7.7E-06	✓	5.4E-09	✓	1.4E-10	✓	1.2E-21	✓
	Abrasion resistance	0.200	X	0.031	✓	0.096	X	0.001	✓
Quarry waste	Density	0.068	X	0.119	X	1.3E-04	✓	3.2E-07	✓
	Porosity	0.001	✓	0.317	X	0.407	X	1.2E-05	✓
	Compressive strength	3.5E-04	✓	0.228	X	0.002	✓	4.5E-08	✓
	Flexural strength	0.009	✓	0.269	X	0.699	X	0.001	✓
	Impact strength	0.753	X	0.881	X	0.900	X	0.988	X
	Permeability	2.1E-04	✓	4.1E-08	✓	2.4E-07	✓	1.4E-18	✓
	Abrasion resistance	2.7E-04	✓	0.003	✓	0.916	X	0.001	✓

Sign.: Statistical significance of the effect of the replacement level of different aggregates.

Table 4. Summary of statistical analysis of results for the aggregate type (river sand and quarry waste).

	Dispersion of values between 4%		Dispersion of values between 8%		Dispersion of values between 12%	
	p-value	Sign.	p-value	Sign.	p-value	Sign.
Density	0.537	X	0.695	X	0.365	X
Porosity	0.011	✓	0.022	✓	0.037	✓
Compressive strength	0.005	✓	0.038	✓	0.002	✓
Flexural strength	0.053	X	0.167	X	0.127	X
Impact strength	0.881	X	0.881	X	0.842	X
Permeability	0.083	X	0.158	X	0.004	✓
Abrasion resistance	3.3E-04	✓	0.020	✓	0.974	X

Sign.: Statistical significance of the effect of the type of aggregate for a particular replacement level.

Table 4 focuses on the statistical significance of the type of aggregate for specific replacement levels. The analysis reveals that, at all replacement levels, both river sand and quarry waste significantly affect compressive strength, with quarry waste showing a stronger and more consistent impact. Quarry waste also exhibits a marked effect on porosity, especially at the lower replacement levels, while the effect of river sand on this property is less consistent. The influence of both river sand and quarry waste on flexural

strength is significant at certain levels; however, neither aggregate exhibits a strong, consistent effect across all levels. Impact resistance remains largely unaffected by either type of aggregate, with p-values indicating no significant differences at any replacement level. Additionally, while both aggregates influence abrasion resistance at lower replacement levels (4% replacement), their impact diminishes at higher levels, suggesting that the effects on abrasion resistance may not be as robust at higher replacement levels.

The results show that both river sand and quarry waste have a significant impact on the properties of pervious concrete, particularly in terms of compressive strength and porosity. Quarry waste, in particular, shows a more consistent and substantial impact on strength and durability properties compared to river sand. These findings suggest that quarry waste could be a more effective alternative to traditional aggregates, particularly in enhancing the strength and durability of pervious concrete. Conversely, while river sand can improve compressive strength at higher replacement levels, its impact on other properties, such as porosity and impact resistance, is less pronounced. These insights are valuable for practitioners designing concrete mixtures, as the choice of aggregate and its replacement level can have significant implications for the performance of pervious concrete in various applications.

3.9. Practical applications

The findings of this study provide a framework for utilizing quarry waste in sustainable infrastructure development. Given that the pervious concrete mixes incorporating quarry waste demonstrated improved mechanical strength and superior abrasion resistance compared to traditional river sand mixes, several practical applications are identified:

- **Sustainable Urban Drainage Systems (SuDS):** The high permeability maintained at the 8% replacement level (4.77 cm/s) makes this material ideal for stormwater management in urban areas to reduce surface runoff and promote groundwater recharge.
- **Pedestrian and Light-Traffic Pavements:** Due to the enhanced flexural strength and significantly improved resistance to mechanical wear (abrasion), these mixes are well-suited for sidewalks, cycling paths, and residential driveways.
- **Low-Speed Parking Areas:** The nearly 31% increase in compressive strength at the optimal 8% quarry waste level suggests that the material can reliably support light vehicular loads without compromising its primary hydrological function.
- **Cost-Effective Eco-Construction:** In regions where natural river sand is scarce or environmentally protected, utilizing locally available quarry waste offers an economically viable and environmentally friendly alternative for large-scale permeable paving projects.

4. Conclusions

This study examined the potential of quarry waste as a replacement for river sand in pervious concrete, with a focus on mechanical strength, permeability, and durability. The key findings of the research are as follows:

- The inclusion of quarry waste significantly improved the compressive strength, flexural strength, and impact strength of pervious concrete, particularly at higher replacement levels. Quarry waste demonstrated superior performance compared to

river sand, particularly in compressive strength, where it showed a nearly 49% improvement over the control mix.

- The use of quarry waste led to a notable decrease in porosity and an increase in density, contributing to a more compact and durable concrete structure. Quarry waste, with its angular shape, enhances the interlocking of particles, resulting in higher packing efficiency compared to river sand.
- While both river sand and quarry waste caused a reduction in permeability, quarry waste demonstrated a slightly higher permeability than river sand at equivalent replacement levels. However, both materials maintained satisfactory hydrological performance, which is crucial for stormwater management.
- Quarry waste-based pervious concrete exhibited enhanced abrasion resistance, indicating better performance in high-traffic or mechanically demanding environments. The improvement in abrasion resistance was more prominent with quarry waste than with river sand, further highlighting its durability advantages.

Based on the comprehensive evaluation of mechanical and hydraulic properties, this study identifies an 8% replacement of coarse aggregate with quarry waste as the optimal mix design. This replacement level (Q8) achieves a significant enhancement in compressive strength (approximately 31% over the control) and improved abrasion resistance without excessively compromising the infiltration capacity of the concrete. Although the 12% replacement level yielded the highest strength, the 8% level maintains a superior permeability-to-strength ratio, ensuring the material remains highly effective for stormwater management applications while providing the necessary structural durability for pedestrian and light-traffic pavements.

While this study provides valuable insights, several areas remain unexplored that could further enhance the understanding of the role of quarry waste in pervious concrete. Future research should focus on:

- Further studies are needed to assess the long-term performance of pervious concrete with quarry waste, particularly under varying environmental conditions such as freeze-thaw cycles, sulfate exposure, and chemical attacks.
- Research should focus on determining the optimal proportion of quarry waste and river sand replacement for different application scenarios to balance mechanical strength and permeability. Advanced modeling techniques could aid in predicting the performance of pervious concrete mixes based on aggregate properties and mix proportions.
- The environmental impact of quarry waste as a replacement for river sand should be further explored through lifecycle assessments (LCA), considering factors such as energy consumption, carbon emissions, and water usage in production processes.
- Investigating the performance of quarry waste-based pervious concrete in extreme weather conditions (e.g., high rainfall, temperature fluctuations) would provide crucial insights for its application in varying climates.

By focusing on these areas, future research can refine pervious concrete technologies, making them more efficient, sustainable, and adaptable to a wide range of construction needs.

Acknowledgements

None declared.

Funding

This research was supported by the National Research Council of Sri Lanka (Grant Number 24-031).

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- Al-Kharabsheh BN, Arbili MM, Majdi A, Ahmad J, Deifalla AF, Hakamy A, Alqawasmeh HM (2022). Feasibility study on concrete made with substitution of quarry dust: a review. *Sustainability*, 14(22), 15304.
- Altheeb A (2022). Quarry dust waste-based cementitious composites - a comprehensive review. *Construction and Building Materials*, 350, 128817.
- ASTM C78/C78M-21 (2021). *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. ASTM International, West Conshohocken, PA, USA.
- ASTM C642-21 (2021). *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*. ASTM International, West Conshohocken, PA, USA.
- ASTM C1747/C1747M-13 (2013). *Standard Test Method for Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion*. ASTM International, West Conshohocken, PA, USA.
- ASTM D2434-22 (2022). *Standard Test Methods for Measurement of Hydraulic Conductivity of Coarse-Grained Soils*. ASTM International, West Conshohocken, PA, USA.
- BS EN 12390-3 (2019). *Testing Hardened Concrete - Compressive Strength of Test Specimens*. British Standards Institution, London, UK.
- Coughlin JP, Campbell CD, Mays DC (2012). Infiltration and clogging by sand and clay in a pervious concrete pavement system. *Journal of Hydrologic Engineering*, 17(1), 68-73.
- de Azevedo ARG, Marvila MT, da Silva Barroso L, Zanelato EB, Alexandre J, de Castro Xavier G, Monteiro SN (2019). Effect of granite residue incorporation on the behavior of mortars. *Materials*, 12(9), 1449.
- Dinh HL, Liu J, Ong DEL, Doh JH (2022). A sustainable solution to excessive river sand mining by utilizing by-products in concrete manufacturing: a state-of-the-art review. *Cleaner Materials*, 6, 100140.
- Elango KS, Gopi R, Saravanakumar R, Rajeshkumar V, Vivek D, Raman SV (2021). Properties of pervious concrete - a state of the art review. *Materials Today: Proceedings*, 45, 2422-2425.
- Febin GK, Abhirami A, Vineetha AK, Manisha V, Ramkrishnan R, Sathyan D, Mini KM (2019). Strength and durability properties of quarry dust powder incorporated concrete blocks. *Construction and Building Materials*, 228, 116793.
- Gunasekaran V, Sathiparan N (2024). Combine the use of rice husk ash and quarry waste for sustainable masonry blocks: mechanical characteristics, durability and eco-benefits. *Journal of Building Engineering*, 98, 111194.
- Hamada HM, Shi J, Abed F, Al Jawahery MS, Majdi A, Yousif ST (2023). Recycling solid waste to produce eco-friendly ultra-high performance concrete: a review of durability, microstructure and environment characteristics. *Science of The Total Environment*, 876, 162804.
- He S, Jiao C, Li S (2023). Investigation of mechanical strength and permeability characteristics of pervious concrete mixed with coral aggregate and seawater. *Construction and Building Materials*, 363, 129508.
- Hong S, Ren H, Hou D, Dong B, Fan S (2023). Investigating mechanism for mortar-porous aggregate interfacial bond improvement based on coupled XCT-DVC analysis. *Journal of Building Engineering*, 80, 107952.
- Islam MMU (2023). A study on the integrated implementation of supplementary cementitious material and coarse aggregate for sustainable concrete. *Journal of Building Engineering*, 73, 106767.
- Ismail MK, Hassan AAA, Lachemi M (2019). Performance of self-consolidating engineered cementitious composite under drop-weight impact loading. *Journal of Materials in Civil Engineering*, 31(3), 04018400.
- Ji T, Chen CY, Zhuang YZ, Chen JF (2013). A mix proportion design method of manufactured sand concrete based on minimum paste theory. *Construction and Building Materials*, 44, 422-426.
- Khankhaje E, Jang H, Kim J, Rafieizonooz M (2025). Utilizing rice husk ash as cement replacement in pervious concrete: a review. *Developments in the Built Environment*, 22, 100675.
- Lori AR, Hassani A, Sedghi R (2019). Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate. *Construction and Building Materials*, 197, 130-142.
- Mahmud H, Ahmed T, Islam MS (2025). Combined effect of rice husk ash and animal bone powder on strength and permeability of concrete. *Challenge Journal of Structural Mechanics*, 11(1), 1-13.
- Meisuh BK, Kankam CK, Buabin TK (2018). Effect of quarry rock dust on the flexural strength of concrete. *Case Studies in Construction Materials*, 8, 16-22.
- Miah MJ, Huaping R, Paul SC, Babafemi AJ, Sharma R, Jang JG (2023). Performance of eco-friendly concrete made from recycled waste tire fine aggregate as a replacement for river sand. *Structures*, 58, 105463.
- Nedeljković M, Visser J, Šavija B, Valcke S, Schlangen E (2021). Use of fine recycled concrete aggregates in concrete: a critical review. *Journal of Building Engineering*, 38, 102196.
- Niroula B, Bhatt MR (2026). Mechanical properties assessment of recycled brick aggregate concrete using demolition waste from century-old masonry buildings in Nepal. *Challenge Journal of Concrete Research Letters*, 17(1), 41-56.
- Nune S, Dakshina Murthy NR (2021). Studies on infiltration rate of pervious concrete. In: Chandrasekaran S, Kumar S, Madhuri S, editors. *Recent Advances in Structural Engineering*. Springer Singapore, Singapore, pp. 21-28.
- Nurul Fazita MR, Abdul Khalil HPS, Nor Amira Izzati A, Rizal S (2019). Effects of strain rate on failure mechanisms and energy absorption in polymer composites. In: Jawaid M, Thariq M, Saba N, editors. *Failure Analysis in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*. Woodhead Publishing, Cambridge, UK, pp. 51-78.
- Pakkijachandran M, Sathiparan N (2025). Comparative study on quarry waste, manufactured sand, quarry dust as river sand replacement in cement mortar: mechanical characteristics, durability, and eco-benefit. *Materialia*, 40, 102395.

- Reddy BS, Sumetha R (2024). Evaluating the influence of fines on the characteristics of pervious concrete. *MATEC Web of Conferences*, 400, 01008.
- Rentier ES, Cammeraat LH (2022). The environmental impacts of river sand mining. *Science of The Total Environment*, 838, 155877.
- Santhosh KG, Subhani SM, Bahurudeen A (2021). Cleaner production of concrete by using industrial by-products as fine aggregate: a sustainable solution to excessive river sand mining. *Journal of Building Engineering*, 42, 102415.
- Sathiparan N, Jaasim JHM, Banujan B (2022). Sustainable production of cement masonry blocks with the combined use of fly ash and quarry waste. *Materialia*, 26, 101621.
- Sukkarak R, Jongpradist P, Voottipruex P, Jamsawang P, Keawsawasvong S, Pansuwannakun T, Meepon I (2025). Using stone dust as an improvement material for cement gravel column. *Case Studies in Construction Materials*, 22, e04300.
- Sundaralingam K, Peiris A, Anburuvel A, Sathiparan N (2022). Quarry dust as river sand replacement in cement masonry blocks: effect on mechanical and durability characteristics. *Materialia*, 21, 101324.
- Şamdan F, Çelikyürek İ, Canbaz M (2024). Determination of waste crushed baked clay aggregate concrete with granular composite material preparations. *Challenge Journal of Concrete Research Letters*, 15(4), 112-119.
- Tie TS, Mo KH, Putra A, Loo SC, Alengaram UJ, Ling TC (2020). Sound absorption performance of modified concrete: a review. *Journal of Building Engineering*, 30, 101219.
- Turan E, Alameri IA, Oltulu M (2025). Long-term durability of red mud-modified cement mortars: effects of high temperature and freeze-thaw cycles. *Challenge Journal of Structural Mechanics*, 11(3), 116-127.
- Ünal S, Canbaz M (2025). Utilization of expired cement and aged roof tile powder in the production of sustainable geopolymers: mechanical and physical properties. *Challenge Journal of Structural Mechanics*, 11(2), 82-88.
- Ünal S, Canbaz M (2026). Development of a sustainable geopolymer structural element with waste glass powder: mechanical characteristics. *Challenge Journal of Structural Mechanics*, 12(1), 22-29.
- Wee Chit WP, Budiea AMA, Mohd Noh H, Muthusamy K, Bamaga SO (2025). Compressive strength and fire resistance of mortar containing spent garnet as partial sand replacement. *Challenge Journal of Concrete Research Letters*, 16(4), 164-172.
- Zhou R, Luo Y, Ba M, Zhang Z, Fang J, Poon CS, Fang X (2024). Value-added recycling of waste concrete fines into alternative aggregates for river sand conservation. *Journal of CO₂ Utilization*, 83, 102802.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Mechanical and durability characteristics of SCC incorporating recycled aggregate and steel slag

Pottur Ramachandra ^{a,*} , Periyapatna Shanthaguptha Niranjana ^b 

^a Department of Civil Engineering, New Horizon College of Engineering, Bengaluru 560103, India

^b Department of Civil Engineering, Acharya Institute of Technology, Bengaluru 560107, India

ABSTRACT

This study presents a detailed investigation of the properties of self-compacting concrete (SCC) incorporating steel slag-based granulated slag aggregates (GSA) and recycled aggregates (RA) as substitutes for M-sand (MS) and natural coarse aggregates (NCA), respectively. NCA was replaced with coarse recycled aggregate (CRA) at levels of 20%, 25%, 30%, and 35% in SCC mixtures containing either MS or GSA as the fine aggregate. Cement was blended with ground granulated blast-furnace slag (GGBFS) and metakaolin (MK). The evaluated fresh properties were within the limits specified by EFNARC. The compressive strength of MS- and GSA-based SCC ranged from 24.2 to 35.9 MPa and from 27.4 to 38.9 MPa at 28 and 56 days, respectively. Increasing the curing period from 28 to 56 days enhanced the compressive strength by 3.4–13.2%. Acid immersion resulted in mass losses of 0.4–2.4% and reductions in compressive strength of 2.60–7.52%. The maximum water absorption (WA) of the SCC mixtures remained below 3%. Increasing the CRA content increased the permeability from 21.9 to 24.8 mm. No significant variations in WA, acid resistance, or permeability were observed in GSA-based SCC containing up to 30% CRA. Overall, the experimental results demonstrated that GSA-based SCC exhibited better performance than MS-based SCC.

ARTICLE INFO

Article history:

Received – February 2, 2026
Revision requested – March 14, 2026
Revision received – April 16, 2026
Accepted – April 24, 2026

Keywords:

Self-compacting concrete
Coarse recycled aggregates
Granulated slag aggregates
Compressive strength
Durability



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

Citation: Ramachandra P, Niranjana PS (2026). Mechanical and durability characteristics of SCC incorporating recycled aggregate and steel slag. *Challenge Journal of Concrete Research Letters*, 17(3), 240–249.

1. Introduction

Workability, strength and durability are the basic requirements of concrete. Due to the scarcity of natural aggregates, cementitious composites have been explored using various alternatives. RA, slag sand, ore tailing etc., have been investigated as substitute to conventional aggregate. More broadly, the valorization of industrial waste streams in construction materials can reduce landfill disposal and natural-resource consumption while supporting circular-economy objectives (Urbánek and Antoš 2026; Ünál and Canbaz 2026). The strength criteria of cementitious composites have been established using alternate aggregates as partial substitution to conventional aggregates.

However, the durability performance of alternative or RA-based composites requires detailed exploration. The durability of composites such as mortars and concrete is evaluated by carbonation, exposure to acidic and alkaline environments, efflorescence, deterioration due to surface wear, thermal resistance and alkali aggregate reactions.

Advancements in concrete technology have led to the development of self-compacting, non-segregating and highly workable composite known as self-compacting concrete (SCC). Ozawa et al. (1992) developed a vibration-free SCC. This workability SCC mitigates formation of honey comb and voids in the composite (Mehta and Monteiro 2014). SCC of grade M40 containing 20% RA (fine and coarse) resulted in an increase in compressive

* Corresponding author. E-mail address: p.ramachandra10@gmail.com (P. Ramachandra)

ISSN: 2548-0928 / DOI: <https://doi.org/10.20528/cjrl.2026.1113>

and split tensile strength by 5% and 1%, respectively (Vinay Kumar et al. 2017). As the recycled concrete aggregate content was increased in SCC, the strength decreased (Guo et al. 2020; Verian et al. 2018). However, blending cement with mineral admixture such as fly ash, silica fumes and slag from 50 to 75%, improves the strength properties (Guo et al. 2020). Such improvements are also sensitive to the type and dosage of mineral admixtures (Shaheen et al. 2025). Low impurity surface treated RA or those sourced from the precast concrete industry are suitable for producing workable and durable SCC (Verian et al. 2018; Santos et al. 2019).

Nomenclature

σ_c	Compressive strength
ADF	Acid durability factor
BPV	Binder paste volume
CA	Coarse aggregate
CRA	Coarse recycled aggregate
FA	Fine aggregate
GGBFS	Ground granulated blast furnace slag
GSA	Granulated slag aggregates
MK	Metakaolin
MS	M sand
NCA	Natural coarse aggregate
NFA	Natural fine aggregate
OPC	Ordinary portland cement
RA	Recycled aggregate
SCC	Self-compacting concrete
WA	Water absorption
ZI-LL	Zone I lower limit
ZI-UL	Zone I upper limit
ZII-LL	Zone II lower limit
ZII-UL	Zone II upper limit

Substituting sand with steel and foundry slag in concrete resulted in increased compressive strength and comparable flexural strength (Olonade et al. 2015; Sharma et al. 2017). Slag with properties similar to M-sand can be used as a substitute for fine aggregate (Thomas et al. 2019). The use of copper slag as a substitute for NFA resulted in a 10% increase in SCC performance (Gupta and Siddique 2020). The compressive strength increased by 21% when iron slag was used as fine aggregates in SCC, with a denser internal structure noted from SEM (Singh and Siddique 2016; Pham et al. 2024; Deepak et al. 2024; Khoman and Owaid 2026). Utilization of oxidizing and reducing slag obtained during manufacture of stainless steel can be used as a replacement to conventional aggregate and cement respectively. Using oxidizing slag as fine and coarse aggregate substitutes and cement blended with 30% reducing slag increased the viscosity of the mix while yielding comparable compressive strength (Sheen et al. 2016). SCC made with blended cement and slag sand resulted in a 14 – 29% reduction in compressive strength (Vageesh et al. 2026; Bala et al. 2025).

Fly ash, and silica fume blended cement based concrete with 40% RA of M40 grade exhibited improved resistance to water absorption and chloride penetration than that of equivalent concrete (Poongodi et al. 2021).

Blending 10% steel slag with Portland cement for SCC with RA exhibited superior durability in aspects of chloride penetration and carbonation resistance (Pan et al. 2019). Replacing 25% of the coarse recycled concrete aggregate had no impact on durability properties of SCC. The increased substitution of fine RA significantly decreased the resistance to chloride permeability (Sasanipour and Aslani 2020).

Effects of mineral admixtures, RA and GSA on the performance of SCC have been reported by the various researchers. However, research on their combination of mineral admixture and alternate aggregates and its influence on SCC remains limited. Thus, the current research focuses on investigating the combined influence of cement blended with two mineral admixtures, GSA as fine aggregate and CRA as a partial substitute to natural coarse aggregate, on the performance of SCC with an emphasis on the durability of SCC.

2. Research Significance

The performance of SCC is influenced by attributes such as aggregate type and its physical and engineering properties. The existing literature reveals the need for further research to holistically understand the suitability of alternate aggregate and its influence on properties of SCC. In this context, the current study investigates the combined influence of three parameters, blended cement, GSA as fine aggregate and CRA as a partial substitute for NCA. A detailed experimental investigation was carried out on the fresh, hardened and durability properties of SCC. Durability studies report the behavior of SCC exposed to acidic environment. Through experiential investigations, this study explores the suitability of CRA and GSA as an alternate source of aggregate in development of SCC.

3. Materials and Methodology

The constituent materials used in the current study were 53 grade ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBFS) and metakaolin (MK) as binders. M-Sand (MS) and Granulated Slag aggregates (GSA) were used as fine aggregate, and Coarse recycled aggregate (CRA) was used as a partial substitute for NCA. The alternate fine and coarse aggregates used in the study are presented in Fig. 1.

A polycarboxylate ether-based superplasticizer (SP) was used as a water-reducing agent. The properties of constituent materials were evaluated according to the Bureau of Indian Standards, and the results are presented in Table 1 and Table 2.

GSA and MS were categorized as Zone I and Zone II fine aggregates as per IS 383 (2016). The grain size distributions of MS and GSA are shown in Fig. 2. It can be noted from the figure that the grain size distribution of GSA presented improved gradation compared to MS, leading to improved packing of GSA. The particle size corresponding to 60%, 30% and 10% finer by weight, viz., D₆₀, D₃₀ and D₁₀ of GSA were greater than that of MS.



Fig. 1. Alternate aggregates: (a) GSA; (b) CRA.

Table 1. Physical and chemical properties of binders.

Properties		OPC	GGBFS	MK	Ref
Physical	Specific gravity	3.02	2.87	2.73	IS 2720-3-1 (1980)
	Bulk density (kg/m ³)	1447	–	–	IS 4031-11 (1988)
	Fineness (%)	4	7.2	3.4	IS 4031-1 (1996)
	Normal consistency (%)	34	–	–	IS 4031-4 (1988)
	Setting time (min)	Initial	–	–	IS 4031-5 (1988)
		Final	–	–	
Chemical	CaO (%)	64	36.23	0.4–1.0	
	SiO ₂ (%)	21	35.82	60–66	
	Al ₂ O ₃ (%)	6	16.98	30–33	
	Fe ₂ O ₃ (%)	4	0.71	1	
	TiO ₂ (%)	–	–	2	
	MgO (%)	3	8.02	0.2–0.8	
	K ₂ O, Na ₂ O (%)	0.5–1.3	–	0.5–1.2	

Table 2. Physical properties of aggregates.

Properties	Fine aggregate		Coarse aggregate		Ref
	MS	GSA	NCA	CRA	
Specific gravity	2.66	2.62	2.75	2.43	IS 2386-3 (1963)
Density (kg/m ³)	1611.0	1449.5	1478.5	1308	IS 2386-3 (1963)
Fineness (%)	2.93	3.41	–	–	IS 383 (2016)
WA (%)	1.12	0.44	1.0	2.75	IS 2386-3 (1963)
Abrasion value (%)	–	–	18.7	35.2	IS 2386-4 (1963)
Impact value (%)	–	–	12.1	33.2	IS 2386-4 (1963)
Crushing value (%)	–	–	16.6	30.2	IS 2386-4 (1963)

3.1. Mix proportions and specimen details

An M30 grade SCC mix was designed with a proportion of 1:2.19:1.75 (Binder: FA: CA) as per IS 10262 (2019). A detailed flow-chart of the criteria's considered in the mix design is presented in Fig. 3. As per EFNARC (2002), the total voids, that is, air content considered in the mix design of SCC was 2% of the total volume. The binder was composed of 64.5% cement, 34.5% GGBFS and 0.6% MK (Vinay Kumar et al. 2017). The water-to-binder ratio and SP dosage were maintained at 0.43 and 0.7% respectively. Two series of SCC mixes were devel-

oped using MS and GSA as fine aggregate. In both series, NCA was partially substituted by CRA from 20% to 35% at an incremental rate of 5%. The fine and coarse aggregate compositions in SCC mixes are presented in Table 3. The aggregate to cement ratio was maintained at 3.94 with a binder paste volume (BPV) of 0.35. A total of ten mixes were investigated and the SCC mix proportions are presented in Table 3. The fresh properties namely slump flow, V-funnel, L-box, U-box, and J-ring test, were evaluated as specified by EFNARC (2002). The hardened properties of SCC constituted of evaluating compressive strength and durability tests.

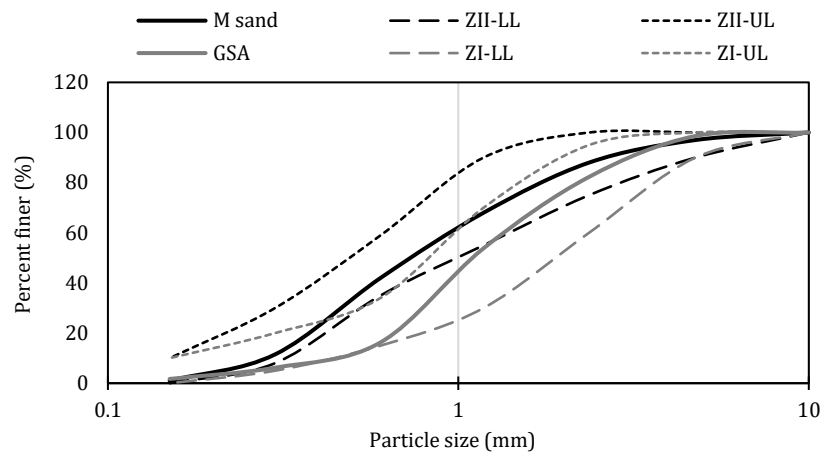


Fig. 2. Grain size distribution of MS and GSA.

Table 3. Mix designation, aggregate composition and mix proportions.

Series	Mix		Aggregate composition (%)				Mix proportions (kg/m ³)						
	No	Id	MS	GSA	NCA	CRA	OPC	GGBS	MK	MS	GSA	NCA	CRA
1	1	MS0	100	–	100	0	278.4	150.3	2.6	945.7	–	753.6	0
	2	MS20	100	–	80	20	275.4	148.7	2.5	935.5	–	596.4	149.1
	3	MS25	100	–	75	25	274.6	148.3	2.5	933.0	–	557.7	185.9
	4	MS30	100	–	70	30	273.9	147.9	2.5	930.5	–	519.1	222.4
	5	MS35	100	–	65	35	273.2	147.5	2.5	928.0	–	480.8	258.8
2	6	GSA0	–	100	100	0	278.6	150.5	2.6	–	946.5	754.2	0.0
	7	GSA20	–	100	80	20	275.6	148.8	2.5	–	936.3	596.9	149.2
	8	GSA 25	–	100	75	25	274.9	148.4	2.5	–	933.7	558.1	186.0
	9	GSA 30	–	100	70	30	274.1	148.1	2.5	–	931.3	519.5	222.6
	10	GSA 35	–	100	65	35	273.4	147.7	2.5	–	928.8	481.2	259.0

Note: Mix Id indicates the type of fine aggregate and CRA content as coarse aggregate.

Ex: Mix Id MS20 indicates SCC made with 100% MS, 20% CRA and 80% NCA.

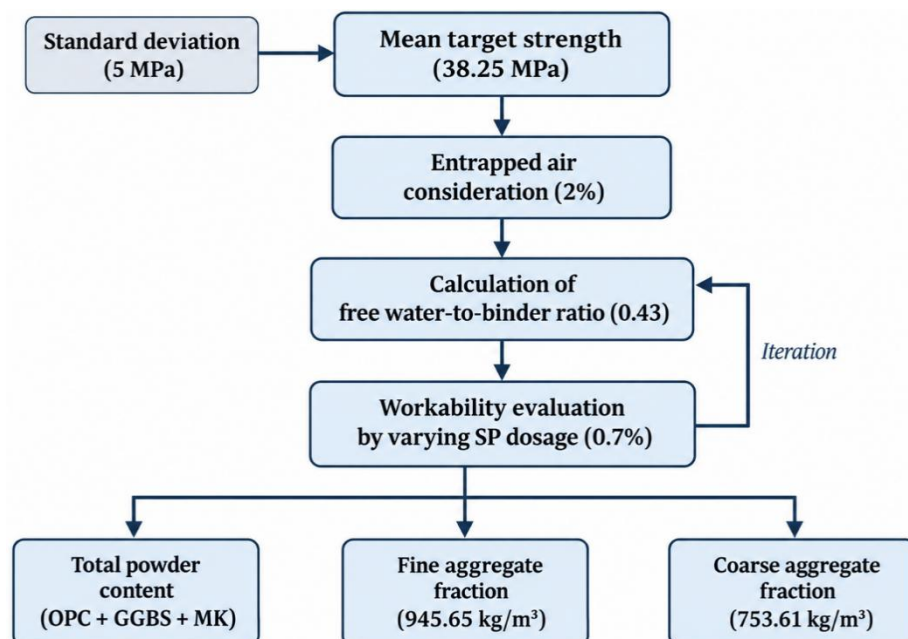


Fig. 3. Flowchart of mix design criteria.

The performance of SCC was investigated by testing cubes of size 150 mm x 150 mm x 150 mm in accordance with various standards (EFNARC 2002; IS 516: Part 1: Sec 1 2021; IS 15658 2021; ASTM C642-13 2013; IS 4456-1 1967). Cubes cast for all mixes were cured in accordance with IS 1199: Part 5 (2018). The cubes were cured for two intervals, 28 and 56 days to investigate the influence of curing duration on characteristics of SCC. Three samples were cast for each property and curing duration.

The acid attack resistance of SCC was evaluated by immersing cubes in 5% sulfuric acid. Three cubes of each mix were immersed in acid solutions for 56 days after 28 days of water curing. The pH of the acid solution was monitored using an electrode-based pH meter with an accuracy of ± 0.01 pH. The acid solution was stored in a shaded room with the temperature variation of 27 ± 1.5 °C. The samples immersed in acid were observed for the development of efflorescence. Degradation of concrete is influenced by acid concentration. The solution was renewed after 30 days to eliminate the neutralization of acid by leaching of alkaline compounds. To ensure consistent degradation, specimens were cleaned to remove deposited salts, loose and disintegrated particles and re-immersed in fresh solution. The water permeability was assessed as per IS 3085 (1965). Permeability was assessed by measuring the depth of water penetration in samples subjected to a hydrostatic pressure of 0.5 MPa for three days.

The degradation resistance of SCC was evaluated by Acid Durability Factor as presented in Eq. (1).

$$\text{Acid Durability Factor (ADF)} = \frac{S_r \times N}{M} \quad (1)$$

where S_r is the relative strength at N days (%), N is the number of days of exposure, and M is the number of days of total test duration.

4. Results and Discussion

4.1. Fresh properties of SCC

The fresh properties of SCC mixes containing CRA and GSA were within the prescribed limits according to EFNARC guidelines. The use of CRA improved the workability of SCC for both series, with MS-based SCC performing marginally better than SCC made with GSA. The limiting slump flow and V-funnel time ranges from 650 to 800 mm and 8 to 12 seconds, respectively for SCC.

M-sand based SCC exhibited marginally higher slump flow values than GSA based SCC with an increase in CRA content. In contrast, with an increase in CRA dosage, M-Sand based SCC attained modestly lower flow time varying from 6 seconds to 10 seconds as compared to GSA based SCC, which varied from 10 to 12 seconds, suggesting slower flow or higher viscosity impeding spread. Figs. 4(a-b) presents the workability based on the slump and V-funnel tests. The variation in workability of MS and GSA mixes containing CRA was less than 2% and 6% for slump and V-funnel test, respectively. The workability of SCC was also ascertained using the L-box and J-ring tests, as shown in Figs. 4(c-d). A stable L-box and J-ring test results were observed for both mixes when the CRA content varied 0 to 25% respectively. However, at higher dosage of CRA, WA characteristics of CRA, resulted in increased L-box and J-Ring test values.

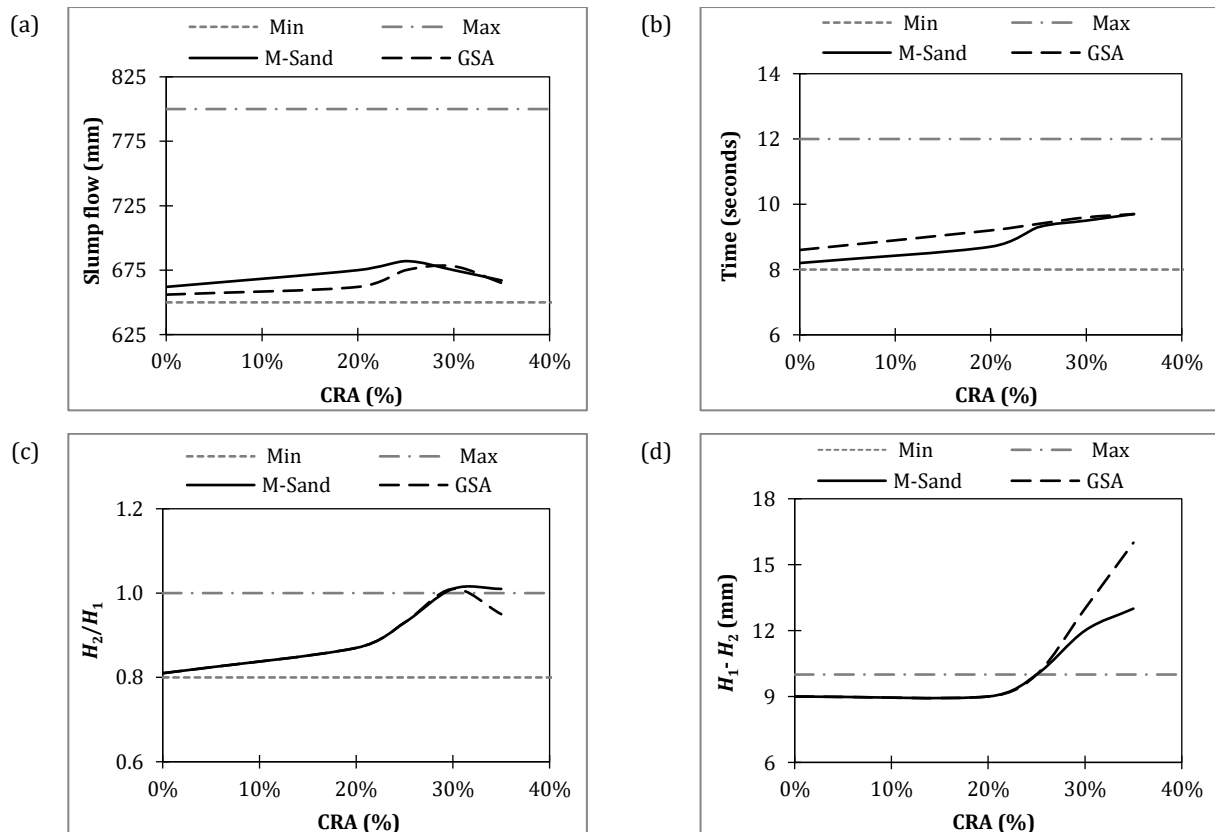


Fig. 4. Workability characteristics of SCC: (a) Slump; (b) V-Funnel; (c) L-box test; (d) J-Ring test.

4.2. Hardened properties of SCC

Cubes samples were tested for compressive strength and water absorption after 28 and 56 days of curing. A total of 120 samples were cast to evaluate various properties. The water permeability and influence of acid attack were evaluated after 28 and 56 days of curing, respectively. Table 4 presents the test results of SCC samples. The Influence of CRA content, curing duration and WA of aggregate on compressive strength and water absorption of SCC is presented in Fig. 5.

The hardened properties of series-2 SCC with NCA substituted by CRA up to 20% were better than those made with MS. Series-2 SCC exhibited 1.90–7.22% higher compressive strength than series-1 SCC. A similar observation was noted by Gupta and Siddique (2020).

Further increment in CRA dosage resulted in 4.5–13.1% reduced compressive strength for GSA based SCC. According to Sasanipour and Aslani (2020), when 25% of NCA was substituted by CRA, compressive strength of SCC decreased by 32%. The loss of compressive strength was less than 10% for series-1 and series-2 SCC with CRA dosages of 25% and 20% for samples tested at 28 and 56 days respectively.

An increase in curing duration resulted in latent strength gain of 7.3% and 3.27% lowered strength loss as compared to 28 days cured samples. Use of GSA resulted in 4.0 to 13.2% improved strength for extended curing duration. This late age strength gain is attributed to presence mineral admixture in binder composition and lower water absorption of GSA. The variation in loss of compressive strength is shown in Figs. 5(a-b).

Table 4. Mechanical and durability properties of SCC.

Series	Mix		σ_c (MPa)				WA (%)		Water permeability (mm)	Mass loss (%)	Acid treatment for 56 days			
	No	Id	28 (day)	CoV (%)	56 (day)	CoV (%)	28 (day)	56 (day)			σ_c (MPa)	CoV (%)	σ_c loss (%)	ADF (%)
1	1	MS0	35.2	1.4	36.3	1.2	1.1	0.5	22.1	1.0	35.1	2.4	3.1	96.9
	2	MS20	34.1	1.5	35.2	1.2	1.6	0.9	22.8	1.3	33.8	2.5	4.0	96.0
	3	MS25	32.8	1.8	34.4	1.3	1.9	1.1	23.6	1.7	32.7	2.8	5.1	94.9
	4	MS30	30.6	2.1	31.7	1.5	2.1	1.5	24.2	1.9	29.7	3.2	6.1	93.9
	5	MS35	27.8	2.6	29.8	1.8	2.3	1.8	24.8	2.4	27.6	4.2	7.5	92.5
2	6	GSA0	35.9	1.4	38.9	1.1	0.2	0.2	21.9	0.4	37.9	1.2	2.6	97.4
	7	GSA20	35.1	1.5	36.5	1.2	0.5	0.4	22.4	0.5	35.2	1.5	3.4	96.6
	8	GSA25	29.1	1.6	32.7	1.2	0.8	0.7	23.2	0.5	31.1	1.6	4.7	95.3
	9	GSA30	27.4	1.8	30.2	1.4	0.9	0.8	23.7	0.5	28.5	1.8	5.6	94.4
	10	GSA35	24.2	2.0	27.4	1.5	1.0	0.9	24.5	0.6	25.5	2.0	6.9	93.1

Note: CoV - coefficient of variation.

Incorporation of CRA also increased the WA of the hardened sample. Maximum WA of the SCC made with MS and GSA was lower than the limiting value of 6% (IS 15658 (2021)). The WA of MS based SCC mixes were 2.3 to 4.8 times higher than that of GSA based SCC. This increased WA of SCC is due to the absorption characteristics of MS, NCA and CRA. WA characteristics of the aggregate fraction were found to vary from 1.07 to 1.34% and 0.69 to 0.96% when the fine aggregate was MS and GSA respectively. This increased WA of aggregate fraction prompted increase in WA of SCC. As the curing duration was doubled from 28 to 56 days, WA of SCC was reduced by 22 to 56% and 11 to 30% for series-1 and series-2 SCC mixes respectively. An increased CRA content (30 and 35%) and curing duration (28 to 56 days) indicated unit increase in WA of SCC. The influence of CRA content and curing duration on WA of SCC mixes is shown in Fig. 5(b). WA of aggregate fraction viz., fine and coarse aggregates was influenced by intrinsic absorption characteristics of aggregates and was found to affect compressive strength and WA of SCC. Increase in

WA of aggregate resulted a decrease in compressive strength and increase in WA of SCC as illustrated in Figs. 5(c-d).

Water penetration depth of NCA based SCC via., permeability test ranged from 21.9 mm (GSA0) to 22.1 mm (MS0). It is interesting to note that GSA based SCC exhibited increased resistance to water penetration compared to series-1 SCC. The coefficient of determination of the percentage of permeability was 0.99. Water penetration increased with increment in CRA content, as presented in Fig. 6(a). This is due to porous nature and water absorption capacity of CRA. Increase in permeability of SCC was noted for every 5% increment in CRA dosage. Maximum water permeability was 24.8 mm, observed for SCC mix MS35. Considering the depth of the sample viz., 150 mm, permeability varied from 14.73 to 16.53% and 14.60 to 16.33% for MS and GSA based SCC respectively as illustrated in Fig. 6(b) with coefficient of determination being of the order 0.98 to 0.99. The coefficients of variation of compressive strength, water absorption and permeability were less than 5%.

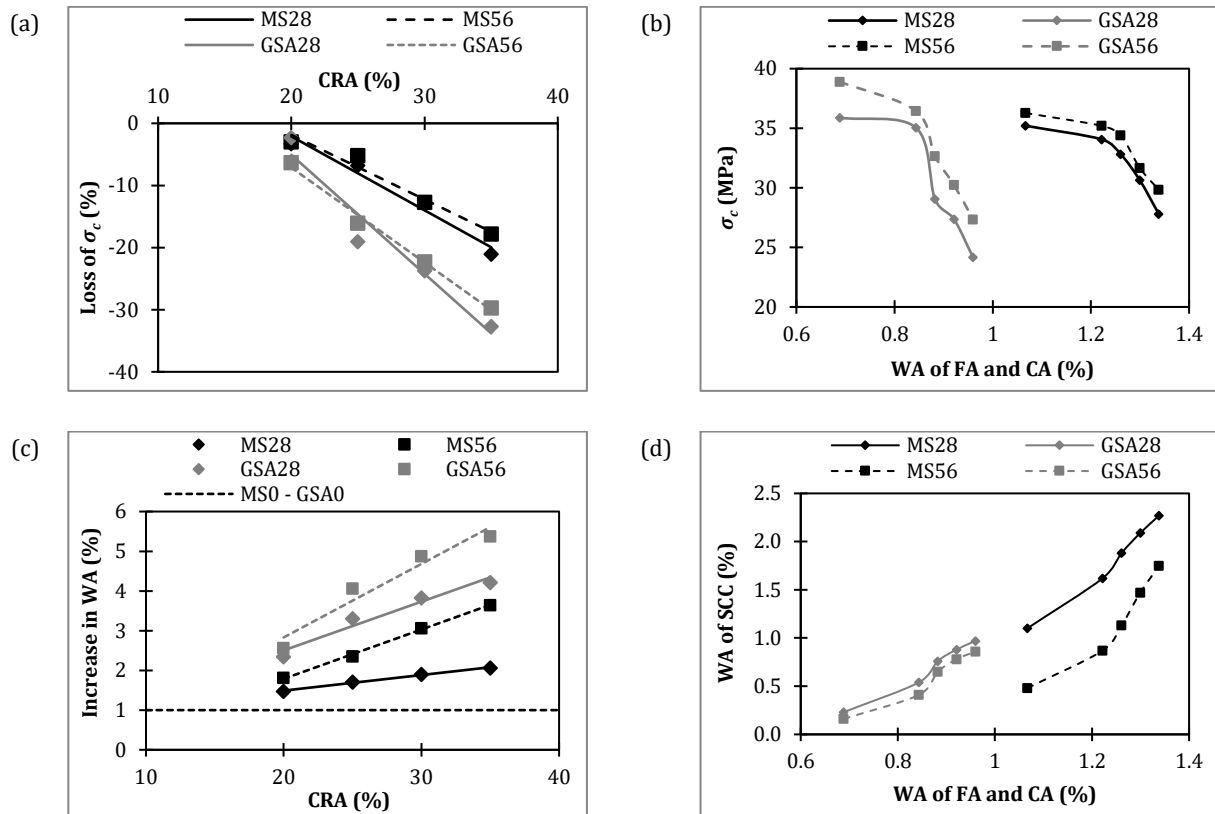


Fig. 5. Influence of CRA content, curing duration and WA of aggregate on: (a) CRA vs Loss of σ_c ; (b) CRA vs water absorption of SCC; (c) WA of aggregate versus σ_c ; (d) WA of aggregate versus WA of SCC.

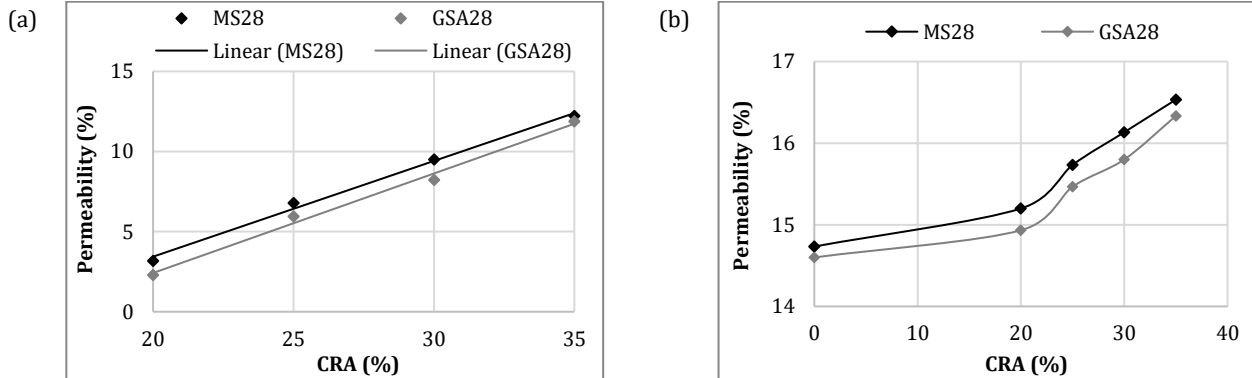


Fig. 6. Influence of CRA on permeability of SCC: (a) Compared with MS0 and GSA0; (b) Compared to depth of cube.

4.3. Effect of acid attack on concrete

SCC samples were immersed in a 5% acidic solution for 56 days. Exposure of SCC cubes to the acid solution did not affect the colour. However, disintegration and scaling were noted in cubes, as shown in Figs. 7(a-b). The cementitious paste around the surface of the specimen was completely disintegrated (pitting of concrete) exposing the central core as indicated in Fig. 7(c). The decomposition of alkaline compounds was predominantly observed in MS-based SCC mixes. The SCC containing GSA exhibited improved resistance to external sulfate attack compared to those made with MS. Samples made with GSA exhibited mild efflorescence at the edges of sample with minimal visual distortion as shown in Fig. 7(d).

The weight loss of GSA based SCC immersed in an acid solution for 56 days was found to vary from 0.41 to 0.56% when CRA was varied from 0 to 35%. However, for MS-based SCC, the loss of mass was 2.41 to 4.27 times higher than that of GSA based mixes at similar CRA contents.

The variation in compressive strength of SCC immersed in an acid solution was also explored. It can be noted from Table 4 that the compressive strength of SCC decreased when exposed to an acidic environment due to decomposition of calcium hydroxide (C) and calcium silicate hydrate (C-S-H). This loss of strength was measured as the difference of compressive strength of samples cured in water and samples immersed in acid, as presented in Eq. (2).

$$\text{Loss of } \sigma_c = \sigma_{c \text{ water cured}} - \sigma_{c \text{ immersed in acid}} \quad (2)$$

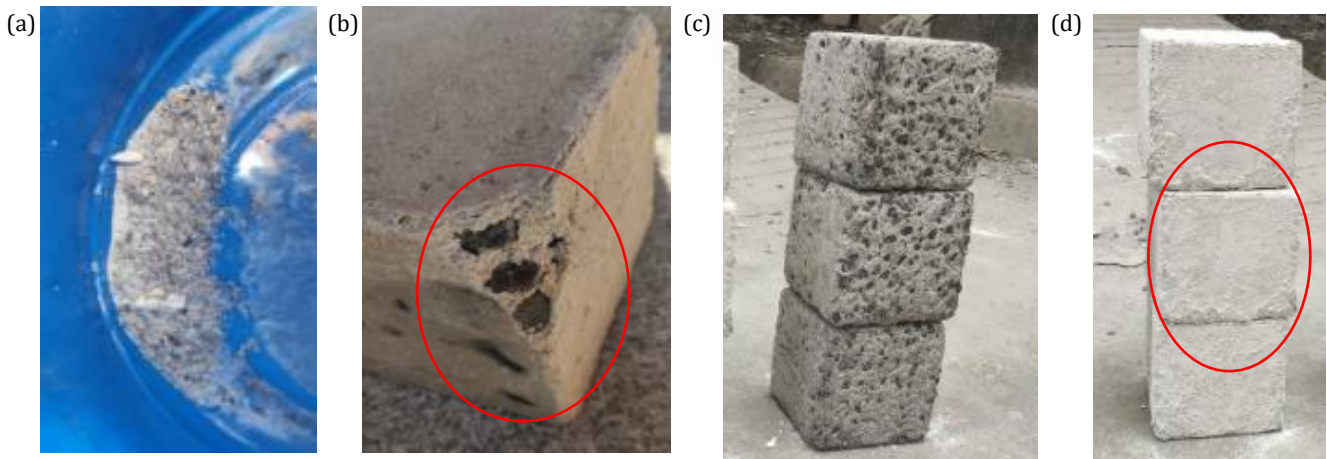


Fig. 7. Effect of acid exposure on SCC:

(a) Disintegrated concrete; (b) Scaling; (c) Pitting - MS56; (d) Efflorescence - GSA56.

It can be noted from Table 4, that series-2 SCC exhibited lower loss of strength than series-1 SCC. As the CRA content varied from 0% to 35%, the loss of strength of series-1 and series-2 SCC varied from 1.1 to 2.2 MPa and 1.0 to 1.9 MPa, respectively.

The effect of acid exposure on the performance properties of SCC is shown in Fig. 8. As compared to water-

cured samples, acid exposed SCC resulted in a progressive reduction in compressive strength from 2.60 to 7.52%. The experimental investigations indicated that series-2 SCC exhibited higher resistance to loss of strength than series-1 SCC as shown in Fig. 8(a). The acid durability factor (ADF) of series-2 SCC outperformed series-1 SCC as shown in Fig. 8(b).

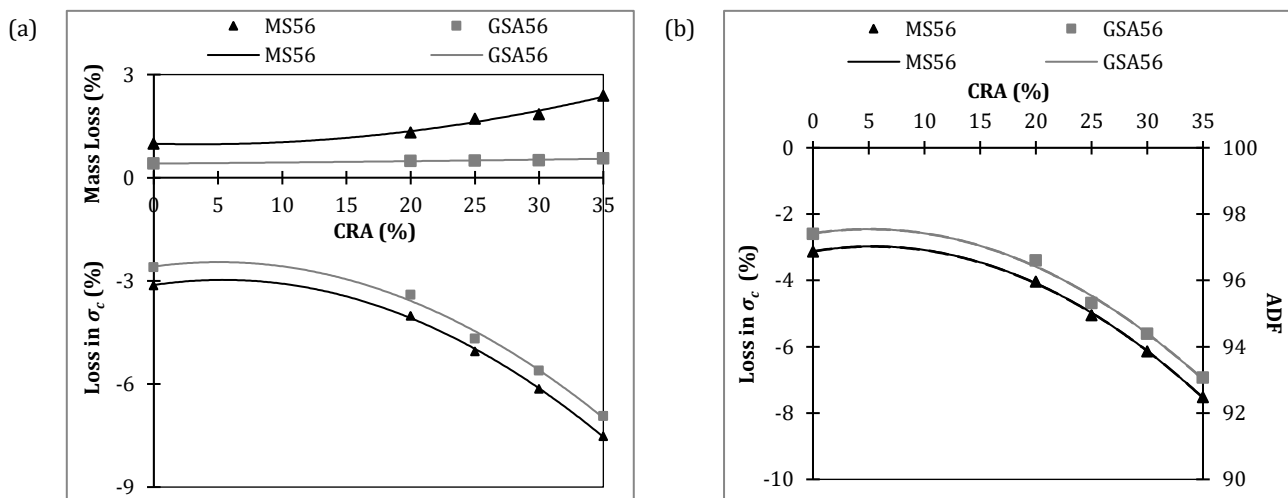


Fig. 8. Performance variation of SCC due to acid exposure:

(a) Effect of acid attack on strength and mass loss; (b) Influence of CRA on strength loss and ADF.

4.4. Microstructure of SCC

In comparison to various SCC mixes explored, utilization of GSA in SCC exhibited improved performance, with 28-day compressive strength of the order of 35 MPa. Topographic analysis of SCC was performed using SEM, for specimens cast with GSA containing 0 and 20% CRA, namely, GSA0 and GSA20 at two magnification levels of 3.00 μm and 10.00 μm as presented in Fig. 9.

The microstructure of samples indicated presence of ettringite (E), void spaces, a clear spread of calcium silicate hydrate (C-S-H) gel and calcium hydroxide (C) as presented in Fig. 9(a).

An increased ettringite formation and low-density sample was observed in SCC with the use of CRA as a partial substitute to NCA as shown in Fig. 9(b). The Interfacial Transition Zone (ITZ) of SCC with NCA indicated dense bonding with aggregate and lower porosity as presented in Fig. 9(c). Utilization of CRA in SCC exhibited increased porosity due to increased voids as shown in Fig. 9(d).

GSA20 SCC was more porous than that of GSA0 SCC which also contributed in an increase in water absorption. This was noticed with increase in permeability and water absorption from 21.9 mm to 22.4 mm and 0.23 to 0.54% respectively, when CRA utilization was varied from 0 to 20%.

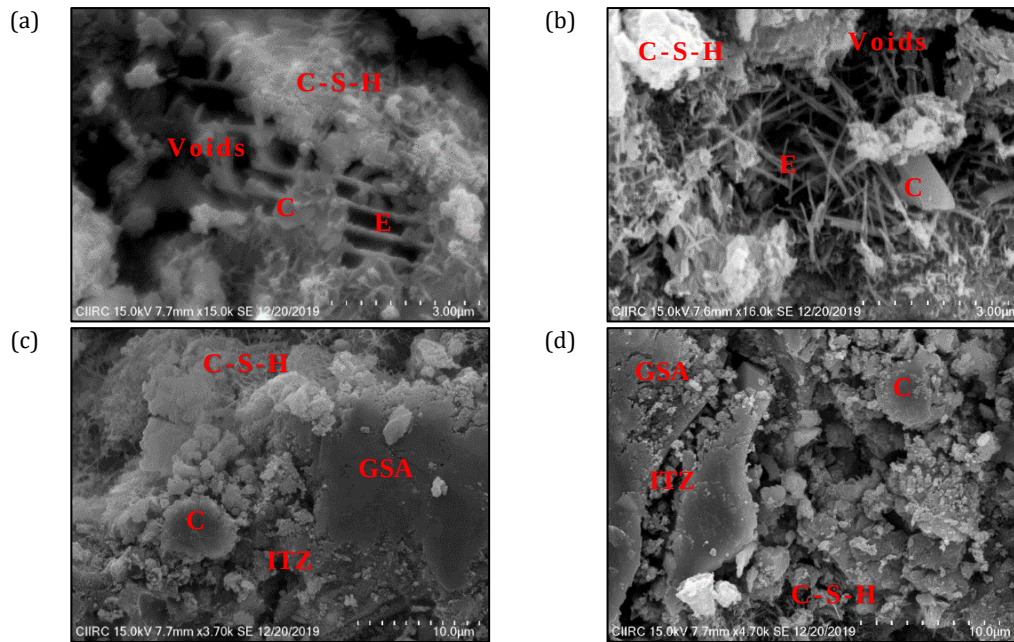


Fig. 9. SEM micrographs: (a) GSA0 at 3 μm ; (b) GSA20 at 3 μm ; (c) GSA0 at 10 μm ; (d) GSA20 at 10 μm .

5. Conclusions

The current study explores the suitability of GSA and CRA in development of SCC. Performance of SCC was investigated for compressive strength, water absorption, permeability and acid attack. A 5% sulfuric acid solution was used to evaluate the resistance of SCC subjected to aggressive environment. The variables governing properties of SCC namely, water to binder ratio and SP dosage were maintained constant at 0.43 and 0.7%, respectively. The Binder paste volume and aggregate to cement ratio was 0.35 and 3.94 respectively. Based on experimental investigations the following conclusions were drawn.

Workability of both SCC series were within the limits prescribed by EFNARC. The variation in workability of MS and GSA mixes containing CRA was found vary from 0% to 6%.

- Use of CRA resulted in reduced performance of SCC. Loss of compressive strength was less than 10% for series-1 and series-2 SCC incorporating CRA contents of 25% and 20%, respectively. Curing duration resulted in an increase in compressive strength by 3.4 to 7.3% and 8.4 to 13.2% for MS and GSA-based SCC, respectively.
- Water absorption of CRA-based SCC made with MS and GSA was less than the limiting value of 6%. Comparable permeability was observed in SCC mixes with 20% CRA. Maximum permeability of 24.8 and 24.5 mm was observed for mixes MS35 and GSA35, respectively.
- Acid attack resulted in decomposition of alkaline compounds with reduction in weight by series-1 and series-2 SCC by 2.39% and 0.56%, respectively. Compressive strength also reduced from 1.1 to 2.2 MPa and 1.0 to 1.9 MPa for MS and GSA based SCC, respectively. The GSA-based SCC exhibited improved performance compared to the MS-based SCC.

The current research indicates that GSA can be used as a substitute for MS in development of SCC, when the

properties of GSA and MS are comparable. The performance of SCC improved with the utilization of GSA as fine aggregate and 20% NCA replaced with CRA, promoting a sustainable approach for SCC production.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- ASTM C642-13 (2013). *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*. ASTM International, West Conshohocken, PA, USA.
- Bala UR, Bhavani R, Jawahar JG (2025). Development of sustainable self-compacting concrete using slag sand and expanded clay aggregates. *Civil Engineering Journal*, 11(10), 4262-4280.

- Deepak M, Reddy YR, Nagendra R (2024). Experimental investigation on strength, durability and micro structural characteristics of slag-based cement mortar. *International Journal of Engineering, Transactions A: Basics*, 37(4), 763-778.
- EFNARC (2002). *Specification and Guidelines for Self-Compacting Concrete*. EFNARC, Farnham, Surrey, UK.
- Guo Z, Jiang T, Zhang J, Kong X, Chen C, Lehman DE (2020). Mechanical and durability properties of sustainable self-compacting concrete with recycled concrete aggregate and fly ash, slag and silica fume. *Construction and Building Materials*, 231, 117115.
- Gupta N, Siddique R (2020). Durability characteristics of self-compacting concrete made with copper slag. *Construction and Building Materials*, 247, 118580.
- IS 383 (2016). *Coarse and Fine Aggregate for Concrete - Specification*. Bureau of Indian Standards, New Delhi, India.
- IS 10262 (2019). *Concrete Mix Proportioning - Guidelines*. Bureau of Indian Standards, New Delhi, India.
- IS 1199 (Part 5) (2018). *Fresh Concrete - Methods of Sampling, Testing and Analysis, Part 5: Making and Curing of Test Specimens*. Bureau of Indian Standards, New Delhi, India.
- IS 15658 (2021). *Concrete Paving Blocks - Specification*. Bureau of Indian Standards, New Delhi, India.
- IS 2386 (Part 3) (1963). *Methods of Test for Aggregates for Concrete, Part 3: Specific Gravity, Density, Voids, Absorption and Bulking*. Bureau of Indian Standards, New Delhi, India.
- IS 2386 (Part 4) (1963). *Methods of Test for Aggregates for Concrete, Part 4: Mechanical Properties*. Bureau of Indian Standards, New Delhi, India.
- IS 2720 (Part 3/Sec 1) (1980). *Methods of Test for Soils, Part 3: Determination of Specific Gravity, Section 1: Fine Grained Soils*. Bureau of Indian Standards, New Delhi, India.
- IS 3085 (1965). *Method of Test for Permeability of Cement Mortar and Concrete*. Bureau of Indian Standards, New Delhi, India.
- IS 4031 (Part 1) (1996). *Methods of Physical Tests for Hydraulic Cement, Part 1: Determination of Fineness by Dry Sieving*. Bureau of Indian Standards, New Delhi, India.
- IS 4031 (Part 4) (1988). *Methods of Physical Tests for Hydraulic Cement, Part 4: Determination of Consistency of Standard Cement Paste*. Bureau of Indian Standards, New Delhi, India.
- IS 4031 (Part 5) (1988). *Methods of Physical Tests for Hydraulic Cement, Part 5: Determination of Initial and Final Setting Times*. Bureau of Indian Standards, New Delhi, India.
- IS 4031 (Part 11) (1988). *Methods of Physical Tests for Hydraulic Cement, Part 11: Determination of Density*. Bureau of Indian Standards, New Delhi, India.
- IS 4456 (Part 1) (1967). *Methods of Test for Chemical Resistant Mortars, Part 1: Silicate Type and Resin Type*. Bureau of Indian Standards, New Delhi, India.
- IS 516 (Part 1/Sec 1) (2021). *Hardened Concrete - Methods of Test, Part 1: Testing of Strength of Hardened Concrete, Section 1: Compressive, Flexural and Split Tensile Strength*. Bureau of Indian Standards, New Delhi, India.
- Khoman RK, Owaid HM (2026). Sustainable high-performance self-compacting concrete with multi blended of materials powders: fresh and hardened properties. *International Journal of Engineering, Transactions B: Applications*, 39(5), 1101-1114.
- Mehta PK, Monteiro PJM (2014). *Concrete: Microstructure, Properties, and Materials*. 4th ed., McGraw-Hill Education, New York, NY, USA.
- Olonade KA, Kadiri MB, Aderemi PO (2015). Performance of steel slag as fine aggregate in structural concrete. *Nigerian Journal of Technology*, 34(3), 452-458.
- Ozawa K, Maekawa K, Okamura H (1992). Development of high performance concrete. *Journal of the Faculty of Engineering, The University of Tokyo (B)*, 41(3), 381-439.
- Pan Z, Zhou J, Jiang X, Xu Y, Jin R, Ma J, Zhuang Y, Diao Z, Zhang S, Si Q, Chen W (2019). Investigating the effects of steel slag powder on the properties of self-compacting concrete with recycled aggregates. *Construction and Building Materials*, 200, 570-577.
- Poongodi K, Murthi P, Awoyera PO, Gobinath R, Olalusi OB (2021). Durability properties of self-compacting concrete made with recycled aggregate. *Silicon*, 13(8), 2727-2735.
- Santos SA, da Silva PR, de Brito J (2019). Durability evaluation of self-compacting concrete with recycled aggregates from the precast industry. *Magazine of Concrete Research*, 71(24), 1265-1282.
- Sasanipour H, Aslani F (2020). Durability properties evaluation of self-compacting concrete prepared with waste fine and coarse recycled concrete aggregates. *Construction and Building Materials*, 236, 117540.
- Shaheen YBI, Etman ZA, Sabiha HL (2025). Design of reactive powder concrete mortar mixes through high strength and durability. *Challenge Journal of Concrete Research Letters*, 16(3), 142-154.
- Sharma D, Sharma S, Goyal A (2017). Comparative studies on mechanical properties of high strength concrete using foundry slag and alccofine. *Challenge Journal of Concrete Research Letters*, 7(1), 1-10.
- Sheen YN, Huang LJ, Sun TH, Le DH (2016). Engineering properties of self-compacting concrete containing stainless steel slags. *Procedia Engineering*, 142, 79-86.
- Singh G, Siddique R (2016). Effect of iron slag as partial replacement of fine aggregates on the durability characteristics of self-compacting concrete. *Construction and Building Materials*, 128, 88-95.
- Son PVH, Nam NV, Tran NP, Le-Hoai L, Ngo TD (2024). Steel slag aggregate low-cement concrete: engineering performance, microstructure and sustainability. *Construction and Building Materials*, 436, 136827.
- Thomas C, Rosales J, Polanco JA, Agrela F (2019). Steel slags. In: de Brito J, Agrela F, editors. *New Trends in Eco-efficient and Recycled Concrete*. Woodhead Publishing, Duxford, UK, pp. 169-190.
- Ünal S, Canbaz M (2026). Development of a sustainable geopolymer structural element with waste glass powder: mechanical characteristics. *Challenge Journal of Structural Mechanics*, 12(1), 22-29.
- Urbánek J, Antoš P (2026). Utilization of fly dust generated during fired shale production for the preparation of aggregates and geopolymers. *Challenge Journal of Concrete Research Letters*, 17(1), 71-81.
- Vageesh HP, Eramma H, Basutkar SM, Anand Kumar BG, Badami SS, Reena K (2026). Influence of jute fiber strengthening on load carrying capacity of SCC short columns. *Journal of Natural Fibers*, 23(1), 2625782.
- Verian KP, Ashraf W, Cao Y (2018). Properties of recycled concrete aggregate and their influence in new concrete production. *Resources, Conservation and Recycling*, 133, 30-49.
- Vinay Kumar BM, Ananthan H, Balaji KVA (2017). Experimental studies on utilization of coarse and finer fractions of recycled concrete aggregates in self compacting concrete mixes. *Journal of Building Engineering*, 9, 100-108.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Effectiveness of TiO₂ coating on concrete surfaces for photocatalytic degradation of solutions

Fatih Şamdan ^{a,*} , Canan Şamdan ^b , Emir Günaltı ^a , Serdal Ünal ^a , Mehmet Canbaz ^a

^a Department of Civil Engineering, Eskişehir Osmangazi University, 26040 Eskişehir, Türkiye

^b Department of Chemical Engineering, Eskişehir Osmangazi University, 26040 Eskişehir, Türkiye

ABSTRACT

In this study, the photocatalytic performance of TiO₂-coated concrete surfaces was systematically investigated with respect to coating configuration and catalyst loading using methylene blue (MB) and Rhodamine B (Rh-B) as model organic pollutants. TiO₂ was applied onto concrete surfaces at different concentrations (5, 10, 15, and 20 wt%) in both single-layer and double-layer configurations, and the degradation behavior of the dyes under UV irradiation was evaluated. The results revealed that increasing TiO₂ content significantly enhanced photocatalytic activity in both coating configurations. However, double-layer coatings consistently outperformed single-layer systems, particularly at higher TiO₂ loadings. The maximum degradation efficiencies reached 52.12% for MB and 77.4% for Rh-B under UV irradiation, demonstrating the effectiveness of TiO₂-coated surfaces in removing organic pollutants. Kinetic analysis indicated that the photocatalytic degradation process followed pseudo-first-order kinetics, with higher apparent rate constants (K_{app}) observed in double-layer systems. This enhancement was attributed to increased availability of active sites, improved light utilization, and more efficient charge-carrier dynamics. Mechanistically, the generation of reactive oxygen species (ROS), such as hydroxyl and superoxide radicals, along with improved charge separation facilitated by surface hydroxyl groups and oxygen vacancies, played a key role in enhancing photocatalytic performance. Overall, the findings demonstrate that optimizing both TiO₂ loading and coating architecture provides an effective strategy for improving the photocatalytic efficiency of cement-based materials. The proposed double-layer TiO₂ coating system offers significant potential for developing self-cleaning, environmentally responsive construction materials for urban applications.

ARTICLE INFO

Article history:

Received – March 3, 2026
Revision requested – March 30, 2026
Revision received – April 17, 2026
Accepted – April 24, 2026

Keywords:

Titanium dioxide
Photocatalytic degradation
Self-cleaning concrete
Coating configuration
Catalyst loading
UV irradiation



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

Citation: Şamdan F, Şamdan C, Günaltı E, Ünal S, Canbaz M (2026). Effectiveness of TiO₂ coating on concrete surfaces for photocatalytic degradation of solutions. *Challenge Journal of Concrete Research Letters*, 17(3), 250–261.

1. Introduction

Rapid urbanization and industrial growth have led to a significant increase in environmental pollution, especially in densely populated areas, where emissions from transportation, industrial processes, and construction activities accumulate on building surfaces. These pollutants, including nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter, not only

worsen environmental quality but also pose serious risks to human health and the durability and appearance of building materials (Wei et al. 2023b). The durability of cementitious materials is likewise sensitive to chemically aggressive environmental exposure (Al-Safi et al. 2025). Conventional pollutant removal strategies include mechanical surface cleaning (Pacheco-Torgal 2014), chemical washing with detergents or oxidizing agents (Chen and Poon 2009; Fujishima et al. 2008), and

* Corresponding author. E-mail address: fatihsamdan@eskisehir.edu.tr (F. Şamdan)

physicochemical processes such as adsorption (Rashed 2013) and filtration (Shannon et al. 2008). However, these approaches are often energy-intensive, require repeated application, and may generate secondary pollution, thereby underscoring the need for more sustainable and passive solutions. This broader sustainability objective is consistent with current construction-material research emphasizing resource efficiency, waste valorization, and reduced environmental impact (Mahmud et al. 2025; Turan et al. 2025; Ünal and Canbaz 2025b, 2026; Wee Chit et al. 2025). In this context, photocatalytic technologies have emerged as a promising approach for environmental cleanup, enabling the breakdown of organic and inorganic pollutants through light-triggered reactions without the need for additional chemicals (Arif et al. 2026). As part of advanced oxidation processes (AOPs), photocatalysis relies on the generation of highly reactive species that convert pollutants into less harmful or inert substances. This makes it particularly suitable for long-term, low-maintenance applications in the built environment (Zhang et al. 2024).

In recent years, photocatalytic materials have been increasingly integrated into functional surfaces to impart self-cleaning properties, particularly in environments where persistent pollutant accumulation poses significant environmental and aesthetic challenges. In this context, photocatalysis is recognized as an effective and sustainable strategy within advanced oxidation processes (AOPs), enabling the degradation of resistant organic contaminants that are often not efficiently removed by conventional treatment methods (Shamim et al. 2026). The self-cleaning concept refers to a material's ability to autonomously decompose and remove surface-bound pollutants under UV irradiation, thereby minimizing the need for external cleaning interventions. This approach is particularly relevant for cementitious materials exposed to urban pollution, where the accumulation of organic and inorganic contaminants can adversely affect both surface appearance and long-term performance. Therefore, incorporating photocatalytic materials such as TiO_2 into construction materials has emerged as a promising strategy for developing multifunctional systems capable of environmental remediation and passive surface maintenance (Paiu et al. 2025).

The self-cleaning behavior of TiO_2 -coated surfaces is generally attributed to two complementary mechanisms: photocatalytic degradation and photo-induced hydrophilicity. Under UV irradiation, TiO_2 generates reactive oxygen species that oxidize and decompose organic contaminants adsorbed on the surface (Singh et al. 2026). Simultaneously, UV exposure induces a transition toward a superhydrophilic surface state, reducing the water contact angle and enabling water to spread uniformly across the surface (Kumar et al. 2025). This process facilitates the removal of degradation products and residual contaminants through a washing effect, preventing their accumulation on the material surface. The synergistic action of these two mechanisms significantly enhances the long-term self-cleaning efficiency of TiO_2 -based systems (Shareef et al. 2026).

Titanium dioxide (TiO_2) is one of the most extensively studied photocatalysts due to its chemical stability, non-

toxicity, cost-effectiveness, and strong oxidative capability under ultraviolet (UV) irradiation (Zhang et al. 2024; Liang et al. 2025). When TiO_2 is exposed to photons with energy equal to or greater than its band gap, electrons are excited from the valence band to the conduction band, resulting in the formation of electron-hole (e^-/h^+) pairs that initiate a series of redox reactions on the catalyst surface (Wang et al. 2026). These photogenerated charge carriers subsequently interact with adsorbed oxygen and water molecules, leading to the formation of various reactive oxygen species (ROS), including hydroxyl radicals ($\bullet\text{OH}$), superoxide radicals ($\bullet\text{O}_2^-$), singlet oxygen ($^1\text{O}_2$), and hydrogen peroxide (H_2O_2). These species play a critical role in degrading organic pollutants. Among them, hydroxyl radicals are highly reactive and non-selective, whereas non-radical species, such as singlet oxygen, possess longer lifetimes and can promote more selective oxidation pathways under specific conditions (Wang et al. 2026; Qi et al. 2025). The generation, distribution, and reactivity of these ROS are strongly governed by the physicochemical properties of the photocatalyst, including its band structure, charge-carrier dynamics, and surface characteristics, which ultimately determine the overall photocatalytic efficiency (Liang et al. 2025; Majeed et al. 2025).

In recent years, the integration of TiO_2 into cementitious materials has attracted significant attention as an effective strategy for developing multifunctional construction materials with self-cleaning and air-purifying capabilities. These systems enable the degradation of atmospheric pollutants, such as nitrogen oxides (NO_x), and organic contaminants directly on building surfaces, thereby improving urban air quality (Bahşi et al. 2022; Yan et al. 2025). The photocatalytic performance of such materials is primarily governed by material-specific parameters, including TiO_2 dosage, particle size, dispersion, and the microstructural characteristics of the cement matrix, which control the exposure of active sites and the accessibility of pollutants (Mostafa et al. 2023). The dosage-dependent influence of nano- TiO_2 on porosity and mechanical response has also been demonstrated in cementitious composites (Srivastava et al. 2025). Furthermore, although increasing TiO_2 content generally enhances photocatalytic activity, an optimum threshold is often observed, beyond which performance may decline due to particle agglomeration, light scattering, and reduced UV penetration (Adebanjo et al. 2024). In addition to dosage, the spatial distribution of TiO_2 within the cementitious matrix and the porosity of the material play a critical role in facilitating mass transfer and enhancing pollutant-surface interactions (Zhang et al. 2024; Hamidi and Aslani 2019). These findings emphasize that optimizing both material composition and microstructural design is essential to achieving efficient, sustainable photocatalytic performance in cement-based systems.

In addition to TiO_2 dosage and material composition, the method of photocatalyst incorporation and the thickness of the applied layer are crucial factors in determining the overall photocatalytic performance of cementitious systems. Previous studies have shown that surface-based applications, in which the photocatalyst is concen-

trated near or on the exposed surface, provide significantly higher utilization efficiency than bulk incorporation methods, primarily due to improved light accessibility and direct contact with pollutants (Si et al. 2021; Seremak et al. 2023). Furthermore, the design of multi-layer systems has attracted increasing attention, as double-layer configurations with a TiO_2 -rich top layer have been reported to enhance photocatalytic activity by maximizing active surface exposure while maintaining the structural integrity of the substrate (Jin et al. 2023). In this context, coating thickness is also a critical parameter influencing photocatalytic efficiency. While increasing the thickness of TiO_2 -based films or coatings can enhance photocatalytic activity by providing more active sites, excessive thickness can reduce light penetration and hinder efficient charge transfer, thereby limiting overall performance (Gómez-Monsivais et al. 2026). These findings indicate that achieving an optimal balance between coating thickness, catalyst distribution, and layer configuration is essential for maximizing photocatalytic efficiency. Despite these advances, a systematic comparison of coating configurations (e.g., single-versus double-layer systems) and varying TiO_2 dosages under controlled, comparable conditions remains limited in the existing literature, particularly for cement-based photocatalytic surfaces. In light of the above considerations, this study aims to provide a systematic, application-oriented evaluation of TiO_2 -based photocatalytic coatings applied to cementitious surfaces by examining the combined effects of coating configuration and TiO_2 dosage under controlled experimental conditions. Unlike many previous studies that focus on either material composition or overall photocatalytic performance, this work adopts a comparative approach, investigating single- and double-layer coating systems with varying TiO_2 contents. Furthermore, a cavity-type experimental configuration was employed to confine the pollutant solution within a defined volume in direct contact with the coated surface, enabling a more controlled assessment of mass transfer, interfacial interactions, and diffusion limitations. This approach allows a more realistic representation of practical application conditions while maintaining experimental consistency. The photocatalytic performance of the developed systems was evaluated using methylene blue (MB) and Rhodamine B (Rh-B) degradation, and the results were analyzed through pseudo-first-order kinetic modeling to elucidate the influence of coating design and TiO_2 loading on degradation behavior.

2. Materials and Methods

2.1. Materials

In this study, a pozzolanic cement conforming to TS EN 197-1 standard, classified as CEM IV/B (P-Q) 32.5 N, was used for specimen production. The cement consisted of Portland clinker, trass, calcined pozzolan, and gypsum, and its chemical and physical properties are presented in Table 1. In this study, type F fly ash was used. The chemical properties of the fly ash produced at the Tunçbilek Thermal Power Plant are given in Table 2. Natural aggregates were used as fine and coarse fractions. The fine aggregate (0–4 mm) and coarse aggregate (4–22.4 mm) were obtained from the Sakarya River located in Bilecik, Türkiye. The physical properties and granulometric distribution of the aggregates are given in Table 3. A polycarboxylate ether-based high-range water-reducing admixture (BASF MasterGlenium 51) was used as a superplasticizer to improve workability. The properties of the superplasticizer are summarized in Table 4. Tap water was used for mixing, and its chemical composition is provided in Table 5. The concrete mix proportions and water-to-cement (w/c) ratio are presented in Table 6, with a w/c ratio of 0.35 used in all mixtures. Cubic specimens measuring $15 \times 15 \times 15$ cm were produced. To simulate a confined reaction environment, hollow cavities 5 cm in diameter and 10 cm high were created within the specimens during casting. All mixtures were prepared in accordance with the procedures specified in TS EN 196-1. The mortar mixtures were prepared using a laboratory pan mixer to ensure uniform and homogeneous mixing of all constituents, including cement, aggregates, water, and admixtures. After casting, the specimens were cured in water at 20 ± 2 °C for 28 days. Following curing, the specimens were dried under laboratory conditions. A total of 48 specimens were prepared for the experimental study. Each condition was evaluated in triplicate to ensure repeatability. The upper surfaces of the specimens were partially treated with MB and Rh-B solutions, while the internal cavities were filled with the same solutions to enable controlled photocatalytic testing. The specimen configuration was illustrated in Fig. 1(a). The TiO_2 used in this study was supplied by Detsan Chemical Company. The photocatalyst had a specific surface area of 85 ± 10 m²/g, an average particle size of 15–25 nm, and anatase phase purity $\geq 99\%$.

Table 1. Physical and chemical properties of cement.

Physical properties			Chemical content (%)			
Density (g/cm ³)	2.85		CaO	32.0–42.0	MgO	1.3–2.0
Blaine (m ² /g)	4800–5300		SiO ₂	33.0–37.0	Na ₂ O	0.8–1.2
Compressive Strength (MPa)	2.day 9.5–13.0	28.day 34.0–38.0	Al ₂ O ₃	8.0–11.0	SO ₃	2.7–3.2
Setting time (min)	Initial 180–220	Final 230–280	Fe ₂ O ₃	2.6–3.0	K ₂ O	0.8–1.10
			LOI	3.0–5.0	Cl	0.02–0.05

Table 2. Chemical properties of fly ash.

Chemical content (%)			
SiO ₂	58.59	CaO	4.43
Al ₂ O ₃	21.89	MgO	1.41
Fe ₂ O ₃	9.31	LOI	0.59
S+F+A	89.79	Pozzolanic	89.40

Table 3. Physical properties of aggregates.

Sieve size (mm)	22.4	16	11.2	8	4	2	1	0.5	0.25	0.125
Granulometry (%)	100.0	88.4	73.8	63.5	44.6	32.8	24.7	16.3	11.2	7.4
Unit weight (kg/dm ³)	0–4 mm			1.44						
	4–22.4 mm			1.56						

Table 4. Properties of NGSP.

Density (kg/dm ³)	Alkaline (%)	Chlorine (%)	Structure
1.082–1.142	< 3	< 0.1	poly carboxylic ether

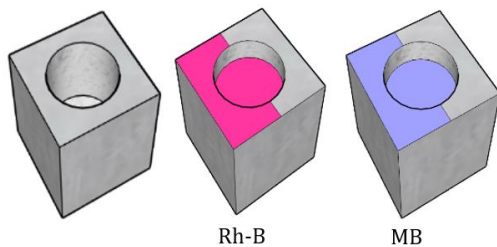
Table 5. Chemical analysis of tap water.

pH	7.28	SO ₄ [*]	70	Cl [*]	43
Hardness (Fr°)	32	NO ₃ [*]	7.5	NH ₄ [*]	<0.05
Turbidity (NTU)	0.10	Al [*]	<0.012	Mn [*]	<0.0007
Conductivity (µS/cm)	664	Fe [*]	<0.0075	*mg/L	

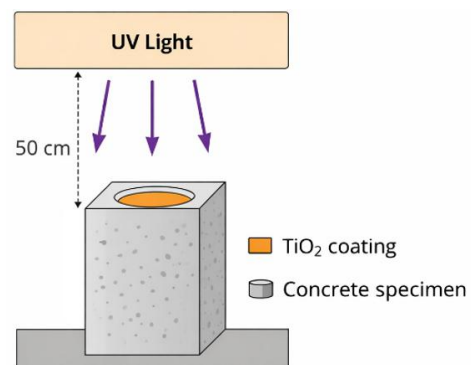
Table 6. Mix proportions.

Cement (kg/m ³)	water /cement	fine aggregate /cement	coarse aggregate /cement	NGSP / cement
300	0.35	2.96	3.68	0.01

(a)



(b)

**Fig. 1.** (a) Schematic representation of the concrete specimens and coating configurations; (b) Schematic illustration of the UV-assisted photocatalytic experimental setup.

2.2. Photocatalytic test

The photocatalytic efficiency of the TiO₂-coated concrete samples was assessed by measuring the breakdown of MB and Rh-B solutions upon exposure to ultra-

violet (UV) light. The experiments were structured to maintain controlled interaction between the pollutant solution and the photocatalytic surface. Before irradiation, solutions of MB and Rh-B were prepared at specific concentrations and placed into cavities created in the

concrete samples. In addition to the cavity setup, the upper surfaces of the specimens were exposed to MB and Rh-B solutions, while the internal cavities were filled with the corresponding dye solutions to ensure consistent contact between the pollutant and the photocatalytic surface and to enable the simultaneous evaluation of surface-based and confined reaction scenarios. A UV light source was utilized to trigger photocatalytic reactions. The lamp emitted light in the UVA (315–400 nm) and UVB (280–315 nm) spectra, with power outputs of 13.6 W and 3.0 W, respectively. The light source was set approximately 50 cm above the specimen surface to ensure uniform irradiation. The irradiance at the sample surface was approximately 0.5–0.8 W/m² at a distance of 50 cm, based on the lamp specifications and the inverse-square law governing irradiance as a function of distance. All tests were performed under laboratory conditions at room temperature, in an environment shielded from natural light to prevent external interference. A schematic representation of the experimental setup, including the UV light source and specimen positioning, is shown in Fig. 1(b). At predetermined time intervals (0, 12, 24, 36, and 48 hours), samples were collected from the cavity region to monitor the degradation process. The concentration changes of MB and Rh-B were monitored using a Thermo Scientific GENESYS 150 UV-Vis spectrophotometer. Absorbance (A) measurements were performed at the characteristic wavelengths of 664 nm for MB and 553 nm for Rh-B. Quartz cuvettes (10 mm path length) were used for all measurements. Distilled water was employed as the blank solution for baseline correction. Each measurement was conducted in triplicate to ensure repeatability and reliability of the results. Calibration curves were established for both dyes prior to analysis, and concentrations were determined from the corresponding absorbance–concentration relationships.

The effectiveness of photocatalytic degradation was determined by the reduction in concentration relative to the initial value. To quantitatively evaluate the reaction kinetics, the degradation data were examined using a pseudo-first-order kinetic model, which is widely used in heterogeneous photocatalytic systems. The kinetic rate constants were derived from the linear relationship between $\ln(C_0/C_t)$ and irradiation time, where C_0 denotes the initial concentration, and C_t denotes the concentration at a given time. A total of 48 independent specimens were prepared and tested, including four TiO₂ concentrations (5, 10, 15, and 20 wt%), two coating configurations (single-layer and double-layer), two dye systems (MB and Rh-B), and three replicates per condition to ensure experimental repeatability. Error analysis was conducted based on the standard deviation of triplicate measurements ($n = 3$). The low variability observed in the data indicates a high level of experimental precision and reliability.

2.3. Preparation of TiO₂ coatings

TiO₂ coatings were applied to the surfaces of the cured concrete samples using a manual spray deposition method. Before applying the coatings, the specimens' surfaces were cleaned and dried in a laboratory setting to remove dust and loosely bound particles, ensuring

proper adhesion between the coating and the substrate. TiO₂ suspensions were prepared by mixing the photocatalyst powder in distilled water at different weight percentages (5, 10, 15, and 20 wt%). The selected TiO₂ loading range (5–20 wt%) was determined based on literature values for photocatalytic coatings applied to cementitious materials. This range was chosen to ensure sufficient photocatalytic activity while avoiding excessive particle agglomeration, light shielding, and reduced UV penetration at higher loadings. Additionally, this range allows the identification of an optimal catalyst dosage and provides a practical balance between performance and material applicability (Hamidi and Aslani 2019; Adebajo et al. 2024).

The suspensions were mixed thoroughly using magnetic stirring before application. The coating process employed a handheld spray device with a small reservoir and a standard nozzle. The TiO₂ suspension was sprayed onto the specimen surfaces from approximately 20 cm away to achieve uniform coverage. The spraying was performed manually under controlled laboratory conditions, with consistent application time and the same preparation methods for all specimens. Two different coating setups were tested: single-layer and double-layer systems. In the single-layer setup, one spray application was applied to the concrete surface. In the double-layer setup, the first layer was applied and left to dry at ambient laboratory conditions (25 ± 2 °C) for about 2 hours before the second layer was applied. After completing the coating process, all specimens were kept under the same laboratory conditions (25 ± 2 °C) for 24 hours.

3. Result and Discussion

The photocatalytic performance of TiO₂-coated concrete surfaces was evaluated by measuring the degradation of MB and Rh-B under UV irradiation (Figs. 2 and 3). A continuous decrease in absorbance values at the characteristic wavelengths of MB and Rh-B was observed over time, indicating effective photocatalytic degradation of the dye molecules. This reduction in absorbance reflects the progressive breakdown of various structures within the dye molecules, confirming the catalytic activity of TiO₂ under UV irradiation.

The observed degradation behavior can be attributed to the generation of reactive oxygen species (ROS), such as hydroxyl radicals ($\bullet\text{OH}$) and superoxide radicals ($\bullet\text{O}_2^-$), which are produced upon UV-induced excitation of TiO₂ (Singh and Soundappan 2026). These highly reactive species attack the dye molecules adsorbed to the concrete surface, leading to bond cleavage and subsequent transformation into smaller, less harmful compounds (Chong et al. 2010). The consistent decrease in absorbance over time during irradiation demonstrates that the photocatalytic process is sustained and effective under the applied experimental conditions. Furthermore, the results confirm that the TiO₂-coated surfaces exhibit clear self-cleaning functionality, with degradation of organic pollutants occurring directly at the material surface without the need for external chemical agents. This behavior is consistent with previous studies on photocatalytic construction materials (Chen and Poon 2009).

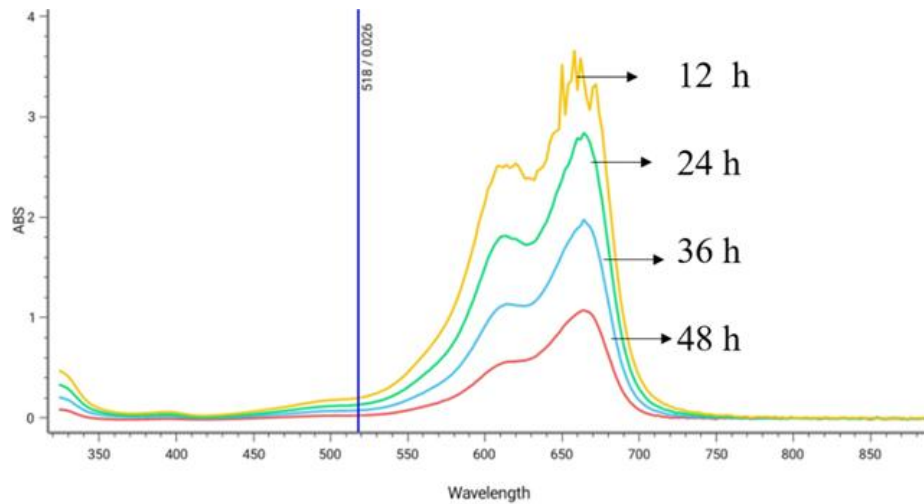


Fig. 2. The effect of exposure time on the photocatalytic activity of double layers of TiO₂-coated self-cleaning concrete (MB).

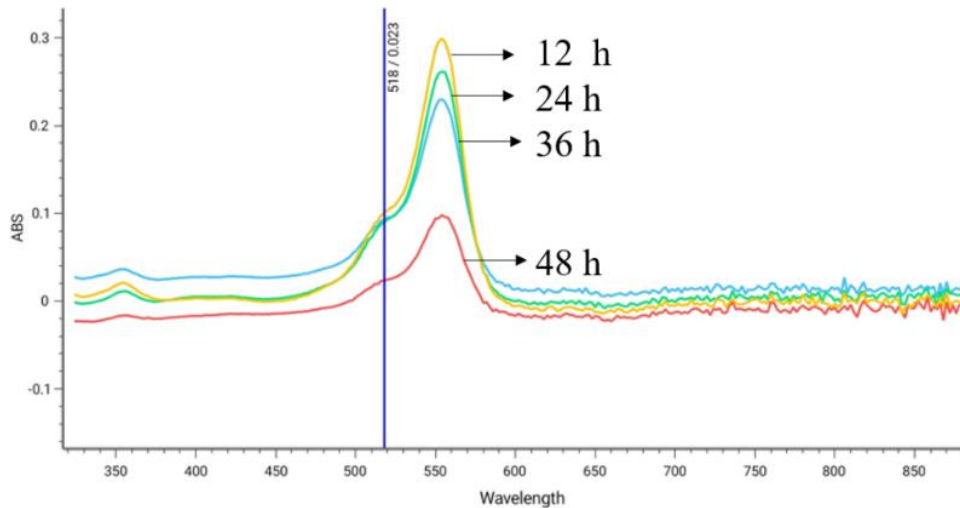


Fig. 3. The effect of exposure time on the photocatalytic activity of double layers of TiO₂-coated self-cleaning concrete (Rh-B).

The normalized concentration profiles (C_t/C_0) of MB and Rh-B in contact with single- and double-layer TiO₂-coated concrete surfaces are presented in Fig. 4. A clear decreasing trend in C_t/C_0 values was observed over time for all samples, indicating progressive photocatalytic degradation of both dyes. However, the extent of degradation strongly depended on both TiO₂ dosage and coating configuration.

For single-layer applications, increasing the TiO₂ content from 5% to 20 wt% resulted in a noticeable reduction in normalized concentrations for both MB and Rh-B, demonstrating that higher catalyst loading enhances photocatalytic activity by increasing the availability of active sites. In contrast, double-layer systems exhibited significantly lower final C_t/C_0 values than single-layer systems at the same TiO₂ dosage. This trend is consistent with previous studies, which show that increasing catalyst loading improves degradation efficiency up to an optimum level due to increased active sites and enhanced generation of reactive oxygen species (ROS) (Atalı et al. 2024; Bendjama and Hamdaoui 2025). This enhancement is attributed to higher surface exposure of TiO₂, im-

proved light absorption, and more efficient charge-carrier utilization, leading to increased ROS generation and faster degradation kinetics (Bendjama and Hamdaoui 2025; Ahouari et al. 2024). The difference between single- and double-layer configurations was more pronounced at higher TiO₂ loadings, suggesting that coating architecture plays a critical role in determining photocatalytic efficiency. In double-layer systems, the TiO₂-rich top layer likely provides improved exposure to UV irradiation and more effective interaction with pollutant molecules, leading to accelerated degradation kinetics. Moreover, photocatalytic degradation of organic dyes generally follows pseudo-first-order kinetics, with the apparent rate constant increasing as catalyst accessibility and surface activity improve (Sharma et al. 2023; Gao et al. 2024). Additionally, the improved distribution of TiO₂ at the surface enhances mass transfer and reduces diffusion limitations, further contributing to the observed performance improvement. Such enhancements facilitate the transport of pollutants to active sites and improve overall reaction efficiency in heterogeneous photocatalytic systems (Bendjama and Hamdaoui 2025).

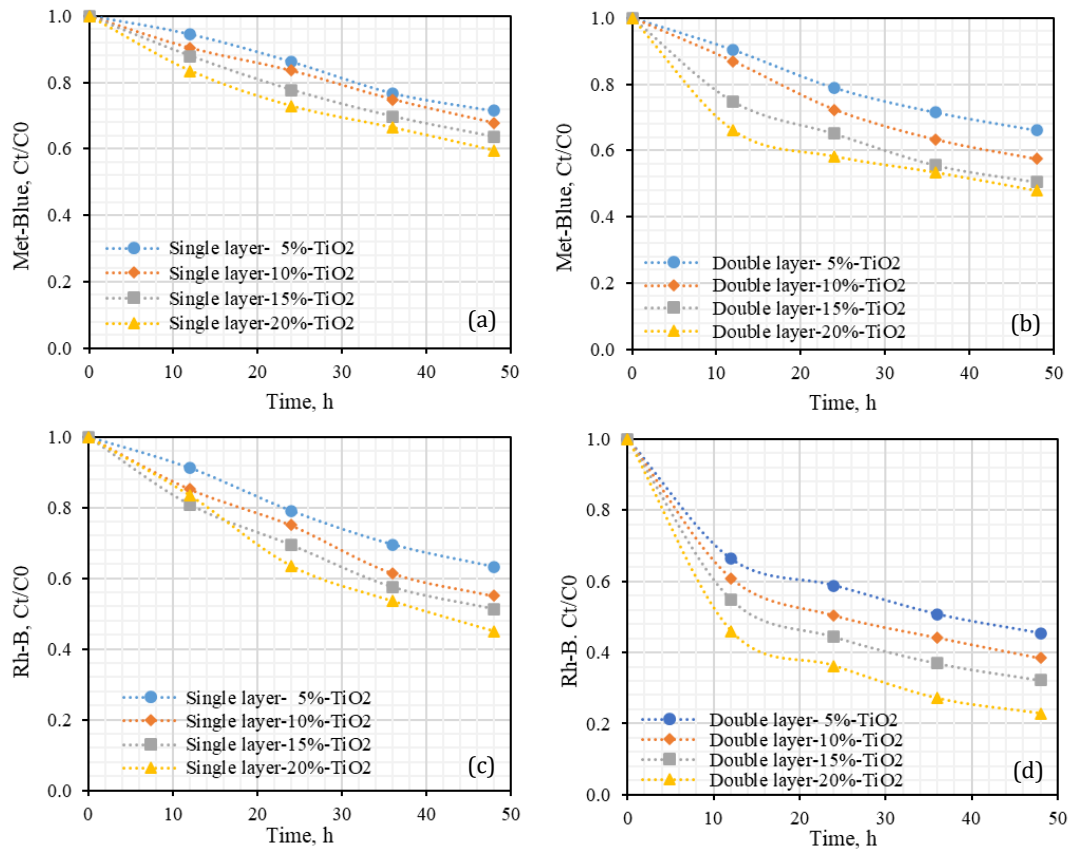


Fig. 4. Effect of single- and double-layer 5, 10, 15, and 20% TiO₂-coated self-cleaning concrete on the normalized concentration (C_t/C_0) concentration of:

(a) Single-layer TiO₂ in MB; (b) Double-layer TiO₂ in MB; (c) Single-layer TiO₂ in Rh-B; (d) Double-layer TiO₂ in Rh-B.

As shown in Fig. 4(a,b), for MB, the normalized concentration decreased from 1.00 to 0.71 for the 5% single-layer TiO₂-coated surface and further to 0.60 for the 20% single-layer coating, confirming the positive effect of increasing TiO₂ dosage. In the double-layer configuration, the normalized concentration decreased more significantly, from 1.00 to 0.60 at 5% TiO₂ and to 0.40 at 20% TiO₂, demonstrating enhanced photocatalytic performance due to increased surface-active sites and improved catalyst distribution.

A similar trend was observed for Rh-B, with the normalized concentration decreasing from 0.63 to 0.45 as the TiO₂ content increased in single-layer coatings (Fig. 4(c)). In double-layer systems (Fig. 4(d)), the normalized concentration decreased more sharply, reaching 0.45 at 5% TiO₂ and 0.23 at 20% TiO₂. These results clearly indicate that both increasing TiO₂ loading and adopting a double-layer coating strategy significantly enhance photocatalytic degradation efficiency. A similar increase in self-cleaning performance with increasing TiO₂ content has also been reported under artificial-light exposure (Ünal and Canbaz 2025a). Overall, the results demonstrate that both TiO₂ dosage and coating configuration are key parameters governing photocatalytic efficiency, with double-layer coatings at higher TiO₂ concentrations exhibiting the most effective degradation behavior for both MB and Rh-B solutions. This behavior indicates an optimal TiO₂ loading, beyond which further increases do not yield proportional improvements in photocatalytic performance. Furthermore, the differences observed between MB and Rh-B degradation behaviors can be at-

tributed to variations in molecular structure, adsorption characteristics, and interaction with reactive oxygen species.

Fig. 5(a-d) shows the degradation efficiency of MB and Rh-B solutions in contact with single-layer and double-layer TiO₂-coated surfaces at different concentrations under UV irradiation. The degradation efficiency is calculated by Eq. (1), where A_0 and A_t represent the initial and residual dye absorbance at time 0 and t , respectively.

$$\text{Degradation efficiency (\%)} = \frac{(A_0 - A_t)}{A_0} \times 100 \quad (1)$$

Figs. 5(c) and 5(d) were used to evaluate the photocatalytic degradation of concrete surfaces coated with single- and double-layer TiO₂ against Rh-B. As observed in the experimental results, the degradation efficiency of both dyes increased progressively with irradiation time, a typical behavior of photocatalytic systems driven by the continuous generation of reactive species under UV exposure (Saefumillah et al. 2025). The results showed that the double-layer TiO₂-coated surface had significantly higher degradation efficiency than the single-layer application. The 20% double-layered surface achieved 77.4% Rh-B degradation within 48 hours, while the single-layered surface achieved only 55% photocatalytic degradation efficiency. Similar results were obtained with MB. The double-layer coating and the high-TiO₂-surface showed the highest MB photocatalytic degradation after 48 hours. On the 20% single-layer-coated surface, MB degradation was 40.50%, whereas on the double-layer surface, the efficiency was 52.12%.

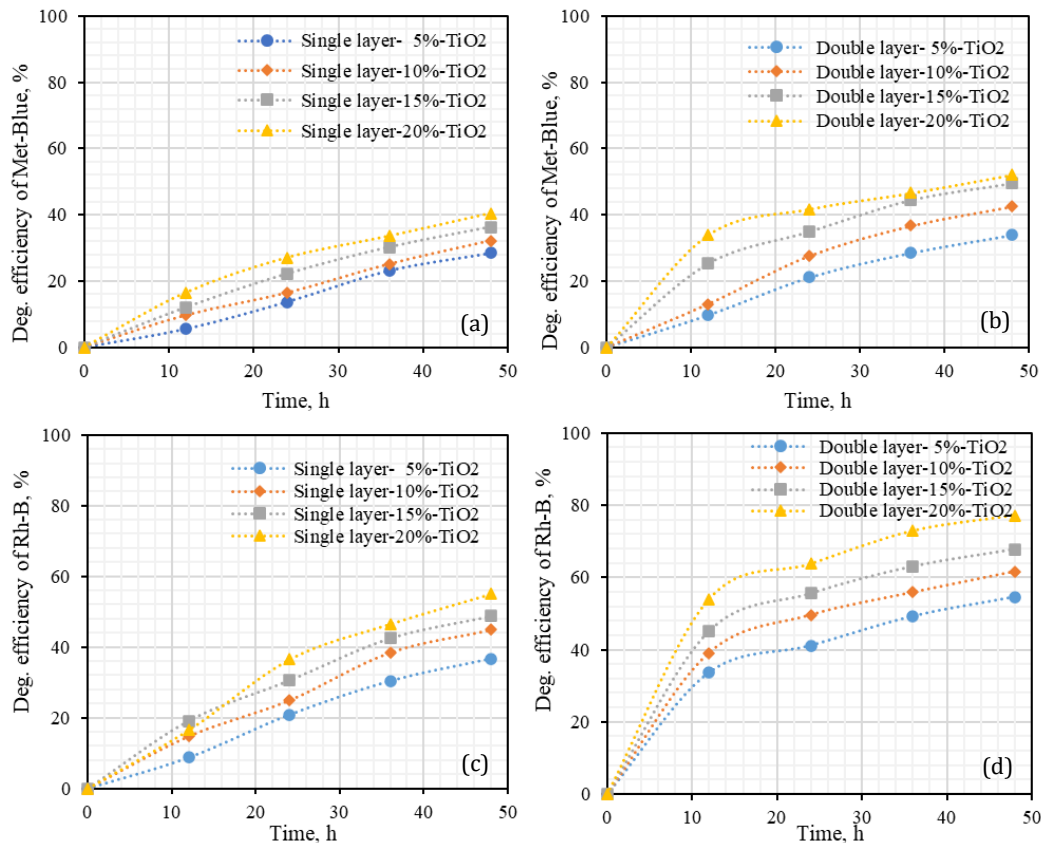


Fig. 5. The degradation efficiency of MB and Rh-B solutions with single- and double-layer 5, 10, 15, and 20% TiO₂-coated self-cleaning concrete: (a) Single-layer TiO₂ in MB; (b) Double-layer TiO₂ in MB; (c) Single-layer TiO₂ in Rh-B; (d) Double-layer TiO₂ in Rh-B.

This improvement is due to the increased number of active photocatalytic sites and better surface exposure in double-layer systems, which enhance light absorption and produce more reactive oxygen species (ROS), ultimately speeding up the degradation reaction (Adaileh et al. 2025; Saefumillah et al. 2025). Under UV light, TiO₂ produces active oxygen species that react with Rh-B molecules adsorbed on the cement surface, thereby mediating photocatalytic degradation. These reactive species, especially hydroxyl radicals ($\bullet\text{OH}$), superoxide radicals ($\text{O}_2\bullet^-$), and photogenerated holes (h^+), control the photocatalytic degradation process as photogenerated charge carriers react with adsorbed oxygen and water to produce highly oxidative species capable of breaking down complex dye molecules into smaller intermediates and ultimately mineralized products. (Ramesh et al. 2024).

The degradation mechanism of Rh-B involves a series of photoinduced reactions, including chromophore cleavage, N-deethylation/demethylation, and subsequent mineralization into simpler inorganic compounds, as extensively reported for TiO₂-based photocatalytic systems. (Sleiman et al. 2007). A similar degradation pathway can be assumed for MB, in which ROS attack the dye's conjugated structure, leading to stepwise degradation and eventual mineralization (Saefumillah et al. 2025).

Increasing the concentration and number of layers of TiO₂ molecules coated on the surface results in more active TiO₂ molecules per unit surface under UV light, forming more oxygen species and degrading more MB

and Rh-B. However, it is well known that excessive catalyst loading can lead to particle agglomeration and light scattering, which can hinder effective photon penetration and reduce photocatalytic efficiency beyond an optimum level, as morphological characteristics and interfacial interactions significantly influence charge transfer and catalytic performance (Yuqin Wei et al. 2023a).

$$\ln \frac{C_0}{C_t} = \ln \frac{A_0}{A_t} = K_{\text{app}} \cdot t \quad (2)$$

The rate constant (K_{app}) for the photocatalytic reaction was evaluated using a pseudo-first-order kinetic model, as described by Eq. (2). This model is widely applied in heterogeneous photocatalysis and reflects the proportional relationship between degradation rate and pollutant concentration at low concentrations (Kadem et al. 2025). The kinetic model is expressed as $\ln(C_0/C_t) = K_{\text{app}} \cdot t$, where C_0 and C_t represent the initial and instantaneous concentrations, respectively, and K_{app} is the apparent rate constant. C_t and A_t represent the pollutant concentration and absorbance at time t , respectively, while C_0 and A_0 denote the initial concentration and absorbance at the beginning of the experiment. The kinetic properties are displayed in Table 7. These parameters were used to evaluate the photocatalytic degradation behavior and kinetic performance of TiO₂-coated concrete surfaces. Figure 6 shows a strong linear correlation between $\ln(C_0/C_t)$ and time for both pollutants, confirming that the photocatalytic degradation process follows pseudo-first-order kinetics, a common behavior in TiO₂-

based photocatalytic systems at low pollutant concentrations.

Error analysis was conducted based on the standard deviation of triplicate measurements ($n = 3$). The exper-

imental error associated with concentration measurements was relatively low, with standard deviations typically ranging from ± 0.3 to ± 0.8 ppm, indicating high precision in the UV-Vis measurements.

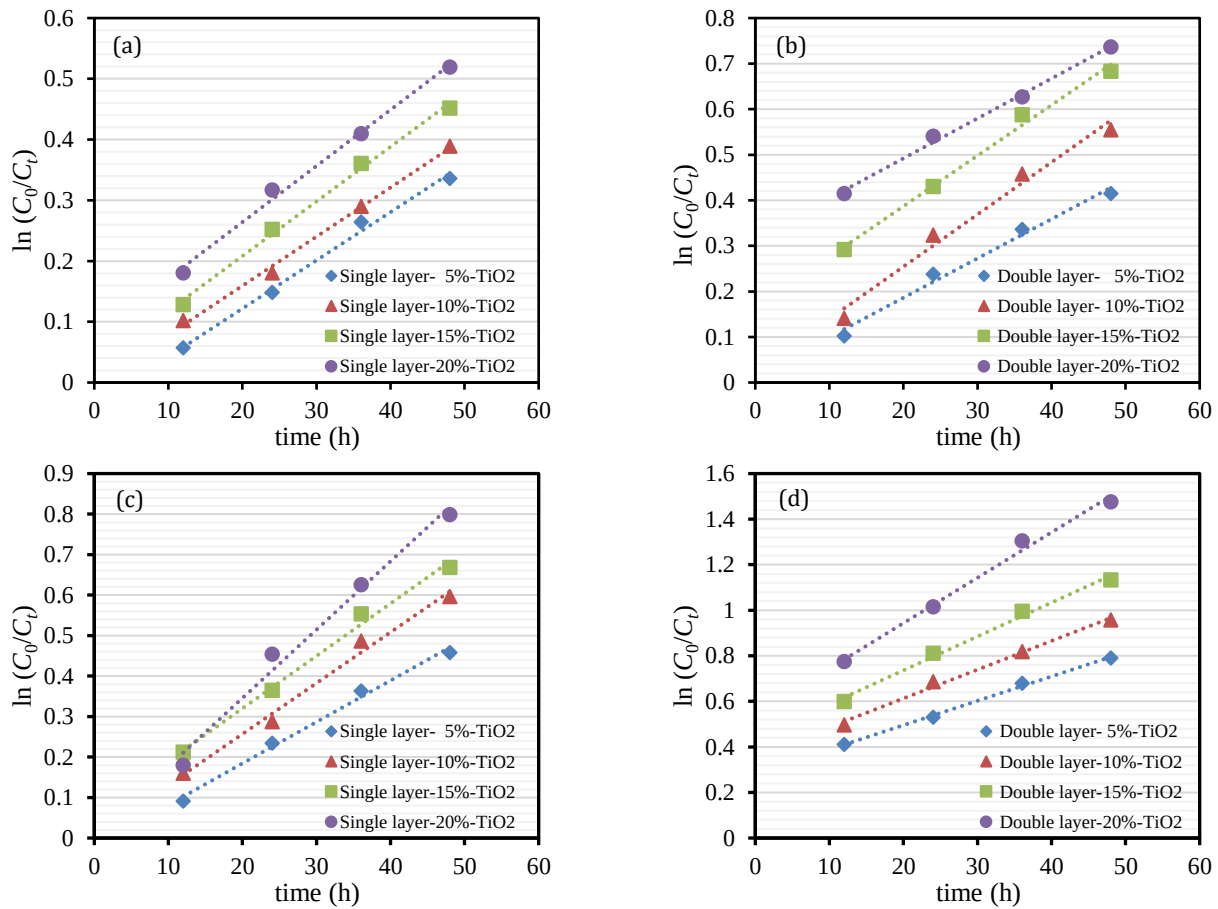


Fig. 6. The pseudo-first-order kinetics model graphs

for single- and double-layer TiO₂-coated self-cleaning concrete at 5, 10, 15, and 20%:

(a) Single-layer TiO₂ in MB; (b) Double-layer TiO₂ in MB; (c) Single-layer TiO₂ in Rh-B; (d) Double-layer TiO₂ in Rh-B.

Fig. 6 shows a strong linear correlation between $\ln(C_0/C_t)$ and time for both pollutants, indicating that the photocatalytic degradation follows pseudo-first-order kinetics, a common behavior in TiO₂-based photocatalytic systems at low pollutant concentrations (Sharma et al. 2023; Kadem et al. 2025). The photocatalytic reaction of coated surfaces against MB showed increases in the K_{app} value of 16.46% and 34.88% for single- and double-layer applications, respectively, when the TiO₂ concentration in the coatings was increased from 5% to 20% wt%. The rate of photocatalytic degradation of concrete surfaces against Rh-B was significantly influenced by TiO₂ concentration. An increase in TiO₂ concentration from 5% to 20% wt% resulted in degradation rate increases of 85.98% and 65.69% for single- and double-layer applications, respectively. These results clearly show that increasing the TiO₂ loading increases the apparent reaction rate by increasing the number of active sites and enhancing surface-pollutant interactions (Adaileh et al. 2025). These surface hydroxyl groups play a crucial role in photocatalytic reactions by acting as active sites for the generation of hydroxyl radicals ($\bullet OH$), while photogenerated electrons reduce oxygen to form

superoxide radicals ($O_2^{\bullet -}$). These reactive oxygen species are primarily responsible for attacking dye molecules, inducing their oxidative degradation, and promoting their mineralization (Bhattacharyya et al. 2025). More TiO₂ particles increase the density of surface hydroxyl groups, which serve as active sites for photocatalytic reactions, facilitating the generation of reactive oxygen species. These hydroxyl groups enhance interfacial charge transfer processes and promote the formation of highly oxidative species responsible for dye degradation. Additionally, surface defects and oxygen vacancies improve charge separation efficiency by trapping photo-generated electrons and suppressing electron-hole recombination (Yubin Wei et al. 2023b). Consequently, the lifetimes and availability of charge carriers are extended, leading to higher apparent rate constants (K_{app}) and enhanced photocatalytic degradation performance, particularly in double-layer systems with higher TiO₂ loading (Xing et al. 2023). These findings clearly demonstrate that the synergistic effect of increased TiO₂ loading and optimized coating architecture significantly enhances both the kinetics and overall efficiency of photocatalytic degradation processes.

Similarly, the standard deviation of the apparent rate constants (K_{app}) was ± 0.0001 to ± 0.0005 h^{-1} , demonstrating low variability and high consistency among replicate measurements. The statistical reliability of the ki-

netic analysis was confirmed by low standard deviation values and high correlation coefficients ($R^2 \approx 0.98$ – 0.99), indicating strong agreement with the pseudo-first-order kinetic model.

Table 7. Pseudo-first-order kinetic model constants (K_{app}) of single- and double-layer 5, 10, 15, and 20 wt% TiO_2 -coated self-cleaning concrete for MB and Rh-B. Values are reported as mean $\pm$ standard deviation ($n = 3$).

	MB		Rh-B	
	$K_{app} (h^{-1})$	R^2	$K_{app} (h^{-1})$	R^2
Single coated				
%5 TiO_2	0.0080 ± 0.0001	0.993	0.0103 ± 0.0002	0.993
%10 TiO_2	0.0081 ± 0.0001	0.996	0.0126 ± 0.0002	0.988
%15 TiO_2	0.0091 ± 0.0001	0.996	0.0130 ± 0.0002	0.992
%20 TiO_2	0.0093 ± 0.0002	0.995	0.0169 ± 0.0003	0.985
Double coated				
%5 TiO_2	0.0086 ± 0.0001	0.985	0.0107 ± 0.0001	0.997
%10 TiO_2	0.0115 ± 0.0001	0.98	0.0126 ± 0.0003	0.992
%15 TiO_2	0.0111 ± 0.0001	0.991	0.0149 ± 0.0002	0.992
%20 TiO_2	0.0088 ± 0.0001	0.995	0.0200 ± 0.0005	0.991

K_{app} values were calculated from the linear regression of $\ln(C_0/C_t)$ versus time. All measurements were performed in triplicate ($n = 3$), and the results are presented as mean $\pm$ standard deviation to ensure repeatability and statistical reliability. The low standard deviation values and high R^2 coefficients confirm the statistical reliability and repeatability of the kinetic analysis.

4. Conclusions

In this study, the photocatalytic performance of TiO_2 -coated concrete surfaces was systematically evaluated with respect to coating configuration and catalyst loading using MB and Rh-B as model pollutants. The results clearly demonstrated that both TiO_2 dosage and coating architecture play a decisive role in governing photocatalytic efficiency and degradation kinetics.

The normalized concentration profiles and degradation efficiency results revealed that increasing TiO_2 content from 5% to 20 wt% significantly enhanced photocatalytic performance. In particular, double-layer coatings consistently exhibited superior activity compared to single-layer systems, achieving up to 77.4% degradation for Rh-B and 52.12% for MB after 48 h of UV irradiation. This improvement was attributed to the higher surface availability of TiO_2 , improved light utilization, and enhanced interaction between the catalyst surface and pollutant molecules.

Kinetic analysis confirmed that the degradation process follows pseudo-first-order kinetics, with higher apparent rate constants (K_{app}) observed at increased TiO_2 loadings and in double-layer configurations. The enhancement in reaction rates was directly associated with increased active site density and improved charge-carrier dynamics.

From a mechanistic perspective, the improved performance of TiO_2 -coated surfaces was attributed to the generation of reactive oxygen species (ROS), such as hydroxyl and superoxide radicals, and to enhanced charge separation facilitated by surface hydroxyl groups and oxygen vacancies. These factors collectively contributed to reduced electron-hole recombination and increased availability of reactive species responsible for pollutant degradation.

This study primarily focuses on the photocatalytic performance of TiO_2 -coated concrete surfaces rather than the mechanical or physical characterization of the concrete substrate. Therefore, the results should be interpreted in the context of surface functionality.

Overall, the findings demonstrate that optimizing both TiO_2 loading and coating configuration provides an effective strategy for improving the photocatalytic efficiency of cement-based materials. These findings are consistent with previous studies (Hamidi and Aslani 2019; Maury-Ramírez et al. 2024) demonstrating that increasing TiO_2 loading and optimizing coating configuration significantly enhance photocatalytic efficiency by improving active-site accessibility, light utilization, and charge-carrier dynamics in cementitious materials. The developed double-layer TiO_2 coating system shows strong potential for practical applications in self-cleaning and environmentally responsive construction materials, particularly for the removal of organic pollutants in urban environments.

Future studies should focus on optimizing TiO_2 loading, evaluating coating thickness, and investigating long-term durability, adhesion strength, and environmental stability under real service conditions to enable practical implementation of photocatalytic concrete systems.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- Adaileh A, Abu-Rayyan A, Khasawneh A, Alahmad W (2025). A comparative study of GO/TiO₂/SiO₂ catalysts for the photocatalytic degradation of methylene blue and phenolic compounds. *Environmental Quality Management*, 34(3), e70058.
- Adebanjo AU, Abbas YM, Shafiq N, Khan MI, Farhan SA, Masmoudi R (2024). Optimizing nano-TiO₂ and ZnO integration in silica-based high-performance concrete: mechanical, durability, and photocatalysis insights for sustainable self-cleaning systems. *Construction and Building Materials*, 446, 138038.
- Ahouari H, Samraoui Z, Soualah A, Tayeb KB (2024). Photodegradation of rhodamine B in aqueous solution using TiO₂ polymorphs: EPR spectroscopy investigation. *Water, Air, & Soil Pollution*, 235, 25.
- Al-Safi S, Altharehi A, Alameri IA, Al-Jolahy A (2025). The mechanical properties of cement mortar reinforced with silica fume subjected to sulfate and chloride environment. *Challenge Journal of Structural Mechanics*, 11(1), 55-69.
- Arif M, Zahid AH, Saghir S, Mahsud A (2026). From sunlight to sustainability: the properties, evolution, and prospects of photocatalytic building materials. *Catalysis Reviews*, 68(2), 350-421.
- Atalı ŞG, Akbal F, Gürbüz M, Turan BC (2024). Granular titanium dioxide and silicon-doped titanium dioxide as reusable photocatalysts for dye removal. *International Journal of Applied Ceramic Technology*, 21(3), 2024-2036.
- Bahşi E, Şahin O, İlcan H, Uzal B, Günel MF, Yıldırım G, Şahmaran M (2022). Role of inclusion size distribution of titanium dioxide on the nitrogen oxides reduction capability and microstructural characteristics of cementitious systems. *Construction and Building Materials*, 318, 125992.
- Bendjama M, Hamdaoui O (2025). Photocatalytic degradation of safranine O: unraveling the roles of dissolved gases, environmental matrices, and reactive species. *Catalysts*, 15, 914.
- Bhattacharyya B, Geetha M, Anwar H, Zaidi SA, Sadasivuni KK, Mohamed M, Sheikh H, Alfawati SM, Jarrar RA (2025). Synergistic effect of TiO₂ nanorods incorporated with graphene oxide for photocatalytic degradation of multiple dyes. *International Journal of Environmental Research*, 19, 34.
- Chen J, Poon CS (2009). Photocatalytic construction and building materials: from fundamentals to applications. *Building and Environment*, 44, 1899-1906.
- Chong MN, Jin B, Chow CWK, Saint C (2010). Recent developments in photocatalytic water treatment technology: a review. *Water Research*, 44, 2997-3027.
- Fujishima A, Zhang X, Tryk DA (2008). TiO₂ photocatalysis and related surface phenomena. *Surface Science Reports*, 63(12), 515-582.
- Gao W, Kang H, Zhong M, Han L, Guo X, Su B, Lei Z (2024). Chitosan-promoted TiO₂-loaded double-network hydrogels for dye removal and wearable sensors. *Biomacromolecules*, 25, 8016-8025.
- Gómez-Monsivais A, Tangirala Venkata Krishna K, Olvera MDLL, Maldonado A, González Vidal JL, Vega-Pérez J, Gómez-Pozos H (2026). A comparative study on the effect of thickness in sol-gel deposited ZnO, SnO₂, and TiO₂ thin films and their photocatalytic performance in methylene blue decolorization. *Journal of Sol-Gel Science and Technology*, 117, 10.
- Hamidi F, Aslani F (2019). TiO₂-based photocatalytic cementitious composites: materials, properties, influential parameters, and assessment techniques. *Nanomaterials*, 9, 1444.
- Jin H, Lee TM, Choi H, Kim KS (2023). Effects of process variables for NO conversion by double-layered photocatalytic mortar with TiO₂ nanoparticles. *Journal of Industrial and Engineering Chemistry*, 117, 461-472.
- Kadem AJ, Lau XJ, Pung SY, Sreekantan S, Ramakrishnan S (2025). Kinetics model and optimization for photocatalytic degradation of methylene blue over Ag/TiO₂ catalyst. *Bulletin of Chemical Reaction Engineering & Catalysis*, 20(3), 517-534.
- Kumar AS, Pabba DP, Reddy NR, Joo SW (2025). Emerging photocatalytic systems for environmental and energy applications: a comprehensive review of mechanisms, materials, and future directions. *Journal of Alloys and Compounds*, 1031, 180934.
- Liang X, Yu S, Meng B, Wang X, Yang C, Shi C, Ding J (2025). Advanced TiO₂-based photoelectrocatalysis: material modifications, charge dynamics, and environmental-energy applications. *Catalysts*, 15(6), 542.
- Mahmud H, Ahmed T, Islam MS (2025). Combined effect of rice husk ash and animal bone powder on strength and permeability of concrete. *Challenge Journal of Structural Mechanics*, 11(1), 1-13.
- Majeed A, Iqbal MA, Do TO (2025). Advances in composite photocatalysts for efficient degradation of organic pollutants: strategies, challenges, and future perspectives. *Catalysts*, 15, 893.
- Maury-Ramírez A, Rinke M, Blom J (2024). Low-carbon embodied, self-cleaning, and air-purifying building envelope components using TiO₂ photocatalysis, 3D printing, and recycling. *Coatings*, 14(9), 1228.
- Mostafa FE-ZM, Smarzewski P, El Hafez GMA, Farghali AA, Morsi WM, Faried AS, Tawfik TA (2023). Analyzing the effects of nano-titanium dioxide and nano-zinc oxide nanoparticles on the mechanical and durability properties of self-cleaning concrete. *Materials*, 16(21), 6909.
- Pacheco-Torgal F (2014). Eco-efficient construction and building materials research under the EU framework programme horizon 2020. *Construction and Building Materials*, 51, 151-162.
- Paiu M, Lutic D, Favier L, Gavrilescu M (2025). Heterogeneous photocatalysis for advanced water treatment: materials, mechanisms, reactor configurations, and emerging applications. *Applied Sciences*, 15(10), 5681.
- Qi Z, Wu X, Li Q, Lu C, Carabineiro SAC, Zhao Z, Liu Y, Lv K (2025). Singlet oxygen in environmental catalysis: mechanisms, applications and future directions. *Coordination Chemistry Reviews*, 529, 216439.
- Ramesh N, Lai CW, Johan MRB, Mousavi SM, Badruddin IA, Kumar A, Sharma G, Gapsari F (2024). Progress in photocatalytic degradation of industrial organic dye by utilising the silver doped titanium dioxide nanocomposite. *Heliyon*, 10(24), e40998.
- Rashed MN (2013). Adsorption technique for the removal of organic pollutants from water and wastewater. In: Rashed MN, editor. *Organic Pollutants - Monitoring, Risk and Treatment*. InTech, Rijeka, Croatia, pp. 168-194.
- Saefumillah A, Apriandanu DOB, Ramadhan R, Fitria RD, Yulizar Y, Shofiyan A, Rahmalia W, Alimuddin AH (2025). Photocatalytic degradation of methylene blue: unraveling structure-activity relationships and performance evaluation of sol-gel synthesized TiO₂ versus commercial TiO₂P25. *Journal of Molecular Structure*, 1347, 143277.

- Seremak W, Jasiorski M, Baszczuk A, Winnicki M (2023). Preliminary study on low-pressure cold spray process parameters: effect on mechanical and photocatalytic properties of TiO₂ coatings. *Journal of Thermal Spray Technology*, 32(7), 1926-1939.
- Shamim A, Abdullah H, Abid MB, Nayyab GE, Daud NK (2026). Advanced oxidation processes for sustainable wastewater treatment. *Journal of Materials Science*, 61, 4857-4893.
- Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Mariñas BJ, Mayes AM (2008). Science and technology for water purification in the coming decades. *Nature*, 452, 301-310.
- Shareef M, Batool H, Shehzadi A, Aftab F, Munir A, Manzoor S, Gohar RS, Rehman Z, Ashiq MN, Nazar MF (2026). Structural functionalized TiO₂-mediated photocatalysts as dye degradation agents: a systematic review. *Materials Research Bulletin*, 195, 113852.
- Sharma S, Devi B, Koiri D, Sharma K, Bhattacharyya KG, Devi A (2023). Visible light photocatalytic degradation of methylene blue and rhodamine B over silver-doped titanium dioxide nanocomposites supported on Fuller's earth. *Environmental Monitoring and Assessment*, 195, 1362.
- Si H, Zhou M, Fang Y, He J, Yang L, Wang F (2021). Photocatalytic concrete for NO_x degradation: influence factors and durability. *Construction and Building Materials*, 298, 123835.
- Singh A, Soundappan T (2026). Multifaceted advances in TiO₂-based photocatalysts for PFAS degradation: a critical review of mechanisms, modifications, and challenges. *Materials Advances*, 7, 3101-3146.
- Singh S, Parveen S, Clarizia L, Kumar P (2026). An insight into photocatalytic degradation mechanism of persistent pollutants with transition metal oxides and their composites: photocatalysis mechanism, rate affecting parameters, and removal pathways. *Catalysis Reviews*, 68(1), 220-268.
- Sleiman M, Conchon P, Ferronato C, Chovelon JM (2007). Iodosulfuron degradation by TiO₂ photocatalysis: kinetic and reactional pathway investigations. *Applied Catalysis B: Environmental*, 71, 279-290.
- Srivastava A, Mishra A, Singh SK (2025). Mechanical and durability study of nano-SiO₂ and nano-TiO₂ on fiber reinforced concrete. *Challenge Journal of Concrete Research Letters*, 16(1), 33-39.
- Turan E, Alameri IA, Oltulu M (2025). Long-term durability of red mud-modified cement mortars: effects of high temperature and freeze-thaw cycles. *Challenge Journal of Structural Mechanics*, 11(3), 116-127.
- Ünal S, Canbaz M (2025a). Photocatalytic activation of fibrous lightweight polymer concrete surfaces under artificial light source. *Challenge Journal of Concrete Research Letters*, 16(1), 15-24.
- Ünal S, Canbaz M (2025b). Utilization of expired cement and aged roof tile powder in the production of sustainable geopolymer: mechanical and physical properties. *Challenge Journal of Structural Mechanics*, 11(2), 82-88.
- Ünal S, Canbaz M (2026). Development of a sustainable geopolymer structural element with waste glass powder: mechanical characteristics. *Challenge Journal of Structural Mechanics*, 12(1), 22-29.
- Wang J, Li W, Yan Y, Liu M, Liu B, Ohno T, Teng Z (2026). Photo-induced reactive oxygen species for selective oxidation of plastics and biomass. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, 66, 100737.
- Wee Chit WP, Budiea AMA, Mohd Noh H, Muthusamy K, Bamaga SO (2025). Compressive strength and fire resistance of mortar containing spent garnet as partial sand replacement. *Challenge Journal of Concrete Research Letters*, 16(4), 164-172.
- Wei Y, Chen Y, Yuan R, Xue Z, Zhao L (2023a). Substitution effects of zinc porphyrin-sensitized TiO₂ nanoparticles for photodegradation of AB1. *Journal of Molecular Structure*, 1277, 134889.
- Wei Y, Meng H, Wu Q, Bai X, Zhang Y (2023b). TiO₂-based photocatalytic building material for air purification in sustainable and low-carbon cities: a review. *Catalysts*, 13, 1466.
- Xing C, Zhang Z, Zhang Y, Han X, Yang L, Li J, Wang X, Martinez P, Demir M, Piveteau L, Florian P, Arbiol J, Guo Y, Llorca J, Cabot A (2023). Synergistic effect of surface oxygen vacancies and hydroxyl groups on Cu-doped TiO₂ photocatalyst for hydrogen evolution. *Materials Today Nano*, 24, 100435.
- Yan W, Bi C, Lu C, Fu J, Zheng M, Ding Q, Liu J (2025). Investigation on the factors affecting the exhaust degradation performance of porous pavement mixtures with nano-TiO₂ photocatalysts. *Materials*, 18, 1139.
- Zhang Y, Zhou Y, Dong X, Xi X, Dong P (2024). Recent advances in TiO₂-based photocatalytic concrete: synthesis strategies, structure characteristics, multifunctional applications, and CFD simulation. *Chemical Engineering Journal*, 496, 154186.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Potential and production of pervious concrete incorporating rice husk as a partial aggregate replacement

Mohd Syahrul Hisyam Mohd Sani ^{a,*} , Nurul Huda Abdullah ^b , Fadhluhartini Muftah ^a

^a Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM) Pahang Branch, 26400 Bandar Jengka, Pahang, Malaysia

^b School of Engineering and Computing, MILA University, 71800 Putra Nilai, Negeri Sembilan, Malaysia

ABSTRACT

Pervious concrete is produced by utilising cement, coarse aggregate, and water. Industrial or agricultural waste products contribute significantly to environmental problems, such as air pollution and carbon dioxide emissions. Therefore, these waste products should be reused or recycled within construction or infrastructure activities to reduce their impacts on the environment. To address environmental problems, this study investigates an agricultural waste product, particularly rice husk (RH), in order to replace natural coarse aggregate in pervious concrete. This research addresses the research gap of employing unprocessed RH as a direct coarse aggregate replacement in pervious concrete. Its novel contribution is the empirical identification of a suitable replacement percentage that balances environmental waste valorisation with the preservation of structural integrity. Pervious concrete was prepared with a proportion of 1:3 (cement to coarse aggregate) and a water–cement ratio of 0.5, with RH replacing coarse aggregate by weight at 2%, 4%, 6%, and 8%. This study aims to investigate the potential of RH as a partial aggregate replacement by producing pervious concrete and assessing its behaviour. Two main experimental activities were conducted: RH surface morphology and elemental analysis, as well as analysis of compressive strength of pervious concrete cubes at 7, 28, and 40 days, with a total of 45 specimens. The design standards for determining the compressive strength were in accordance with BS EN 12390-3. The results indicated that the specimen with 2% RH replacement exhibited the highest compressive strength among all specimens, achieving 13.4 MPa at 7 days, 16.3 MPa at 28 days, and 18.0 MPa at 40 days. Overall, the compressive strength of pervious concrete decreased as the proportion of coarse aggregate replaced by RH increased. Therefore, it can be concluded that RH has the potential to replace coarse aggregate at proportions of less than 4% in pervious concrete based on the testing.

ARTICLE INFO

Article history:

Received – January 4, 2026
Revision requested – February 8, 2026
Revision received – May 3, 2026
Accepted – May 11, 2026

Keywords:

Pervious concrete
Rice husk
Partial aggregate replacement
Coarse aggregate
Agricultural waste
Environmental mitigation



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

Citation: Mohd Sani MSH, Abdullah NH, Muftah F (2026). Potential and production of pervious concrete incorporating rice husk as a partial aggregate replacement. *Challenge Journal of Concrete Research Letters*, 17(3), 262–277.

1. Introduction

This section provides a brief discussion on pervious concrete, problem statement, rice husk (RH), RH as both a cement and aggregate replacement, and coarse aggregate replacement in pervious concrete. Additionally, this section addresses the objective of the study.

The rapid expansion of impermeable urban surfaces has markedly disturbed natural hydrological cycles, resulting in heightened stormwater runoff, groundwater depletion and frequent waterlogging. For mitigating and addressing these environmental challenges, pervious concrete has emerged as a critical component of sustainable infrastructure. Pervious concrete is categorised as a

* Corresponding author. E-mail address: msyahrul210@uitm.edu.my (M. S. H. Mohd Sani)

ISSN: 2548-0928 / DOI: <https://doi.org/10.20528/cjcr.2026.1083>

special concrete produced using cement or binder, coarse aggregate, and water, either without or with minimum use of sand. It contains a high volume of air voids or porosity, allowing water to flow or penetrate. Pervious concrete is also referred to as water-permeable concrete, porous concrete, or no-fines concrete, and is commonly used in pavement applications. Shende et al. (2019) highlighted the use of pervious concrete in pavement construction, which typically helps to replenish groundwater and reduce waterlogging; however, such pavements are unsuitable for heavy loads. Due to its low compressive strength, pervious concrete is typically employed in sidewalks, low-load parking areas, pathways, and driveways. Kováč and Sičáková (2018) reported that impermeable surfaces, especially concrete surfaces, hinder natural water movement through the surface and underlying soil during heavy rainfall, resulting in water runoff, stormwater accumulation, and snow melting. According to Lo et al. (2021), pervious concrete is classified as green infrastructure for managing stormwater runoff in urban environments, with compressive strengths ranging from 2.8 to 28 MPa in cube shape. Talsania et al. (2015) highlighted concerns regarding the ease with which pervious concrete disperses stormwater compared to conventional concrete, the restoration of groundwater that eliminates the need for retention ponds or other stormwater management systems, and the costs associated with manufacturing pipe systems. According to previous research, pervious concrete is gaining popularity as it is more durable, flexible, and less expensive to build and maintain.

Agricultural waste products, such as crop residues and animal waste from husbandry, are a major source of waste products in developing countries or those with agriculture-based economies. Most countries in the Association of Southeast Asian Nations (ASEAN), including Malaysia, Thailand, and Vietnam, are well known for their agricultural sectors, which employ various technologies that contribute to national income. However, waste management processes in these countries are still lacking. Typically, these waste products are either incinerated or deposited in certain dumpsites or landfills for disposal. The burning of agricultural waste causes numerous problems, such as human health problems, as well as emissions of carbon dioxide (CO_2), toxic chemicals, and nitrogen oxides. Sahoo et al. (2021) noted that rice harvesting requires a large area for disposal, while burning this waste leads to air and soil pollution. Chabi et al. (2018) reported that producing concrete using agricultural waste products has garnered considerable interest and awareness, as these materials are renewable and generate lower CO_2 emissions. Currently, the primary goal of innovation, invention, and research in building and construction materials is to promote the use of materials that enhance energy efficiency and environmental performance, such as locally sourced renewable materials.

Rice husk (RH) is a by-product of rice milling, consisting of the shells produced during paddy husking, and is classified as agricultural waste. Winarno (2019) stated that RH, also known as rice hull, has a hard surface composed of lignin and silica, which protects the seed during its growth. Due to its structural arrangement of silica-

cellulose and its non-biodegradable nature, RH exhibits several benefits, including resistance to flaring or smouldering (Chabannes et al. 2014). Additionally, RH has a wide range of applications, such as thermal insulation, fuel production, removal of phenols from water, and absorption of pigments, heavy metal ions, and dyes from wastewater (Chen et al. 2018). Rice husk is used in concrete or mortar as a cement replacement when processed into ash; however, there is limited information regarding the use of RH as a replacement for fine or coarse aggregate. In general, RH is processed by burning at a certain temperature to produce small, fine particles. The production of RH has increased in line with population growth in ASEAN countries. Nowadays, many researchers have studied RH as a biomass resource and a cement replacement in concrete. Patil et al. (2020) reported that RH had not previously been utilised in concrete manufacturing and described RH as a dried, thin coating covering rice seeds. Chabannes et al. (2014) noted that the utilisation of raw RH in concrete without prior burning is considered a research limitation. In earlier research, Chabannes et al. (2016) added whole raw RH with other materials, such as lime-based binders, in concrete.

Rice husk undergoes various processes to alter its shape, colour, and condition, using a grinder and furnace to produce rice husk ash (RHA). The ash is ground and burned at high temperatures, approximately 900–1,000 °C, to produce RHA with a high presence of silicon dioxide (SiO_2). Rice husk ash is used as a partial or full replacement for cement in concrete, and is sometimes combined with other waste products as a blended material for cement replacement or as other concrete components, such as aggregate replacement. The ash is also utilised as a cement replacement in various types of concrete. Rattanachu et al. (2020) discussed the use of RH ground to cement size and replaced 20–50% cement by weight with the ground RH in concrete, followed by the determination of strength and chloride penetration depth. Reddy et al. (2021) evaluated the comprehensive strength properties at 7 and 28 days of concrete age, especially compressive, tensile, and flexural strength, by incorporating RHA as a partial cement replacement in proportions of 5%, 7.5%, 10%, 12.5%, and 15%, along with the addition of a superplasticiser.

Rice husk ash is used as a cement replacement and is combined with other waste products, such as agricultural waste and industrial waste. Shende et al. (2019) assessed the compressive strength and permeability of pervious concrete using RHA as a partial cement replacement at 8% and 10%, in addition to glass fibre content of 0%, 0.2%, 0.4%, and 0.6%. Maryoto and Sudibyo (2019) noted that approximately 2.825 million tons of RH are produced annually in Indonesia, which are usually used for producing bricks and lightweight concrete. Rice husk contains about 90% SiO_2 , with the remaining percentages comprising other chemicals such as ferric oxide, aluminium oxide, and calcium oxide (Maryoto and Sudibyo 2019). Chetan and Aravindan (2020) tested the compressive and tensile strength of concrete using RHA as a partial cement replacement at proportions of 0%, 5%, 10%, 15%, and 20%, together with robo sand as a sand replacement. Based on their observation, the compres-

sive and tensile strength increased by 3.12% and 5.63%, respectively, when using 10% RHA as a cement replacement for 28 days. Varadharajan et al. (2020) investigated concrete made with RHA as a partial cement replacement with proportions of 0–20%, marble waste powder (MWP) as a partial sand replacement with proportions of 0–30%, and hooked steel fibre (HSF) at 1.5% by weight of cement to determine its mechanical properties. They reported that the concrete prepared with 15% RHA, 30% MWP, and 1.5% HSF achieved optimal mechanical performance.

Rice husk is used as an aggregate replacement in normal or specialised concrete, either in the form of RHA or RH in various shapes or conditions. Fernandes et al. (2019) reported the compressive strength of concrete containing glass foam pellets as a partial replacement for coarse aggregate at 10%, 20%, and 30%, produced using RHA, soda-lime glass waste, and calcium carbonate, which was measured at 3, 7, 28, 56, and 90 days. Samantaray et al. (2016) found that concrete strength increased when incorporating 10–30% RHA as a partial fine aggregate replacement, but decreased when using 40–50% RHA. Obilade (2014) investigated the use of RH as a sand replacement in concrete by weight and volume at 0%, 5%, 10%, 15%, 20%, and 25%, utilising a mix design ratio of 1:2:4. The study showed that a 5% sand replacement by both weight and volume yielded the highest compressive strength of the concrete. Winarno (2019) studied RH with particle widths of 2–4 mm, a maximum length of 10 mm, and a density of 690 kg/m³ as a sand replacement in concrete blocks, with Portland cement-to-RH weight ratios of 0.67–2.00. The literature consistently demonstrates that RHA enhances concrete performance due to its high silica content and pozzolanic activity at replacement percentages up to 20%. In contrast, the use of raw RH waste presents a more strict structural limitation, generally restricted to 5% or less due to its lower density and inferior bonding properties.

Several studies have investigated pervious concrete with coarse aggregate replacement for producing sustainable materials, improving mechanical properties, and reducing the environmental impact. The coarse aggregate replacement materials can be divided into two groups: industrial waste and agricultural waste. Two types of coarse aggregate (limestone with an angular shape (size of 6.35 mm) and pea gravel with a rounded shape (size of 9.54 mm)) were used to produce pervious concrete (Torres et al., 2020). Lopez et al. (2019) reported the physical and mechanical properties of pervious concrete made using high-density polyethylene pellets as a partial coarse aggregate replacement, with various sizes and ratios. Chen et al. (2024) studied the crushing morphology, durability, and strength of pervious concrete using corn cob as a coarse aggregate replacement at 0%, 25%, 50%, 75%, and 100%, and determined that 50% replacement yielded the best compressive strength at 28 and 50 days of curing. Supit and Priyono (2022) evaluated the effect of using polyethylene terephthalate plastic waste as a 5% coarse aggregate replacement, with sizes of 5–10 mm and 10–20 mm, across three mix proportions (cement–aggregate ratios of 1:2, 1:3, and 1:4). Wang et al. (2024) evaluated the compres-

sive strength and effective porosity of pervious concrete made with recycled coarse aggregate of different gradings (5–15 mm, 15–20 mm, and 20–25 mm) and water–cement ratios (0.4, 0.45, and 0.5). Tijani et al. (2022) reported on the production of pervious concrete using sorghum husk ash as a cement replacement and palm kernel shell as a coarse aggregate replacement at 20%, 40%, 60%, 80%, and 100% by weight, noting that 20% and 40% of palm kernel shell replacements met the required minimum compressive strength of 2 N/mm². Torres et al. (2020) highlighted the production of pervious concrete with high compressive strength by considering several factors, such as specimen compaction, type and size of coarse aggregate, water–cement ratio, and the use of superplasticiser.

The current literature reveals considerable variation in the optimal replacement percentage, ranging from 5% to 50%, highlighting the sensitivity of pervious concrete to the distinct morphology and chemical properties of different waste materials. This inconsistency suggests that a strategy or approach is unfeasible, as the structural performance of the mixes depends entirely on the specific physical properties of the selected industrial or agricultural by-product. This study addresses the research gap concerning the limited exploration of raw or unprocessed agricultural waste as a direct alternative to mineral coarse aggregates in pervious concrete, given that most existing literature focuses on processed ashes rather than the bulk physical husk. Although pervious concrete is conventionally optimised for high void connectivity using gravel, there is a lack of empirical data about the impact of the cellular morphology and organic surface of RH on the mechanical structure of certain mix designs. The novel contribution of this study is the identification of a specific percentage of RH as gravel replacement, establishing a precise baseline for waste valorisation that balances environmental mitigation with functional load-bearing requirements. The main objective of this study was to produce pervious concrete with partial coarse aggregate replacement using RH and determine the behaviour of pervious concrete, especially its compressive strength. Besides, the objective is to determine an accurate baseline for the replacement percentage that balances environmental waste valorisation with the functional demands of compressive strength.

2. Material Preparation and Experimental Setup

The methodology of this study is divided into two parts: the production of pervious concrete and the evaluation of its behaviour.

2.1. Materials and characteristics

This study utilised RH, with the chemical composition data referenced from a previous study. The RH was stored in a plastic sack for 3 months prior to use. It was then cleaned to remove dirt, dust, and foreign matter that could weaken the bonding between the RH and other concrete materials. Chabi et al. (2018) reported that the size of RH ranged between 1 and 4 mm, and siev-

ing was conducted using a 1-mm sieve to remove impurities, such as sand, silt, and clay. The chemical composition of RH was observed and compared with ground RHA, raw RHA, ordinary Portland cement, and natural aggregate from previous studies, as shown in Table 1. This initial comparative study is important to identify the major chemical components to avoid adverse effects on concrete behaviour. Additionally, the incorporation of both raw RH and its ash derivatives (RH) is scientifically essential to demonstrate the substantial chemical transformation that occurs during thermal processing

which directly informs the focus of the study on raw waste valorisation. The comparison of key chemical compositions is illustrated in Fig. 1. Shang et al. (2024) reported the elemental content of RH as follows: carbon (C) 35.42%, nitrogen (N) 0.36%, hydrogen (H) 5.34%, and oxygen (O) 58.88%. Rice husk is an organic, carbon-based material whose surface consists of complex cellulose and silica, which can chemically inhibit the setting of cement. Ordinary Portland cement is a reactive binder based on lime, while natural aggregates are stable minerals like silica or limestone.

Table 1. Chemical composition of RH in different conditions.

Chemical composition (%)	Rice husk (Mareya et al. 2023)	Ground rice husk ash (Rattanachu et al. 2020)	Raw rice husk ash (Alomayri et al. 2021)	Ordinary portland cement (Alyami et al. 2023)	Natural aggregate (Shariati et al. 2023)
Silicon dioxide (SiO ₂)	13.91	93.5	96.70	22.75	19.42
Aluminium oxide (Al ₂ O ₃)	0.04	0.2	0.30	5.58	0.83
Iron oxide (Fe ₂ O ₃)	0.04	0.4	1.26	3.87	0.55
Calcium oxide (CaO)	0.36	0.9	0.57	59.94	31.12
Sulphur trioxide (SO ₃)	0.07	0.2	–	2.14	0.03
Magnesium oxide (MgO)	0.07	0.4	0.27	2.32	9.64
Sodium oxide (Na ₂ O)	0.01	–	0.05	0.86	0.98
Potassium oxide (K ₂ O)	1.19	3.3	0.45	0.75	1.19

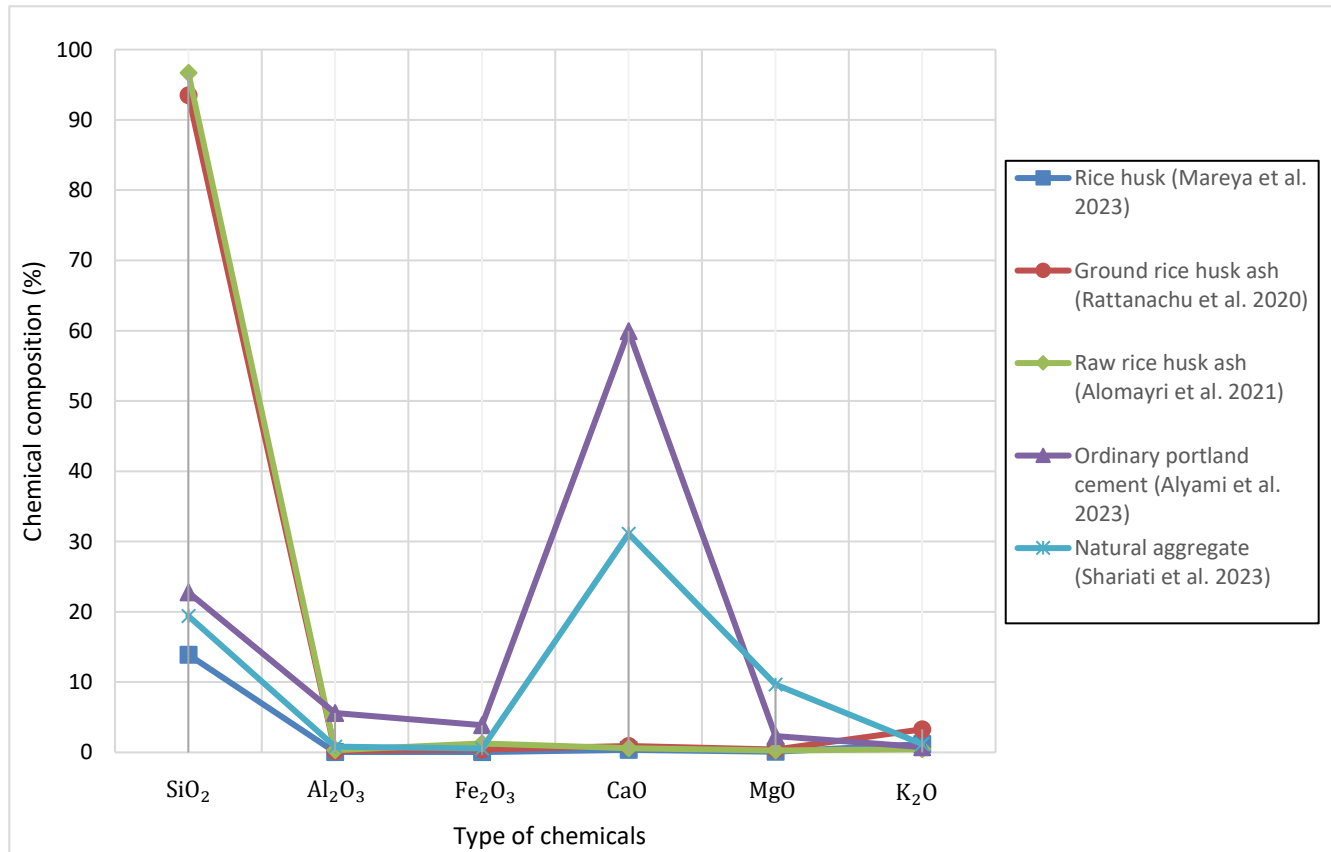


Fig. 1. A comparison study on the importance of chemical composition.

Although the synthesis of strength-giving silicates in Portland cement requires a precise calcium oxide (CaO) concentration of 60% to 65%, raw RH and gravel are chemically unable to replenish this lime content due to their minimal calcium profiles. The suitability of RH in pervious concrete is determined by its physical geometry and silica-rich surface which offer a lightweight, porous scaffold that increases the chemical binding energy of the cement paste without participating in the primary hydraulic reaction, rather than by its role as a chemical donor. Calcium oxide, sometimes referred to as lime, has the ability to increase strength and reduce cracking. The percentage differences in CaO content between RH and ground RHA, raw RHA, ordinary Portland cement, and natural aggregate are 60%, 36.84%, 99.40%, and 98.84%, respectively. Secondly, an important chemical in cement is SiO₂, commonly known as silica, which helps to impart strength. However, an excess of silica can affect the setting time of cement. The SiO₂ content of RH was recorded as 85.12%, 85.62%, 38.86%, and 28.37% when compared to ground RHA, raw RHA, ordinary Portland cement, and natural aggregate, respectively. Although RH has a low SiO₂ content of 13.91%, the comparison study indicates that post-combustion of SiO₂ concentrations increases to over 90%, transforming the function of the material from a physical aggregate replacement to a reactive pozzolanic binder. By presenting this profile, the data provides a necessary chemical justification for the research gap. It highlights that while processed RHA is chemically optimised for cementitious reactivity, the RH employed in this study functions under a different mechanical mechanism, thus requiring a separate investigation of its performance as a coarse aggregate replacement. The chemical composition of SiO₂ is reported to have the lowest percentage compared to that of other specimens. Thirdly, Al₂O₃, or alumina, facilitates the rapid setting of cement. The combination of RH, aggregate, and ordinary Portland cement is suitable within the range of 2–8%. The comparative percentage of RH relative to other specimens ranges from 80% to 99%. Chen et al. (2018) reported that the chemical composition of RH varies depending on weather patterns, geography, and fertilisers used during paddy cultivation. Observations indicate that the ash component of RH has a high SiO₂ content, making it suitable as a source for silicon compounds. Rice husk is appropriate for use as an additive or aggregate replacement in concrete because its chemical composition, especially CaO and SiO₂, is sufficient and not excessively high. The chemical composition of RH provides a critical baseline for its utilisation as a coarse aggregate replacement. This comparison is also essential because RH acts as a physical filler that reduces the overall density and thermal conductivity of the mix. A thorough understanding of its elemental makeup is necessary to balance the trade-off between the resulting structural voids in the concrete and its compressive strength.

In this study, RH was analysed using scanning electron microscopy (SEM) to determine its surface morphology, and energy-dispersive X-ray spectroscopy (EDS) was employed to carry out elemental analysis. The SEM and EDS analyses were conducted using a thermal field emission scanning electron microscope at an accelerating voltage of 20 kV, providing the necessary beam

energy for high-resolution morphological imaging and characteristic X-ray excitation. Samples were prepared by mounting them on aluminium stubs and sputter-coating to ensure surface conductivity. Morphological analysis was conducted in secondary electron mode, with magnifications ranging from 100× to 5,000× at a working distance of approximately 14.5 mm. The EDS map sum spectrum was utilised to quantify elemental distribution, providing a chemical depth of field that complements the structural insights obtained from SEM micrographs alone. Chabannes et al. (2014) noted that RH contains very small pores with a size less than 0.1 µm, and from the SEM images, RH with appropriate shape and size could be used as aggregates or fibres in concrete. Chabi et al. (2018) reported that SEM observations revealed a high concentration of silica on the surface of RH grains. Subsequently, RH was tested for its physical properties, including density, void content, and sieve size, before being used in the mixing process of pervious concrete.

2.2. Mix design and specimen preparation

Pervious concrete was produced using gravel (coarse aggregate), RH, cement, and water, as shown in Fig. 2. The proportion of cement to gravel (coarse aggregate) in the pervious concrete was 1:3, with a water–cement ratio of 0.5. The coarse aggregate used in the concrete mix was well graded with a size below 20 mm. For pervious concrete, a water–cement ratio of 0.5 is often considered high, where numerous designs range from 0.27 to 0.35. Outside this range, the paste may possess sufficient fluidity to flow off the gravel and RH, which accumulate at the bottom of the mould and form an impermeable layer. A cement–gravel ratio of 1:3 and a water–cement ratio of 0.5 are commonly chosen as they offer the best compromise between strength and paste thickness required to coat the gravel without blocking voids. The mix is designed and formulated to achieve a target theoretical void ratio of 22%, where pervious concrete is normally designed for a void content of 18–35% (Obla 2010) and 15–30% (Firouzi et al. 2012). The void content in pervious concrete is determined by the synergistic interaction among aggregate structure, material composition, and paste rheology. The utilisation of larger, consistently graded aggregates creates the primary skeletal framework for open pores, while the 1:3 mix design ensures sufficient cementitious paste to cover these particles without obstructing the established air channels. Furthermore, the selection of the cement–gravel ratio of 1:3 is based on studies by Malayali and Chokkalingam (2018) and Abd Rahman et al. (2019).

Rice husk replaced the coarse aggregate by weight at proportions of 2%, 4%, 6%, and 8%, with one specimen without RH serving as a control mix. A complete description is provided in Table 2. These percentages are commonly used in exploratory studies as they represent low to moderate replacement levels, allowing for gradual observation of the effects on strength, bonding, and void connectivity, while minimising the risk of mixture instability or excessive clogging. The replacement of gravel with RH was carried out on a weight-to-weight basis to ensure a consistent mass–cement ratio and to improve precision during batching. The approach was chosen to

reduce errors associated with the bulking effect of organic materials, which often causes volumetric measurements to be inconsistent under varying moisture conditions. Regarding the achievement of the required compressive strength, weight-based mixing is more accurate than volume-based mixing. This is because the latter method can be affected by changes in material density and compaction, whereas the former method guarantees consistent material proportions. Finally, the decision to replace coarse aggregate by weight is based on the stud-

ies by Singh and Singh (2020), Supit and Priyono (2022), and Bhujel et al. (2025), which used lightweight materials in pervious concrete. Although the RH replacement is based on weight percentage, the volumetric implications of the density mismatch have been thoroughly determined. The density ratio between coarse aggregate and RH is approximately 15, and a 2% replacement by weight results in a 19.6% increase in solid volume, leading to a measurable increase in void ratio and a decrease in packing density.

Table 2. Mix design information and description.

Specimen label	Description	Coarse aggregate (kg/m ³)	Rice husk (kg/m ³)	Cement (kg/m ³)	Water (kg/m ³)
RH0 (control)	Mix without rice husk (RH)	1050	0		
RH2	Mix with gravel replacement of 2% by weight of RH	1029	21		
RH4	Mix with gravel replacement of 4% by weight of RH	1008	42	350	175
RH6	Mix with gravel replacement of 6% by weight of RH	987	63		
RH8	Mix with gravel replacement of 8% by weight of RH	966	84		

This study provides a direct evaluation of the impact of low-density organic fibres on the overall mechanical properties and density of pervious concrete mixes by maintaining uniform weight across all mixes. To achieve a homogeneous mix, the gravel and cement were thoroughly mixed before adding RH and water to the mixer to prevent segregation. This study deliberately omits superplasticiser to establish a baseline performance for a simplified 1:3 mix design intended for low-tech applications and also to evaluate the fundamental behaviour of the cement–aggregate bond. Fig. 3(a) shows the mixing process before the addition of water, while Fig. 3(b) illustrates the completed mixing process. The fully mixed specimen, which was mixed for approximately 8–10 min,

was placed in a concrete mould of 100 mm × 100 mm × 100 mm and compacted using a vibrating table for 3 s. The specimen was then left at room temperature for rapid hardening, as shown in Fig. 4. After removal from the mould, the cube specimen was placed in a curing tank for 7, 28, and 40 days. Lastly, the cube specimen was tested to determine the compressive strength of the pervious concrete in accordance with BS EN 12390-3 (2019).

A total of 45 specimens were prepared across all mixes for the compressive strength test. Fig. 5 illustrates the hardened cube specimens with 8% RH. A clear flowchart of the material preparation and experimental setup activities is illustrated in Fig. 6.



Fig. 2. The basic ingredient of pervious concrete with RH.



Fig. 3. Pervious concrete mixing: (a) Before adding water; (b) Completing the mixing process.



Fig. 4. The process of moulding of pervious concrete on the vibrator table.



Fig. 5. The cube specimen with 8% of RH in pervious concrete.

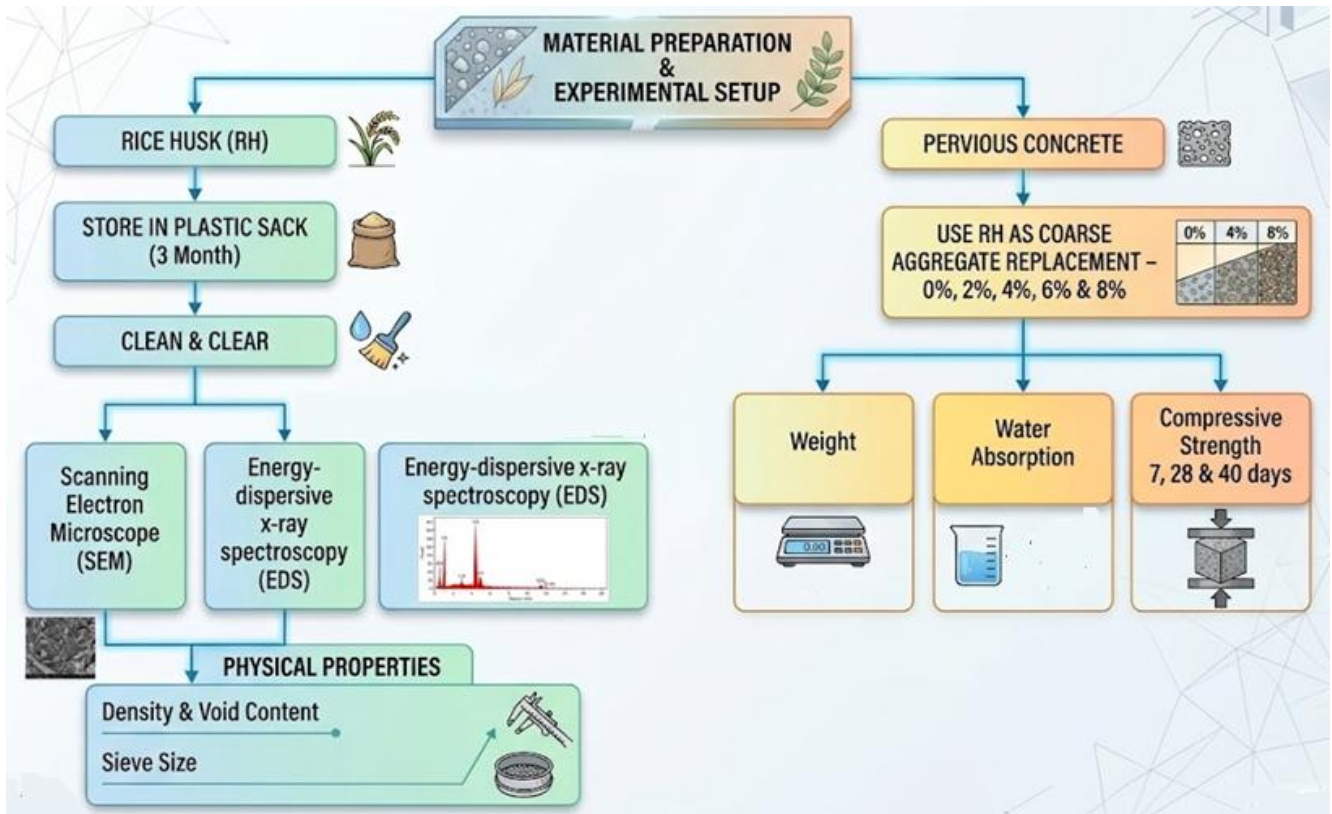


Fig. 6. The material preparation and experimental setup flowchart.

3. Results and Discussion

This section is composed of four parts: surface morphology and elemental analysis of RH, physical properties of RH, water absorption of hardened pervious concrete, and compressive strength of hardened pervious concrete.

3.1. Surface morphology and elemental analysis of rice husk

In this section, SEM micrographs were used to study the surface morphology of RH, with high-resolution images providing a comprehensive report on the examination of the RH surface. Nevertheless, it is acknowledged that EDS analysis offers more insights into the surface material compared to SEM analysis. The SEM micrograph of the RH surface was recorded and illustrated in Fig. 7, exhibiting properties similar to the study of Naraththa et al. (2024). From the observation, the curved region on the RH surface was detected, exhibiting wavy, furrowed, and conical borders. Furthermore, the surface displays well-organised micro-bumps, while the outermost layer is irregular, featuring a highly ridged structure along with protrusions that contribute to frictional properties. Consequently, the surface of RH, characterised by a combination of bumps and voids, is very suitable for being filled with coarse aggregate to create a strong surface upon the hardening of the concrete.

Fig. 8 presents the EDS elemental analysis for the RH surface, and the major elements recorded are tabulated in Table 3. Across the four locations, the major elements with high percentages are O (42–52%), Ca (13–27%),

and C (11–32%). Conversely, the major elements with low percentages are potassium (K, 0–1.2%), iron (Fe, 0–1.4%), and aluminium (Al, 0–2.0%). The percentage differences between the highest experimental values and the data from Sudhir et al. (2024) are 2.42% for O, 74.61% for Si, 85.07% for C, and 17.28% for K. Similarly, the percentage differences between the lowest experimental values and the data from Sudhir et al. (2024) for O, Si, C, and K are 19.99%, 90.31%, 56.93%, and 23.58%, respectively. The surface morphology analysis helps determine the bonding and packing of RH particles within the pervious concrete structure, while the elemental analysis verifies material consistency and identifies factors potentially affecting durability. These assessments ensure that RH is an appropriate and reliable replacement for gravel.

3.2. Physical properties of rice husk

The physical properties of RH, particularly the density, void content, and sieve size, were analysed and reported in this section. The density of RH was determined to be 140 kg/m^3 . This value was compared with densities reported in previous studies, including those by Sreesvarna et al. (2019) with 14.29% difference, Yuzer et al. (2013) with 12.86% difference, and Chabannes et al. (2014) with 26.29% difference. An explicit evaluation of material density differences was performed by comparing RH with several other low-density coarse aggregate replacements documented in the literature such as raw corn cobs (Chen et al. 2024), unmodified bamboo (Wang et al., 2024), and oil palm kernel shell (Khankhaje et al. 2016). The density of RH is approximately 7.16%

less than that of raw corn cobs, indicating that both materials are within a comparable lightweight range. In contrast, RH has a significantly greater density gap compared to unmodified bamboo, which is around 65% denser than RH, and oil palm kernel shell which is roughly 78.66% denser than RH. These comparisons highlight that, among often examined agricultural or biomass-based aggregates, Rh is situated at the lowest end of the density spectrum. This underscores the importance of properly addressing volumetric equivalence, packing

behaviour and mix proportioning when replacing RH in concrete mix. The void content of RH was measured to be 85.83%. The sieve size of RH is presented in Table 4. The highest percentage retained corresponds to a sieve pan size of 2.00 mm, and the highest percentage passing corresponds to a sieve pan size of 300 μm . The fineness modulus of RH was calculated as 3.31, classifying it as a coarse material. The fineness modulus affects concrete mix design by reducing workability, enhancing strength potential, and reducing blending and shrinkage.

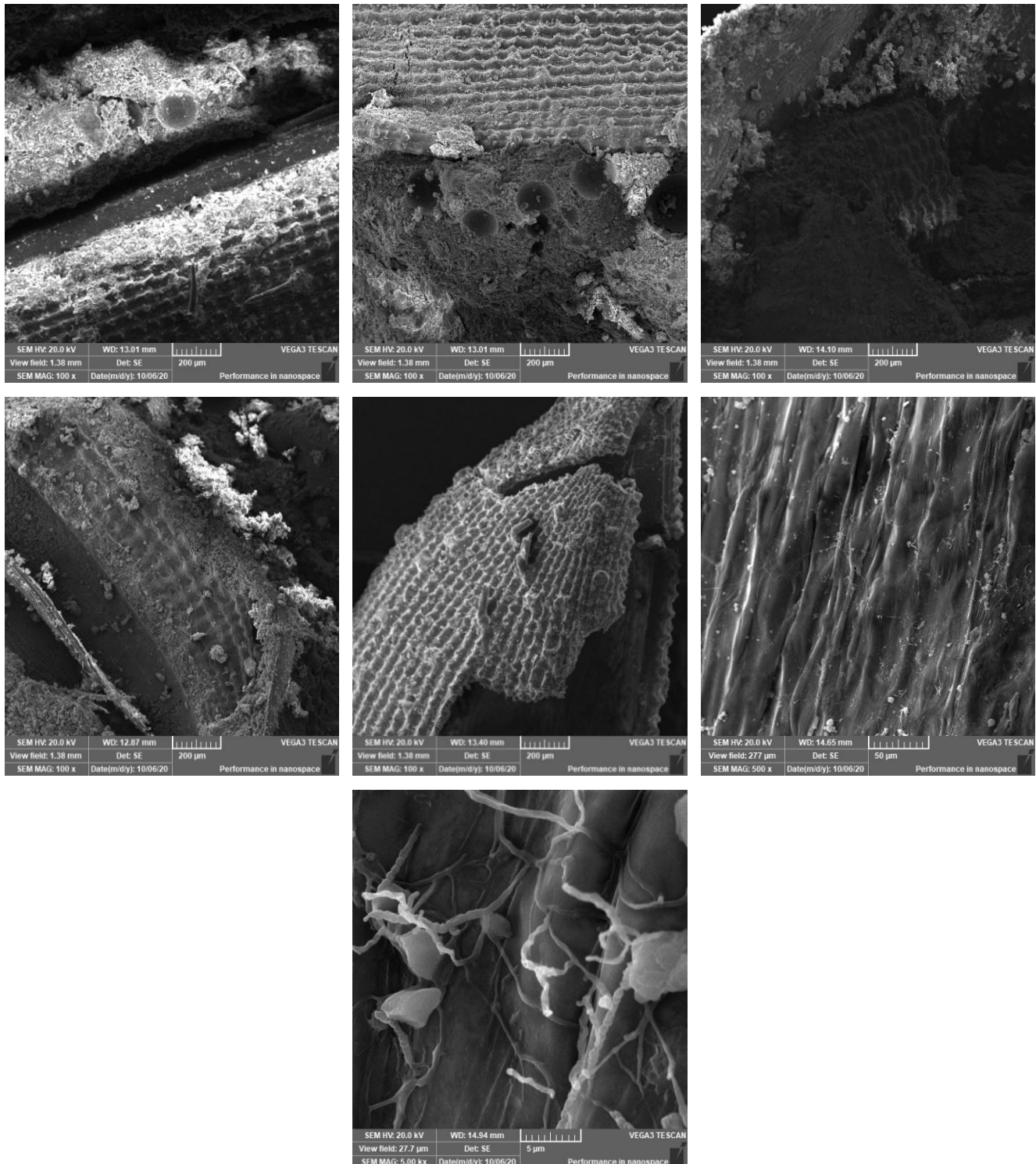


Fig. 7. The surface morphology of rice husk with 200 μm , 50 μm , and 5 μm .

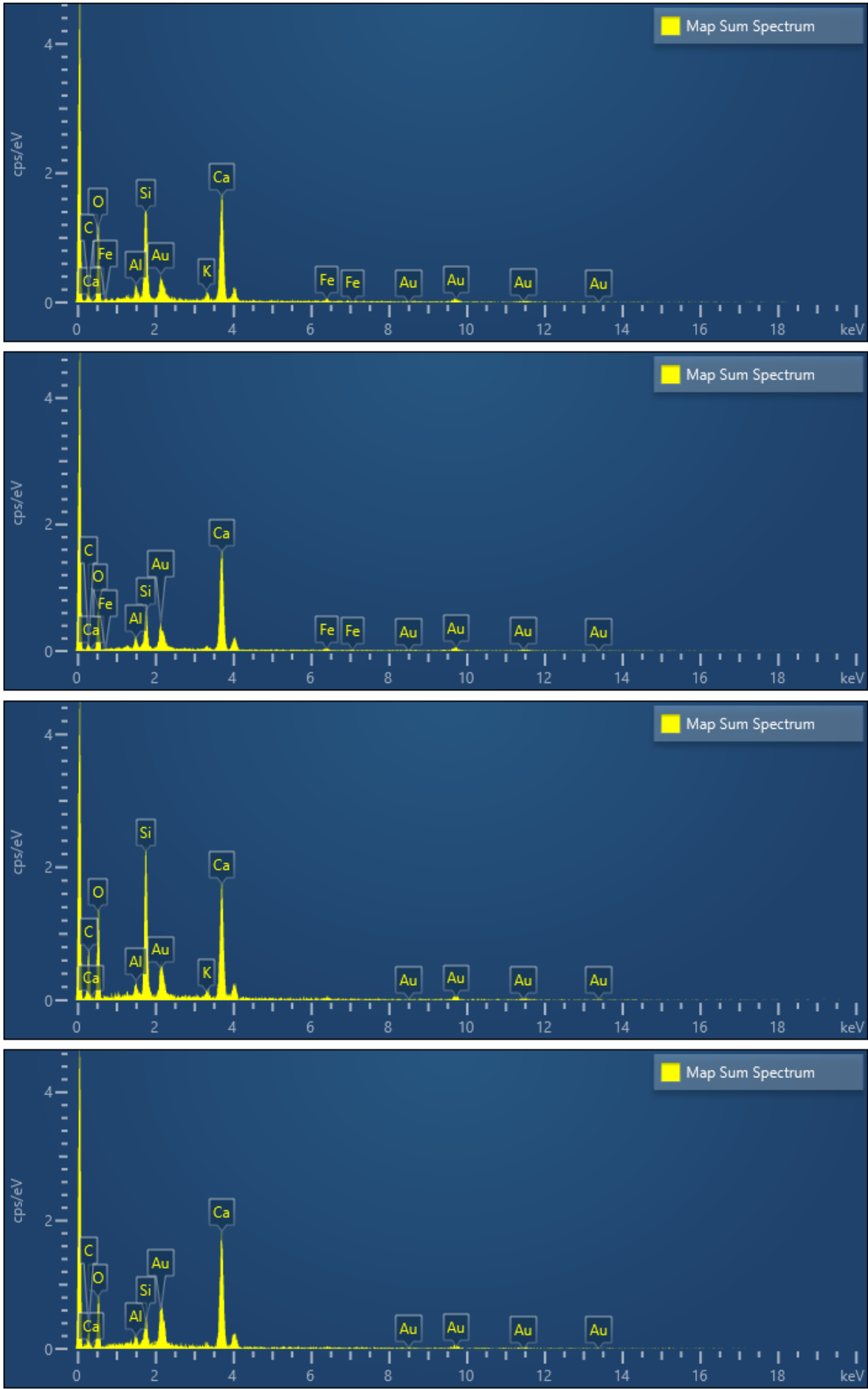


Fig. 8. EDS elemental analysis graph for the RH surface in four locations.

Table 3. The major element from the EDS elemental analysis graph.

Element	Weight (%)	Weight (%)	Weight (%)	Weight (%)	Weight (%) (Sudhir et al. 2024)
Oxygen, O ₂	52.38	51.23	42.95	51.18	53.68
Silicon, Si	9.54	6.02	9.31	3.64	37.57
Calcium, Ca	19.01	27.84	13.25	25.19	–
Aluminium, Al	1.47	2.08	0.79	1.45	–
Carbon, C	15.12	11.40	32.89	18.54	4.91
Potassium, K	1.20	0	0.81	0	1.06
Iron, Fe	1.28	1.44	0	0	–

Table 4. The sieve size analysis of the rice husk.

Sieve pan size	Percentage retained (%)	Percentage passing (%)
5.00 mm	0	100
3.35 mm	0	100
2.00 mm	48.72	51.28
1.18 mm	38.46	61.54
600 µm	7.69	92.31
300 µm	5.13	94.87
150 µm	0	100
75 µm	0	100
0	0	100

3.3. Weight and water absorption of hardened pervious concrete

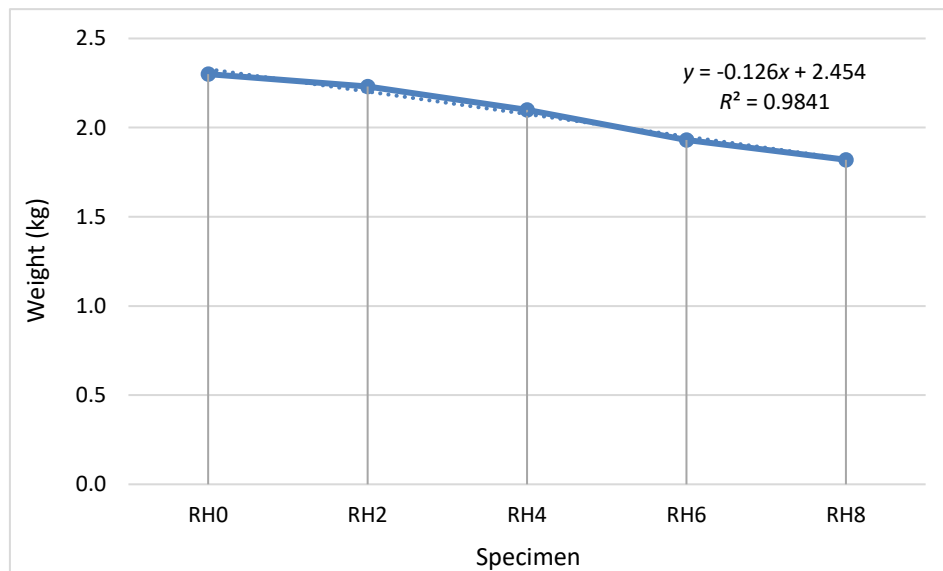
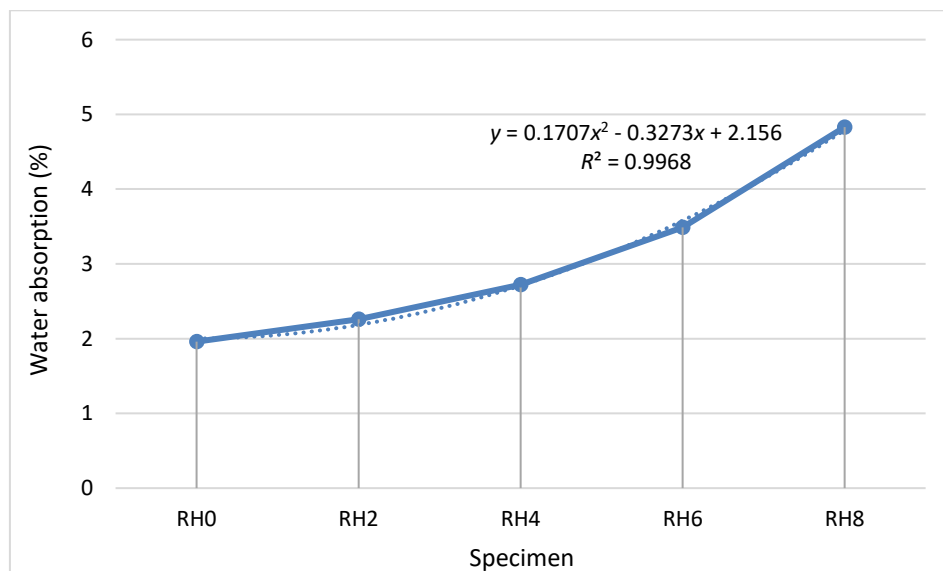
Table 5 presents the average amount of water that pervious concrete can absorb at atmospheric pressure, along with the average weight of the specimens. The relationship between specimen type and weight is illustrated in Fig. 9. The specimen weight decreased as the percentage of RH in pervious concrete increased, as previously noted, since RH is lighter than coarse aggregate. The percentage weight differences are as follows: 3.04% (between RH0 and RH2), 8.70% (between RH0 and RH4), 16.09% (between RH0 and RH6), and 20.87% (between RH0 and RH8). The weight percentage difference between the highest and lowest values, comparing RH2 and RH8, is 18.39%. The line graph in Fig. 9 shows a clear and consistent inverse relationship between specimen type and corresponding weight. The weight steadily decreased from approximately 2.3 kg for RH0 to about 1.8 kg for RH8. The high coefficient of determination (R^2) value of 0.9841 indicates that the linear regression model provides a good fit for the observed data points, reflecting a strong linear trend.

In the previous study, the percentage of water absorption increased with the increase of RH proportion due to its high water-absorption capacity. In addition, the water absorption percentages of all specimens are relatively low because pervious concrete typically facilitates the movement of water through its solid body and is characterised by a porous structure. The percentage differences in water absorption between RH0 and RH2, RH4,

RH6, and RH8 are 13.27%, 27.94%, 43.84%, and 59.42%, respectively. The relationship between water absorption and the pervious concrete specimens is shown in Fig. 10. Water absorption values vary by approximately 53.21% between RH8, which has the highest absorption, and RH2, which has the lowest absorption. Furthermore, the percentage difference in water absorption between RH2 and RH4 is 16.91%, and between RH2 and RH6 is 35.24%. According to Golewski (2023), normal concrete with water absorption of 4–6% is considered to have excellent durability, while normal concrete with water absorption below 5% is regarded as high quality. This study uses water absorption exclusively to observe the moisture uptake behaviour associated with RH rather than to assess durability. Pervious concrete, unlike normal concrete, features substantial interconnecting voids, rendering conventional durability standards unsuitable. The increasing absorption values indicate the high porosity of RH and its effect on the internal moisture absorption of the mix rather than a lack of durability. Based on the water absorption values, RH8 is classified as having good durability, and all specimens are classified as good quality. In conclusion, when considering the relationship between weight and water absorption, the weight of the specimen decreases as the percentage of water absorption increases. Fig. 10 illustrates an R^2 value of 0.9968, indicating an almost perfect fit of data and suggesting that the modification represented by the RH specimen systematically enhances capillary action or increases the internal surface area available for water retention.

Table 5. The weight and water absorption of every specimen.

Specimen	Weight (kg)	Water absorption (%)
RH0	2.30	1.96
RH2	2.23	2.26
RH4	2.10	2.72
RH6	1.93	3.49
RH8	1.82	4.83

**Fig. 9.** The relationship of weight and the specimens of coarse aggregate replacement.**Fig. 10.** The relationship of water absorption and specimens with different amounts of coarse aggregate replacement.

3.4. Compressive strength of hardened pervious concrete

The compressive strength and maximum load of the pervious concrete specimens for 7, 28, and 40 days were recorded and presented in Table 6. Both compressive strength and maximum load increased with curing age, reflecting the strength development of pervious con-

crete from its initial to mature state. All specimens exhibited lower compressive strength and maximum load compared to RH0, the control mix. The highest compressive strength values at 7, 28, and 40 were observed in RH2, while the lowest values were recorded for RH8. When comparing the highest and lowest compressive strength values, reductions of 81.21% at 7 days, 84.08% at 28 days, and 83.80% at 40 days were noted. Relative

to the control mix, the early compressive strength (7 days) of RH2, RH4, and RH6 was 10.07%, 34.23%, and 60.40%, respectively. At the mature age of 28 days, the percentage differences in compressive strength between the control mix and other specimens were 18.91% for RH2, 38.81% for RH4, and 70.15% for RH6. Fig. 11 illus-

trates the relationship between compressive strength and curing age of pervious concrete. Based on the results, a 2% replacement is identified as the optimum value when compared with other replacement percentages in terms of the compressive strength of pervious concrete.

Table 6. The compressive strength and maximum load of pervious concrete for 7 days, 28 days, and 40 days.

Specimen	Maximum load (N)	Compressive strength (MPa)	Maximum load (N)	Compressive strength (MPa)	Maximum load (N)	Compressive strength (MPa)
	7 days		28 days		40 days	
RH0	148.80	14.9	201.23	20.1	216.3	21.6
RH2	133.70	13.4	163.00	16.3	180.2	18.0
RH4	98.26	9.8	123.30	12.3	124.0	12.4
RH6	58.69	5.9	60.47	6.0	61.25	6.1
RH8	27.83	2.8	31.82	3.2	34.97	3.5

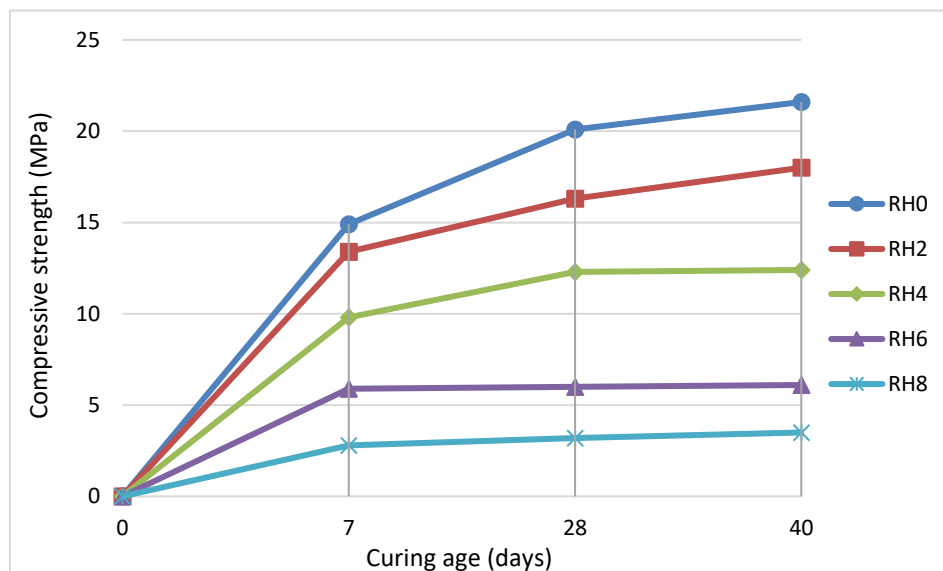


Fig. 11. The relationship of compressive strength and curing age for pervious concrete specimens.

If the relationship between compressive strength and specimens is examined with respect to curing age, as shown in Fig. 12, the compressive strength values for RH6 and RH8 are close to each other at 7, 28, and 40 days. Thus, pervious concrete with reasonable compressive strength is suitable for replacing coarse aggregate with RH at levels below 4%. Moura et al. (2021) reported that the compressive strength of pervious concrete using waste glass powder as a cement replacement by mass ranged from 11.1 to 23.0 MPa, which is within the standard of the compressive strength for pervious concrete (4–28 MPa) for cube specimens, and exceeds the Brazilian and American Concrete Institute standard of 20 MPa. However, according to Moura et al. (2021), all specimens met the standard except for the RH8 specimen. The compressive strength of pervious concrete decreased as the percentage of coarse aggregate replacement increased for all curing ages. This is because using a high percentage of RH for substituting coarse aggregate affects the bonding among RH, coarse aggregate, and cement, whereas using a low percentage of coarse aggregate results in poor compressive strength.

The failure pattern of the high RH utilisation in pervious concrete specimens differs from that of normal concrete, as shown in Fig. 13. Normal concrete generally demonstrates a brittle, clean fracture characterised by well-defined cracks due to its dense matrix and strong aggregate interlock. Conversely, the RH specimens exhibit irregular, crumbly and fibrous disintegration after testing, with loose RH particles and poorly bonded regions. This behaviour demonstrates the low density, porous structure and insufficient stiffness of the RH specimen which disrupts the aggregate framework and reduces load-transfer efficiency. The figure shows a specimen after being tested or compressed, demonstrating that it is not brittle, unlike the control mix. Although it is well known that adding or replacing RH in pervious concrete may reduce compressive strength due to its lightweight and porous nature, this study is important not only to confirm this trend but also to determine the degree of reduction, understand the influence on pore structure, and identify the optimum replacement level that balances compressive strength with enhanced sustainability or material efficiency.

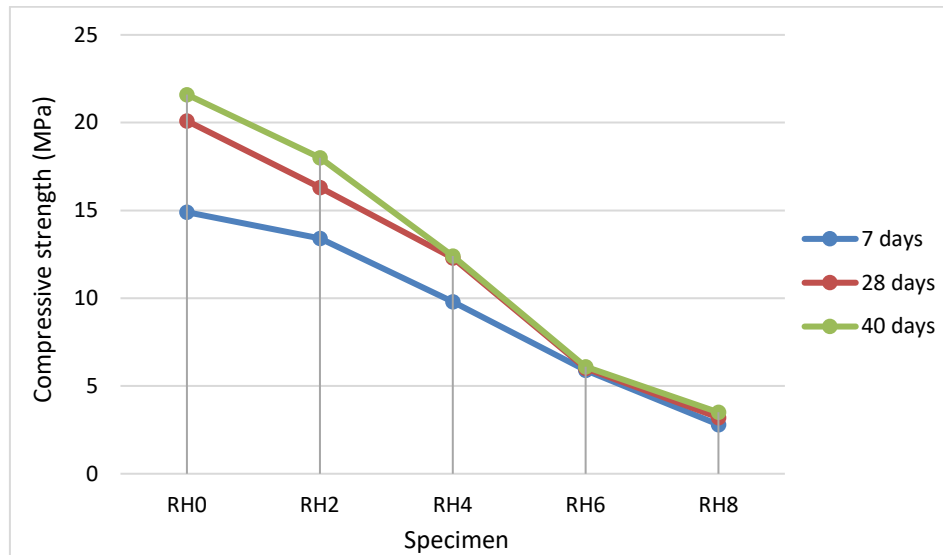


Fig. 12. The compressive strength values according to curing age.



Fig. 13. Photographs of the specimens after testing.

The study specifically concentrated on the structural integrity and material durability phases to determine the maximum gravel replacement limit of RH that preserves the mechanical properties and functionality. The focus on compressive strength is essential because RH, as an organic material, tends to weaken the interfacial transition zone, whereas water absorption serves as an initial indicator of the microporosity of the material. Furthermore, the study primarily examined the waste valorisation potential of agricultural by-products as a replacement for coarse aggregate. Although porosity and permeability are essential metrics for pervious concrete, these properties will be optimised in future phases after determining the viable mix proportions. Rice husk shows potential as a sustainable alternative in pervious concrete; however, its effectiveness is limited to replacement levels below 4%, as higher concentrations cause a significant reduction in compressive strength due to inadequate mechanical bonding between the organic fibres and the cement matrix.

4. Conclusions

From the experimental activity and analysis, the following comprehensive conclusions can be drawn:

- The surface morphology analysis demonstrates that RH is suitable for replacing coarse aggregate due to its rough surface texture, which is irregular and wavy rather than smooth. Moreover, elemental analysis revealed that RH has three major elements: O, Ca, and C.
- The weight of pervious concrete decreases as the percentage of RH, which is used as a coarse aggregate replacement, increases; while the water absorption of the pervious concrete increases with higher RH content. The water absorption of pervious concrete remains relatively low because water easily seeps through the porous solid parts of the concrete.
- The compressive strength of the pervious concrete decreases as the proportion of coarse aggregate replaced by RH increases. Additionally, the percentage difference in compressive strength at 28 days between the control mix and the other specimens ranges from 18% to 70%. Thus, pervious concrete containing 2% RH as a replacement for coarse aggregate exhibits the highest compressive strength at 7, 28, and 40 days. Therefore, RH2 is classified as a potential replacement for coarse aggregate in the production of pervious concrete.

By limiting the study to the compressive strength and water absorption of pervious concrete, other physical

and mechanical properties should also be tested to obtain comprehensive data. Several adjustments and further chemical processes are required (e.g., the addition of a superplasticiser) to improve the water absorption and compressive strength of the pervious concrete. Furthermore, the potential of RH as a replacement for concrete materials, especially as an aggregate in specialised concrete, should be studied and investigated. Finally, future studies should expand upon the preliminary findings regarding mechanical properties by incorporating standardised porosity and permeability tests to comprehensively evaluate the hydraulic performance of RH-integrated pervious concrete.

Acknowledgements

The authors would like to express their gratitude to Universiti Teknologi MARA (UiTM) Pahang Branch, for providing laboratory equipment and facility support. The authors also appreciate the lecturers and laboratory assistant engineers from the Faculty of Civil Engineering, UiTM Pahang Branch, for their encouragement and assistance throughout the experimental activities.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- Abd Rahman NA, Muhamad Shah MA, Muhamad NS, Yacob AA, Zardasti L (2019). Compressive strength and infiltration characteristic of pervious concrete using recycled concrete aggregate. *IOP Conference Series: Materials Science and Engineering*, 601(1), 012031.
- Alomayri T, Adesina A, Das S (2021). Influence of amorphous raw rice husk ash as precursor and curing condition on the performance of alkali activated concrete. *Case Studies in Construction Materials*, 15, e00777.
- Alyami M, Hakeem IY, Amin M, Zeyad AM, Tayeh BA, Agwa IS (2023). Effect of agriculture olive, rice husk and sugarcane leaf waste ashes on sustainable ultra-high-performance concrete. *Journal of Building Engineering*, 72, 106689.
- Bhujel L, Baral P, Ranabhat S, Subedi S, Aalam T, Gyawali TR (2025). Utilization of Prunus cerasoides shell (PCS) as sustainable substitute for natural aggregates in concrete. *Cleaner Waste Systems*, 12, 100348.
- BS EN 12390-3 (2019). *Testing Hardened Concrete - Compressive Strength of Test Specimens*. British Standards Institution, London, UK.
- Chabannes M, Benezet JC, Clerc L, Garcia-Diaz E (2014). Use of raw rice husk as natural aggregate in a lightweight insulating concrete: an innovative application. *Construction and Building Materials*, 70, 428-438.
- Chabannes M, Garcia-Diaz E, Clerc L, Benezet JC (2016). Effect of curing conditions and Ca(OH)₂-treated aggregates on mechanical properties of rice husk and hemp concretes using a lime-based binder. *Construction and Building Materials*, 102, 821-833.
- Chabi E, Lecomte A, Adjovi EC, Dieye A, Merlin A (2018). Mix design method for plant aggregates concrete: example of the rice husk. *Construction and Building Materials*, 174, 233-243.
- Chen S, Zhou J, Liu J, Bie Y, Hu Q (2024). Sustainable ecological pervious concrete (SEPC) based on modified corn-cob coarse aggregate: crushing morphology, strength, pore properties, and durability. *Construction and Building Materials*, 426, 136194.
- Chen Z, Xu Y, Shivkumar S (2018). Microstructure and tensile properties of various varieties of rice husk. *Journal of the Science of Food and Agriculture*, 98(3), 1061-1070.
- Chetan D, Aravindan A (2020). An experimental investigation on strength characteristics by partial replacement of rice husk ash and Robo sand in concrete. *Materials Today: Proceedings*, 33, 502-507.
- Fernandes FAS, Arcaro S, Tochtrop Junior EF, Valdés Serra JC, Pérez Bergmann C (2019). Glass foams produced from soda-lime glass waste and rice husk ash applied as partial substitutes for concrete aggregates. *Process Safety and Environmental Protection*, 128, 77-84.
- Firouzi M, Shamsudin S, Nekooie MA, Abd Rahis AJ, Taherkhani R, Mohamad MI (2012). Pervious concrete texture analysis for infiltration rate evaluation. *Advanced Science Letters*, 13, 877-878.
- Golewski GL (2023). Assessing of water absorption on concrete composites containing fly ash up to 30% in regards to structures completely immersed in water. *Case Studies in Construction Materials*, 19, e02337.
- Kováč M, Sičáková A (2018). Pervious concrete as an environmental solution for pavements: focus on key properties. *Environments*, 5(1), 11.
- Lo FC, Lee MG, Lo SL (2021). Effect of coal ash and rice husk ash partial replacement in ordinary Portland cement on pervious concrete. *Construction and Building Materials*, 286, 122947.
- Lopez N, Collado E, Diacos LA, Morente HD (2019). Evaluation of pervious concrete utilizing recycled HDPE as partial replacement of coarse aggregate with acrylic as additive. *MATEC Web of Conferences*, 258, 01018.
- Malayali AB, Chokkalingam RB (2018). Mechanical properties of geopolymer pervious concrete. *International Journal of Civil Engineering and Technology*, 9(11), 2394-2400.
- Mareya M, Bahurudeen A, Varghese J, Thomas BS, Sithole NT (2023). Transformation of rice husk modified basic oxygen furnace slag into geopolymer composites. *Journal of Materials Research and Technology*, 24, 6264-6278.
- Maryoto A, Sudibyo GH (2019). The influence of rice husk on the physical properties of Portland Pozzoland cement at the cement industry scale. *MATEC Web of Conferences*, 258, 01005.
- Moura JMBM, Pinheiro IG, Aguado A, Rohden AB (2021). Sustainable pervious concrete containing glass powder waste: performance and modeling. *Journal of Cleaner Production*, 316, 128213.
- Narattha C, Wattanasiriwech S, Wattanasiriwech D (2024). Sustainable, multifunctional fly ash geopolymer composite with rice husk aggregates for improved acoustic, hygric, and thermal performance. *Construction and Building Materials*, 445, 137743.
- Obilade IO (2014). Experimental study on rice husk as fine aggregates in concrete. *The International Journal of Engineering and Science*, 3(8), 9-14.
- Obla KH (2010). Pervious concrete - an overview. *Indian Concrete Journal*, 84(8), 9-18.
- Patil AR, Sawant SK, Meshram PM (2020). Intelligent replaced of natural aggregate and cement with recycled concrete aggregate, rice husk ash. *International Journal of Recent Technology and Engineering*, 8(5), 3852-3856.
- Rattanachu P, Toolkasikorn P, Tangchirapat W, Chindaprasirt P, Jaturapitakkul C (2020). Performance of recycled aggregate concrete with rice husk ash as cement binder. *Cement and Concrete Composites*, 108, 103533.

- Reddy KR, Harihanandh M, Murali K (2021). Strength performance of high-grade concrete using rice husk ash (RHA) as cement replacement material. *Materials Today: Proceedings*, 46, 8822-8825.
- Sahoo S, Parhi PK, Panda BC (2021). Durability properties of concrete with silica fume and rice husk ash. *Cleaner Engineering and Technology*, 2, 100067.
- Samantaray SS, Panda KC, Mishra M (2016). Rice husk ash as fine aggregate sustainable material for strength enhancement of conventional and self compacting concrete. *Key Engineering Materials*, 692, 94-103.
- Shang X, Wu S, Liu Y, Zhang K, Guo M, Zhou Y, Zhu J, Li X, Miao R (2024). Rice husk and its derived biochar assist phytoremediation of heavy metals and PAHs co-contaminated soils but differently affect bacterial community. *Journal of Hazardous Materials*, 466, 133684.
- Shariati M, Kamyab H, Habibi M, Ahmadi S, Naghipour M, Gorjinezhad F, Mohammadirad S, Aminian A (2023). Sulfuric acid resistance of concrete containing coal waste as a partial substitute for fine and coarse aggregates. *Fuel*, 348, 128311.
- Shende A, Borkar P, Borghare R, Manvar S, Raza R, Bhaisare S, Kammerkar S, Bais S, Nandi T, Meshram S (2019). Analysis of strength of pervious concrete by adding rice husk ash and glass fibre. *International Journal of Research in Engineering, Science and Management*, 2(3), 534-537.
- Singh D, Singh SP (2020). Influence of recycled concrete aggregates and blended cements on the mechanical properties of pervious concrete. *Innovative Infrastructure Solutions*, 5(3), 66.
- Sreesvarna B, Pugalendhi S, Subramanian P, Gitanjali J (2019). Characterization of rice husk for sustainable applications. *Madras Agricultural Journal*, 106(Special), 279-283.
- Sudhir S, Soren S, Chowdhury GM, Jaiswal RK, Nirala A, Khan MA, Alkahtani MQ, Islam S, Algburi S (2024). Utilization of rice husk substituting fossil fuel for pelletization process of goethite iron ore. *Environmental Technology & Innovation*, 34, 103597.
- Supit SWM, Priyono (2022). Utilization of recycled PET plastic waste as replacement of coarse aggregate in pervious concrete. *Materials Today: Proceedings*, 66, 2990-2995.
- Talsania S, Pitroda J, Vyas CM (2015). Effect of rice husk ash on properties of pervious concrete. *International Journal of Advanced Engineering Research and Studies*, 4(2), 296-299.
- Tijani MA, Ajagbe WO, Agbede OA (2022). Recycling sorghum husk and palm kernel shell wastes for pervious concrete production. *Journal of Cleaner Production*, 380, 134976.
- Torres A, Aguayo F, Gaedicke C, Nerby P, Cavazos M (2020). Developing high strength pervious concrete mixtures with local materials. *Journal of Materials Science and Chemical Engineering*, 8(1), 20-34.
- Varadharajan S, Jaiswal A, Verma S (2020). Assessment of mechanical properties and environmental benefits of using rice husk ash and marble dust in concrete. *Structures*, 28, 389-406.
- Wang ZY, Chen L, Zhang WL, Zhang K (2024). Environmental compatibility of pervious concrete with recycled coarse aggregate applying in riparian buffer area. *Construction and Building Materials*, 411, 134590.
- Winarno S (2019). Comparative strength and cost of rice husk concrete block. *MATEC Web of Conferences*, 280, 04002.
- Yuzer N, Cinar Z, Aköz F, Biricik H, Gurkan YY, Kabay N, Kizilkanat AB (2013). Influence of raw rice husk addition on structure and properties of concrete. *Construction and Building Materials*, 44, 54-62.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Effect of crushed brick chips as coarse aggregate on the mechanical properties, water absorption and cost of concrete

Md. Rashedul Haque ^{a,*} , Md. Saied Sakib ^a , Abu Saeed ^a , Md. Abu Sufian ^a

^a Department of Civil Engineering, Hajee Mohammad Danesh Science and Technology University, Dinajpur 5200, Bangladesh

ABSTRACT

In Bangladesh, natural coarse aggregates (NCA) are limited in availability and more expensive to transport than other materials. On the other hand, brick chips (BC) are a more affordable, widely available option for use as coarse aggregate in concrete production. Also, owners tend to use stone chips in particular structural components, such as foundations and columns, and brick chips in others, such as beams and slabs. This leads to non-homogeneous structural strength, which increases differential shrinkage and the development of cracks. Therefore, replacing NCA with BC may help reduce structural dead load, improve cost-effectiveness, and mitigate the problems associated with NCA. The objective of this research is to evaluate the effects of replacing NCA with BC (0%, 20%, 40%, 60%, 80%, and 100% of NCA) on selecting the optimal BC replacement percentage and on the mechanical properties and water absorption capacity of concrete. This study was designed to attain a target compressive strength of 25 MPa and was evaluated at 7, 14, and 28 days. In this study, standard cylindrical specimens measuring 100 mm × 200 mm were cast, cured, and tested for mechanical properties at 7, 14, and 28 days to evaluate the effect of increasing the brick chip content on concrete performance. This study identified an optimal replacement ratio of 40% BC replaced with NCA, resulting in a 6.90% reduction in unit weight, a 6.28% reduction in compressive strength, a 17.97% reduction in splitting tensile strength, and a 3.25% reduction in modulus of elasticity. Additionally, a trend of rising water absorption is observed with higher replacement levels.

Citation: Haque MR, Sakib MS, Saeed A, Sufian MA (2026). Effect of crushed brick chips as coarse aggregate on the mechanical properties, water absorption and cost of concrete. *Challenge Journal of Concrete Research Letters*, 17(3), 278–292.

ARTICLE INFO

Article history:

Received – March 8, 2026
Revision requested – April 11, 2026
Revision received – May 20, 2026
Accepted – May 26, 2026

Keywords:

Crushed brick chips
Sustainable concrete
Mechanical properties
Water absorption capacity
Cost analysis



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

1. Introduction

Concrete is one of the most extensively utilized artificial materials in the world because of its strength, durability, and resilience, as well as its formability into any shape, which has significantly boosted its popularity and is projected to drive a 30 billion-tonne direct material demand per annum (Miller and Moore 2020; Monteiro et al. 2017). Since concrete production accounts for nearly 8% of worldwide human-induced greenhouse gas (GHG) emissions and 3% of global energy consumption, assessing anticipated mitigation approaches in this sector is vital for creating low- or zero-carbon emission path-

ways (Miller et al. 2016; Monteiro et al. 2017). In 2019, the building sector accounted for 36% of total energy demand and 38% of total CO₂ emissions, ranking among the top three energy-intensive sectors and a key contributor to both direct and indirect carbon emissions. In response to increasing public anxiety about global warming and the role of GHGs in worsening it, scientists have investigated various innovative CO₂ capture and storage (CCS) options in various structures (UNEP 2022; Wani et al. 2023). Approximately 5-7% of universal CO₂ emissions are attributed to the extensive use of OPC concrete, making it essential to develop sustainable concrete by modifying existing materials and re-evaluating their

* Corresponding author. E-mail address: rashed.civil@hstu.ac.bd (M. R. Haque)

uses (Hamouda et al. 2020; He et al. 2019; Wani et al. 2024), with waste valorization increasingly emphasized as a means of conserving natural resources and reducing the environmental burden of construction materials (Mahmud et al. 2025; Ünal and Canbaz 2025, 2026). At the microscopic scale, concrete is a heterogeneous material containing voids that confer porosity, increasing the likelihood of physical and chemical assaults that can degrade concrete and further corrode the steel reinforcement (Turner and Collins 2013; Wani et al. 2024). Moreover, concrete can be moulded into any desired shape; it is functionally and aesthetically more admissible (Bhushal et al. 2025; Haque et al. 2021). Concrete aggregates are generally derived from natural rocks, but now in Bangladesh, natural rock deposits are very scarce and not available everywhere. Due to the scarcity of natural aggregate, availability, and low-cost brick aggregates are commonly utilized in Bangladesh, which may result in overall cost effectiveness. Similar waste-derived aggregate substitution strategies have been investigated to reduce reliance on natural resources while maintaining satisfactory material performance at appropriate replacement levels (Wee Chit et al. 2025). Due to having a weight range of 1,121–1,922 kg/m³, brick chips may be utilized as lightweight aggregate (Malešev et al. 2010; Uddin et al. 2017). However, brick chip (BC) concrete usually exhibits lower strength and often undergoes durability issues (Afroz et al. 2015; Basak et al. 2024; Haque et al. 2021). Thus, the study on the dynamic application of BC in the construction sector is very significant from a Bangladeshi perspective. Among all concrete components, aggregates account for about 75% of the concrete body and impart greater volumetric stability and improved durability compared to hydrated cement paste (Rashid et al. 2012; Mimi et al. 2023). Crushed brick concrete is conventionally used in the construction of reinforced cement concrete (RCC) pavements, culverts and bridges, and is fit for six-story buildings (Ali et al. 2022; Mansur et al. 1999). Additionally, the density of concrete made with brick chips has been recorded to be considerably less than that of concrete made with stone aggregate (Rashid et al. 2008). In the feasibility study concerning the complete or partial volumetric substitution of stone aggregate with brick chips in concrete, this research aims to examine the characteristics of concrete made with mixed aggregates (Hasan et al. 2007; Bhowmik and Pal 2022). Using brick chips as an alternative to stone aggregates in a building structure can substantially decrease dead load on columns and the foundation. Thus, the substitution (partially or entirely) of stone chips with brick chips could result in cost savings. Concrete has often been found to be a sustainable choice for various structures, from domestic to industrial buildings, bridges, and foundations. Moreover, concrete's structural integrity provides additional safeguards against earthquakes and extreme weather. Azunna and Ogar (2021) investigated the properties of concrete with partial replacement of stone chips with burnt brick waste and found that compressive strength increases from 0% to 20% burnt brick waste, but decreases as the percentage of over-burnt brick waste increases. Joshi (2020) explored the use of over-burnt brick as a coarse aggregate in concrete, comparing its properties with nat-

ural stone aggregates, revealing that burnt brick aggregates performed comparably well, with compressive strengths of 24.9 MPa at a w/c ratio of 0.45 at 28 days, slightly higher than natural stone aggregates in similar conditions. Apebo et al. (2014) studied the use of over-burnt brick bats as coarse aggregates. Their results indicated that compressive strength increased when up to 20% of coarse aggregate was replaced with brick bats. Lonth et al. (2018) examined the mechanical properties of concrete containing brick chips. Their study revealed a 46% decrease in cylindrical compressive strength. This indicates that 25% of the virgin aggregate in concrete can be substituted without altering the mix design. Rashid et al. (2012) investigated the effects of replacing natural stone chips with crushed clay-brick aggregate in concrete. The results reveal that replacing stone with brick aggregate lowers compressive strength by 33%. Habib et al. (2022) emphasized the benefits of internal curing in concrete mixes with partial brick chip replacement. By utilizing different proportions of brick chips (e.g., 50%, 75%, and 100%), the study found that curing conditions like 7-WP (seven days underwater with polythene cover) and 3-WP (three days underwater with polythene cover) improved the compressive strength of brick chip-based concrete. Chen et al. (2019) highlighted the potential of recycled clay brick aggregate (RBA) concrete for sustainable construction. Studies indicate that RBA improves internal curing, significantly enhancing compressive strength at 14 days, especially at replacement ratios between 40% and 60%. Optimal results show a 20-28% gain at 28 days. More recent findings also indicate that recycled brick aggregate can retain acceptable mechanical performance at moderate replacement levels, whereas higher replacement ratios may lead to more pronounced strength reductions (Niroula and Bhatt 2026).

The study on the effects of replacing natural stone aggregate with crushed clay-brick chips in concrete found that replacing stone with brick chips reduced the unit weight by 14.5%. Dwivedi (2017) investigated the properties of concrete with burnt brick chips and C&D waste. The study supported the viability of burnt bricks as an eco-friendly alternative, particularly in light-load applications. Rashid et al. (2012) inspected the effects of replacing natural stone aggregate with crushed clay-brick chips in concrete, suggesting that mixed aggregates can provide structural benefits, such as lower dead load, particularly in areas where natural aggregates are scarce. Proposed methods for estimating the mechanical characteristics of mixed-aggregate concrete are presented. Daniel (2025) explored the properties of concrete with partial substitution of stone chips with burnt bricks and reported a high-water absorption rate of 12-20% by mass.

Despite the growing interest in sustainable construction materials, the utilization of brick aggregates in structural concrete remains limited due to concerns regarding their mechanical and durability performance. However, brick chips have the potential to provide an alternative coarse aggregate, particularly in regions where natural stone chips are scarce or where large quantities of brick waste are generated from demolition activities. Therefore, a comprehensive understanding of the fresh

and hardened properties of brick chips concrete is necessary to evaluate its suitability for structural applications, such as non-structural elements and lightweight construction. In this study, concrete mixtures incorporating different proportions of brick chips (0%, 20%, 40%, 60%, 80%, and 100%) as a replacement for stone chips were evaluated. The workability, unit weight, mechanical properties, and water absorption characteristics of concrete were experimentally assessed and compared with those of normal concrete. The outcome of this research is intended to provide insights into the feasibility of using brick chips as a sustainable aggregate material in concrete production and to contribute to the enhancement of more sustainable construction practices.

2. Materials and Methodology

2.1. Raw materials

In this study, Portland cement has been utilized as the binding agent. Specifically, PREMIER Cement, a Portland cement, has been utilized and originates from the town of Dinajpur. Fine aggregates are small-sized filler mate-

rials used in construction. In this study, sand is treated as a fine aggregate. The maximum size of stone chips is determined by the nature of the work. This study employed locally available stone chips of a maximum size of 19 mm. The aggregates were washed to eliminate dust and grime, then dried to a saturated surface-dry (SSD) condition. This study employed brick chip aggregates from Dinajpur's brick field, conforming to ASTM C33 (2023), with a nominal maximum brick chip size of 19 mm. The raw materials utilized in this study are presented in Fig. 1; the gradation curves of sand, stone and brick chips are displayed in Fig. 2; and the physical properties are depicted in Table 1.

2.2. Mixing and preparation

Workability tests were performed for each concrete mix in accordance with ASTM C 143/C143M (2026). In this study, the volumetric substitution of stone chips with brick chips examined was 0%, 20%, 40%, 60%, 80% and 100%, while all other parameters remained constant. The quantities of materials required per m³ to produce 25 MPa grade concrete with different brick percentages are specified in Table 2.



(a) Cement



(b) Sand



(c) NCA



(d) BC

Fig. 1. Raw materials utilized in this study.

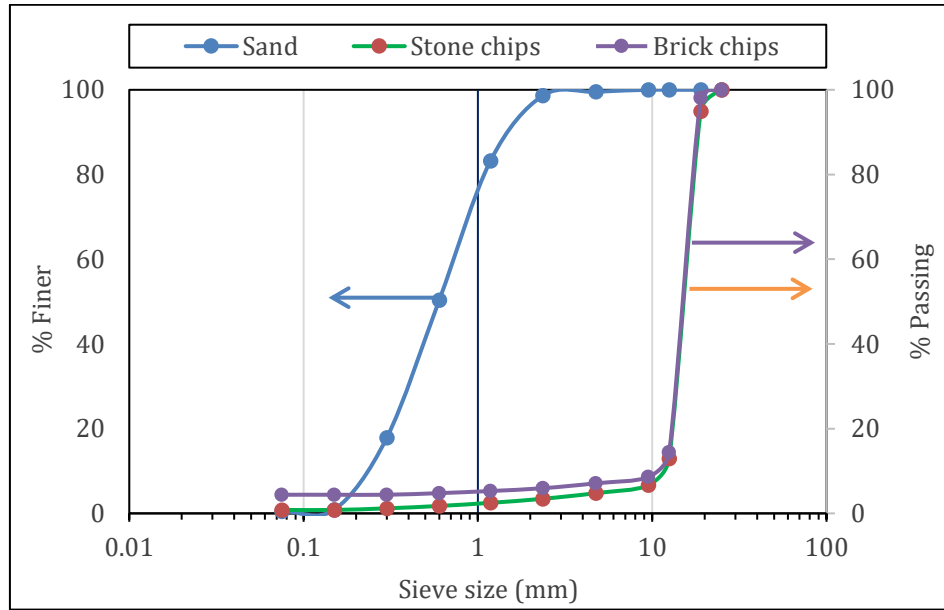


Fig. 2. Gradation curve of sand, stone and brick chips.

Table 1. Physical characteristics of raw material used in this study.

Physical properties	Fine aggregate	Coarse aggregate	
		Stone chips	Brick chips
Bulk specific gravity (SSD) (ASTM C127 2025; ASTM C128 2025)	2.70	2.78	2.18
Water absorption (%) (ASTM C127 2025; ASTM C128 2025)	3.14	0.50	8.90
Fineness modulus (ASTM C136 2015)	2.51	3.84	3.90
Unit weight (kg/m ³) (ASTM C29 2023)	1590	1545	1135

Table 2. Concrete mix proportion used in this study.

Mix ID	Cement	Sand	Brick chips	Stone chips	Water
M0	388	772	0	1031.0	185.1
M20	388	772	206.2	824.8	185.1
M40	388	772	412.4	618.6	185.1
M60	388	772	618.6	412.4	185.1
M80	388	772	824.8	206.2	185.1
M100	388	772	1031.0	0	185.1

** All units of the table are in kg/m³.

The test samples were separated into six series, and the subsequent concrete mixes were categorized as M₀, M₂₀, M₄₀, M₆₀, M₈₀ and M₁₀₀. Where ‘M’ refers to ‘concrete mix’ and the subscript refers to the “percentage of stone chips replaced by brick chips from the total coarse aggregate”. In each series, 3 concrete cylinders were cast, cured, and tested for mechanical properties (3 specimens for each property). In this study, a total of 54 cylinders were prepared for compressive strength and 54 for splitting tensile strength, and tested at 7, 14, and 28 days.

The cylindrical molds were demolded and transferred to a water container for approximately 24 hours of curing after casting. Curing was performed by immersing the cylindrical specimen in water in accordance with ASTM C192 (2026). In this study, both fine and coarse aggregates (stone and brick chips) were used in the SSD condition, with normal tap water. Curing was performed for 7, 14, and 28 days, per ASTM C31 (2019). The summary of the experimental program in this study is depicted in Table 3.

Table 3. Summary of experimental program.

Test type	Codes	Specimen size (mm)	Number of samples	Age of samples (days)
Compressive strength	ASTM C39/C39 M (2023)	100 × 200	Type of mixture×3×3	7, 14, and 28
Splitting tensile strength	ASTM C496 (2017)	100 × 200	Type of mixture×3×3	7, 14, and 28
Elastic modulus	ACI CODE-318-19 (2022)	100 × 200	Type of mixture×3×3	7, 14, and 28
Water absorption capacity	ASTM C642 (2001)	100 × 200	Type of mixture×3×3	28

** Type of mixture = 6, 3 = samples for each test and 3 = number of curing days.

2.3. Experimental methodology

2.3.1. Material testing

Concrete specimens (100 mm × 200 mm) were tested for compressive strength based on ASTM C39/C39M (2023) and splitting tensile strength based on ASTM C496 (2017) using a CTM with a capacity of 1500 kN at

7, 14, and 28 days of curing, with loading rates of 0.33 MPa/s for compressive and 0.067 MPa/s for splitting tensile strength, respectively.

The specimen was placed under a bearing block, and a gradual load application was started. The loading was displayed on the screen and noted down. Fig. 3 shows the set-up for the mechanical property tests of concrete.

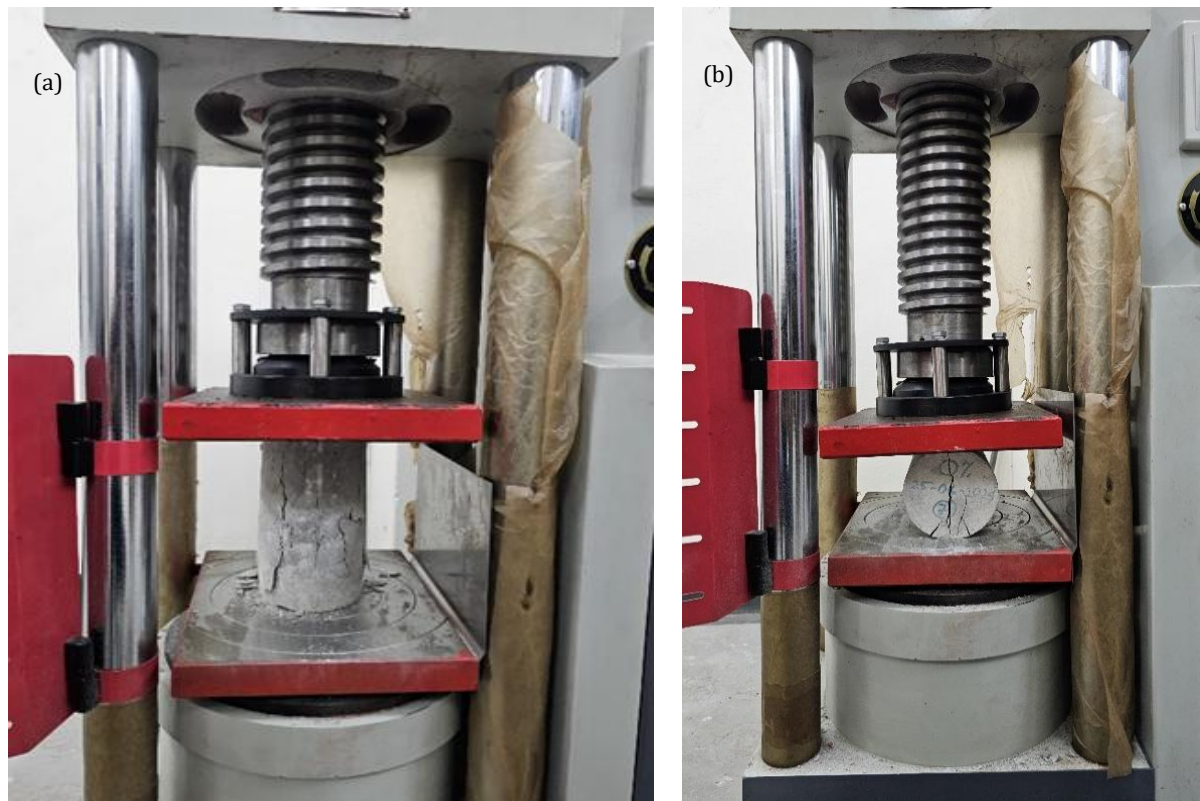


Fig. 3. (a) Compressive and (b) splitting tensile strength test set-up used in this study.

2.3.2. Modulus of elasticity

The modulus of elasticity of a concrete specimen, commonly known as Young's modulus, is generally a measure of resistance to deformation under loading. As per ACI CODE-318-19 (2022), the modulus of elasticity of the specimens can be obtained from the compressive strengths at 7, 14, and 28 days, as per ASTM C39/C39 M (2023). The modulus of elasticity of concrete specimens is described by Eq. (1), as it can be used as normal-strength concrete.

$$E_c = 4700 \sqrt{f'_c} \text{ (MPa)} \quad (1)$$

where f'_c is the compressive strength of concrete at the corresponding curing age, in MPa.

2.3.3. Water absorption capacity

The concrete cylinders were evaluated for water absorption capacity after 28 days of curing, in accordance with ASTM C642 (2001). At first, the weights of specimens were recorded in the SSD condition. After that, the specimens were left in an oven at 100–110 °C for 24 hours, and the oven-dried (OD) weights were recorded again. Fig. 4 represents the water absorption capacity (WAC) test of cylindrical specimens conducted in this study.



Fig. 4. Water absorption capacity test conducted in this study.

Finally, the water absorption capacity (WAC) was estimated using Eq. (2).

$$\text{Water Absorption Capacity (\%)} = \left(\frac{B-A}{A} \right) \times 100 \quad (2)$$

where A is the weight of oven-dried specimen in air (g) and B is the weight of SSD conditioned specimen in air (g).

2.3.4. Unit weight

The term unit weight of the cylindrical specimen, expressed in kg/m^3 , according to ASTM C138 (2023), refers to the weight of a concrete specimen per unit volume. To evaluate the unit weights of concrete specimens with various BC percentages (0% to 100%), weights were recorded in both the SSD and OD conditions. This was followed by dividing these values by the measured specimen volume.

3. Results and Discussion

3.1. Slump test

The slump value of concrete mixtures containing different proportions of BC as a replacement for natural coarse aggregates was determined using the workability test specified in ASTM C143 (2026). The results are displayed in Fig. 5. As observed, the slump value of the control mix (0% BC) was approximately 110 mm, indicating good workability of the conventional concrete mixture.

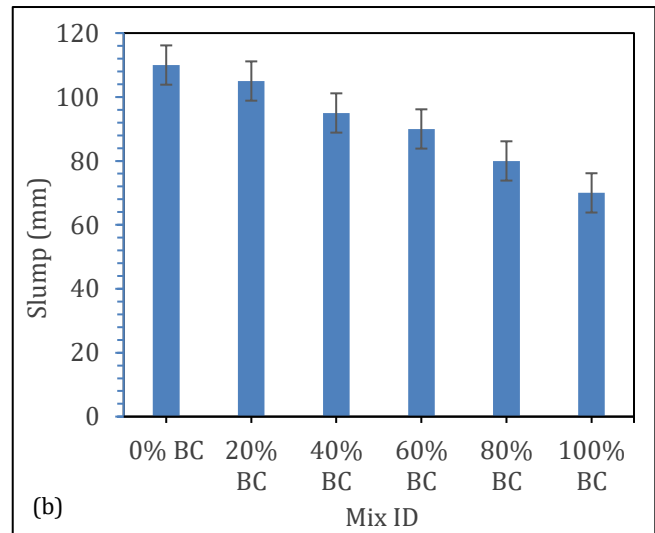


Fig. 5. (a) Workability measurement; (b) Variation of the slump value of the concrete.

With the incorporation of brick chips, a gradual decrease in slump was monitored. The slump decreased to about 105 mm, 95 mm, 90 mm, 80 mm, and 70 mm for mixes containing 20%, 40%, 60%, 80%, and 100% BC, respectively. The reduction in slump with increasing brick chip content can be attributed primarily to the higher WAC and rough, porous surface texture of brick aggregates compared to natural coarse aggregates. These characteristics increase the internal friction between particles and reduce the free water present in the mix, thereby decreasing the flowability of fresh concrete.

Similar trends have been reported in previous studies on recycled brick aggregate concrete (Debieb and Kenai 2008; Mansur et al. 1999).

3.2. Mechanical properties

At 7, 14, and 28 days, the compressive strengths of BC concrete for various replacement levels of stone chips by brick chips (0%, 20%, 40%, 60%, 80%, and 100%) are depicted in Fig. 6.

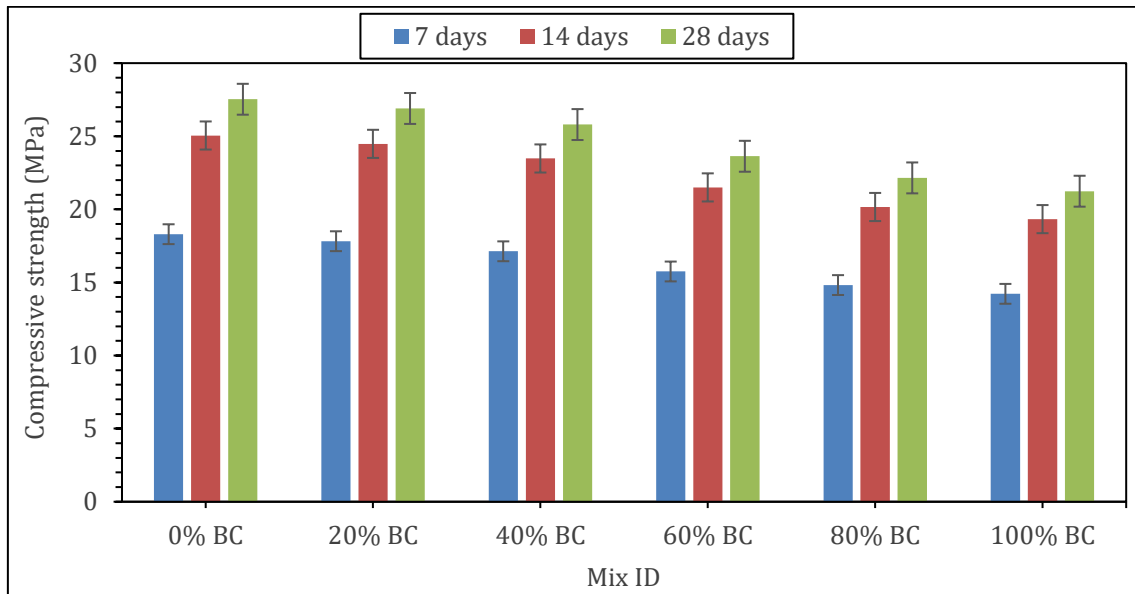


Fig. 6. Compressive strength of concrete at 7, 14, and 28-days.

From Fig. 6, the highest compressive strength at 7 days was observed by 0% BC, at 18.30 MPa. For 20%, 40%, 60%, 80%, and 100%, the values were 17.82, 17.13, 15.75, 14.82, and 14.22 MPa, respectively. For compressive strength at 14 days, a significant increase is observed. The compressive strength of the control mix has been found to be 25.05 MPa. The highest compressive strength was observed with a 20% replacement of SC by BC. From Fig. 6, the concrete specimen with 40% replacement of stone chips with brick chips attains a compressive strength of 25.80 MPa, exceeding the design value of this research. Higher replacement levels of stone chips with brick chips (60%, 80%, and 100%) have not yielded satisfactory compressive strength (Cachim 2009; Debieb and Kenai 2008; Yang et al. 2011). The variation in compressive strength was observed as 2.62%, 6.39%, 13.93%, 19.02%, and 22.30% for 20%, 40%, 60%, 80%, and 100% BC, respectively, compared to 0%

BC concrete at 7 days of curing. Alternatively, in 28 days, the variation in compressive strength was 2.29%, 6.28%, 14.17%, 19.54%, and 22.85% for 20%, 40%, 60%, 80%, and 100% BC, respectively. The decrease in compressive strength with increasing brick chip replacement can primarily be attributed to the inferior mechanical properties and higher porosity of brick aggregates compared to those of natural coarse aggregates. Brick chips generally have lower crushing strength and stiffness, thereby reducing the load-carrying capacity of concrete under tensile stress (Debieb and Kenai 2008). In addition, brick aggregates have a highly porous, rough microstructure, leading to greater water absorption. This may create a more porous cement matrix, ultimately weakening the concrete structure.

The split tensile strength of BC concrete as a substitution for natural coarse aggregate at 7, 14, and 28 days is presented in Fig. 7.

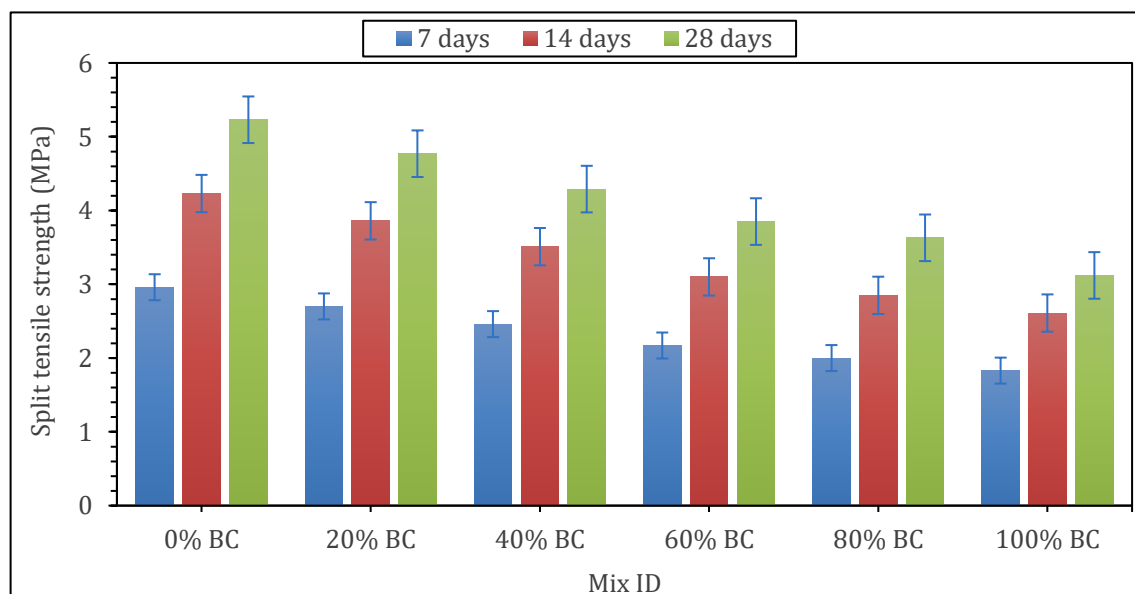


Fig. 7. Splitting tensile strength of concrete at 7, 14, and 28-days.

The results indicate that the split tensile strength increases with curing age for all mixtures, reflecting the normal hydration and strength development of cementitious materials. The control (0% BC) showed the highest tensile strength at the tested ages, with values of approximately 3.0, 4.2, and 5.2 MPa at 7, 14, and 28 days, respectively. As the percentage of brick chips increased, a gradual decrease in split tensile strength was monitored. For mixtures containing 20% and 40% BC, the reduction in strength was relatively moderate. The 28-day tensile strength for these mixes was about 4.7 MPa and 4.3 MPa, respectively, indicating that partial replacement of natural aggregates with brick chips still maintains reasonable tensile performance. However, when the replacement

level exceeded 60%, the reduction in tensile strength became more pronounced. The mixes containing 60%, 80%, and 100% BC exhibited 28-day strengths of approximately 3.8, 3.6, and 3.1 MPa, respectively. The decrease in splitting tensile strength with increasing brick chip content can be attributed to lower mechanical strength of BC concrete, higher porosity, and a weaker interfacial transition zone (ITZ) between the cement paste and brick aggregates, compared with natural coarse aggregates (Cachim 2009; Debieb and Kenai 2008; Yang et al. 2011). Brick chips also possess a more porous structure, which can reduce effective bonding and load transfer within the concrete matrix. The correlation between compressive and splitting tensile strength is depicted in Fig. 8.

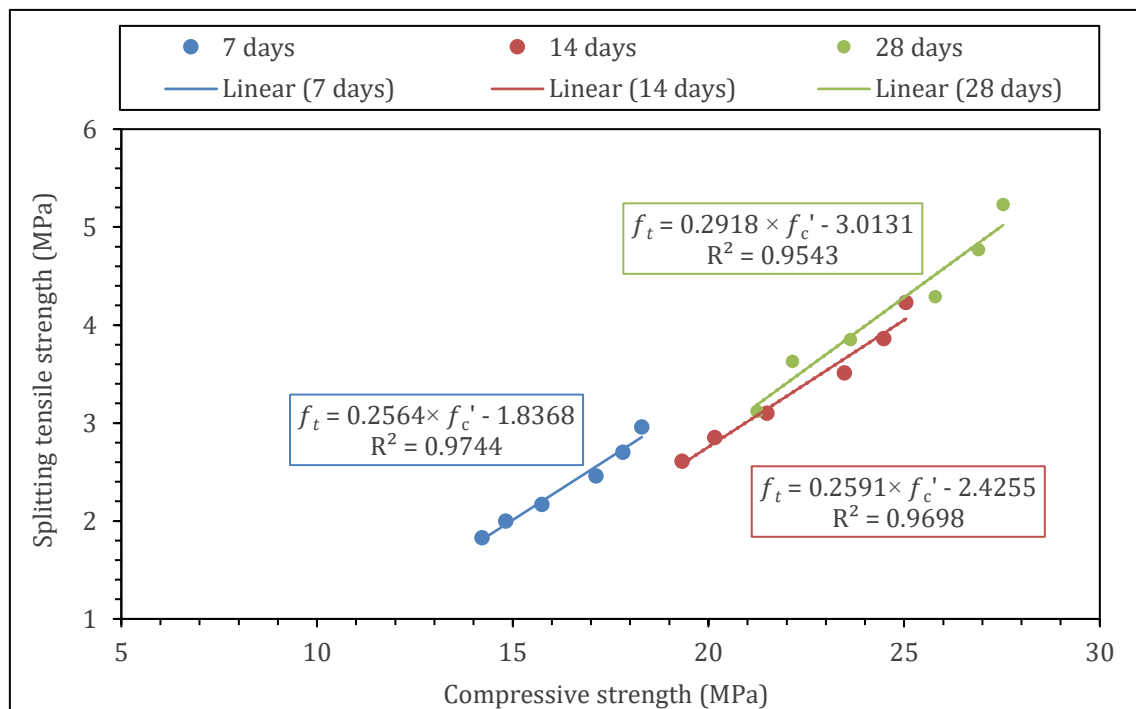


Fig. 8. Correlation between compressive and splitting tensile strength.

The results from Fig. 8 show a positive linear correlation among mechanical properties for all curing ages. The regression equations obtained from (3) to (5) are defined.

At 7 days ($R^2 \approx 0.9744$), the relationship is expressed as:

$$f_t = 0.2564 \times f'_c - 1.8368 \quad (3)$$

where, f_t represents splitting tensile strength (MPa) and f'_c denotes compressive strength (MPa).

The very high R^2 value indicates that approximately 97.44% of the variation in tensile strength was governed by compressive strength development. The relatively steep slope suggests that early-age hydration products effectively contributed to both compressive load-bearing capacity and crack-bridging resistance. However, the lower intercept reflects the incomplete microstructural densification at early ages, which is typical for concrete containing supplementary cementitious materials (SCMs).

While for 14 days ($R^2 \approx 0.9698$) and 28 days ($R^2 \approx 0.9543$), the relationships are:

$$f_t = 0.2591 \times f'_c - 2.4255 \quad (4)$$

$$f_t = 0.2918 \times f'_c - 3.0131 \quad (5)$$

where, f_t represents splitting tensile strength (MPa) and f'_c denotes compressive strength (MPa).

The increase in compressive strength corresponded with a proportional increase in tensile strength, indicating continued hydration and improved interfacial transition zone (ITZ) characteristics. The slightly reduced R^2 value for 14 days compared to 7 days may be attributed to the transitional pozzolanic activity of concrete particles, where different replacement levels could exhibit varying hydration kinetics during intermediate curing ages. The higher slope at 28 days indicates a greater rate of tensile strength enhancement relative to compressive strength development. This behavior suggests that prolonged curing promoted secondary hydration and pozzolanic reactions, resulting in a denser microstructure and stronger aggregate–paste bonding (Debieb and Kenai 2008). The improvement in tensile capacity may also

be associated with pore refinement and reduced microcrack propagation due to the filler and nucleation effects of fine particles. However, compared to the modulus of elasticity relationship, the correlation is slightly weaker, reflecting the greater sensitivity of tensile strength to microstructural defects and heterogeneity. A key observation is that the slope of the regression line increases with curing age, indicating that the rate of tensile-strength gain relative to compressive-strength gain becomes more pronounced at later ages. This may be attributed to the progression of the ITZ and enhanced bonding between cement paste and aggregates over time. However, the intercepts are negative for all ages,

which is physically unrealistic at very low compressive strengths. This suggests that the linear model is valid only within the tested strength range and should not be extrapolated beyond the experimental data (Khan et al. 2020).

3.3. Failure modes

Failure modes of the concrete specimens in compression and splitting tensile tests are illustrated in Figs. 9 and 10, respectively. In this case, columnar vertical cracking through both ends was found, and no well-formed cones were visible after the completion of the test.

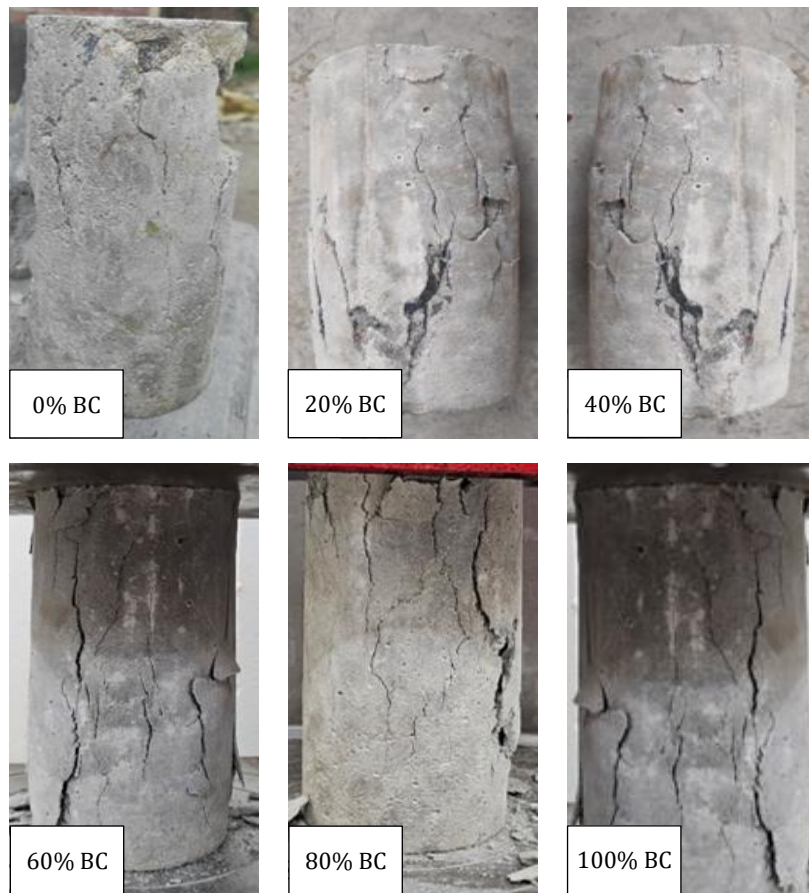


Fig. 9. Failure pattern of concrete specimens at 28 days due to compression load.

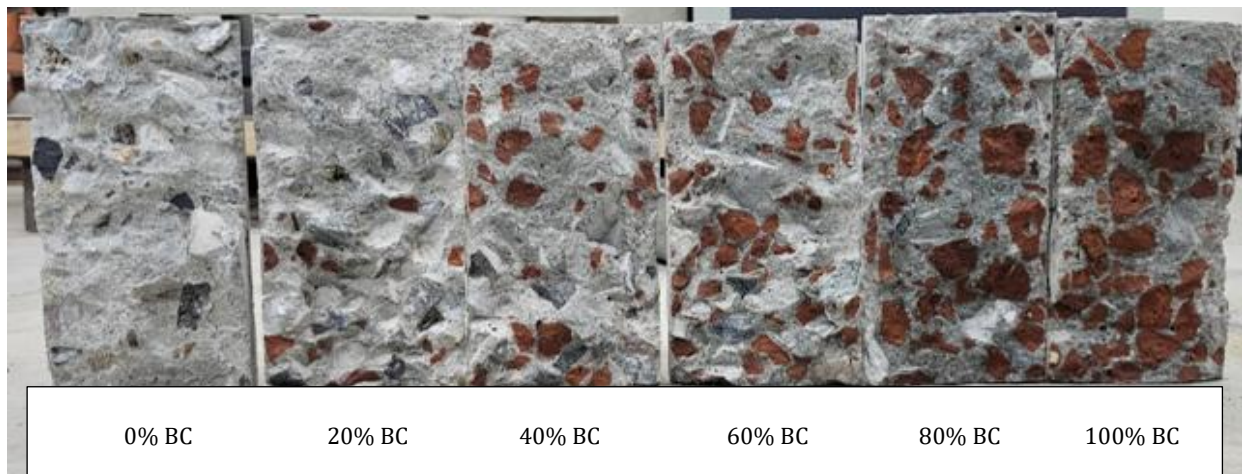


Fig. 10. Failure pattern of concrete specimens at 28 days for splitting tensile load.

Under compressive loading, the concrete specimens generally exhibited a brittle mode of failure, characterized by the formation of vertical cracks parallel to the loading direction (Fig. 9). Initially, microcracks develop within the ITZ and propagate through the cement matrix and aggregate as the load increases (Akhtaruzzaman and Hasnat 1983; Lee 1993; Debieb and Kenai 2008; Poon and Chan 2006). At peak load, these cracks coalesce, resulting in sudden crushing of the specimen. For conventional concrete, failure is typically accompanied by well-defined diagonal or columnar cracking. However, concrete containing brick chips, the failure tends to be more irregular and less explosive, with cracks propagating through the weaker brick aggregates. The presence of porous brick particles leads to localized crushing and earlier crack initiation, thereby reducing the overall load-bearing capacity. In the splitting tensile test, the specimens predominantly failed by longitudinal splitting along the vertical diameter (Fig. 10). A major crack formed along the loading plane, dividing the cylinder into two halves. This crack is initiated due to tensile stresses perpendicular to the applied compressive load. In mixes with brick chip aggregates, the failure surface was rougher and more irregular, indicating a weaker

bond between the cement paste and the aggregate. Crack propagation was often influenced by the porous structure of brick particles, leading to multiple secondary cracks and reduced tensile resistance compared to conventional concrete (Akhtaruzzaman and Hasnat 1983; Debieb and Kenai 2008; Poon and Chan 2006). Overall, the failure patterns indicate that while conventional concrete shows relatively uniform, well-defined cracking, brick aggregate concrete exhibits more heterogeneous, less stable failure behaviour, with weaker ITZ characteristics.

3.4. Modulus of elasticity

The estimated modulus of elasticity of BC concrete, calculated using the ACI CODE-318-19 (2022) empirical equation, is presented in Fig. 11. As shown in Fig. 11, the modulus of elasticity increased with curing age for all concrete mixtures, which is attributed to the continued cement hydration and the progressive densification of the cementitious matrix. The control mix (0% BC) exhibited the highest modulus values at all curing periods, ranging from approximately 20.0 to 24.5 GPa at 7, 14, and 28 days, respectively.

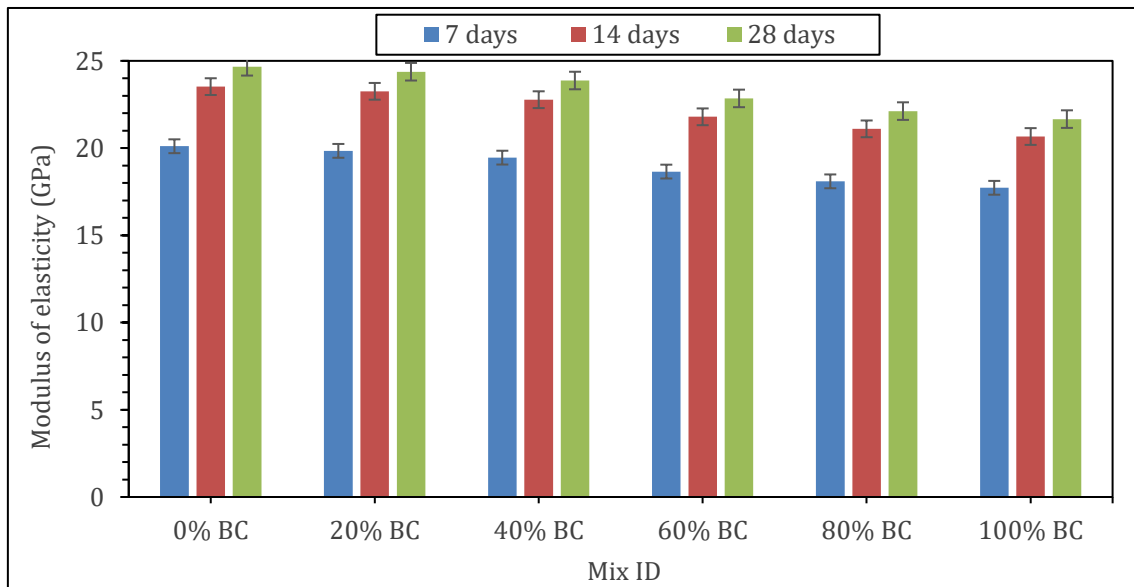


Fig. 11. Modulus of elasticity of concrete at different mix levels.

With the incorporation of brick chips as coarse aggregate, a gradual fall in the modulus of elasticity was noted. For mixtures containing 20% and 40% BC, the reduction was relatively small, with 28-day modulus values of approximately 24.3 and 23.8 GPa, respectively. However, as the replacement level increased to 60%, 80%, and 100%, the modulus values decreased further to around 22.8, 22.1, and 21.7 GPa, respectively. The decline in elastic modulus as brick chip content increases is due to the reduced stiffness and increased porosity of brick chips compared with those of stone chips. Brick particles generally exhibit a more porous microstructure and lower elastic stiffness, thereby reducing the overall rigidity of the concrete composite (Mohammed et al. 2023). Despite this decrease, the results indicate that

moderate replacement levels (up to about 40%) still provide relatively high modulus values, suggesting that partial substitution of natural aggregates with brick chips can produce concrete with acceptable elastic properties. The correlation between the elastic modulus and the compressive strength of concrete is shown in Fig. 12.

The high correlation is expected because the elastic modulus values were calculated directly from compressive strength using an empirical equation. Therefore, this relationship should not be interpreted as an independent experimental correlation. This indicates that the elastic stiffness of concrete is highly dependent on its compressive strength, which is consistent with established theoretical and empirical relationships in concrete mechanics. The regression equations obtained from (6) to (8) are defined.

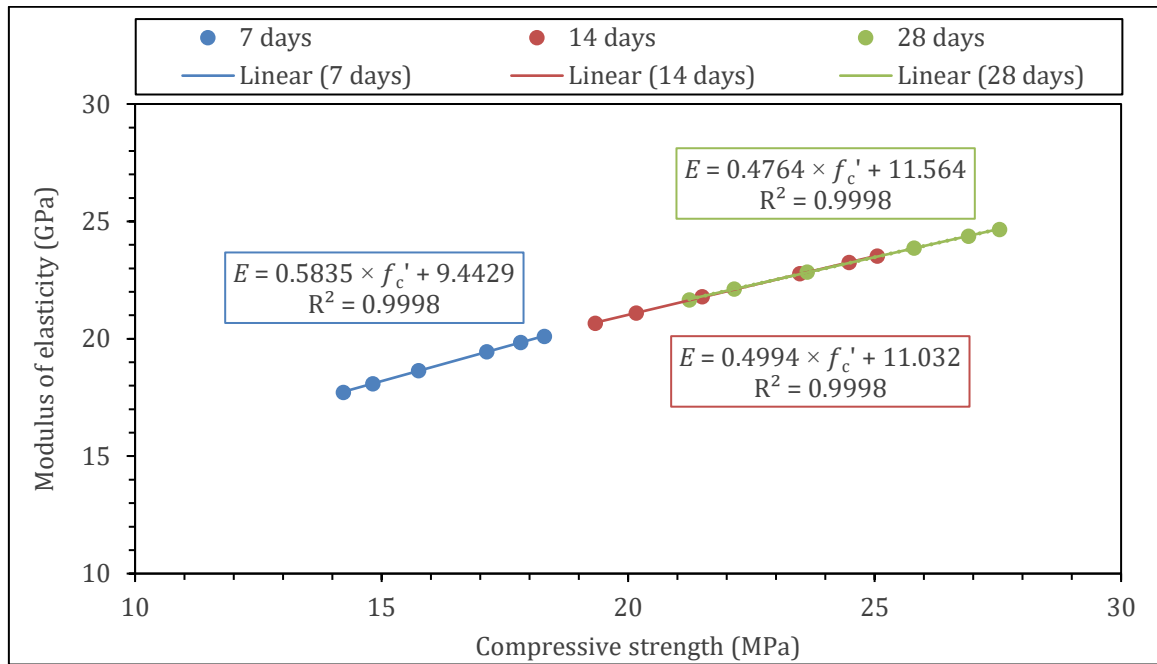


Fig. 12. Correlation between modulus of elasticity and compressive strength.

At 7 days, the relationship is expressed as:

$$E = 0.5835 \times f'_c + 9.4429 \quad (6)$$

where E represents the modulus of elasticity (GPa) and f'_c denotes compressive strength (MPa). The relatively steeper slope at an early age suggests that initial increases in compressive strength significantly influenced the development of stiffness. This behaviour is primarily associated with the rapid formation of hydration products and the progressive development of a rigid cementitious skeleton during early curing.

While for 14 and 28 days, the relationships are:

$$E = 0.4994 \times f'_c + 11.032 \quad (7)$$

$$E = 0.4764 \times f'_c + 11.564 \quad (8)$$

where E represents the modulus of elasticity (GPa) and f'_c denotes compressive strength (MPa). The continued linearity indicates that elastic stiffness consistently increased with compressive strength as hydration progressed. The slightly lower slope at 14 days compared with the 7-day relationship suggests that, although compressive strength continued to increase, the rate of stiffness gain became comparatively moderate due to gradual microstructural stabilization. The 28-day mixtures exhibited the highest modulus of elasticity values, reaching approximately 24–25 GPa at higher compressive strengths. The improvement in stiffness at later ages may be attributed to continued hydration and the pozzolanic contribution, which likely enhanced matrix densification and aggregate–paste interaction. The reduced slope at 28 days indicates that, once the concrete microstructure becomes relatively mature and compact, additional compressive-strength increments contribute less to elastic stiffness enhancement. It should be noted that the modulus of elasticity values reported in this

study were estimated using the empirical ACI equation based on compressive strength, rather than being determined experimentally through direct mechanical testing. Therefore, the exceptionally high correlations observed between compressive strength and elastic modulus are inherently mathematical in nature and should not be interpreted as independent experimental validation of elastic behaviour. Future investigations should incorporate direct modulus testing in accordance with ASTM C469 (2014) to provide a more reliable assessment of the elastic performance of DBS concrete.

3.5. Unit weight

The unit weight of the produced cylindrical mold was investigated at various percentages of stone chips replaced by brick chips. The data obtained are presented in Fig. 13.

Concrete with 0% BC replacement resulted in OD and SSD unit weights of 2381.28 kg/m³ and 2562.13 kg/m³, respectively. But when a 20% BC replacement is introduced, the OD and SSD unit weights tend to decrease to 2224.66 kg/m³ and 2429.57 kg/m³, respectively. A similar decrease in unit weight is observed at 40%, 60%, 80%, and 100% BC replacement. In mixtures with low replacement levels (20–40% BC), the reduction in unit weight is usually small because natural aggregates still dominate the mixture. However, at higher replacement levels (60–100%), the decrease becomes more pronounced as a larger portion of the dense natural aggregates is replaced by lighter brick particles. The unit weight (density) of concrete containing brick chips (BC) as coarse aggregate generally decreases with increasing brick chip replacement levels (Debieb and Kenai 2008; Zihan 2017). This behaviour is mainly due to the lower density and higher porosity of brick aggregates compared with natural stone aggregates. This trend indicates that varying BC percentages result in lower unit weight and, consequently, reduced overall dead load.

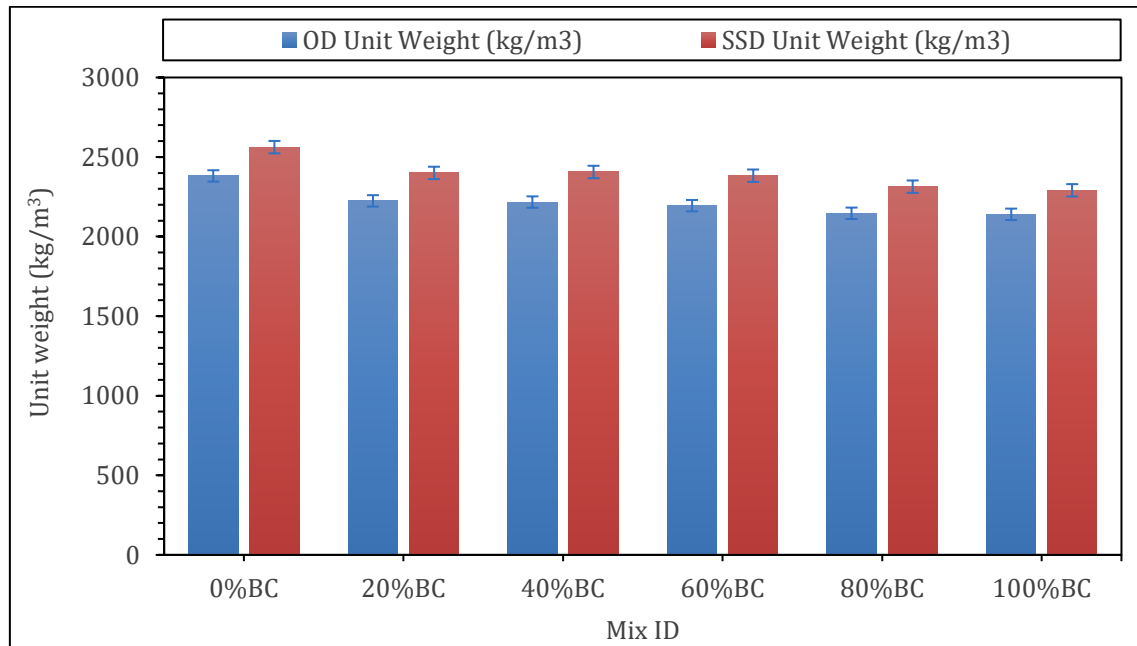


Fig. 13. Comparison between unit weights of various concrete mixes with different percentage replacements.

3.6. Water absorption capacity

The WAC of the cylindrical specimens is shown in Fig. 14. An increasing trend in water absorption is observed as the volumetric replacement increases. At 0% BC replacement, the absorption is 7.59%; it increases to 7.89% with 20% BC replacement. A significant 0.64% increase is evident in the case of 40% BC compared to 20% BC, that is 8.53%. The absorption capacity has gradually increased by 60% and 80% BC. In mixtures containing low to moderate brick chip replacement levels (e.g., 20–40%), the increase in water absorption is usually moderate and may still fall within acceptable durability limits. Eq. (9) shows the exponential equation for the WAC of concrete with $R^2 \approx 0.9178$.

$$y = 7.4342 \times e^{0.0343 \cdot x} \quad (9)$$

where y is the % of water absorption, and x is the % of brick chips. However, at higher replacement levels (60–100%), the water absorption tends to increase more significantly owing to the cumulative consequence of the porous brick aggregates and the weaker ITZ between the brick particles and the cement paste (Debieb and Kenai 2008; Mansur et al. 1999). As the percentage of brick chips in the concrete mixture increases, the concrete matrix's overall porosity tends to increase, leading to higher water absorption. Brick aggregates possess a more porous microstructure and rough surface texture, which allows them to absorb more water during mixing and curing.

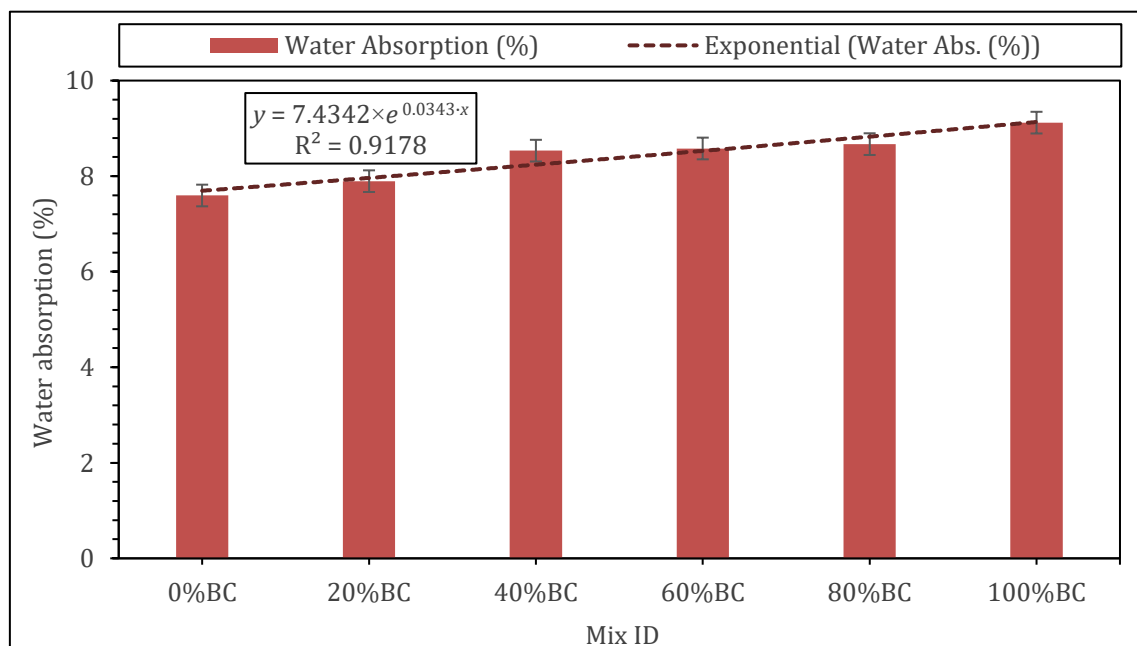


Fig. 14. Water absorption capacity of a concrete specimen with mixed BC proportions.

3.7. Cost analysis

The cost in BDT of 1 m³ of concrete with different proportions of BC, and the variation in cost with % brick chips, is depicted in Fig. 15. Here, the cost of concrete production is shown in Bangladeshi Taka (BDT).

Fig. 15 shows a decreasing trend in the cost of concrete made with different proportions of brick chips. It is clear that the overall cost of concrete decreases progressively as brick chip replacement increases. The control mix (0% BC) has the highest cost at approximately

16,700 BDT, while the 100% BC mix has a cost of around 13,600 BDT, representing a total reduction of about 18–20%. This decreasing trend can primarily be attributed to the lower cost and greater availability of brick chips compared to conventional natural coarse aggregates. In many regions, brick chips are obtained as construction or demolition waste, significantly reducing material procurement costs. As the proportion of brick chips increases, the reliance on relatively expensive natural aggregates decreases, resulting in a more economical concrete mixture.

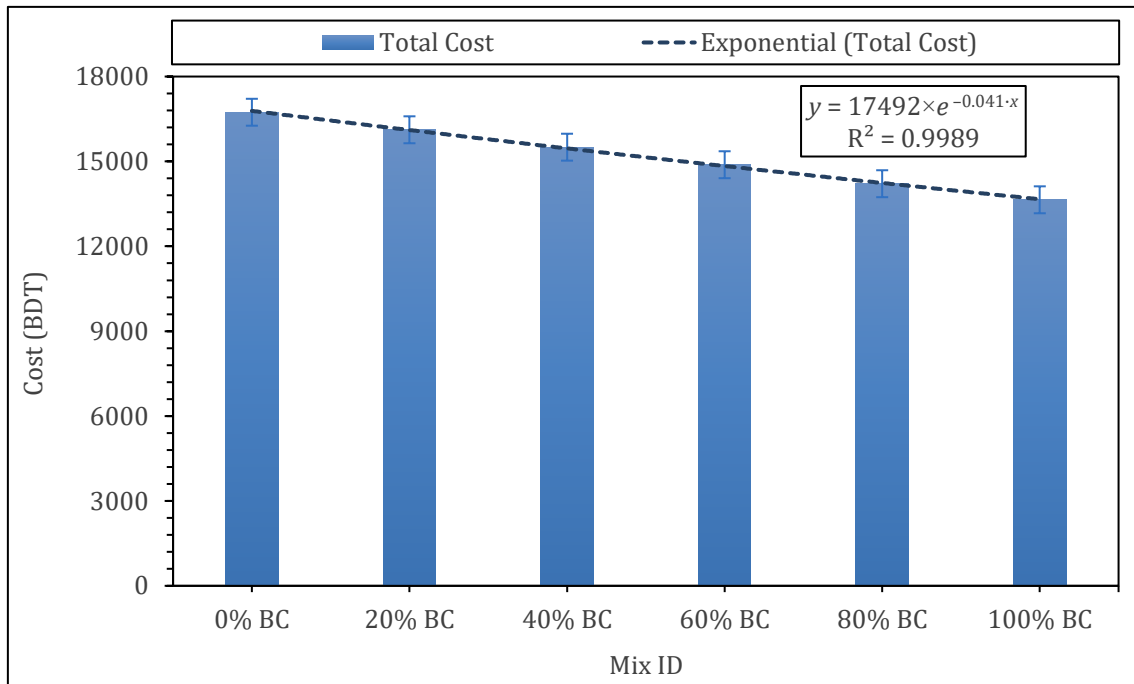


Fig. 15. Comparison between production cost and various BC concrete mixes.

Eq. (10) shows the total production cost (BDT) of concrete mixed with various proportions of brick chips with $R^2 \approx 0.9989$.

$$y = 17492 \times e^{-0.041 \cdot x} \quad (10)$$

where y is the cost of concrete in BDT, and x is the % of brick chips.

However, a critical evaluation of this trend indicates that the cost reduction is not linear with respect to performance efficiency. While the economic benefit is clear, higher replacement levels (above 60%) are associated with notable reductions in mechanical properties and modulus of elasticity, as well as increased water absorption and reduced durability. Therefore, although the 100% BC mix is the most cost-effective, it may not be suitable for all structural applications. From a sustainability perspective, the use of brick chips contributes to waste valorization and reduction in natural resource depletion, further enhancing the environmental and economic benefits. Nevertheless, an optimum replacement level (typically 40%) may provide a balanced compromise between cost efficiency and mechanical performance, making it more appropriate for practical applications.

4. Conclusions

This study examined the effects of replacing natural coarse aggregates (NCA) with brick chips (BC) on concrete properties. The results provided key insights into the behaviour and performance of brick-chip concrete.

- The optimum brick chip replacement percentage obtained in this study is 40% based on mechanical properties. Replacement percentages above this do not yield satisfactory results.
- A 40% replacement of stone chips with brick chips achieved a compressive strength of 25.80 MPa, exceeding the design strength of 25 MPa.
- A 40% substitution of stone chips with brick chips also results in a significant reduction in total concrete production cost.
- The slump value decreased as the proportion of brick chips increased. This reduces workability due to the rough surface texture and higher porosity of brick chips, which absorb more water compared to natural aggregates.
- The unit weight of concrete decreased with increasing brick chip content, thereby reducing the overall dead load. This reduction in weight may offer benefits in certain applications where lower weight is desirable.

(e.g., non-load-bearing structures or lightweight concrete solutions).

- The study found greater water absorption capacity, up to around 9%, in 100% BC mixes with higher brick chip replacement than in natural aggregate mixes. The porous nature of brick chips increased absorption, potentially affecting the durability of concrete under certain environmental conditions.
- Although higher brick-chip replacement levels significantly reduce concrete costs, an optimal balance (40% BC) between economic benefits and engineering performance must be achieved to ensure structural reliability.

Further studies are recommended that focus on the experimental modulus of elasticity and the long-term durability of brick-chip concrete, including resistance to freeze-thaw cycles, corrosion, and chemical exposure, to assess its suitability for environmental exposure.

Acknowledgements

The authors are grateful to the Department of Civil Engineering, Hajee Mohammad Danesh Science and Technology University (HSTU), Bangladesh, for providing specific facilities and academic assistance to perform this research.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- ACI CODE-318-19(22) (2022). *Building Code Requirements for Structural Concrete and Commentary*. American Concrete Institute, Farmington Hills, MI, USA.
- Afroz S, Rahman F, Iffat S, Manzur T (2015). Sorptivity and strength characteristics of commonly used concrete mixes of Bangladesh. In: *International Conference on Recent Innovation in Civil Engineering for Sustainable Development (IICSD-2015)*, Gazipur, Bangladesh, 39-44.
- Akhtaruzzaman AA, Hasnat A (1983). Properties of concrete using crushed brick as aggregate. *Concrete International*, 5(2), 58-63.
- Ali ME, Moin MK, Haque MR, Aziz SB (2022). Performance evaluation of structural lightweight concrete using jhama brick as a partial replacement of coarse aggregate. *Journal of Cement Based Composites*, 2, 5676.
- Apebo N, Agunwamba J, Ezeokonkwo J (2014). The suitability of crushed over burnt bricks as coarse aggregates for concrete. *International Journal of Engineering Science and Innovative Technology*, 3(1), 315-321.
- ASTM C29/C29M-23 (2023). *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*. ASTM International, West Conshohocken, PA, USA.
- ASTM C31/C31M-19 (2019). *Standard Practice for Making and Curing Concrete Test Specimens in the Field*. ASTM International, West Conshohocken, PA, USA.
- ASTM C33/C33M-23 (2023). *Standard Specification for Concrete Aggregates*. ASTM International, West Conshohocken, PA, USA.
- ASTM C39/C39M-23 (2023). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA, USA.
- ASTM C127-25 (2025). *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. ASTM International, West Conshohocken, PA, USA.
- ASTM C128-25 (2025). *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*. ASTM International, West Conshohocken, PA, USA.
- ASTM C136/C136M-14 (2014). *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. ASTM International, West Conshohocken, PA, USA.
- ASTM C138/C138M-23 (2023). *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*. ASTM International, West Conshohocken, PA, USA.
- ASTM C143/C143M-26 (2026). *Standard Test Method for Slump of Hydraulic-Cement Concrete*. ASTM International, West Conshohocken, PA, USA.
- ASTM C192/C192M-26 (2026). *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. ASTM International, West Conshohocken, PA, USA.
- ASTM C469/C469M-14e1 (2014). *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. ASTM International, West Conshohocken, PA, USA.
- ASTM C496/C496M-17 (2017). *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA, USA.
- ASTM C642-97 (1997). *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*. ASTM International, West Conshohocken, PA, USA.
- Azunna SU, Ogar JO (2021). Characteristic properties of concrete with recycled burnt bricks as coarse aggregates replacement. *Computational Engineering and Physical Modeling*, 4(1), 56-72.
- Basak S, Haque MR, Azad AK, Rahman MM (2024). Performance of ceramic tiles waste as a partial replacement of brick aggregate on mechanical and durability properties of concrete. *Journal of Engineering Advancements*, 5(1), 9-13.
- Bhowmik R, Pal J (2022). A comparative study between brick and stone aggregate concrete using rice husk ash as partial cement replacement. *Materialwissenschaft und Werkstofftechnik*, 53(9), 987-1008.
- Bhushal T, Haque MR, Islam MR, Al Mohmud H (2025). Investigation of the mechanical properties and durability performance of jute fiber concrete. *Journal of Engineering Advancements*, 6(4), 138-146.
- Cachim PB (2009). Mechanical properties of brick aggregate concrete. *Construction and Building Materials*, 23(3), 1292-1297.
- Debieb F, Kenai S (2008). The use of coarse and fine crushed bricks as aggregate in concrete. *Construction and Building Materials*, 22(5), 886-893.
- Dwivedi K (2017). Study on properties of concrete using overburnt brick chips and demolished concrete waste as partial replacement of coarse aggregate. *IOSR Journal of Mechanical and Civil Engineering*, 14, 52-56.
- Habib MZ, Hoque MM, Raka RN, Fahad MA, Islam MT, Islam MZ, Ether MZH (2022). Properties of internally cured concrete made of partially replaced stone chips with brick chips. *Journal of Civil Engineering (IEB)*, 50(1), 13-20.
- Hamouda AS, Eldien M, Abadir M (2020). Carbon dioxide capture using an ammonium hydroxide solution and its potential application in the cement industry. *Ain Shams Engineering Journal*, 11(4), 1061-1067.
- Haque MR, Mostafa MS, Sah SK (2021). Performance evaluation for the mechanical behaviour of concrete incorporating recycled plastic bottle fibres as locally available materials. *Civil Engineering Journal*, 7(4), 713-719.

- Hasan MK, Khan MMU, Uddin MS (2007). *Properties of concretes obtained by replacing stone chips with brick aggregates*. B.Sc. Engineering thesis, Dhaka University of Engineering & Technology, Gazipur, Bangladesh.
- He Z, Zhu X, Wang J, Mu M, Wang Y (2019). Comparison of CO₂ emissions from OPC and recycled cement production. *Construction and Building Materials*, 211, 965-973.
- Joshi BR (2020). Analysis of overburned brick in concrete as a coarse aggregate. *International Journal of Research in Engineering and Science*, 8(1), 30-38.
- Khan MT, Jahan I, Amanat KM (2020). Splitting tensile strength of natural aggregates, recycled aggregates and brick chips concrete. *Proceedings of the Institution of Civil Engineers - Construction Materials*, 173(2), 79-88.
- Lee SC (1993). *Crushed bricks as coarse aggregate for concrete*. Ph.D. Thesis, University of Malaya, Kuala Lumpur, Malaysia.
- Lonth CF, Thomas J, Joseph N (2018). Mechanical properties of concrete containing brick chips. *IOP Conference Series: Materials Science and Engineering*, 396, 012003.
- Mahmud H, Ahmed T, Islam MS (2025). Combined effect of rice husk ash and animal bone powder on strength and permeability of concrete. *Challenge Journal of Structural Mechanics*, 11(1), 1-13.
- Malešev M, Radonjanin V, Marinković S (2010). Recycled concrete as aggregate for structural concrete production. *Sustainability*, 2(5), 1204-1225.
- Mansur MA, Wee TH, Lee SC (1999). Crushed bricks as coarse aggregate for concrete. *ACI Materials Journal*, 96(4), 478-484.
- Miller SA, Horvath A, Monteiro PJM (2016). Readily implementable techniques can cut annual CO₂ emissions from the production of concrete by over 20%. *Environmental Research Letters*, 11(7), 074029.
- Miller SA, Moore FC (2020). Climate and health damages from global concrete production. *Nature Climate Change*, 10(5), 439-443.
- Mimi MM, Shakil AMOR, Haque MR, Hasan MR (2023). Effect of addition of CaO on compressive strength of high-volume fly ash concrete. *Journal of Civil Engineering, Science and Technology*, 14(1), 64-76.
- Mohammed TU, Mahmood AH, Sakib A, Khan FA, Sopnil SI (2023). Fresh and hardened properties of brick aggregate concrete with maximum aggregate sizes of 10 mm to 75 mm. *Construction Materials*, 3(4), 337-353.
- Monteiro PJM, Miller SA, Horvath A (2017). Towards sustainable concrete. *Nature Materials*, 16(7), 698-699.
- Niroula B, Bhatt MR (2026). Mechanical properties assessment of recycled brick aggregate concrete using demolition waste from century-old masonry buildings in Nepal. *Challenge Journal of Concrete Research Letters*, 17(1), 41-56.
- Poon CS, Chan D (2006). Paving blocks made with recycled concrete aggregate and crushed clay brick. *Construction and Building Materials*, 20(8), 569-577.
- Rashid MA, Hossain T, Islam MA (2008). Higher-strength concrete using crushed brick as coarse aggregate. *Indian Concrete Journal*, 82(10), 18-23.
- Rashid MA, Salam MA, Shill SK, Hasan MK (2012). Effect of replacing natural coarse aggregate with brick aggregate on the properties of concrete. *DUET Journal*, 1(3), 17-22.
- Turner LK, Collins FG (2013). Carbon dioxide equivalent (CO₂-e) emissions: a comparison between geopolymers and OPC cement concrete. *Construction and Building Materials*, 43, 125-130.
- Uddin MT, Mahmood AH, Kamal MRI, Yashin SM, Zihan ZUA (2017). Effects of the maximum size of brick aggregate on properties of concrete. *Construction and Building Materials*, 134, 713-726.
- UNEP (2022). *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. United Nations Environment Programme, Nairobi, Kenya.
- Ünal S, Canbaz M (2025). Utilization of expired cement and aged roof tile powder in the production of sustainable geopolymer: mechanical and physical properties. *Challenge Journal of Structural Mechanics*, 11(2), 82-88.
- Ünal S, Canbaz M (2026). Development of a sustainable geopolymer structural element with waste glass powder: mechanical characteristics. *Challenge Journal of Structural Mechanics*, 12(1), 22-29.
- Wani S, Selvaraj T, Faria P, Mehra A, Shukla R (2023). Study on ancient green materials and technologies used in the Udaipur Palace, India: an input to abate climate change in modern construction. *Environmental Science and Pollution Research*, 30(41), 93952-93969.
- Wani S, Geça MJ, Selvaraj T, Priya TS (2024). Assessing the influence of *Bacillus megaterium* and *Bacillus sphaericus* in cementitious materials: promoting sustainability towards strength, durability and crack repair. *Ain Shams Engineering Journal*, 15(6), 102748.
- Wee Chit WP, Budiea AMA, Mohd Noh H, Muthusamy K, Bamaga SO (2025). Compressive strength and fire resistance of mortar containing spent garnet as partial sand replacement. *Challenge Journal of Concrete Research Letters*, 16(4), 164-172.
- Yang J, Du Q, Bao Y (2011). Concrete with recycled concrete aggregate and crushed clay bricks. *Construction and Building Materials*, 25(4), 1935-1945.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Effect of different activations of supplementary cementitious materials on the early-age compressive strength of mortars based on quaternary binders

Ali Abbache^a , Zoubir Makhloufi^b , Hichem Berkak^{a,b,*} ,
Rachid Rabehi^a , Mohammed Seghir Ammari^c

^a Department of Structures and Materials, Built Environment Research Laboratory "Tamayouz" (LBE), Faculty of Civil Engineering, University of Science and Technology Houari Boumediene (USTHB), 16111 Algiers, Algeria

^b Structure Rehabilitation and Materials Laboratory (SREML), Amar Telidji University of Laghouat, 03000 Laghouat, Algeria

^c New Technologies and Local Development Laboratory (NTLDL), University of El Oued, 39000 El Oued, Algeria

ABSTRACT

In recent years, building materials have seen the widespread use of supplementary cementitious materials (SCMs) due to important environmental considerations. However, most SCMs exhibit slow development of compressive strength in the early stages. This study aims to evaluate and compare three combined activation strategies of SCMs, namely natural pozzolana (NP), blast furnace slag (BFS) and limestone filler (LF), incorporated with a replacement level of 50% of cement. SCMs activation was achieved through three approaches: mechanical (grinding to Blaine fineness values of 3800 and 6000 cm²/g), thermal (curing at 20 and 40 °C), and chemical (addition of 1% NaOH by mass of binder). Early compressive strength (2 and 7 days) was measured and analyzed using a fractional factorial design. The results demonstrate that all investigated combinations of SCM activations generate synergistic effects by significantly improving the mechanical performance of early-age quaternary mortars, due to an acceleration of hydration reactions and an improvement in the densification of the material's microstructure. Statistical analysis (ANOVA) revealed that curing temperature is one of the most influential parameters on early compressive strength. Increasing the temperature from 20 to 40°C accelerates hydration and pozzolanic reactions, thus promoting faster calcium silicate hydrate C-S-H gel formation and a significant improvement in strength gain. Furthermore, the binder composition and the degree of substitution of SCMs strongly influence mechanical performance. Formulations containing adequate proportions of BFS and NP exhibit higher reactivity during activation.

Citation: Abbache A, Makhloufi Z, Berkak H, Rabehi R, Ammari MS (2026). Effect of different activations of supplementary cementitious materials on the early-age compressive strength of mortars based on quaternary binders. *Challenge Journal of Concrete Research Letters*, 17(3), 293–304.

ARTICLE INFO

Article history:

Received – March 6, 2026
Revision requested – April 14, 2026
Revision received – May 30, 2026
Accepted – June 8, 2026

Keywords:

Quaternary binder
SCM activation
Early-age compressive strength
Fractional factorial design
Synergistic effects



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

1. Introduction

Cement production is among the most energy-intensive industrial processes, accounting for 3% of annual global energy production and contributing to about 8%

of anthropogenic greenhouse gas emissions (Miller and Moore 2020; UNEP 2026; Yu et al. 2024). In the context of the energy transition, political, regulatory and technological pressures are leading to a reconsideration of traditional manufacturing pathways and underline the ur-

* Corresponding author. E-mail address: hichem.berkak@usthb.edu.dz (H. Berkak)

ISSN: 2548-0928 / DOI: <https://doi.org/10.20528/cjcr.2026.1131>

gency of low-carbon cement manufacturing approaches. Indeed, one of the proposed and effective solutions consists in partial replacement of Portland cement clinker by alternative materials exhibiting pozzolanic or latent hydraulic properties.

Various Supplementary Cementitious Materials (SCMs), such as blast furnace slag (BFS), fly ash (FA), metakaolin (MK), silica fume (SF), natural pozzolan (NP) and limestone filler (LF), have been widely used in mortar and concrete mixtures (Khan et al. 2022; Pang et al. 2022; Berkak et al. 2025; Al-Safi et al. 2025; Chenafi et al. 2026). The impact of SCMs on the future of the cement industry will depend on multiple factors, including the availability, production efficiency and profitability of these SCMs. Their effects on mortar performance are also strongly dependent on replacement level and binder composition (Mohamad et al. 2025).

In addition, the development of quaternary composite cements combines scientific and technological advances in the fields of cement and concrete. It effectively meets mechanical performance requirements while promoting sustainable development and environmental preservation (Alcan et al. 2024; Makhloufi et al. 2012; Vignesh and Rahim 2022; Makhloufi et al. 2015). In quaternary mixtures, an optimal LF replacement level in the binder of between 8 and 17% leads to an early-age reaction equivalent to or greater than that of OPC and to a compressive strength at 28 days comparable to that of binary mortar mixtures (Mounanga et al. 2011). The detrimental effect of silica fume (SF) on the workability of fresh mortar can be compensated by the simultaneous use of SF and LF (Zelić et al. 2009; Li et al. 2019). Moreover, mortars and concretes containing a quaternary binder, composed of cement simultaneously incorporating fly ash (FA), LF and metakaolin (MK), may also be more efficient than CEM I cement in terms of compressive strength after 28 days of curing, but they have a low initial strength due to the dilution effect of LF; furthermore, when the LF content increases from 5% to 10%, the reduction in strength becomes significant (Lin et al. 2021). According to work of Rojo-López et al. (2020), quaternary binder mortars containing granulated blast furnace slag (GGBS) and MK have better performance in terms of permeability and compressive strength than those using LF.

The pozzolanic reaction occurs through the chemical interaction between the amorphous silica or silica and alumina present in SCMs and calcium hydroxide ($\text{Ca}(\text{OH})_2$), generated during cement hydration. This reaction leads to the formation of additional hydration products, mainly C-S-H and C-A-S-H gels, which contribute to the enhancement of mechanical strength (Allahverdi and Salem 2010). Dave et al. (2016) reported that quaternary blended cements, incorporating metakaolin (MK) at a high replacement level of 50% with fly ash (FA) and silica fume (SF), can achieve compressive strength comparable to that of the control mortar at early ages. Moreover, the compressive strength was found to increase significantly during the early age as the MK content in the quaternary system increases. This enhancement is primarily attributed to the activation of tricalcium aluminate (C_3A) and tricalcium silicate (C_3S) phases in Portland cement (Dave et al. 2017).

Nevertheless, the use of SCMs, especially with high substitution rates, is often limited by a slow strength development during the early ages of cement hydration (Dong et al. 2002). An improvement in its responsiveness is therefore required through the use of SCM activation techniques (Dong et al. 2002; Sajedi and Razak 2011a, 2011b). Several methods have been implemented to increase the reactivity of pozzolanic materials in the short term. They can be classified into three categories: mechanical (grinding), thermal (thermal curing), and chemical (Go et al. 2010; Allahverdi and Mahinroosta 2013; Ababneh et al. 2025; Li et al. 2013; Elbar et al. 2018). Each method of SCM activation has advantages and limitations.

Mechanical activation, induced by grinding, results from a set of transformations: particle fracture, various physicochemical changes in volume and surface (Kumar and al. 2008), while generating defects (dislocations, surface amorphization) (Sobolev 2005). The accumulated mechanical energy during grinding increases the specific surface area and reactivity of the material, thereby enhancing early-age strength through the greater availability of reactive silica for the formation of calcium silicate hydrate (C-S-H) (Zivanovic et al. 2002; Indrawati and Manaf 2008; Ababneh et al. 2025), hence the sustained interest and numerous studies on the subject (Kumar et al. 2008; Oner et al. 2003; Fu et al. 2008).

Allahverdi and Mahinroosta (2013) reported that all the results show that mechanical activation is an effective approach, used in addition to other techniques, to improve the performance of cementitious systems containing a high proportion of chemically activated slag. However, extended milling duration increases energy consumption, which can limit large-scale adoption. Moreover, the cost-effectiveness of mechanical activation remains a concern.

Moreover, thermal curing at high temperature inevitably induces significant changes in the physicochemical and mechanical properties of SCMs (Sajedi and Razak 2011a; Allahverdi and Saffari 2011). Increasing the curing temperature accelerates hydration kinetics in accordance with Arrhenius's law, thereby promoting the development of higher early-age mechanical strength in slag cement mortars (Ezziane 2010). When the curing temperature exceeds 30 °C, a reduction in the final setting time is generally observed, thus reflecting an acceleration of the curing process of pozzolanic mortars (Ababneh et al. 2025).

However, the application of thermal activation remains poorly adapted to conventional concretes, mainly due to its high energy consumption and technical constraints related to practical conditions. The prolonged exposure to high temperatures can cause thermal shrinkage phenomena and promote the appearance of cracks, particularly in mass concrete structures (Ababneh et al. 2025).

Chemical activation involves the incorporation of alkaline activators, such as sodium hydroxide (NaOH) or sodium sulfate (Na_2SO_4), aimed at giving the material a cementitious character and/or activating its latent hydraulic properties (Bellmann and Stark 2009; Sajedi and Razak 2011b). The type of alkaline activator can also significantly influence the resulting mechanical perfor-

mance (Ünal and Canbaz 2025). In concretes incorporating pozzolans, chemical activators (e.g., NaOH, Na₂SO₄), introduced either during SCM grinding or at the mixing stage, accelerate the pozzolanic reaction and enhance strength development (Shi and Day 2001).

Although the introduction of one or more activators increases the overall cost of the materials, the cost relative to the enhancement in mechanical strength obtained decreases (Shi and Day 2001).

However, this activation method remains limited by the long-term stability of the reaction products and by the environmental impacts associated with the use of chemical reagents. Moreover, the effectiveness of chemical activation depends closely on the composition of the pozzolan, which differs from one region to another (Ababneh et al. 2025).

1.1. Scope and significance

SCMs, such as natural pozzolan and blast furnace slag, generally develop lower compressive strengths at early ages compared to Portland cement, especially at high replacement levels (Ghrici 2007). Despite the extensive research devoted to the activation of a SCM by a single and isolated approach, studies on the combined influence of mechanical, chemical and thermal activations on the physico-mechanical properties of mortars with quaternary binders and high substitution rates remain insufficient. Moreover, the lack of systematic experimental approaches limits the understanding of both individual and interaction effects of these activation strategies. In the context, the present study aims to fill this gap by evaluating, using a fractional factorial plan, the joint effect of these three SCM activation methods on the compressive strength of quaternary binder mortars at early-age with a substitution rate of 50% of Portland cement. A fractional factorial design is employed to not only assess the overall effect of these activation methods but also to quantify their main and interaction effects on early-age compressive strength. This approach provides new in-

sights into the synergistic behavior of multiple activation strategies in highly substituted quaternary systems.

2. Materials and Experimental Procedures

2.1. Raw materials

Binders used in this research include ordinary Portland cement (OPC) and SCMs, such as limestone fillers (LF), blast furnace slag (BFS) and natural pozzolan (NP). The chemical and mineralogical compositions of OPC and SCMs, determined by X-ray fluorescence (XRF), are presented in Table 1. The densities of OPC, LF, BFS, and NP are 3.0, 2.7, 2.8, and 2.6 g/cm³, respectively. The Blaine specific surface area (cm²/g) of the cement is 3500 while that of the SCM is 3800 and 6000 (± 100). X-ray diffraction analyses of the SCMs used are shown in Fig. 1.

Crushed limestone sand was used. The filler content passing through the 80 µm diameter sieve is 8.25 %, which is acceptable according to standard NF P 18-301 (1983). The physical characteristics of the sand are reported in Table 2. The fineness modulus is 2.30 and the sand equivalent is 76.46%, indicating clean and negligible clay fraction.

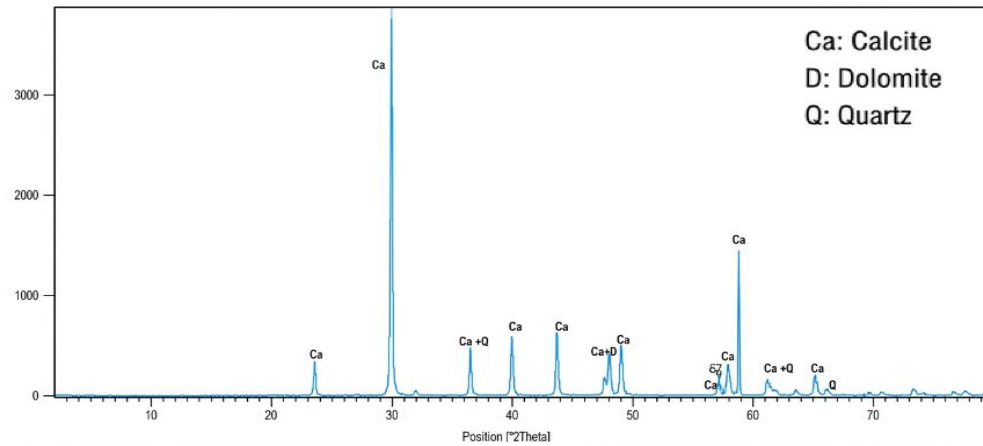
2.2. Design of mixtures

In order to identify the most suitable SCMs activation process for quaternary mixtures, a Design of Experiments (DOE) approach based on the fractional factorial design was applied. Four main factors were considered in the DOE for the proportions of the mixture: (i) the compositions of the cementitious binders (noted from C1 to C7), (ii) mechanical activation, (iii) thermal activation and (iv) chemical activation. Each factor was evaluated at two levels, namely -1 (low level) and +1 (high level), except that the composition of the binders which was tested with 7 levels, in accordance with the modalities mentioned in Table 3.

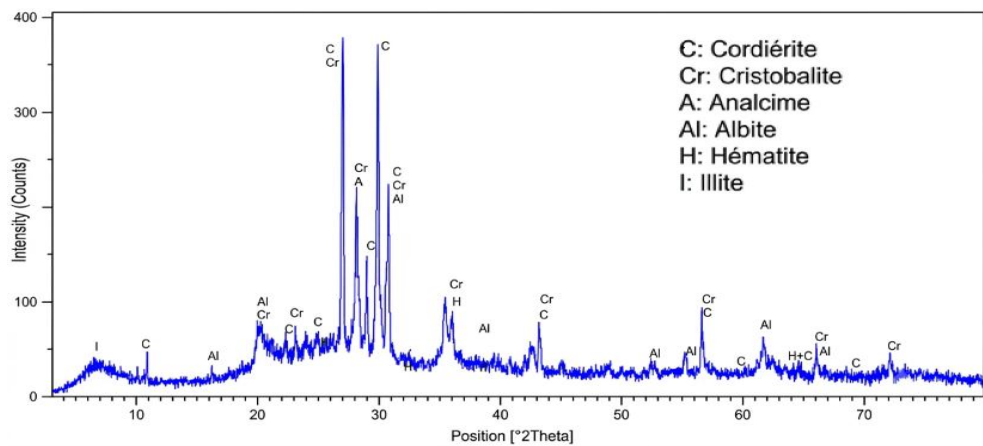
Table 1. Chemical and mineralogical composites of different compounds (%).

Composition	OPC	LF	NP	BFS
SiO ₂	38.21	0.76	10.57	39.38
Al ₂ O ₃	5.59	0.41	15.82	5.64
Fe ₂ O ₃	3.21	0.23	6.16	2.3
CaO	65.26	54.9	5.95	40.3
MgO	1.72	0.61	2.09	4.50
K ₂ O	0.47	0.24	2.0	0.46
Na ₂ O	0.19	0.04	1.1	0.13
SO ₃	0.56	0.61	0.28	0.90
Cl ⁻	0.02	0.005	1.40	–
LOI*	0.58	36.3	1.2	0.8
Cement mineralogy (%)	C ₂ S	C ₃ S	C ₃ A	C ₄ AF
	64.15	97.60	9.39	9.76

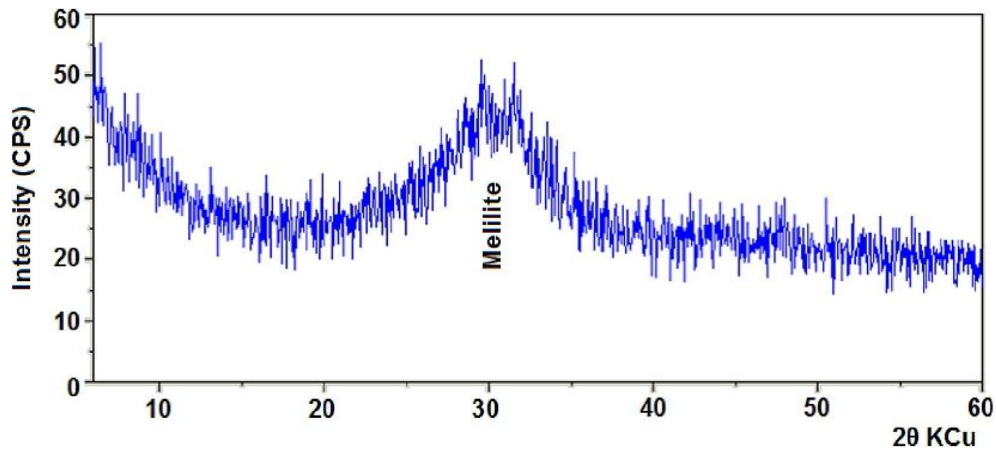
*Loss on ignition.



(a) Limestone Filler



(b) Natural pozzola



(c) Blast furnace slag

Fig. 1. X-ray diffraction of SCMs used.**Table 2.** Physical properties of sand used.

Physical characteristics	Values
Specific density (g/cm ³)	2.70
Apparent density (g/cm ³)	1.53
Fineness modulus	2.30
Compactness (%)	56.70
Porosity (%)	43.30
Absorption coefficient (%)	4.30
Visual sand equivalent (%)	34.71
Piston sand equivalent (%)	46.76

Table 3. Factors and levels used in the fractional factorial design (2^{3-1}).

Factor	Description	Level 1 (-1)	Level 2 (+1)
F	Mechanical activation (fineness) (cm^2/g)	3800	6000
T	Thermal activation ($^{\circ}\text{C}$)	20	40
A	Chemical activation (% NaOH)*	0	1

*% in mass of binder.

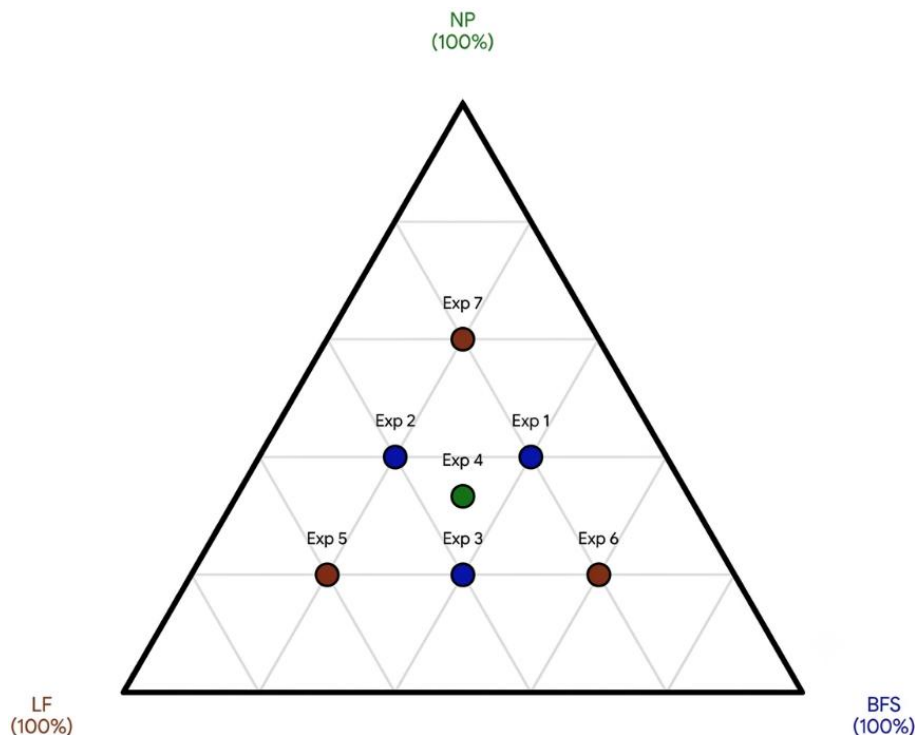
In the regression analysis, composition variable “Comp” was treated as a categorical (nominal) factor comprising seven levels (C1 to C7). To incorporate this factor into the regression model and avoid multicollinearity, the categories were transformed into numerical variables using dummy coding. Specifically, each level was represented by a binary variable (0 or 1), with category C1 defined as the reference baseline level to ensure proper model estimation.

For the three activation factors, a fractional factorial design 2^{3-1} was adopted in order to reduce the number of experimental runs while still allowing estimation of the main effects and selected interaction effects. In this design, the defining relation was selected so that the most influential effects could be estimated with minimal confounding; thus, main effects were considered unaliased

with each other, whereas higher-order interactions were assumed to be negligible.

The effects of the studied factors (responses) on compressive strength at early-age (2 and 7 days) were examined, in order to evaluate the early-age performance of the quaternary binders. Each response was analyzed separately. The experimental results were statistically processed using analysis of variance (ANOVA), which made it possible to identify the significant factors and interactions and to assess their relative contribution to strength development.

On the other hand, the binder compositions (Fig. 2) were prepared using a mixture design of experiments, by substituting 50% of OPC by SCMs. The composition of the various binders, including the reference mortar, is presented in Table 4. Thus, the total number of experiments carried out for each response is 36.

**Fig. 2.** Triangular representation of seven compositions studied.**Table 4.** Composition of binders.

Composition (%)	C0	C1	C2	C3	C4	C5	C6	C7
Clinker	95.0	47.5	47.5	47.5	47.5	47.5	47.5	47.5
Gypsum	5.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Limestone	0	10	20	20	16.67	30	10	10
Slag	0	20	10	20	16.67	10	30	10
Pozzolana	0	20	20	10	16.67	10	10	30

2.3. Mix proportions and specimens preparation

All the mixtures prepared were produced with a water to binder ratio (W/B) of 0.50, where the binder is defined as the sum of cement and SCMs forming the quaternary system. For the reference mortar (100% cement), the W/B ratio is indeed equal to the water-to-cement ratio ($W/C = 0.50$). In addition, a sand-to-binder ratio of 3 was used and the dosage of the superplasticizer is determined so as to ensure appropriate handling of the mixtures, while keeping the W/B ratio constant. It should be noted that the dosage of the superplasticizer varied from

1.1 to 2.9% by weight of the binder. The results, illustrated by Fig. 3, revealed that the superplasticizer saturation doses were significantly higher than those recommended by the manufacturer for common concretes and mortars (1.5% by weight of the binder).

Fig. 4 compares the water demand of the control mortar with and without superplasticizer. It is clearly apparent that the incorporation of the superplasticizer allows a significant reduction in the water/cement ratio while retaining equivalent workability, which results in a notable improvement in the mechanical properties.

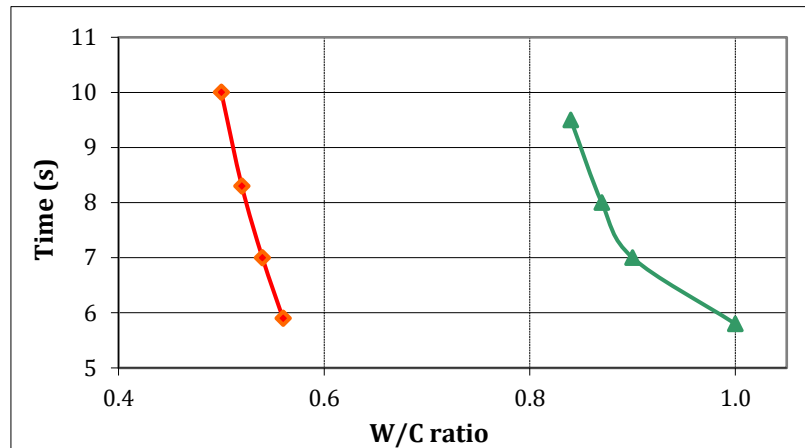


Fig. 3. Evolution of flow time of reference mortar as a function of the W/C ratio.

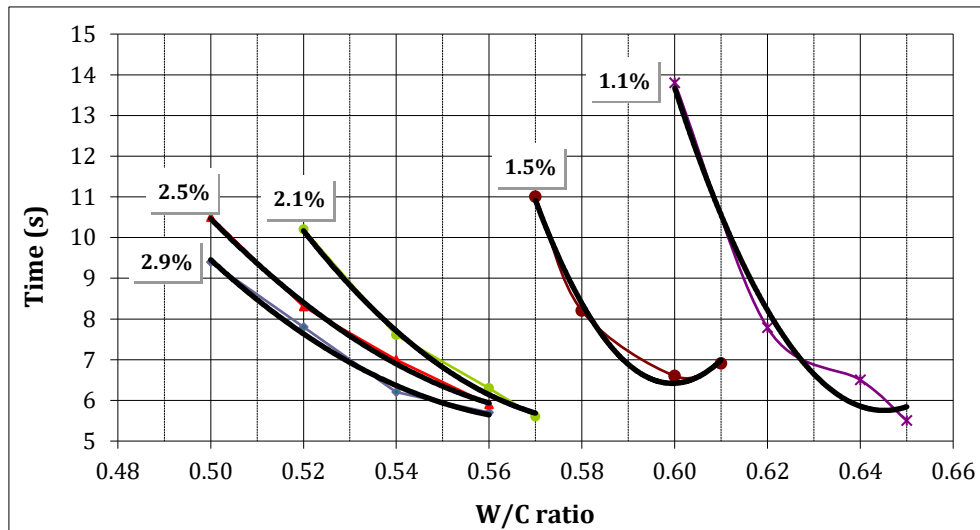


Fig. 4. Comparison of flow-time as a function of W/C ratio for control mortar with and without superplasticizer.

The processes for mixing and preparing the samples, with dimensions of $40 \times 40 \times 160 \text{ mm}^3$, were defined in accordance with standard NF EN 206-1 (2004). The prepared mortar samples were covered with a polyethylene film and maintained in their molds for 24 h under laboratory conditions. After demolding, they were immersed in water for an additional 24 h to ensure uniform early hydration. Subsequently, the samples were cured at $20 \pm 2^\circ\text{C}$ with 65% RH in laboratory condition until the time of testing. This curing procedure was adopted to combine reproducible early-age curing with storage conditions repre-

sentative of the practical exposure targeted in this study.

The chemical activator NaOH was used as an alkaline activator at a dosage of 1% of the weight of the binder. To do this, it was dissolved in the mixing water. Finally, for thermal activation, two ambient temperatures were selected (20°C and 40°C). These temperatures in the cool state were controlled using an electrically regulated enclosure. After demolding, the specimens were stored either under laboratory conditions at 20°C or in an oven maintained at 40°C , depending on the temperatures previously selected in the design.

2.4. Test methods

In order to improve the reactivity of the SCMs used, this study aims to analyze the effect of different activation processes, namely mechanical, thermal or chemical, on the evolution of mechanical performance at early-age, especially the compressive strength at 2 and 7 days. Compressive strength tests were conducted in accordance with the standard EN 196-1 (2005). For each mix and testing age, six replicate measurements were performed. The reported value was calculated as the arithmetic mean of these measurements. If one result deviated by more than $\pm 10\%$ from the mean, it was discarded, and a new average was calculated based on the remaining five values.

3. Results and Discussion

3.1. 2-day compressive strength

Fig. 5 presents the results of the compressive strength at 2 days of the control mortar C0, based on 100% OPC, as well as those of the activated and non-activated quaternary binder mortars. The main result shows that the C0 reference mortar develops a higher compressive strength at 2 days (7.5 MPa), compared to mortars with non-activated quaternary binders, whose strength does not exceed 3.5 MPa. This decrease corresponds to a reduction rate of more than 53%. In addition, all activated quaternary binder mortars show a clear improvement, both compared to the reference mortar and compared to non-activated quaternary binder mortars. This behavior highlights the beneficial effect of activation processes, regardless of the type of activation used.

Moreover, it is clear that the combined activation process « T:40 F:6000 A:1 » is the most efficient process for all the mortars studied, in comparison with the other activation processes. This improvement is often due to the acceleration of hydration reactions and the increase in microstructure by synergistic mechanisms: (i) the increased fineness of SCMs improves Interfacial Transition Zone (ITZ), reduces capillary porosity and accelerates the precipitation of hydration products; (ii) the high temperature (20–40 °C) increases the rate of hydration, resulting in a higher early-age strength; (iii) the NaOH activator (0–1 %) increases pH and increases the dissociation of the vitreous network from the slag as well as the solubility of pozzolan.

While the two activation modes « T:20 F:3800 A:0 » and « T:40 F:6000 A:1 » have fairly similar compressive strengths. This can be explained by compensation between effects such as reaction acceleration, increased porosity and the formation of early-age hydration products with lower intrinsic strength.

It is also observed that mortars C1 and C6, containing 20% and 30% of blast furnace slag respectively, develop very high compressive strengths at 2 days. This improvement is particularly marked for the two activation modes « T:40 F:3800 A:0 » and « T:40 F:6000 A:1 ». The 2-day compressive strengths of C1 and C6 under the activation mode “T:40 F:6000 A:1” reach 20 and 21 MPa, respectively, compared to 2.5 and 2 MPa for the corresponding non-activated mortars (i.e., the same formulations without activation), corresponding to increases of approximately 700% and 950%, respectively. This is attributed to the combined effect of activation processes on the hydration reaction and slag activation (Biricik and Karapinar 2021).

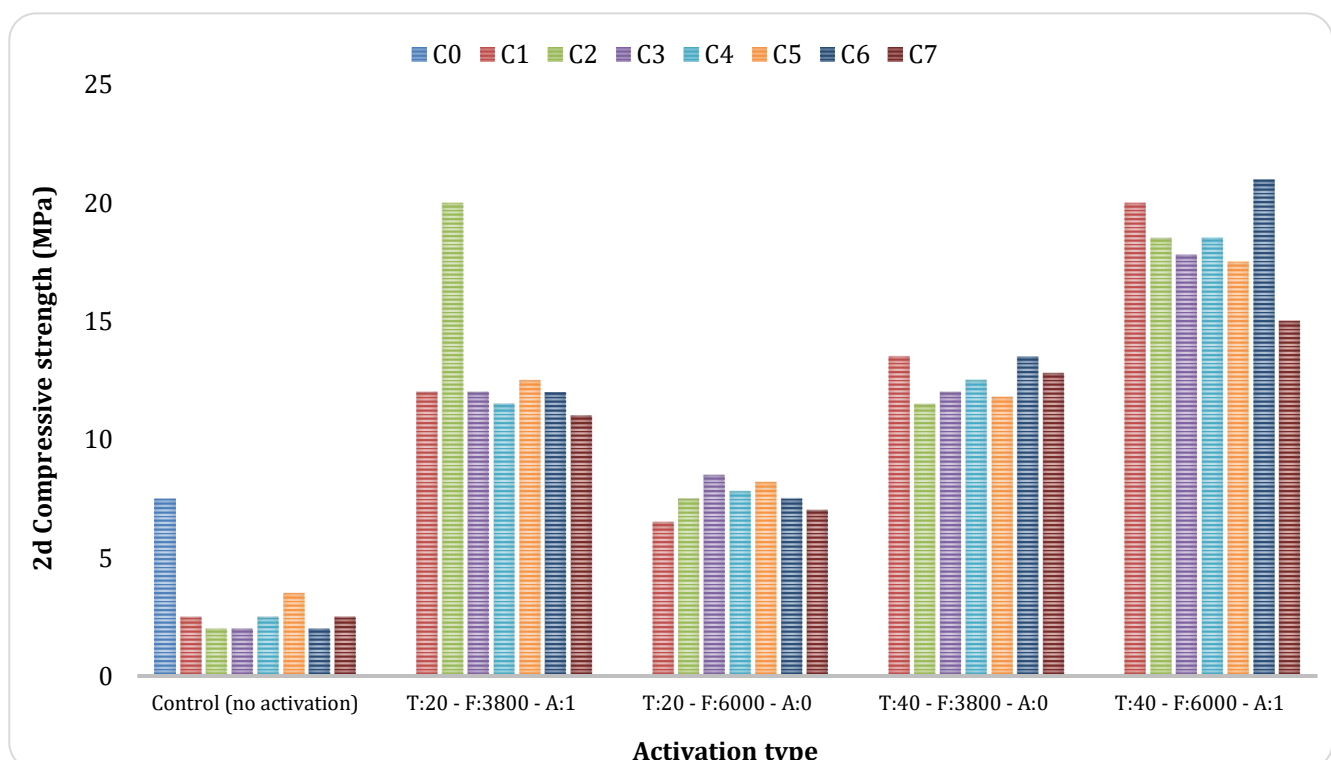


Fig. 5. Compressive strength at 2 days of activated and non-activated quaternary binder mortars.

A fractional factorial experimental design (2^{3-1}) was used to identify the SCM activation processes that exert a statistically significant effect on the 2-day compressive strength of quaternary binder mortars. This choice has reduced the experimental trials, time and costs, while ensuring high-quality results. The observed and predicted compressive strengths at 2 days of the activation

modes studied are presented in Table 5, making it possible to evaluate the effect of each variable studied.

The main factors influencing the compressive strength of 2-day quaternary binder mortars were determined by an analysis of variance (ANOVA). The values of « Prob > F » below 0.0500 indicate that the terms of the model are significant (Table 6).

Table 5. Factorial design matrix with experimental and predicted responses.

Run	Coded values of independent variables				2-day compressive strength (MPa)		7-day compressive strength (MPa)	
	Composition	T	F	A	Observed	Predicted	Observed	Predicted
1	C1	-1	1	-1	12.66	12.12	16.0	15.32
2		-1	1	1	6.72	8.25	19.0	17.66
3		1	-1	-1	13.44	13.02	19.5	19.85
4		1	-1	1	20.31	18.59	21.0	23.66
5	C2	-1	-1	1	19.84	20.00	16.0	16.50
6		-1	1	1	6.88	7.12	15.0	16.73
7		1	-1	-1	11.25	11.88	20.5	21.26
8		1	1	-1	18.28	18.50	23.0	24.50
9	C3	-1	-1	-1	12.19	11.70	19.0	19.03
10		-1	1	1	8.59	7.83	17.0	16.70
11		1	-1	1	12.50	12.60	22.0	21.23
12		1	1	-1	18.12	18.17	26.0	25.04
13	C4	-1	-1	1	11.88	11.70	19.5	19.25
14		-1	1	-1	8.12	7.83	14.0	14.83
15		1	-1	-1	12.19	12.60	18.0	17.50
16		1	1	1	18.59	18.17	24.5	25.52
17	C5	-1	-1	-1	12.66	11.63	17.5	17.50
18		-1	-1	1	8.12	7.76	16.0	16.27
19		1	1	-1	11.88	12.52	21.0	20.81
20		1	1	1	16.56	18.09	28.5	25.04
21	C6	-1	-1	-1	12.19	13.27	16.5	16.70
22		-1	1	1	7.66	7.50	15.0	14.57
23		1	-1	1	13.59	13.50	17.5	19.03
24		1	1	-1	21.09	19.73	22.0	22.91
25	C7	-1	-1	-1	10.94	10.58	16.5	16.27
26		-1	1	-1	7.81	6.71	14.5	14.57
27		-1	1	1	12.97	11.47	20.0	21.23
28		1	-1	-1	14.84	17.04	21.0	22.91

Table 6. Analysis of variance (ANOVA) for selected factorial model for 2-day compressive strength.

Source	Sum of squares	DF	Mean square	F-value	Prob>F	Status
Model	475.21331	13	36.5549	28.3743	<0.0001	Significant
Comp.	10.78033	6	1.79672	1.3946	0.2836	Not significant
T	53.04381	1	53.04381	41.1732	<0.0001	Significant
F	18.13714	1	18.13714	14.0782	0.0021	Significant
A	124.03125	1	124.03125	96.2744	<0.0001	Significant
T*F	14.22004	1	14.22004	11.0377	0.0050	Significant
T*A	7.20857	1	7.20857	5.5954	0.0330	Significant
F*A	9.71524	1	9.71524	7.5411	0.0158	Significant
T*F*A	7.03125	1	7.03125	5.4577	0.0349	Significant
Residual	18.03633	14	1.2883	R ²		0.963434
Cor. Total	493.24964	27	/	Adj. R ²		0.929479
RMSE	1.135037			Pred. R ²		0.881613
Mean	12.85357					
Coefficient of variation (%)	8.83					
Predicted residual error of sum of squares	58.39426					

The ANOVA analysis shows the developed model is highly significant, as evidenced by a high F-value of 28.37 and a p-value of less than 0.0001. The reliability of the model is confirmed by an excellent determination coefficient ($R^2 = 0.9634$), indicating that the factorial design accounts for over 96% of the response variance. Furthermore, the adjusted R^2 (0.9295) and the predicted R^2 (0.8816) are in strong agreement (difference < 0.2), demonstrating that the model possesses a robust predictive capability without overfitting the experimental data.

Regarding the specific design parameters, the main effects of variables T, F, and A are statistically significant ($p < 0.05$). Notably, all two-way interactions ($T \times F$, $T \times A$, $F \times A$) as well as the three-way interaction ($T \times F \times A$) are also significant. This highlights the presence of complex synergistic effects between these factors governing the early-age strength development of the matrix. Finally, the low coefficient of variation ($CV = 8.83\%$) underscores the high precision and reproducibility of the experimental testing procedures.

To understand the physical meaning behind these statistical interactions, it is essential to examine the synergistic mechanisms between the activation parameters. For ($T \times F$) interaction, the NaOH activator alone increases the pH to initiate the dissociation of the vitreous network of the slag, its chemical efficiency is significantly amplified when coupled with a higher temperature (40 °C). The added thermal energy helps overcome the activation energy barrier for the dissolution of the SCMs, creating a strong synergistic effect. Similarly, the interaction ($F \times A$) is physically manifested by the fact that an increased fineness (6000 cm^2/g) exposes a much larger specific surface area to the alkaline solution. This ampli-

fies the chemical attack and accelerates the precipitation of hydration products far more effectively than if the activator were applied to coarser particles.

The statistical significance of the three-way interaction ($T \times F \times A$) highlights a profound multi-physics synergy. The chemical activation provided by the alkaline solution (A) is drastically amplified by the thermal curing (T), which accelerates the reaction kinetics. However, this thermo-chemical acceleration can only translate into massive early-age strength development if there is simultaneously a highly extended specific surface area (F) available for the rapid precipitation of hydration products. This three-way interdependency confirms that the exceptional performances of the 'T:40 F:6000 A:1' mode are the result of eliminating all kinetic bottlenecks during the early stages of hydration. This profound interdependence explains the exceptional compressive strength peaks and the massive improvement rates observed in mortars with high slag content, such as C1 and C6, under the combined 'T:40 F:6000 A:1' mode (Humad et al. 2019).

The simplified mathematical model obtained is represented by Eq. (1).

$$\text{CS 2d} = 13.73 + 1.83T + 0.96F + 3.65A - 1.18 T \cdot F - 0.59 T \cdot A + 1.03 F \cdot A - 1.23 T \cdot F \cdot A \quad (1)$$

3.2. 7-day compressive strength

Fig. 6 illustrates the results of the compressive strength at 7 days of the reference mortar C0, as well as those of the mortars with quaternary binders, whether they are activated or not.

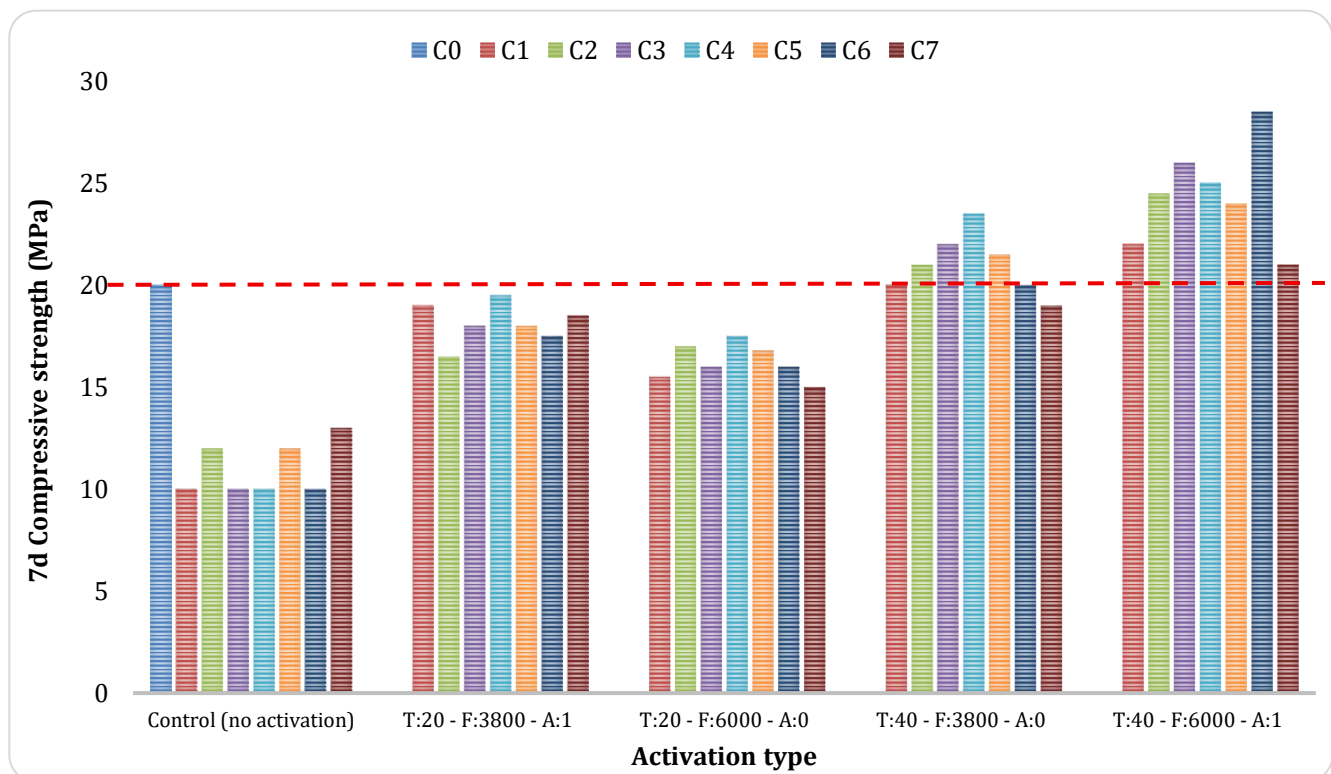


Fig. 6. Evolution of the 7-day compressive strength of activated and non-activated quaternary binder mortars.

The results of Fig. 4 clearly show that the compressive strengths at 7 days of all the non-activated quaternary mixtures are lower than that of the C0 reference mortar, which confirms that the partial replacement of the cement by non-activated SCMs leads to a remarkable decrease in the compressive strength at an early-age. On the other hand, the activation of SCMs significantly improves the compressive strength at 7 days for all the quaternary compositions studied, thus demonstrating the effectiveness of the activation processes in compensating for the initial loss of performance and optimizing the early development of the mechanical properties.

The activation of the SCMs for a temperature of 20 °C. remains insufficient for all the compositions tested, despite the increase in the fineness of the SCMs and the incorporation of 1% of NaOH. In fact, the increase in the fineness of the SCMs to 6000 cm²/g at 20 °C. improves the mechanical strength, but this improvement remains limited due to the low curing temperature.

On the other hand, the increase in the curing temperature from 20 to 40° C. markedly increases the compressive strength at 7 days of the mortars containing quaternary binders, which can be interpreted by the acceleration of the pozzolanic reactions and the accelerated and denser formation of the C-S-H gels in the system studied. It appears that the increase in temperature is a crucial factor for improving the compressive strength, thus making it possible to obtain better performance.

Furthermore, this effect is particularly marked for C3,

C4, C5 and C6, which have a particularly favorable response to the activation mechanisms, with the highest strength values. The difference in compressive strength between formulations C1 to C7, under the same activation conditions, demonstrates that the nature of the SCMs and their degree of substitution significantly influence the mechanical performance of the mortar. The results also indicate that some SCMs, especially pozzolan and slag, exhibit better reactivity to thermomechanical activation mechanisms, thus promoting the development of early-age strength.

Moreover, the combination of three activation modes leads to a notable improvement in the compressive strengths at 7 days, which exceed those of the reference mortar C0 for all the mortars with a quaternary binder. This activation method thus appears to be the most optimal mode for improving mechanical performance at an early-age (7 days), indicating the synergistic effect between the curing temperature, the high fineness and the alkaline activation.

These results thus show that the combined activation constitutes an effective strategy for compensating for the initial loss of strength of the mortars with non-activated quaternary binders.

An analysis of variance (ANOVA) also identified the main parameters influencing the compressive strength of 7-day quaternary binder mortars. Model terms with a « Prob > F » value less than 0.0500 are considered statistically significant (Table 7).

Table 7. Analysis of variance (ANOVA) for selected factorial model for 7-day compressive strength.

Source	Sum of squares	DF	Mean square	F-value	Prob>F	Status
Model	295.49890	13	22.7307	9.8861	<0.0001	Significant
Comp.	16.81033	6	2.80172	1.2185	0.3536	Not significant
T	128.97524	1	128.97524	56.0942	<0.0001	Significant
F	0.06095	1	0.06095	0.0265	0.8730	Not significant
A	5.28125	1	5.28125	2.2969	0.1519	Not significant
T*F	2.98289	1	2.98289	1.2973	0.2738	Not significant
T*A	2.57524	1	2.57524	1.1200	0.3078	Not significant
F*A	2.57524	1	2.57524	1.1200	0.3078	Not significant
T*F*A	0.03125	1	0.03125	0.0136	0.9088	Not significant
Residual	32.18967	14	2.2993	R ²		0.963434
Cor. Total	327.68857	27	/	Adj. R ²		0.929479
RMSE	1.516332			Pred. R ²		0.881613
Mean	19.95714					
Coefficient of variation (%)	7.60					
Predicted residual error of sum of squares	85.48427					

The ANOVA analysis shows the overall model remains highly significant ($p < 0.0001$), with a strong coefficient of determination ($R^2 = 0.9469$). The acceptable difference of less than 0.20 between the adjusted R^2 (0.8976) and the predicted R^2 (0.7391) confirms the model's adequate predictive capability for this curing age.

A critical observation at 7 days is the shift in the significance of the experimental factors compared to the early-age results. The main effect of factor T remains highly significant and becomes the dominant driver of

compressive strength ($p < 0.0001$). Conversely, the previously significant factors (F and A) and all of their interaction terms (T*F, T*A, F*A, and T*F*A) are statistically insignificant at this stage. This microstructural evolution suggests that while complex synergistic activation mechanisms govern initial hydration kinetics, the intermediate-term strength development of the mortar matrix is primarily controlled by parameter T. Furthermore, the reduced coefficient of variation ($CV = 7.60\%$) reflects the stabilization of the matrix and the high reliability of the crushing test protocol.

At early ages (2 days), the synergy of high fineness and chemical activation is critical to overcome the activation energy and dissolve the slag's vitreous network. By 7 days, however, the reactive surfaces are coated with hydration products and the activator is consumed (Bernal et al. 2011; Ke et al. 2019). Consequently, the initial advantages of fineness and chemical activation lose statistical dominance, and thermal curing becomes the sole driving factor, providing the necessary thermodynamic energy to accelerate ionic diffusion through the dense matrix (Bakharev et al. 1999).

After elimination of the non-significant terms ($p > 0.05$), the reduced model selected comprises the factors Comp, T and the interaction T×F. The simplified mathematical model obtained is represented by Eq. (2).

$$\text{CS 7d} = 19.91 + 3.07T - 0.07F + 0.81A + 0.7225T \cdot F + 0.43T \cdot A - 0.43F \cdot A + 0.06T \cdot F \cdot A \quad (2)$$

4. Conclusions

This research examines the combined effects of the three SCMs activation methods on the compressive strength of quaternary binder mortars at early-age, while proposing a statistical analysis of the main effects and their interactions. The results obtained provide a better understanding of the synergistic role of the different activation techniques, thus contributing to the optimization of the early mechanical performance of quaternary cement systems. The main results of this study are presented below:

- Partial replacement of Portland cement with non-activated SCMs leads to a significant decrease in the compressive strength of quaternary binder mortars at an early-age, due to their relatively low initial reactivity compared to cement.
- The SCM activation processes significantly improve the mechanical performance of quaternary mortars at early ages (2 and 7 days), by compensating for the early-age strength loss observed in the non-activated formulations, indicating an acceleration of hydration reactions and an improvement in the densification of the material microstructure.
- Statistical analysis (ANOVA) revealed that curing temperature is one of the most influential parameters on the compressive strength of quaternary binder mortars.
- Increasing the temperature from 20 °C to 40 °C accelerates hydration reactions and pozzolanic reactions, thus promoting faster formation of C–S–H gels and a significant improvement in mechanical strength.
- The combination of several activation processes, including the increase in the fineness of the SCMs, the increase in the curing temperature and the alkaline activation, leads to a notable improvement in the mechanical performance of the mortars studied. This combined activation generates synergistic effects that accelerate chemical reactions and improve the microstructure of the cement material.
- The composition of the binder and the degree of substitution of the SCMs strongly influence the mechanical performance. The formulations containing suitable

proportions of blast furnace slag and pozzolan exhibit a higher reactivity under activation, leading to higher compressive strengths than the other formulations studied.

- Future work should investigate the mechanical performance of these quaternary binder systems at intermediate and long cure ages (28 and 90 days) to better understand the delayed pozzolanic reactions and the long-term microstructural evolution of activated SCM binders.
- A limitation of this study is the absence of microstructural characterization. Future work will incorporate SEM and XRD analyses to directly validate the proposed mechanisms and provide deeper insight into hydration processes in quaternary binder systems.

These large amounts of experimental data can also be used to develop machine learning models capable of predicting the mechanical behavior of quaternary binder systems. Such data-driven approaches can contribute to improving the design of cementitious formulations and accelerating the development of high-performance, sustainable cementitious materials.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- Ababneh AN, Al-Thiab EH, Al-Shorman BH (2025). Early strength development in cement mortars containing high proportions of Jordanian natural pozzolan. *Results in Engineering*, 27, 105868.
- Al-Safi S, Altharehi A, Alameri IA, Al-Jolahy A (2025). The mechanical properties of cement mortar reinforced with silica fume subjected to sulfate and chloride environment. *Challenge Journal of Structural Mechanics*, 11(1), 55-69.
- Alcan HG, Dheyaaldin MH, Toklu K, Bayrak B, Kaplan G, Aydın AC (2024). Effect of quaternary binder slag-based geopolymer slurries on mechanical durability and microstructural properties of green pre-packed composites. *Construction and Building Materials*, 450, 138571.
- Allahverdi A, Salem S (2010). Simultaneous influences of microsilica and limestone powder on properties of Portland cement paste. *Ceramics-Silikáty*, 54(1), 65-71.

- Allahverdi A, Saffari M (2011). Chemical activation of phosphorous slag with a solid compound activator. In: *4th International Conference on Non-Traditional Cements and Concretes*, Brno, Czech Republic, pp. 573-580.
- Allahverdi A, Mahinroosta M (2013). Mechanical activation of chemically activated high phosphorous slag content cement. *Powder Technology*, 245, 182-188.
- Bakharev T, Sanjayan JG, Cheng YB (1999). Effect of elevated temperature curing on properties of alkali-activated slag concrete. *Cement and Concrete Research*, 29(10), 1619-1625.
- Bellmann F, Stark J (2009). Activation of blast furnace slag by a new method. *Cement and Concrete Research*, 39(8), 644-650.
- Berkak H, Makhloufi Z, Chenafi MH (2025). Impact of supplementary cementitious materials (SCMs) on physical-mechanical properties and microstructure of styrene polyacrylic (SPA) polymer modified mortars. *Revista de la Construcción*, 24(2), 256-276.
- Bernal SA, Provis JL, Rose V, de Gutiérrez RM (2011). Evolution of binder structure in sodium silicate-activated slag-metakaolin blends. *Cement and Concrete Composites*, 33(1), 46-54.
- Biricik H, Karapinar IS (2021). Effect of slag fineness and curing conditions on the mechanical properties of alkali-activated blast furnace slag mortars. *International Journal of Engineering Technologies*, 7(2), 33-38.
- Chenafi MH, Makhloufi Z, Bekkai AO, Berkak H (2026). Enhancing the performance of sustainable geopolymers: insights into liquid-to-solid and alkali ratios. *Research on Engineering Structures & Materials*, 12(1), 247-263.
- Dave N, Misra AK, Srivastava A, Kaushik SK (2016). Experimental analysis of strength and durability properties of quaternary cement binder and mortar. *Construction and Building Materials*, 107, 117-124.
- Dave N, Misra AK, Srivastava A, Sharma AK, Kaushik SK (2017). Study on quaternary concrete micro-structure, strength, durability considering the influence of multi-factors. *Construction and Building Materials*, 139, 447-457.
- Dong XL, Lin C, Xu ZZ, Luo ZM (2002). A blended cement containing blast furnace slag and phosphorous slag. *Journal of Wuhan University of Technology-Materials Science Edition*, 17(2), 62-65.
- Elbar M, Senhadji Y, Benosman AS, Khelafi H, Mouli M (2018). Effect of thermo-activation on mechanical strengths and chlorides permeability in pozzolanic materials. *Case Studies in Construction Materials*, 8, 459-468.
- EN 196-1 (2005). *Methods of Testing Cement - Part 1: Determination of Strength*. European Committee for Standardization, Brussels, Belgium.
- Ezziane K, Kadri EH, Hallal A, Duval R (2010). Effect of mineral additives on the setting of blended cement by the maturity method. *Materials and Structures*, 43(3), 393-401.
- Fu X, Li Q, Zhai J, Sheng G, Li F (2008). The physical-chemical characterization of mechanically-treated CFBC fly ash. *Cement and Concrete Composites*, 30(3), 220-226.
- Ghrici M, Kenai S, Said-Mansour M (2007). Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements. *Cement and Concrete Composites*, 29(7), 542-549.
- Go SS, Chung CW, Struble LJ, Lee HC (2010). Pozzolanic activity of Hwangtoh clay. *Construction and Building Materials*, 24(12), 2638-2645.
- Humad AM, Habermehl-Cwirzen K, Cwirzen A (2019). Effects of fineness and chemical composition of blast furnace slag on properties of alkali-activated binder. *Materials*, 12(20), 3447.
- Indrawati V, Manaf A (2008). Mechanical strength of trass as supplementary cementing material. *Journal of Physical Science*, 19(2), 51-59.
- Ke X, Bernal SA, Provis JL (2019). Layered double hydroxides modify the reaction of sodium silicate-activated slag cements. *Green Materials*, 7(2), 52-60.
- Khan K, Amin MN, Usman M, Imran M, Al-Faiad MA, Shalabi FI (2022). Effect of fineness and heat treatment on the pozzolanic activity of natural volcanic ash for its utilization as supplementary cementitious materials. *Crystals*, 12(2), 302.
- Kumar S, Kumar R, Bandopadhyay A, Alex TC, Kumar BR, Das SK, Mehrotra SP (2008). Mechanical activation of granulated blast furnace slag and its effect on the properties and structure of Portland slag cement. *Cement and Concrete Composites*, 30(8), 679-685.
- Li C, Wu M, Yao W (2019). Eco-efficient cementitious system consisting of belite-ye'elimite-ferrite cement, limestone filler, and silica fume. *ACS Sustainable Chemistry & Engineering*, 7(8), 7941-7950.
- Li Y, Yao Y, Liu X, Sun H, Ni W (2013). Improvement on pozzolanic reactivity of coal gangue by integrated thermal and chemical activation. *Fuel*, 109, 527-533.
- Lin RS, Han Y, Wang XY (2021). Experimental study on optimum proportioning of Portland cements, limestone, metakaolin, and fly ash for obtaining quaternary cementitious composites. *Case Studies in Construction Materials*, 15, e00691.
- Makhloufi Z, Kadri EH, Bouhicha M, Benaissa A, Bennacer R (2012). The strength of limestone mortars with quaternary binders: leaching effect by demineralized water. *Construction and Building Materials*, 36, 171-181.
- Makhloufi Z, Chettih M, Bederina M, Kadri EH, Bouhicha M (2015). Effect of quaternary cementitious systems containing limestone, blast furnace slag and natural pozzolan on mechanical behavior of limestone mortars. *Construction and Building Materials*, 95, 647-657.
- Miller SA, Moore FC (2020). Climate and health damages from global concrete production. *Nature Climate Change*, 10(5), 439-443.
- Mohamad N, Embong R, Othman NH, Muthusamy K, Md Jaafar MF (2025). Flowability and compressive strength of ternary blended cement mortar of coal bottom ash and ground cockle shell ash. *Challenge Journal of Concrete Research Letters*, 16(1), 25-32.
- Mounanga P, Khokhar MIA, El Hachem R, Loukili A (2011). Improvement of the early age reactivity of fly ash and blast furnace slag cementitious systems using limestone filler. *Materials and Structures*, 44(2), 437-453.
- NF EN 206-1 (2004). *Concrete - Part 1: Specification, Performance, Production and Conformity*. Association Française de Normalisation (AFNOR), Paris, France.
- NF P 18-301 (1983). *Granulats - Granulats naturels pour bétons hydrauliques*. Association Française de Normalisation (AFNOR), Paris, France.
- Öner M, Erdoğan K, Günlü A (2003). Effect of components fineness on strength of blast furnace slag cement. *Cement and Concrete Research*, 33(4), 463-469.
- Pang L, Liu Z, Wang D, An M (2022). Review on the application of supplementary cementitious materials in self-compacting concrete. *Crystals*, 12(2), 180.
- Rojo-López G, Nunes S, González-Fontboa B, Martínez-Abella F (2020). Quaternary blends of Portland cement, metakaolin, biomass ash and granite powder for production of self-compacting concrete. *Journal of Cleaner Production*, 266, 121666.
- Sajedi F, Razak HA (2011a). Effects of thermal and mechanical activation methods on compressive strength of ordinary Portland cement-slag mortar. *Materials & Design*, 32(2), 984-995.
- Sajedi F, Razak HA (2011b). Comparison of different methods for activation of ordinary Portland cement-slag mortars. *Construction and Building Materials*, 25(1), 30-38.
- Shi C, Day RL (2001). Comparison of different methods for enhancing reactivity of pozzolans. *Cement and Concrete Research*, 31(5), 813-818.
- Sobolev K (2005). Mechano-chemical modification of cement with high volumes of blast furnace slag. *Cement and Concrete Composites*, 27(7-8), 848-853.
- UNEP International Resource Panel (n.d.). *Global Material Flows Database*. <https://www.resourcepanel.org/global-material-flows-database> [accessed 01-01-2026].
- Ünal S, Canbaz M (2025). Utilization of expired cement and aged roof tile powder in the production of sustainable geopolymer: mechanical and physical properties. *Challenge Journal of Structural Mechanics*, 11(2), 82-88.
- Vignesh R, Rahim AA (2022). Mechanical and microstructural properties of quaternary binder system containing OPC-GGBS-metakaolin-lime. *Materials Today: Proceedings*, 64, 970-975.
- Yu W, Yao J, Zhang S, Bu Y, Huang X, Zhao Y, Mu Y, Ni W (2024). Steering the early strength of clinker-free cementitious mortar by chemical environment. *Construction and Building Materials*, 456, 139138.
- Zelić J, Jozić D, Krpan-Lisica D (2009). Synergistic action of a ternary system of Portland cement-limestone-silica fume in concrete. In: Bittnar Z, Bartos PJM, Němeček J, Šmilauer V, Zeman J, editors. *Nanotechnology in Construction 3*. Springer, Berlin, Germany, pp. 425-434.
- Živanović BD, Srećković TV, Komljenović M (2002). The influence of mechanical activation on the process of reaction sintering of Portland cement clinker. *Science of Sintering*, 34(1), 95-100.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Mechanical performance evaluation of conventional and pervious concrete reinforced with steel and nylon fibers

Md. Izharul Haque Azad ^{a,*} , Md. Abu Helal ^b , Md. Abdul Malek ^b ,
Rahat Ali ^c , Md. Ahmadullah Hossain Raihan ^c , Md. Washim Akram ^c

^a Department of Civil Engineering, Gopalganj Science and Technology University, Gopalganj 8105, Bangladesh

^b Department of Civil Engineering, Khulna University of Engineering & Technology, Khulna 9203, Bangladesh

^c Department of Civil Engineering, Bangladesh Army University of Science and Technology, Saidpur 5310, Bangladesh

ABSTRACT

Performance enhancement of concrete to meet modern infrastructure demands has become essential in the construction industry. This study presents an experimental investigation of the incorporation of steel and nylon fibers in conventional and pervious concrete to evaluate their mechanical strength and permeability behavior. Fibers were added to the mix at 0.25%, 0.50%, 0.75%, and 1.0% by weight of cement. The studied parameters were the compressive strength, split tensile strength, density, porosity, and permeability. The experimental results revealed that, with optimum dosage, both fibers affected the mechanical properties of conventional and pervious concrete. The tensile strength showed a remarkable increase (approximately 45% for steel fibers), primarily through crack-bridging mechanisms within the matrix. Higher dosages of steel fibers were more effective than lower contents. Nylon fibers at a low dosage (0.25%) provided optimum performance, whereas 0.75% content also showed a notable strength increase. The density of both concrete types demonstrated only marginal variation. The permeability of pervious concrete, however, exhibited a slight increase at low fiber content, followed by a decrease with further fiber addition, indicating a trade-off between strength and hydraulic functionality. A comparative analysis of both concrete types was also performed. The findings demonstrate that controlled incorporation of steel and nylon fibers enhances the load resistance of both types of concrete while an optimal dosage is required to maintain adequate permeability, thereby contributing to more durable and sustainable construction practices.

ARTICLE INFO

Article history:

Received – April 11, 2026

Revision requested – June 2, 2026

Revision received – July 4, 2026

Accepted – July 11, 2026

Keywords:

Fiber-reinforced concrete

Pervious concrete

Steel fiber

Nylon fiber

Split tensile strength

Permeability



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

Citation: Azad MIH, Helal MA, Malek MA, Ali R, Raihan MAH, Akram MW (2026). Mechanical performance evaluation of conventional and pervious concrete reinforced with steel and nylon fibers. *Challenge Journal of Concrete Research Letters*, 17(3), 305–318.

1. Introduction

In the construction industry, concrete plays the role of a prime component on a global scale and has become one of the most consumed materials worldwide after water (Gagg 2014; Nouri et al. 2025; Xiao et al. 2025). It is used in the construction and development of infrastructures and urbanization due to its high compressive strength, durability, stiffness, and ease of production

(Kosmatka et al. 2008; Varshney et al. 2021). The strength of concrete depends on the properties and strength behavior of its constituent elements – cement, fine aggregate, coarse aggregate, and mixing water (Konitufe et al. 2023; Rashid and Mansur 2009). However, plain concrete has some inherent limitations such as very low tensile strength, approximately one-tenth of its compressive strength (Akinpelu et al. 2019; Badarloo et al. 2018; McCormac and Brown 2013); brittle failure

* Corresponding author. E-mail address: izharce@gstu.edu.bd (M. I. H. Azad)

ISSN: 2548-0928 / DOI: <https://doi.org/10.20528/cjcr.2026.1160>

behavior, strength degradation at higher temperature, and limited crack-resisting ability (McCormac and Brown 2013). In order to enhance these capacities, steel reinforcing bars are commonly used in concrete structures. These reinforcements can provide strength in the designed direction only, not ensuring uniform tensile and flexural strength in all directions. To overcome this, fiber reinforced concrete (FRC) has emerged as an effective strengthening approach to improve the mechanical properties of concrete through crack bridging and fracture resistance in all directions (Lee et al. 2022; Li et al. 2023; Urtekin and Çelik 2025). Various types of fibers have been incorporated into concrete to improve its strength and mechanical properties, each offering distinct reinforcement mechanism and performance characteristics (Anas et al. 2022; Khan and Abbas 2025).

Steel fibers have been widely reported for improving the mechanical strength of concrete, its ductility, and toughness, due to their inherent stiffness and high bond with the cement matrix (Amin et al. 2022; Faustmann et al. 2024; Sitorus et al. 2025). It also enhances the flexural and shear strength of concrete structural elements (Koo et al. 2023; Krassowska and Kosior-Kazberuk 2021). On the other hand, synthetic fibers such as polypropylene and nylon fibers contribute to improved ductility and crack resistance by controlling the microcrack formation during the early loading stages (Ali et al. 2022; Bheel et al. 2021; Tanash et al. 2025; Nandaraj and Mourougane 2026). The incorporation of natural fibers such as jute, coconut, and kenaf has also been investigated experimentally. However, their performance varies significantly depending on their durability, surface treatment, and compatibility with the cement paste (Bheel et al. 2021; Kameli et al. 2024; Nur et al. 2025). The synergistic effect of hybrid fiber systems combining steel with synthetic fibers or basalt fibers indicates improvements in both strength and toughness (Khan and Abbas 2025). The performance of fiber-reinforced mortar (FRM) also demonstrates promising potential (Akyüncü 2021; Doğan et al. 2022). Recent studies have also shown a trend of combining recycled aggregate-fiber reinforcement for sustainable and eco-friendly concrete development with improved mechanical performance (Ali et al. 2022; Doğan et al. 2022). Again, the special types of fibers such as carbon and basalt fibers have also been proved to have the potential of strengthening FRC (Doğan et al. 2022; Khan et al. 2025; Ünal et al. 2024). Overall, among the types of fibers used in concrete, steel fibers are widely appreciated and recognized for their strength, ductility, durability, and impact on tensile and flexural strength (Anas et al. 2022; Li et al. 2023). In contrast, synthetic fibers such as polypropylene, nylon, or hybrid fibers are known for improving the microstructural integrity of the matrix through crack resistance (Jahangir Qureshi et al. 2023).

The focus of FRC, however, has been conventional concrete-centered, while pervious or permeable concrete (PC) has also gained growing interest in the research arena due to its multiple advantages. It represents a porous concrete designed to allow water to infiltrate through for sustainable drainage and for smooth runoff management, especially in urban areas. This concrete contains cement and coarse aggregate with very lit-

tle or no filler, and is also referred to as no-sand concrete or no-fine concrete (ACI 522R-10 2010; Meininger 1988). The absence of fine aggregate results in high porosity through interconnected voids between coarse particles which eventually lowers its mechanical strength as compared to the conventional concrete (CC) used in construction (Lee et al. 2022).

Pervious concrete has the capability to mitigate surface runoff and recharge the groundwater making it a suitable material for sustainable pavement construction. Since, its limited load carrying capacity narrows down its structural application (ACI 522R-10 2010), pervious concrete is primarily used for low-traffic roadways with limited vehicular movement (Scholz and Grabowiecki 2007). Pavement construction with impermeable conventional concrete prevents rainwater from directly infiltrating into the ground creating environmental and climate issues (Yavuz 2024). Water accumulation on or near roadways during heavy or moderate rains is one of these issues which disrupts the traffic flow and safety (Yavuz 2024). Thus, the pavement construction in low-traffic regions such as pedestrian walkways and interior road networks in residential areas using porous concrete is highly recommended. It will facilitate the rapid water transmission into the ground, eventually preventing waterlogging on roads. The porosity of permeable concrete varies within a range, generally reported in the literature to be 15–25% (Xie et al. 2023) though the value recommended by ACI 522R is 15% to 35% (ACI 522R-10 2010). Regarding its mechanical strength, the compressive strength of PC may vary from 2.8 to 28 MPa and flexural strength ranges from 1.5 to 3.2 MPa, as suggested by researchers (Yavuz 2024). These strength properties are particularly influenced by various factors such as water/cement ratio, degree of compaction, binder content, aggregate type, and proportion (Ferić et al. 2023).

Research on pervious concrete has so far been focused mostly on its permeability. Different combinations of parameters such as content of cement and aggregates, type and size of aggregate, water content, additives, etc. have been explored to achieve balanced permeability (Ferić et al. 2023; Sun et al. 2025; Zhan and Yin 2024). In parallel with this, the mechanical strength properties of pervious concrete have also been extensively investigated. Recent initiatives on the enhancement of strength of pervious concrete using nano-materials and fibers have demonstrated promising results (Sun et al. 2025; Wu et al. 2023; Pehlivan 2022). Despite these advances in hydraulic and mechanical performance of PC, several research gaps remain. Optimization of both mechanical strength and porosity simultaneously continues to be a critical challenge, reflecting the more extensive need to balance mechanical performance with transport properties in sustainable concrete systems (Mahmud et al. 2025). Again, a comparative experimental analysis of fiber effect on both CC and PC under identical testing conditions is rarely reported in the literature. In addition, most experimental studies conducted on FRC rely on commercially manufactured fibers having standardized mechanical properties; little attention has been given to the use of locally available fiber materials. Furthermore, the role of fiber geometry combined with local resources

utilization in influencing the hydraulic functionality of pervious concrete remains insufficiently explored.

Therefore, this research work aims to experimentally evaluate the effects of locally sourced steel-wire fibers and commercially available nylon fibers on the mechanical properties of both conventional concrete and pervious concrete. These fibers offer potential advantages such as local resource availability, cost-effectiveness, and sustainability for developing regions. Moreover, by comparing both concrete typologies with similar fiber types and dosages, this study aims to provide insight into the balanced behavior of mechanical strength and hydraulic functionality, in terms of sustainable construction techniques.

2. Experimental Program

2.1. Materials and mix proportions

In this experimental work, fresh hydraulic cement (CEM I, Type A) was used as a binder for the preparation of both conventional and pervious concrete. River sand with FM of 2.68 and 19 mm downgrade stone chips were used as fine and coarse aggregates, respectively, in conventional concrete. The mix ratio was 1:1.5:3 by weight, with a water/cement ratio (w/c) of 0.45. The ratio was chosen to represent a typical structural grade concrete (target compressive strength of 20 MPa after 28 days of curing) used for most of the reinforced concrete (RC) structural components. For pervious concrete, a conventional mix ratio of 1:5 (cement: coarse aggregate) with w/c ratio of 0.33 was adopted without sand. The coarse aggregate consisted of 12 mm downgrade broken stone chips. The physical properties of the materials are given in Table 1. The selection of the maximum coarse aggregate sizes was intended to satisfy the functional requirements of the two concrete types commonly used in construction practice. Although cementitious mixtures without coarse aggregate are frequently adopted in some steel fiber-reinforced cementitious composites to facilitate fiber dispersion, the present study employed 19 mm downgrade (¾" downgrade) coarse aggregate for CC to represent typical structural concrete used in practice. In contrast, a 12 mm downgrade aggregate was used in PC to facilitate interconnected void formation while maintaining adequate aggregate interlock. Since larger coarse aggregates may influence fiber dispersion, relatively low

fiber dosages were adopted in this study and the controlled mixing procedure was followed to minimize the possibility of severe fiber balling and to promote satisfactory fiber distribution within the concrete matrix.

Steel fibers were obtained from readily available galvanized iron (GI) wires commonly used for binding in construction sites. The diameter of steel wires was 0.7 mm and a length of 60 mm was used, resulting in an aspect ratio (length/diameter) of 85.7. The nylon fibers were sourced from market-available twisted nylon ropes with a strand diameter of roughly 8–10 mm. The fiber diameter was 0.08 mm (80 μ m) and the fibers were cut into short discrete lengths of 20 mm with an aspect ratio of 250. Unlike industrially produced fibers with predefined mechanical and physical properties, the fibers used in this study were locally sourced and were not accompanied by manufacturer-specified data. The mechanical properties of these fibers were adopted from the literature and previous research works. This approach was followed because direct characterization of locally sourced fibers was beyond the scope of the present experimental program. Studies report a wide range of properties for the fibers depending on their type, manufacturing process, modifications, and geometric configuration. Thus, the properties used in this study are derived from the research sources that correspond to fibers with similar geometric and composite characteristics to ensure consistency in the experimental analysis. The geometric and mechanical properties of the fibers are summarized in Table 2, while Tables 3 and 4 present the mix proportions per unit volume for both CC and PC.

Fiber dosage was selected as percentage of cement weight, however, to facilitate comparison with previous studies, equivalent volumetric content of fibers is also shown in the respective tables. Fiber dispersion in concrete was carried out during dry mixing to avoid clustering and ensure uniform distribution of fibers, particularly at high dosage. All mixtures were prepared following the same mixing sequence, compaction procedure, and curing conditions to minimize variations associated with specimen preparation. The materials used in the lab work are illustrated in Figs. 1 and 2. Steel fibers were anchored at both ends for better bonding and nylon fibers were added in their original twisted shape obtained from the rope or strand to replicate real field conditions. Fig. 3 represents the gradation curves of the coarse and fine aggregates.

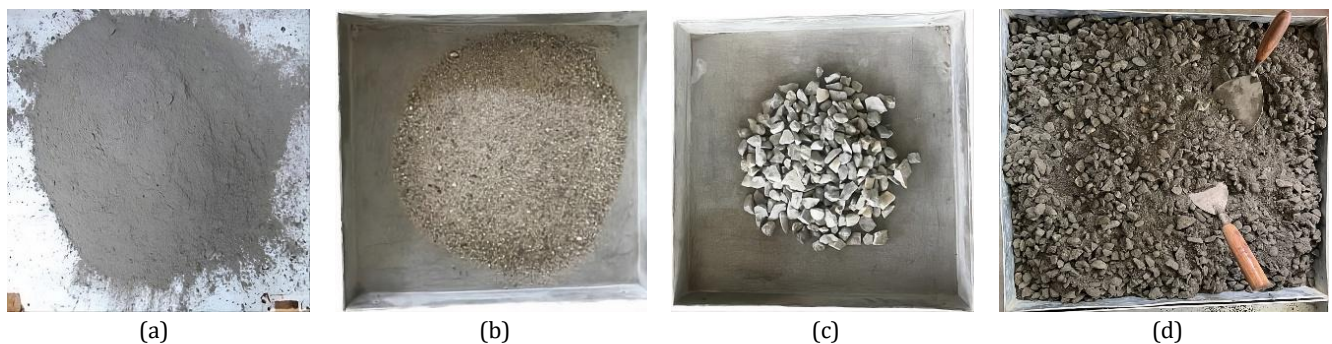


Fig. 1. Materials for concrete sample preparation: (a) Cement; (b) Fine aggregate; (c) Coarse aggregate; (d) Mixing of materials.

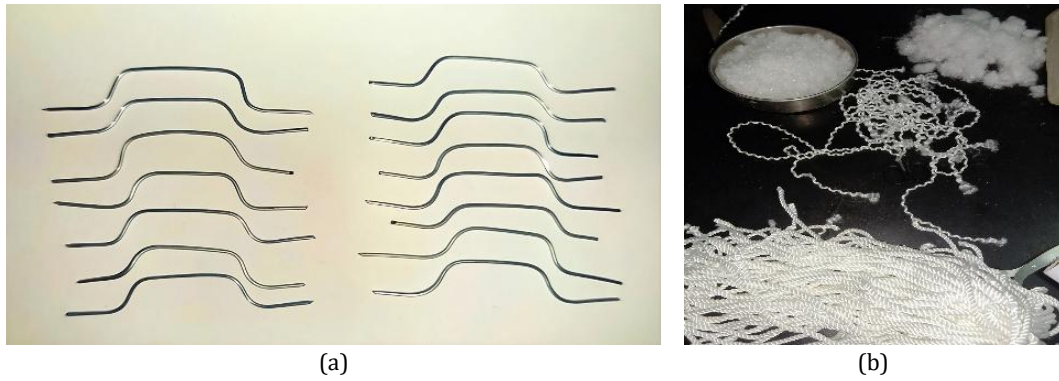


Fig. 2. Fibers used in concrete: (a) Steel fibers with end anchorage; (b) Nylon fiber.

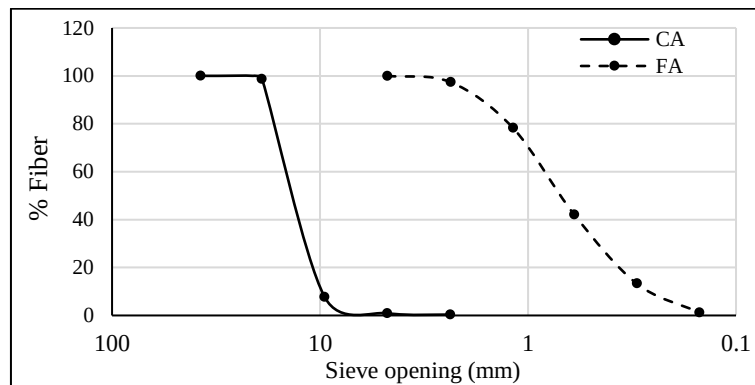


Fig. 3. Gradation curves for coarse aggregate (CA) and fine aggregate (FA).

Table 1. Material properties obtained in the laboratory.

Material	Properties evaluated	Values obtained
Cement	Specific gravity	3.12
	Normal consistency (%)	31
	Unit weight (kg/m ³)	1475
	Initial setting time (min)	36
	Final setting time (min)	580
Coarse aggregate	Specific gravity	2.97
	Water absorption (%)	1.08
	Unit weight (kg/m ³)	1764.2
Fine aggregate	Fineness modulus (FM)	2.68
	Specific gravity	2.72
	Water absorption (%)	2.04
	Unit weight (kg/m ³)	1680

Table 2. Geometric and mechanical properties of fibers.

Parameters	Steel fiber	Reference	Nylon fiber	Reference
Diameter (mm)	0.70	(Measured in study)	0.08	(Measured in study)
Length (mm)	60.0	(Measured in study)	20.0	(Measured in study)
Aspect ratio (L/D)	85.7	(Calculated)	250	(Calculated)
Yield strength (MPa)	440–470	(Emon et al. 2017)	Not applicable	–
Tensile strength (MPa)	610–630	(Emon et al. 2017)	800–1000	(Halabi et al. 2023; Song et al. 2005; Yew et al. 2011)
Elastic modulus (GPa)	190–210	(Zheng et al. 2024)	5.10–5.30	(Halabi et al. 2023; Song et al. 2005; Yew et al. 2011)
Density (kg/m ³)	7800–7850	(Zheng et al. 2024)	1140	(Halabi et al. 2023; Song et al. 2005; Yew et al. 2011)

Table 3. Mix proportion for conventional concrete.

Fiber (%)	Cement (kg/m ³)	FA (kg/m ³)	CA (kg/m ³)	Mixing water (kg/m ³)	Fiber (kg/m ³)	Steel vol. fraction (%)	Nylon vol. fraction (%)
0.00	403	605	1209	181	0	0	0
0.25	403	605	1209	181	1.01	0.013	0.089
0.50	403	605	1209	181	2.02	0.026	0.177
0.75	403	605	1209	181	3.03	0.039	0.266
1.00	403	605	1209	181	4.04	0.052	0.354

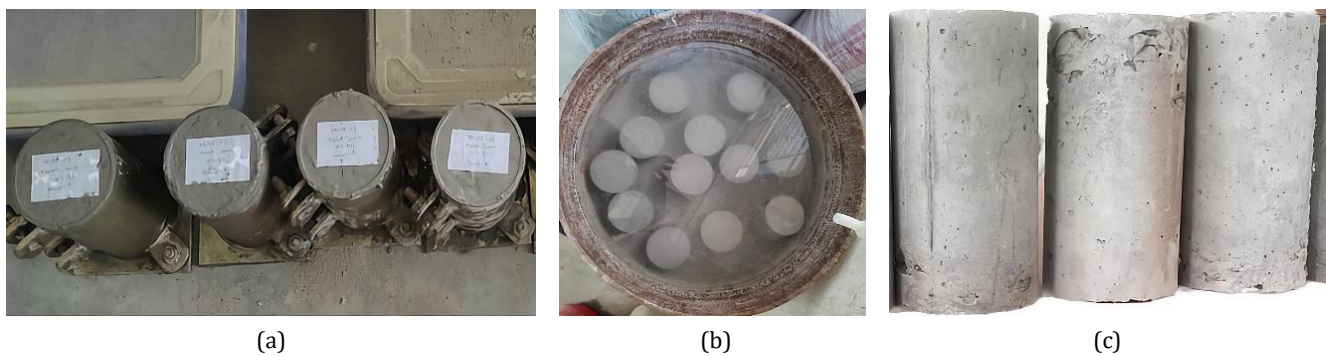
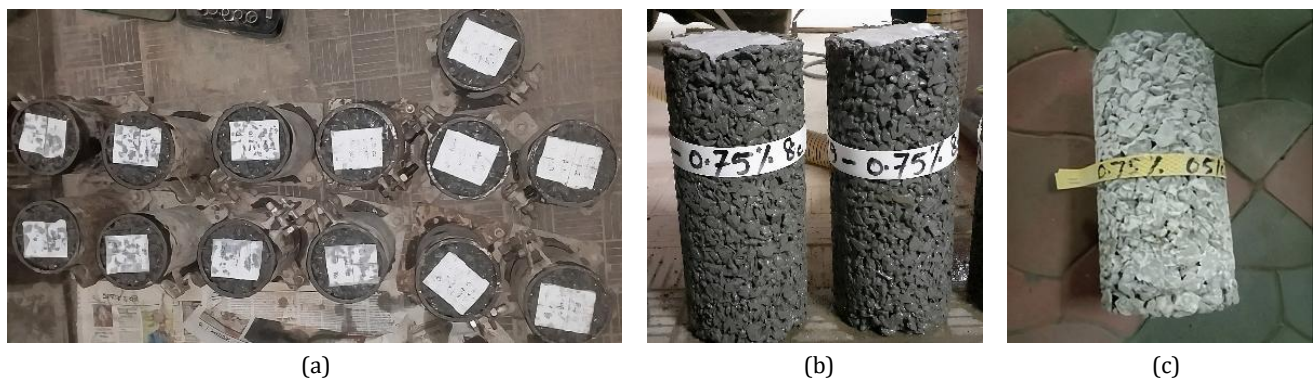
Table 4. Mix proportion for pervious concrete.

Fiber (%)	Cement (kg/m ³)	CA (kg/m ³)	Mixing water (kg/m ³)	Fiber (kg/m ³)	Steel vol. fraction (%)	Nylon vol. fraction (%)
0.00	300	1500	99	0	0	0
0.25	300	1500	99	0.75	0.010	0.066
0.50	300	1500	99	1.5	0.019	0.132
0.75	300	1500	99	2.25	0.029	0.197
1.00	300	1500	99	3.0	0.038	0.263

2.2. Concrete sample casting and curing

Cylindrical concrete samples of 100 mm diameter and 200 mm height (4 in. × 8 in.) were prepared with materials and mix ratio as stated in the previous section and summarized in Tables 3 and 4. Fibers were added separately as a weight percentage of cement (0.25%, 0.50%, 0.75%, and 1.0%). Samples were prepared following the standard mixing, casting, and compaction (Rodding) procedure stated in ASTM C192/C192M for conventional concrete. A total of nine (9) batches of the mix

were prepared for both CC and PC: 1 for the control specimen, 4 for steel fiber, and 4 for nylon fiber. The number of samples was determined as per the test requirements. For each mix, three (3) samples were prepared for each curing period (7 days and 28 days) under each test category (compressive and split tensile) e.g., three cylindrical samples for compressive strength after 7 days, three for compressive strength after 28 days, and so forth. This resulted in a total of 12 samples (3 samples × 2 curing periods × 2 tests) per batch or mix and with 9 batches, the total sample count was 108 for CC only.

**Fig. 4.** Preparation of conventional concrete: (a) Cast samples; (b) Curing; (c) Samples ready for testing.**Fig. 5.** Preparation of pervious concrete: (a) Casting; (b) Samples with steel fiber; (c) Samples with nylon fiber.

Pervious concrete samples were prepared in a similar manner using a mix ratio of 1:5. The mixing water quantity was determined by a trial method starting from a 0.30 w/c ratio. A certain quantity of material with the mentioned ratio was mixed and different amounts of water were added to check the consistency of the mix. After several trials, an optimum water/cement ratio of 0.33 was finalized based on the matrix's ability to retain its wet state without showing fluid-like behavior or a very dry condition. The fibers were added to the mix with the proportions mentioned in Table 4. Gradual mixing was adopted to prevent any clumping or balling of fibers inside the matrix. The number of samples followed a similar distribution as for CC with 3 additional specimens for the permeability test from each batch, which resulted in a total sample count of 135 for PC. The samples were prepared following

standard concrete casting procedure in ASTM C192/C192M with some modification for compaction as per ACI 522R. Figs. 4 and 5 show the preparation of concrete samples for testing.

2.3. Sample testing

Samples from each batch were cured in water for 7 and 28 days as per the test requirements. After curing, they were tested in accordance with the standard procedure for the compressive strength test and the split tensile strength test (ASTM C39 and ASTM C496, respectively). Prior to testing, each sample was dried at room temperature and then the sample dimensions were measured and their weight was noted to determine the density or unit weight. The testing arrangements are illustrated in Fig. 6.

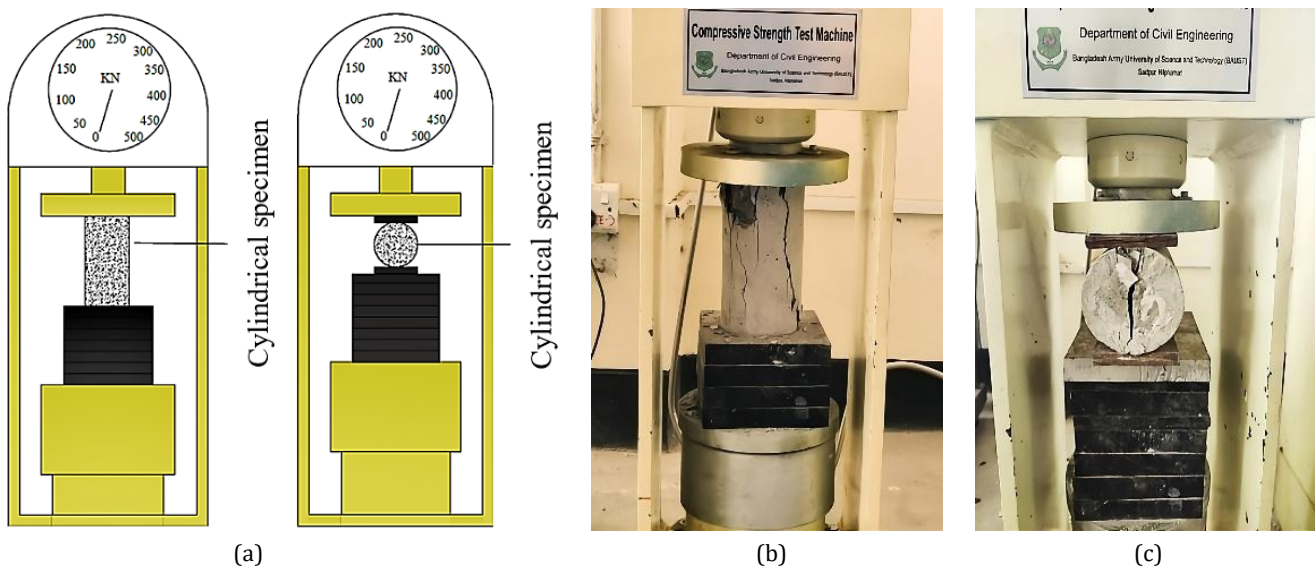


Fig. 6. Test set-up for compressive and split tensile strength: (a) Schematic diagram; (b) Compressive strength test; (c) Split tensile strength test.

For the permeability test, a disc-shaped slice of 50 mm thickness was taken out from the inside of the sample. The disc was then fitted into a PVC pipe of inner diameter of 100 mm to ensure proper fitting of the slice. Silicone putty was used around the perimeter of the disc adjacent to the inner surface of the pipe to prevent any potential water leakage or seepage from the sides. A constant water vol-

ume (1 L) was then poured over the disc inside the setup and the time for the water to pass through the sample was recorded. The test was conducted as per ACI 522R (Report on Pervious Concrete). The infiltration rate through the sample was calculated on the basis of discharge through the specimen and its cross-sectional dimension. Fig. 7 shows sliced specimens and the test setup.

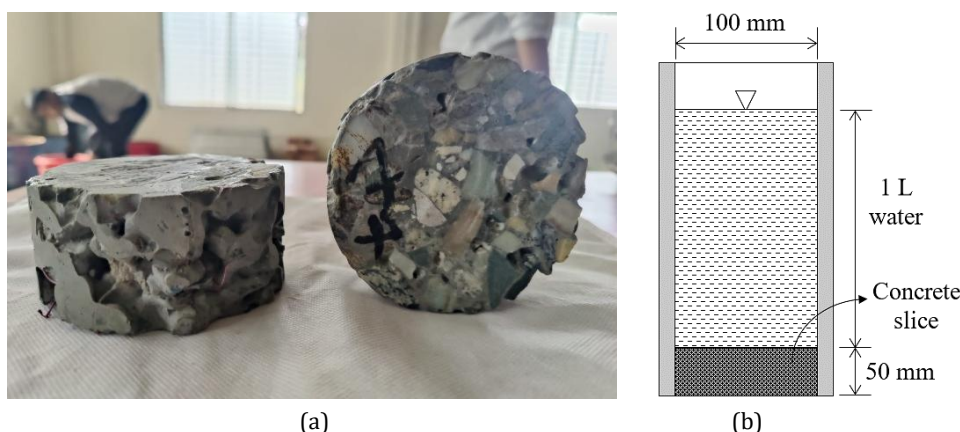


Fig. 7. Permeability test: (a) Concrete slice; (b) Schematic test setup.

3. Results and Discussion

3.1. Compressive strength of CC

The compressive strength of cylindrical samples from conventional concrete after 7 and 28 days of curing was determined. The control specimen after 7 days of curing achieved a strength of 14.26 MPa. After incorporation of steel fibers, the strength increased with the increasing content of fibers – the higher the percentage of fiber, the higher the strength, with maximum obtained for 1.0% fiber content. This increasing trend in particular is consistent with previous research as studies reported that steel fibers enhance the compressive strength of CC through improved crack-bridging capacity and better stress redistribution within the matrix (Amin et al. 2022; Zheng et al. 2024). Similar improvements have also been observed with increasing steel fiber dosage, although the optimum fiber content depends on the concrete mix and fiber characteristics (Zheng et al. 2024).

Regarding nylon fiber, the strength values show a fluctuating pattern – strength increased at 0.25% of fiber content and then decreased for the successive two percentages (0.50% and 0.75%) and increased again for 1.0%.

This behavior may be attributed to reduced fiber dispersion at higher nylon fiber dosages. The increased fiber content may increase the likelihood of fiber clustering, formation of localized voids and weaker fiber–matrix interaction. These factors may have contributed to reduced effectiveness of crack-bridging under compressive loading as suggested by studies on fiber-reinforced concrete and fiber-reinforced cementitious composites (Bakir and Yagmur 2026; Jahangir Qureshi et al. 2023; Nur et al. 2025).

In contrast, nylon fibers at 0.25% were more effective (22.3% increase) in this case than steel fibers (17.1% increase) with the same content. After 28 days of curing, the control specimen gained a crushing strength value of 22.97 MPa. Steel fibers slightly increased the strength, although not strictly in a linear trend, following a similar pattern as obtained from 7-day test. Nylon fiber once again showed a fluctuating pattern after 28 days of curing, due to the same potential reason stated earlier. However, this time, only one optimum value was obtained and that is for 0.25% which gained strength up to 24.15 MPa (5.1% increase), while the other contents of nylon proved to be ineffective. The graphical representation of data is shown in Fig. 8. Table 5 enlists the experimental data obtained.

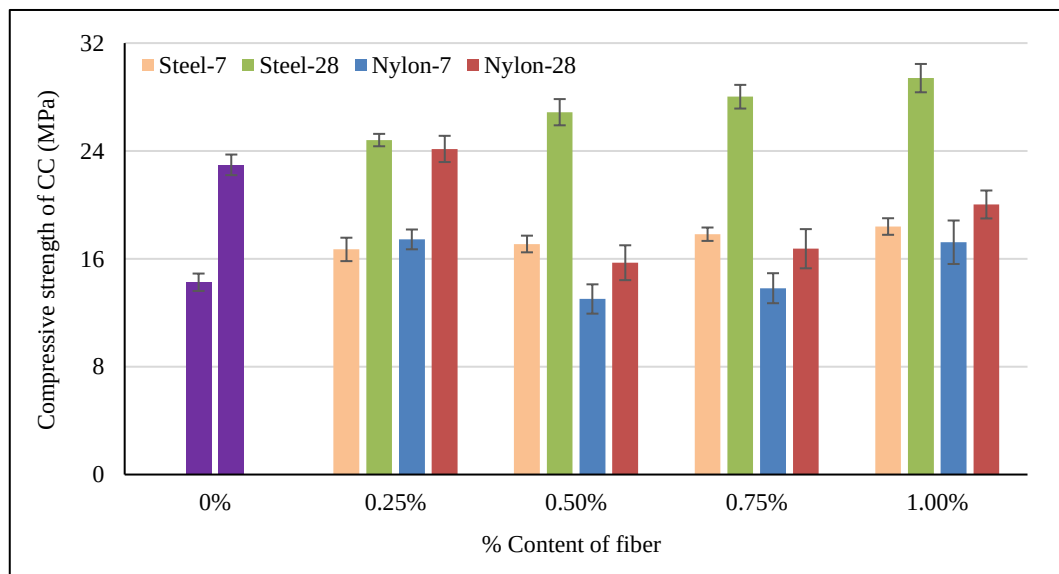


Fig. 8. Compressive strength comparison for conventional concrete.

(Note: The first two bars at 0% represent the strength values of CC after 7 and 28 days of curing, respectively.)

3.2. Split tensile strength of CC

Experimental data of the split tensile strength test shows that the control specimen gained a strength of 1.97 MPa after 7 days of curing. The addition of steel fiber followed the same pattern as for 7-day compressive strength test data – the higher the fiber content, the higher the strength. Maximum strength was obtained at 1.0% fiber content. Nylon fibers also followed the previous pattern: 0.25% and 1.0% increased the tensile strength. The 28-day tensile strength was similarly influenced. Nylon fiber showed an optimum fiber content at 0.25%, with an increase in strength of about 12.0%, while other percentages remained ineffective (similar to that observed for the compressive strength). The ob-

served enhancement in split tensile strength may be attributed to the crack-bridging action of the fibers across the tensile cracks. Higher crack-resistance provided by steel fibers may be attributed to their greater stiffness and stronger mechanical bond with the cement matrix, thereby improving tensile load transfer (Gul et al. 2021; Koo et al. 2023; Sitorus et al. 2025), highlighting the broader importance of fiber–matrix bond quality for effective stress transfer (Tarhan et al. 2025). In contrast, nylon fibers are more effective in controlling the initiation and propagation of microcracks at lower dosages which is consistent with findings of previous experimental studies (Nur et al. 2025). However, increasing the nylon fiber content may reduce fiber dispersion and fiber–matrix interaction, which can limit their contribu-

tion to tensile strength. Similar dosage-dependent behavior is observed in reported studies on nylon fiber-reinforced concrete. Findings demonstrated an improved crack control at lower fiber contents, while excessive fi-

ber addition reduced the effectiveness due to weaker fiber–matrix interaction and poorer fiber distribution (Ali et al. 2022; Bheel et al. 2021). The graphical representation of the strength values is given in Fig. 9.

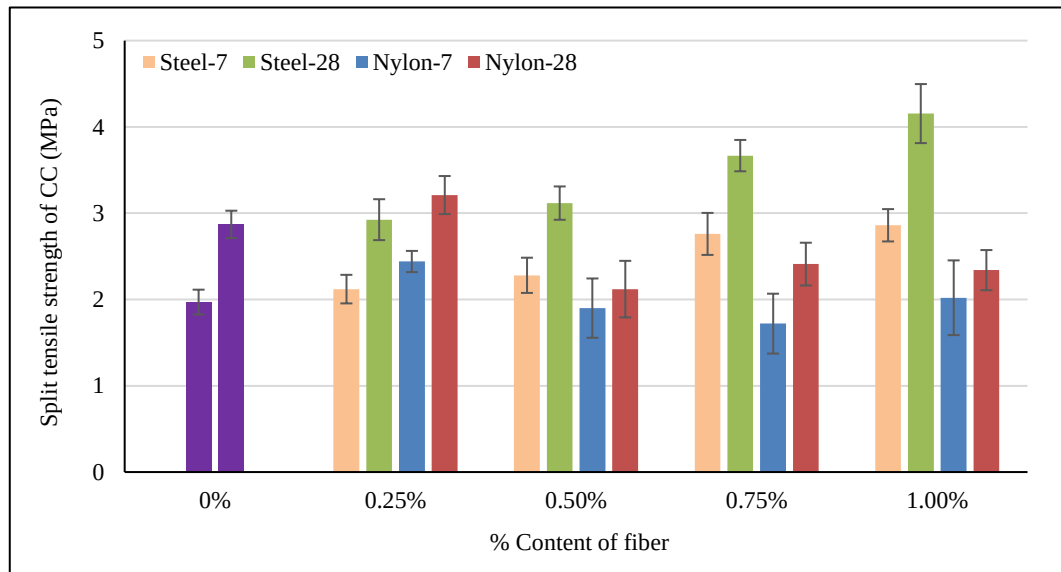


Fig. 9. Split tensile strength comparison for conventional concrete.

(Note: The first two bars at 0% represent the strength values of CC after 7 and 28 days of curing, respectively.)

3.3. Failure pattern of CC

The control specimen from conventional concrete showed failure patterns typically observed in compression and tension tests. However, the addition of fibers influenced the failure modes. During compression testing, fibers prevented the total collapse or detachment of aggregates and in the split tensile test, fibers, especially

with higher content, prevented the sample from being split apart longitudinally, as illustrated in Fig. 10. The observed failure patterns suggest that the fibers delayed crack opening and restrained crack propagation through improved fiber–matrix interaction. This behavior is consistent with the crack-bridging mechanism of the fibers reported more comprehensively in fibrous concrete systems (Youssef et al. 2026).

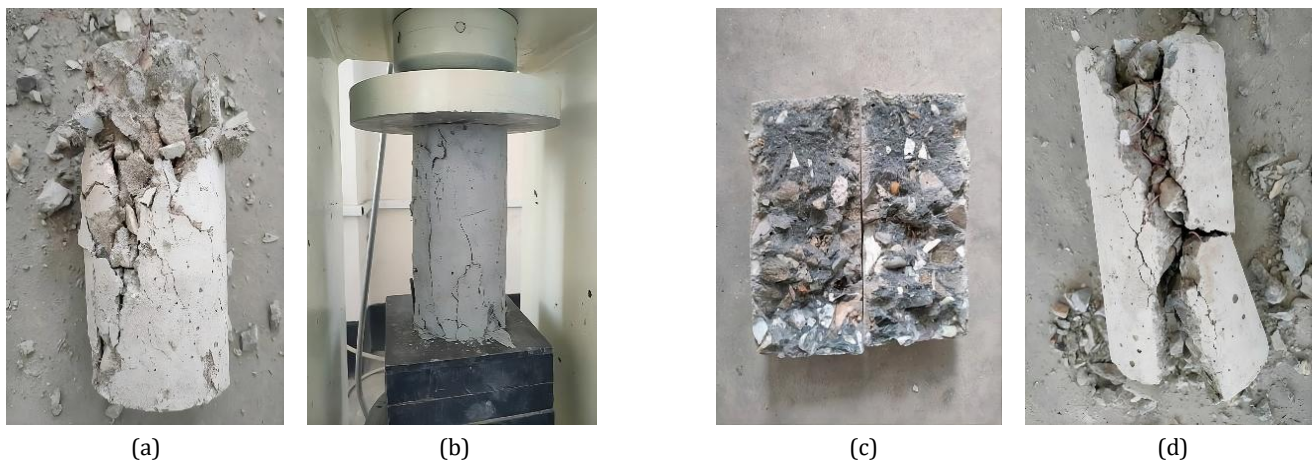


Fig. 10. Failure pattern of conventional concrete:

Compression failure without (a) and with (b) fiber; Split tensile failure without (c) and with (d) fiber.

3.4. Compressive strength of PC

The compressive strength of the control specimen of pervious concrete (PC-C) had values of 6.19 MPa and 9.59 MPa after 7 and 28 days of curing, respectively. Steel fibers helped strength gain at an early stage (7

days). Strength rose with increasing content of fiber up to 0.75% and then dropped at 1.0%. A similar trend for pervious concrete reinforced with steel fibers has been reported in literature, where moderate fiber contents improved compressive strength, whereas excessive fiber addition had an adverse effect (Lee et al. 2022). How-

ever, the compressive strength after 28 days of curing was effectively influenced by all fiber contents; with 0.75% showing optimum behavior. The observed decline in strength at higher fiber content (1%) may be attributed to the high volume of fibers affecting compaction and workability. This may have affected the interlocking between coarse particles at an early stage (Lee et al. 2022; Li et al. 2023). On the other hand, nylon fibers showed inconsistent and non-linear behavior in this regard. The effectiveness of fibers in pervious concrete also depends on the bond developed with the interconnected aggregate skeleton and the surrounding cement paste. The highly porous structure within the PC matrix

may reduce the available bonding area. Despite this, the fibers appeared to improve crack resistance and maintaining particle interlock at appropriate dosages. However, excessive fiber content may reduce these benefits by affecting fiber dispersion and matrix continuity (Ali et al. 2022; Nur et al. 2025). The strength increased after 7 days with 0.25% (18.4% increase) and 0.75% (13.0% increase) of fiber content, and had a similar effect on 28-day compressive strength as well. The changes in strength are illustrated in Fig. 11. A lower dose (0.25%) of nylon fiber was more effective than steel fibers with similar content in the pervious concrete after both curing periods.

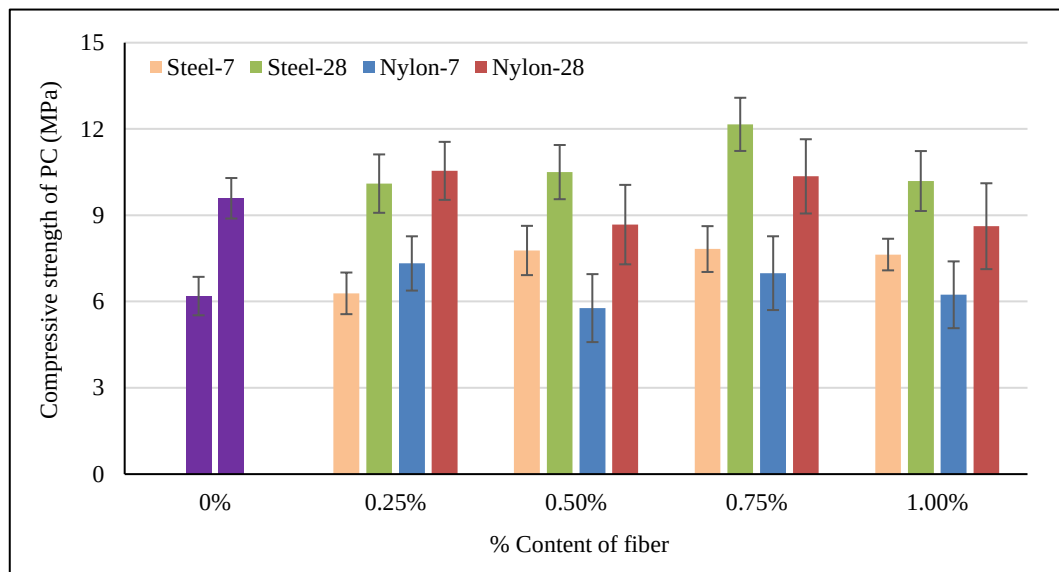


Fig. 11. Compressive strength comparison for pervious concrete.

(Note: The first two bars at 0% represent the strength values of PC after 7 and 28 days of curing, respectively.)

3.5. Split tensile strength of PC

The split tensile test was conducted on the same samples and the control specimen of PC achieved strength of 0.54 MPa and 1.61 MPa after 7-day and 28-day tests, respectively. Steel fibers improved the tensile load resistance for both curing ages. This behavior may be attributed to their high toughness and elastic modulus (Lee et al. 2022; Sitorus et al. 2025). The capability of nylon fiber in controlling tensile cracks after 7 days of curing was also noteworthy. Its influence on the 28-day split tensile strength was more impactful than that of steel fiber. Nylon fiber at 0.25% boosted the strength up to 33.7%, whereas steel fiber with the same content showed a 19% strength gain. A similar enhancement in tensile behavior due to the crack-bridging ability of nylon fibers has also been reported by Nur et al. (2025). The remaining fiber contents also enhanced the split tensile strength, although the response was not consistent. Steel fibers at 0.75% contributed to 27.8% increase in split tensile strength after 28 days.

The higher percentage increase in strength with steel fiber may be influenced through high durability, strength, and stiffness of the fiber itself as compared to nylon fibers. Again, the quantity of steel fibers per volume is smaller than that of nylon fibers due to density

variation. Large amounts of nylon fiber may contribute to the reduction in split tensile strength, which can be ascribed to the effect of low self-stiffness, flexibility, and non-uniform distribution. Possible clustering and lump formation within the concrete matrix may reduce the uniformity of the mixture and create local weak zones with poor crack bridging capacity (Ali et al. 2022). However, nylon fibers at a small dosage appeared to be more effective in resisting microcrack formation, whereas steel fibers were more effective in limiting the propagation of macrocracks. Fig. 12 illustrates the strength values of the split tensile test for PC. The experimental data are summarized in Table 5 with percentage change in strength.

3.6. Failure pattern of PC

The failure patterns of control specimens from pervious concrete showed typical bond failure between coarse particles, localized in weak regions (usually at top or bottom of samples). However, the fibers prevented the samples from being torn apart under both compression test and in split tensile test. The fibers, even after the strength was compromised, prevented the total split and held the detached portions together. Higher fiber content appeared to be more effective in holding the bro-

ken parts together. Some of the failure patterns are shown in Fig. 13. The overall performance of nylon fiber in resisting and bridging tensile cracks between particles may be associated with its larger numbers of fibers per vol-

ume compared to that of steel fibers. These observations suggest that the fibers remained effective in bridging cracks and maintaining the integrity of the porous concrete matrix despite its interconnected void structure.

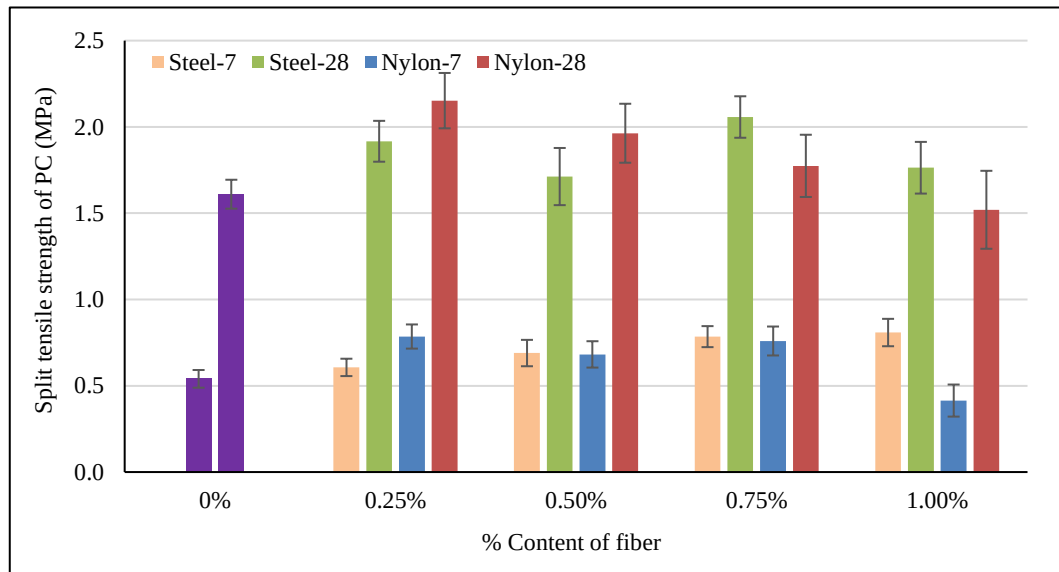


Fig. 12. Split tensile strength comparison for pervious concrete.

(Note: The first two bars at 0% represent the strength values of PC after 7 and 28 days of curing, respectively.)

Table 5. Strength test results of concrete specimens.

Sample ID	Fiber (%)	Compressive strength (MPa)				Split tensile strength (MPa)			
		7-days	% Change	28-days	% Change	7-days	% Change	28-days	% Change
CC-C	0.00	14.26 ± 0.65	–	22.97 ± 0.76	–	1.97 ± 0.14	–	2.87 ± 0.16	–
CC-S1	0.25	16.70 ± 0.87	+17.1	24.81 ± 0.46	+8.0	2.12 ± 0.17	+7.9	2.92 ± 0.24	+2.1
CC-S2	0.50	17.10 ± 0.62	+19.9	26.87 ± 0.97	+17.0	2.28 ± 0.20	+16.0	3.12 ± 0.19	+8.8
CC-S3	0.75	17.83 ± 0.50	+25.0	28.02 ± 0.88	+22.0	2.76 ± 0.24	+40.5	3.67 ± 0.18	+28.0
CC-S4	1.00	18.40 ± 0.61	+29.0	29.40 ± 1.05	+28.0	2.86 ± 0.19	+45.5	4.15 ± 0.34	+45.0
CC-N1	0.25	17.44 ± 0.73	+22.3	24.15 ± 0.97	+5.1	2.44 ± 0.12	+24.2	3.21 ± 0.22	+12.0
CC-N2	0.50	13.02 ± 1.09	–8.7	15.71 ± 1.29	–31.6	1.90 ± 0.34	–3.3	2.12 ± 0.33	–26.0
CC-N3	0.75	13.82 ± 1.11	–3.1	16.75 ± 1.45	–27.1	1.72 ± 0.35	–12.5	2.41 ± 0.25	–15.9
CC-N4	1.00	17.23 ± 1.61	+20.8	20.03 ± 1.04	–12.8	2.02 ± 0.43	+2.8	2.34 ± 0.23	–18.3
PC-C	0.00	6.19 ± 0.67	–	9.59 ± 0.70	–	0.54 ± 0.05	–	1.61 ± 0.08	–
PC-S1	0.25	6.28 ± 0.72	+1.6	10.10 ± 1.02	+5.4	0.61 ± 0.05	+13.3	1.92 ± 0.12	+19.0
PC-S2	0.50	7.77 ± 0.86	+25.7	10.50 ± 0.94	+9.5	0.69 ± 0.08	+28.9	1.71 ± 0.17	+6.3
PC-S3	0.75	7.82 ± 0.80	+26.5	12.16 ± 0.92	+26.9	0.78 ± 0.06	+46.7	2.06 ± 0.12	+27.8
PC-S4	1.00	7.63 ± 0.55	+23.4	10.19 ± 1.04	+6.3	0.81 ± 0.08	+51.1	1.76 ± 0.15	+9.5
PC-N1	0.25	7.32 ± 0.94	+18.4	10.54 ± 1.01	+10.0	0.79 ± 0.07	+46.8	2.15 ± 0.16	+33.7
PC-N2	0.50	5.77 ± 1.18	–6.7	8.67 ± 1.38	–9.5	0.68 ± 0.08	+27.4	1.96 ± 0.17	+21.9
PC-N3	0.75	6.99 ± 1.28	+13.0	10.35 ± 1.29	+8.0	0.76 ± 0.08	+41.9	1.77 ± 0.18	+10.2
PC-N4	1.00	6.24 ± 1.16	+0.8	8.62 ± 1.49	–10.1	0.41 ± 0.09	–22.6	1.52 ± 0.23	–5.6

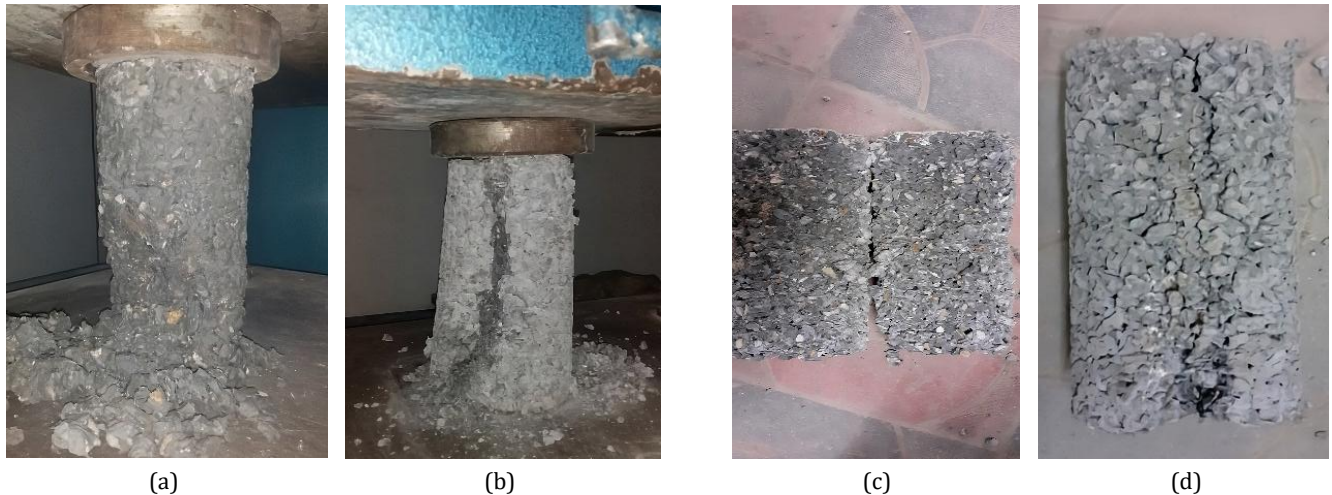
Notations: CC: Conventional Concrete; PC: Pervious Concrete; CC-C: Conventional Concrete Control Specimen;

PC-C: Pervious Concrete Control Specimen; S: Steel Fiber; N: Nylon Fiber;

Numbers 1,2,3,4 denote the chronological order of fiber % (S1: 0.25% steel fiber, N3: 0.75% nylon fiber, and so on).

Table 6. Density, porosity, and permeability data of concrete samples.

Fiber (%)	Density (kg/m ³) – CC		Density (kg/m ³) – PC		Porosity (%) – PC		Permeability (mm/s) – PC	
	Steel	Nylon	Steel	Nylon	Steel	Nylon	Steel	Nylon
0.00	2319.6 ± 33.2	2319.6 ± 33.2	1956.5 ± 13.8	1956.5 ± 13.8	15.65 ± 0.60	15.65 ± 0.60	0.253 ± 0.022	0.253 ± 0.022
0.25	2321.1 ± 42.4	2320.5 ± 20.0	1958.2 ± 20.2	1958.7 ± 12.6	15.58 ± 0.87	15.56 ± 0.54	0.293 ± 0.009	0.259 ± 0.008
0.50	2323.2 ± 36.1	2322.0 ± 18.8	1959.9 ± 16.4	1960.1 ± 9.0	15.51 ± 0.71	15.50 ± 0.39	0.309 ± 0.004	0.263 ± 0.017
0.75	2324.1 ± 29.1	2323.9 ± 12.8	1961.0 ± 9.6	1961.2 ± 15.5	15.46 ± 0.41	15.45 ± 0.67	0.287 ± 0.019	0.253 ± 0.004
1.00	2325.4 ± 26.4	2324.9 ± 10.1	1962.9 ± 16.4	1962.5 ± 21.0	15.38 ± 0.71	15.40 ± 0.91	0.229 ± 0.012	0.185 ± 0.003

**Fig. 13.** Failure pattern of pervious concrete: Compression failure without (a) and with (b) fiber; Split tensile failure without (c) and with (d) fiber.

3.7. Unit weight or density of CC and PC

The concrete samples were used to determine the variation of unit weight or density based on the direct ratio of their measured mass to geometric volume. The unit weight of pervious concrete is smaller compared to that of conventional concrete due to having a large amount of porosity. The incorporation of fibers influenced the density of the concrete samples by adding a small amount of weight, as anticipated. The slight variation may be associated with the mixing and distribution of fibers inside the matrix. A similar marginal increase in density with fiber incorporation has also been reported, where the increase was mainly associated with the presence of additional reinforcing material within the concrete matrix (Ali et al. 2022; Lee et al. 2022). The density data for both conventional and pervious concrete is shown in Table 6.

3.8. Porosity and permeability of PC

The absence of sand in pervious concrete creates interconnected voids or pores inside the matrix which allows the water to easily infiltrate through the medium. The porosity of the samples was calculated from the bulk density of conventional and pervious concrete as per ASTM C1754. The addition of fibers influenced the porosity and permeability, as illustrated in Fig. 14.

The permeability demonstrates a non-linear relationship with fiber content and was positively affected in the

initial stage of fiber incorporation. The porosity decreased with increasing fiber content in the pervious concrete, however, the permeability slightly increased for small fiber incorporation. Fiber contents of 0.25%, 0.50%, and 0.75% for steel fibers and 0.25% and 0.50% for nylon fiber improved the permeability (steel showing higher value), while 0.75% nylon had a neutral effect. For 1% fiber incorporation, permeability dropped in both cases. The improved permeability at lower fiber content may be attributed to the ability of the fibers to maintain the interconnected void within the aggregate skeleton. This may have facilitated the water flow through the interconnected pore networks. Similar permeability trends and their underlying mechanisms have been reported in previous studies investigating the influence of fibers on interconnected pore structure, tortuosity, and permeability (Wu et al. 2023). The proposed mechanisms are based on the observed permeability trends together with findings reported in the literature (Li et al. 2023; Wu et al. 2023; Xie et al. 2023), since direct microstructural investigation of the pore network was beyond the scope of the present study. A similar mechanism may also explain the behavior observed from nylon fiber. Since the quantity per unit volume of nylon fiber was larger than steel, their influence on permeability may differ because of their interaction with the pore structures. Lastly, the higher fiber content (1%) may have hindered the water flow by increasing the likelihood of partial blockage of interconnected pores within the matrix (Xie et al. 2023).

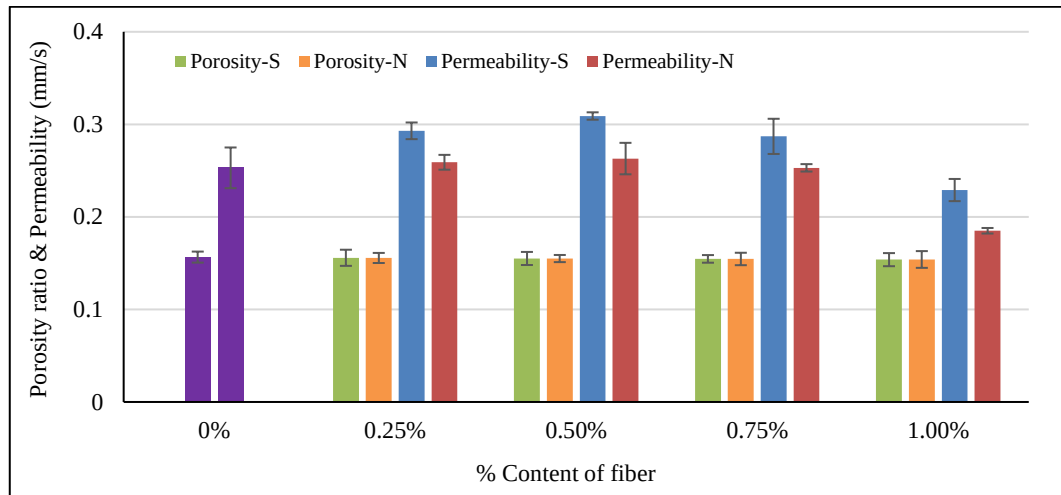


Fig. 14. Variation in porosity and permeability in pervious concrete.

(Note: The first two bars at 0% represent the porosity ratio and permeability values of PC, respectively.)

3.9. Comparison between the response of CC and PC

Pervious concrete, having lower material content and more voids, shows weaker strength (both compressive and tensile) as compared to the conventional one under

similar curing conditions. The increase in strength due to the fibers (steel and nylon) followed a similar pattern (Table 5). However, 0.25% nylon fiber in PC had slightly higher strength (2.15 MPa) than 0.5% content in CC (2.12 MPa), as illustrated in Figs. 15 and 16.

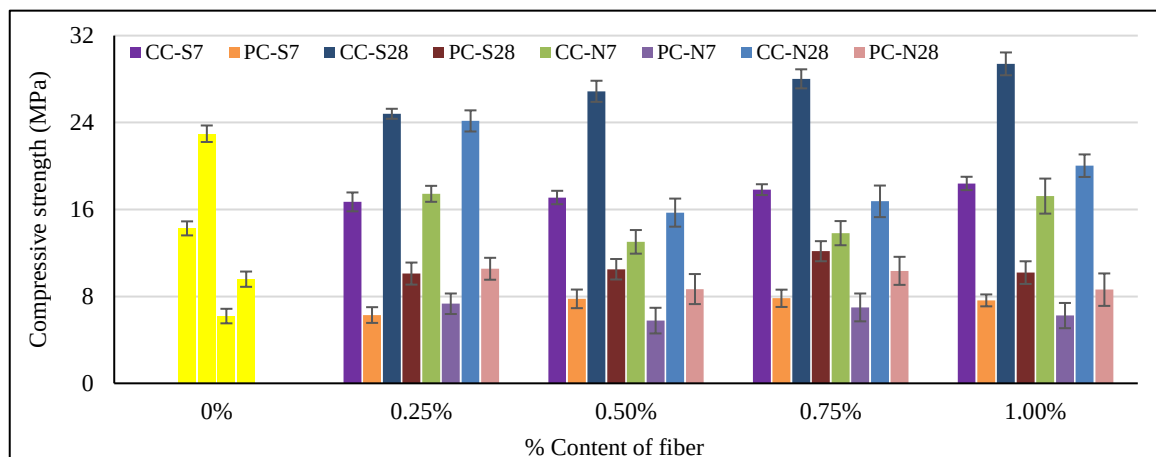


Fig. 15. Compressive strength comparison between CC and PC.

(Note: The first four bars at 0% represent the strength values of CC (7 and 28 days) and PC (7 and 28 days), respectively.)

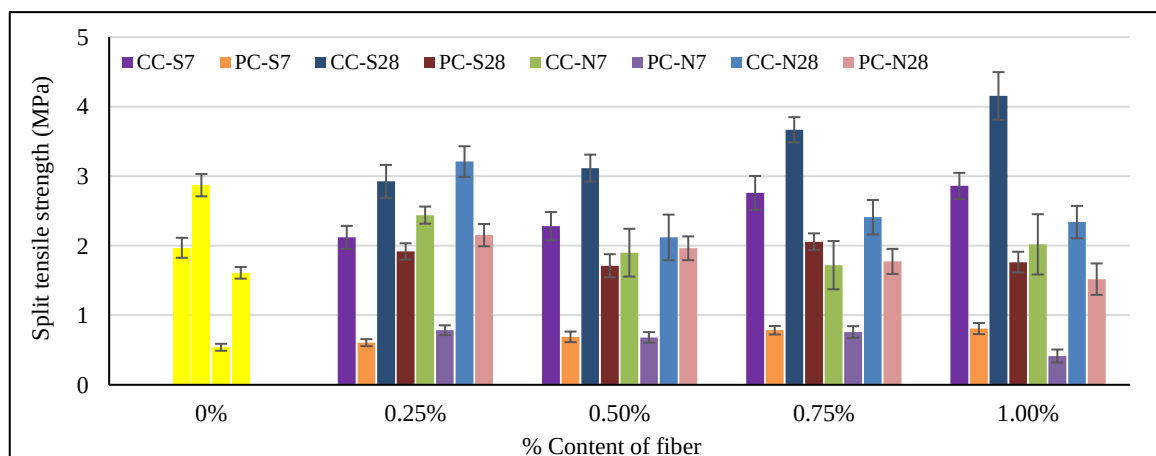


Fig. 16. Split tensile strength comparison between CC and PC.

(Note: The first four bars at 0% represent the strength values of CC (7 and 28 days) and PC (7 and 28 days), respectively.)

This behavior may be attributed to improved interfacial interaction between the coarse particles and nylon fibers due to their higher volume fraction. Moreover, fibers in the compact and impermeable CC might have been clustered inside the matrix. The agglomeration of fibers creates potentially weak regions responsible for crack development under load. While for pervious concrete, existing pore networks accommodate the fibers added later, which in turn create a bridging effect between particles through interfacial transition zones (ITZ). The relevant comparative analysis between them is illustrated in Figs. 15 and 16.

4. Conclusions

Two commonly used concrete types from two different construction sectors were strengthened using steel and nylon fibers to observe their mechanical performance. The findings indicate that, with controlled dosages, the compressive and split tensile strengths were affected by fiber incorporation. Steel fibers generally produced a consistent improvement in the mechanical performance of conventional concrete owing to their high pull-out resistance and high elastic modulus that contribute to a transition of the failure mode from brittle to ductile. In contrast, a large steel fiber content in PC led to a marginal reduction in strength, showing an inconsistent response. Nylon fibers demonstrated a dosage-dependent and non-uniform effect. Strength improvement at a lower dosage of nylon fiber may be attributed to high distribution efficiency, which enhances fiber-matrix interlocking across interfacial transition zones (ITZ). However, excessive content likely triggered premature failure due to fiber clustering and reduced matrix integrity. Fiber incorporation also affected the density, porosity, and permeability of pervious concrete. The findings demonstrate a trade-off between mechanical strength and hydraulic functionality of pervious concrete. From an engineering perspective, the findings of this study demonstrate that appropriate fiber selection and controlled dosage can improve the structural performance of both CC and PC. This can be achieved while maintaining their intended functional requirements. The results further support the feasibility of using locally available fibers as sustainable reinforcement materials in construction practice. Such an approach provides a practical basis for selecting locally available fibers in sustainable pavement and structural applications. Though the primary function of PC is to allow smooth drainage, this study suggests that with an optimum fiber content, improved mechanical strength can be achieved without significantly compromising permeability. This balanced response supports the effectiveness of pervious concrete for pavement construction with low to moderate traffic levels. Lastly, the present study focused on the mechanical properties of CC and PC in terms of compressive strength, split tensile strength, density, porosity, and permeability. Moreover, the mechanical property determination of locally sourced fibers, concrete workability and other mechanical properties of concrete such as modulus of elasticity, stress-strain behavior, and flexural behavior were beyond the scope of this study. Therefore, further

studies are recommended to examine these aspects, together with the effects of chemically modified fibers, microstructural characteristics and finite element analysis for a better understanding of the governing mechanisms behind the mechanical and physical behavior.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- ACI 522R-10 (2010). *Report on Pervious Concrete*. American Concrete Institute, Farmington Hills, MI, USA.
- Akinpelu MA, Odeyemi SO, Olafusi OS, Muhammed FZ (2019). Evaluation of splitting tensile and compressive strength relationship of self-compacting concrete. *Journal of King Saud University - Engineering Sciences*, 31(1), 19-25.
- Akyüncü V (2021). Investigation of mechanical and permeability properties of fiber mortars. *Journal of Sustainable Construction Materials and Technologies*, 6(1), 29-35.
- Ali B, Fahad M, Mohammed AS, Ahmed H, Elhag AB, Azab M (2022). Improving the performance of recycled aggregate concrete using nylon waste fibers. *Case Studies in Construction Materials*, 17, e01468.
- Amin MN, Ahmad W, Khan K, Ahmad A (2022). Steel fiber-reinforced concrete: a systematic review of the research progress and knowledge mapping. *Materials*, 15(17), 6155.
- Anas M, Khan M, Bilal H, Jadoon S, Khan MN (2022). Fiber reinforced concrete: a review. *Engineering Proceedings*, 22, 3.
- Badarloo B, Kari A, Jafari F (2018). Experimental and numerical study to determine the relationship between tensile strength and compressive strength of concrete. *Civil Engineering Journal*, 4(12), 2787-2800.
- Bakir BB, Yagmur E (2026). Shear strength prediction for fiber reinforced concrete beams. *Mechanics of Advanced Materials and Structures*, 33(1), 2542545.
- Bheel N, Tafsirojjaman T, Liu Y, Awoyera P, Kumar A, Keerio MA (2021). Experimental study on engineering properties of cement concrete reinforced with nylon and jute fibers. *Buildings*, 11(10), 454.
- Doğan F, Dehghanpour H, Subaşı S, Maraşlı M (2022). Characterization of carbon fiber reinforced conductive mortars filled with recycled ferrochrome slag aggregates. *Journal of Sustainable Construction Materials and Technologies*, 7(3), 145-157.
- Emon MAB, Manzur T, Sharif MS (2017). Suitability of locally manufactured galvanized iron (GI) wire fiber as reinforcing fiber in brick chip concrete. *Case Studies in Construction Materials*, 7, 217-227.

- Faustmann S, Kronau M, Fischer O (2024). Direct tensile tests on steel fiber reinforced concrete with focus on wall effect and fiber orientation. *Materials and Structures*, 57(8), 185.
- Ferić K, Sathish Kumar V, Romić A, Gotovac H (2023). Effect of aggregate size and compaction on the strength and hydraulic properties of pervious concrete. *Sustainability*, 15(2), 1146.
- Gagg CR (2014). Cement and concrete as an engineering material: an historic appraisal and case study analysis. *Engineering Failure Analysis*, 40, 114-140.
- Gul A, Alam B, Iqbal MJ, Ahmed W, Shahzada K, Javed MH, Khan EA (2021). Impact of recycled steel fibers on mechanical properties of concrete. *Civil Engineering Journal*, 7(10), 1650-1666.
- Halabi Y, Xu H, Yu Z, Alhaddad W, Dreier I (2023). Experimental-based statistical models for the tensile characterization of synthetic fiber ropes: a machine learning approach. *Scientific Reports*, 13(1), 17768.
- Jahangir Qureshi H, Ahmad J, Aljabr A, Garcia-Troncoso N (2023). Review on characteristics of concrete reinforced with nylon fiber. *Journal of Engineered Fibers and Fabrics*, 18, 1-15.
- Kameli S, Shahi AH, Mahboob A (2024). Investigating the mechanical properties of natural fiber-reinforced concrete with kenaf, jute, and coconut fibers. *Journal of Civil Engineering Researchers*, 6(4), 32-39.
- Khan MB, Houda M, Zada NS, Imran M, Benjeddou O (2025). Hybrid effect of basalt fibers and carbon fibers on concrete mechanical and environmental properties. *Results in Engineering*, 25, 103780.
- Khan MI, Abbas YM (2025). Synergistic enhancement of high-strength concrete's mechanical strength through the utilization of steel, synthetic, and hybrid fiber systems. *International Journal of Concrete Structures and Materials*, 19, 18.
- Konitufe C, Abubakar A, Baba AS (2023). Influence of aggregate size and shape on the compressive strength of concrete. *Construction*, 3(1), 15-22.
- Koo DH, Kim JS, Kim SH, Suh SW (2023). Evaluation of flexural toughness of concrete reinforced with high-performance steel fiber. *Materials*, 16(20), 6623.
- Kosmatka SH, Kerkhoff B, Panarese WC (2008). *Design and Control of Concrete Mixtures*. 14th ed., Portland Cement Association, Skokie, IL, USA.
- Krassowska J, Kosior-Kazberuk M (2021). The effect of steel and basalt fibers on the shear behavior of double-span fiber reinforced concrete beams. *Materials*, 14(20), 6090.
- Lee MG, Wang WC, Wang YC, Hsieh YC, Lin YC (2022). Mechanical properties of high-strength pervious concrete with steel fiber or glass fiber. *Buildings*, 12(5), 620.
- Li J, Xia J, Di Sarno L, Gong G (2023). Fiber utilization in pervious concrete: review on manufacture and properties. *Construction and Building Materials*, 406, 133372.
- Mahmud H, Ahmed T, Islam MS (2025). Combined effect of rice husk ash and animal bone powder on strength and permeability of concrete. *Challenge Journal of Structural Mechanics*, 11(1), 1-13.
- McCormac JC, Brown RH (2013). *Design of Reinforced Concrete*. 9th ed., Wiley, Hoboken, NJ, USA.
- Meininger RC (1988). No-fines pervious concrete for paving. *Concrete International*, 10(8), 20-27.
- Nandaraj K, Mourougane R (2026). Experimental study on the effect of polypropylene fiber on bond behavior, corrosion resistance, and microstructural characteristics of high-strength flowable concrete. *Challenge Journal of Concrete Research Letters*, 17(2), 147-161.
- Nouri Z, Massumi A, Asadollahfardi G, Majedi Ardakani MH (2025). Structural and environmental impacts of concrete quality: a comparative life cycle assessment. *Scientific Reports*, 15, 16257.
- Nur SA, Sarkar S, Mutsuddy R, Shahriar MF (2025). An investigative study on the mechanical properties of jute, nylon, and coconut fiber reinforced concrete. *Discover Civil Engineering*, 2, 211.
- Pehlivan AO (2022). Effect of nanosilica addition on the mechanical properties of cement mortars with basalt fibers with or without silica fume. *Journal of Sustainable Construction Materials and Technologies*, 7(1), 17-23.
- Rashid MA, Mansur MA (2009). Considerations in producing high strength concrete. *Journal of Civil Engineering (IEB)*, 37(1), 53-63.
- Scholz M, Grabowiecki P (2007). Review of permeable pavement systems. *Building and Environment*, 42, 3830-3836.
- Sitorus MS, Afiah IN, Ibrahim Z, Muhibuddin AF (2025). The effect of steel fiber content on the splitting tensile strength of steel fiber reinforced concrete (SFRC). *Journal of Civil Engineering*, 40(2), 211-215.
- Song PS, Hwang S, Sheu BC (2005). Strength properties of nylon- and polypropylene-fiber-reinforced concretes. *Cement and Concrete Research*, 35(8), 1546-1550.
- Sun M, Sun M, Zhang Y, Ma L (2025). Evaluation of high-performance pervious concrete mixed with nano-silica and carbon fiber. *Buildings*, 15(14), 2407.
- Tanash AO, Budiea AMA, Md Jaafar MF, Muthusamy K, Zulkarnain F (2025). Experimental study on the mechanical performance of polypropylene fiber-reinforced concrete incorporating palm oil fuel ash as partial cement replacement. *Challenge Journal of Concrete Research Letters*, 16(3), 115-124.
- Tarhan Y, Tarhan IH, Perrot A (2025). Improving bond performance of 3D-printable earth-based mortar reinforced with jute fibers. *Challenge Journal of Structural Mechanics*, 11(2), 99-105.
- Urtekin Y, Çelik Z (2025). Investigation of the effects of re-curing on mechanical properties of basalt-polypropylene hybrid fiber concretes after exposure to high temperature. *Challenge Journal of Structural Mechanics*, 11(1), 14-23.
- Ünal MT, Bin Hashim H, Gökçe HS, Ayough P, Köksal F, El-Shafie A, Şimşek O, Pordesari A (2024). Development and characterization of basalt fiber-reinforced green concrete utilizing coconut shell aggregates. *Sustainability*, 16(17), 7306.
- Varshney H, Khan RA, Khan IK (2021). Sustainable use of different wastewater in concrete construction: a review. *Journal of Building Engineering*, 41, 102411.
- Wu J, Hu L, Hu C, Wang Y, Zhou J, Li X (2023). Impact of polypropylene fiber on pervious concrete. *Buildings*, 13(8), 1966.
- Xiao J, Zou S, Poon CS, Sham ML, Li Z, Shah SP (2025). We use 30 billion tonnes of concrete each year - here's how to make it sustainable. *Nature*, 638, 888-890.
- Xie HZ, Li LG, Ng PL, Liu F (2023). Effects of solid waste reutilization on performance of pervious concrete. *Sustainability*, 15(7), 6105.
- Yavuz D (2024). The effect of recycled pervious concrete aggregate substitution on properties of pervious concrete. *Journal of Sustainable Construction Materials and Technologies*, 9(4), 412-420.
- Yew MK, Othman I, Yew MC, Yeo SH, Mahmud HB (2011). Strength properties of hybrid nylon-steel and polypropylene-steel fibre-reinforced high strength concrete at low volume fraction. *International Journal of Physical Sciences*, 6(33), 7584-7588.
- Youssef MM, Bashandy AA, Abbas RN, Nasser AAH (2026). Effect of bacteria and fibers on the mechanical and structural behavior of self-healing fibrous concrete. *Challenge Journal of Concrete Research Letters*, 17(1), 13-29.
- Zhan Q, Yin C (2024). A novel pervious concrete improved by hexagonal boron nitride and basalt fiber. *Buildings*, 14(3), 778.
- Zheng Y, Lv X, Hu S, Zhuo J, Wan C, Liu J (2024). Mechanical properties and durability of steel fiber reinforced concrete: a review. *Journal of Building Engineering*, 82, 108025.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Evaluation of the effectiveness of glass waste powder in improving the durability of sand concretes

Mohammed Seghir Ammari ^{a,*} , Madani Bederina ^b , Issam Zaiz ^a , Boubaker Fethiza Ali ^{c,d} , Ahmed Merah ^e , Hichem Berkak ^{b,f} , Hiyam Khezzane ^d , Reguia Zellouma ^d

^a New Technologies and Local Development Laboratory (NTLDL), University of El Oued, 39000 El Oued, Algeria

^b Structure Rehabilitation and Materials Laboratory (SREML), Amar Telidji University of Laghouat, 03000 Laghouat, Algeria

^c Laboratory of Environment, Water, Geomechanics and Structures (LEEGO), Faculty of Civil Engineering, University of Science and Technology Houari Boumediene (USTHB), 16111 Algiers, Algeria

^d Department of Hydraulics and Civil Engineering, University of El Oued, 39000 El Oued, Algeria

^e Civil Engineering Research Laboratory (LRGC), Amar Telidji University of Laghouat, 03000 Laghouat, Algeria

^f Department of Structures and Materials, Built Environment Research Laboratory "Tamayouz" (LBE), Faculty of Civil Engineering, University of Science and Technology Houari Boumediene (USTHB), 16111 Algiers, Algeria

ABSTRACT

The accumulation of municipal solid waste, including glass, poses significant environmental challenges worldwide. This study aims to evaluate the effect of waste glass powder (GP), used as a partial cement replacement in sand concrete, on its durability properties. Sand concrete mixtures were prepared by substituting cement with GP at mass proportions of 0%, 10%, 20%, 30%, and 40%. The durability performance was assessed through accelerated carbonation, total water immersion absorption, capillary water absorption, freeze-thaw cycling, wetting-drying cycling, and resistance to hydrochloric acid attack (5% HCl). Scanning electron microscopy (SEM) analysis was also conducted on specimens exposed to the acid solution. The results showed that increasing GP content generally increased the carbonation depth; however, the mixture containing 10% GP (SC-GP10%) exhibited the best resistance to accelerated carbonation, with a reduction in carbonation depth of approximately 15.41% compared to the control mix (SC-WGP). Similarly, the 10% GP mix exhibited superior resistance to freeze-thaw and wetting-drying cycles, with reductions in compressive strength loss reaching approximately 9.40% and 40.70%, respectively, relative to the control mix. Nevertheless, the incorporation of waste glass powder in sand concrete increased both total immersion absorption and capillary absorption. SEM observations on acid-exposed specimens revealed progressive surface degradation at the microstructural level, including the formation of micro-cracks and the presence of fine voids across the specimen surfaces, indicating a gradual deterioration of the cementitious matrix under hydrochloric acid attack. These findings indicate that, among the studied proportions, the incorporation of 10% waste glass powder as a partial cement replacement represents the optimal dosage for enhancing the overall durability of sand concrete. This approach not only offers a viable and sustainable solution for improving concrete performance but also contributes to the reduction of solid waste accumulation and the promotion of eco-friendly construction practices.

Citation: Ammari MS, Bederina M, Zaiz I, Fethiza Ali B, Merah A, Berkak H, Khezzane H, Zellouma R (2026). Evaluation of the effectiveness of glass waste powder in improving the durability of sand concretes. *Challenge Journal of Concrete Research Letters*, 17(3), 319–340.

ARTICLE INFO

Article history:

Received – April 5, 2026
Revision requested – June 26, 2026
Revision received – July 17, 2026
Accepted – July 24, 2026

Keywords:

Sand concrete
Waste glass powder
Durability
Accelerated carbonation
Microstructure



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

* Corresponding author. E-mail address: ammari-mohammedseghir@univ-eloued.dz (M. S. Ammari)

1. Introduction

In recent years, the demand for raw materials in construction has increased significantly. Given the high costs associated with transporting conventional aggregates from one region to another, the exploitation of locally available materials, such as dune sand, river sand, and large deposits of natural and artificial fines, has become an economically viable solution, either to partially or totally replace a main constituent of ordinary concrete (aggregates or cement), or to formulate alternative concrete types, such as sand concrete (Chauvin and Grimaldi 1988). Although sand concrete and cement mortar are both produced without coarse aggregates, they differ in their mix design, performance, and intended applications. Cement mortar is generally composed of cement, fine sand, and water and is mainly used for masonry, plastering, and repair works, where high structural strength is not the primary objective. In contrast, sand concrete is specifically proportioned using optimized grading of one or more sand fractions, often combined with mineral additions and chemical admixtures, to obtain a dense granular skeleton with enhanced mechanical strength and durability. Consequently, sand concrete is regarded as a structural cement-based material, whereas cement mortar is primarily intended for non-structural applications (Bederina et al. 2005; Chauvin and Grimaldi 1988).

On the other hand, environmental pollution resulting from the extraction of raw materials, such as cement, and the increasing volume of waste, particularly industrial waste, has led researchers to explore the recovery and integration of waste materials into concrete compositions. Several studies have demonstrated that the incorporation of waste, in various forms, into concrete can improve its properties (Chen et al. 2002; Shi and Zheng 2007; Zeghichi et al. 2012). Incorporating waste into concrete, therefore, represents a technical, environmental, and economic solution for reducing raw material consumption and landfill accumulation (Mathur 2006; Schwarz et al. 2008; Idir et al. 2010; Nassar and Soroushian 2012; Aly et al. 2012; Mahmud et al. 2025; Ünal and Canbaz 2025).

Among the various types of waste, glass has attracted considerable attention from researchers due to its wide availability, low recycling cost, and its ability to be recycled without loss of quality (Sobolev et al. 2007). Glass powder is generally considered a pozzolanic material owing to its relatively high amorphous silica content (Idir et al. 2011; Shi et al. 2005). The potential of waste glass powder to support resource-efficient construction and circular-economy practices has also been demonstrated (Ünal and Canbaz 2026). Several studies have explored the use of waste glass as either an aggregate substitute or a partial cement replacement in concrete (Meyer et al. 2001; Park et al. 2004; Topcu and Canbaz 2004; Sangha et al. 2004; Shao et al. 2000; Chen et al. 2002; Shayan and Xu 2006; Taha and Nounu 2008). Moreover, replacing 20% of cement with glass powder has been reported to reduce CO₂ emissions by approximately 18% (Islam et al. 2017).

Regarding durability performance, several investigations have been conducted on the effect of glass powder

on the durability of ordinary concrete and mortar. Schwarz et al. (2008) reported that fine glass powder improved the resistance of concrete to chloride ion penetration, showing performance comparable to that of fly ash. Jain and Neithalath (2010) confirmed that glass-powder-modified concretes exhibited lower chloride diffusion coefficients. Matos and Sousa-Coutinho (2012) found that mortar containing waste glass powder as a cement replacement showed enhanced resistance to chloride ingress and acceptable carbonation performance. Jain et al. (2020) demonstrated improved durability of concrete incorporating waste glass powder, particularly in terms of water absorption and acid resistance. Bulut (2024) evaluated capillary water absorption and acid resistance in waste-modified concrete as key indicators of durability performance. Siad et al. (2016) investigated the effect of glass powder on sulfuric acid resistance and reported improved performance of glass-powder-containing cementitious materials. Adesina and Das (2020) showed that glass powder enhanced the durability properties of engineered cementitious composites. Furthermore, Salim and Mosaberpanah (2021) reported improved durability of high-performance mortar containing waste glass powder under different curing regimes. Ramakrishnan et al. (2017) also observed enhanced durability when glass powder was used as a supplementary cementitious material combined with ground granulated blast furnace slag.

However, a critical review of the existing literature reveals that the majority of durability studies on glass powder have been conducted on ordinary concrete and mortar, while very limited research has addressed the durability behavior of sand concrete incorporating glass powder as a partial cement replacement. Sand concrete differs fundamentally from ordinary concrete in its composition, as it lacks coarse aggregates and relies on fine sand as the primary aggregate, resulting in a distinct pore structure and transport properties that may significantly influence durability performance. This gap in the literature is particularly important given the growing interest in sand concrete as a sustainable construction material in regions with abundant sand resources and limited gravel availability.

In a previous study, Ammari et al. (2023) investigated the effect of glass powder incorporation on the physical and mechanical properties of sand concrete, considering different dosages of glass powder from 0 to 40%. The results showed that glass powder effectively enhanced the physical and mechanical properties of sand concrete, with 10% identified as the optimal replacement level for mechanical performance. Nevertheless, the durability behavior of these glass-powder-based sand concrete mixtures remained unexplored, which is essential for validating the practical applicability of this material in real construction environments.

Therefore, the present study aims to fill this gap by comprehensively evaluating the durability performance of sand concrete containing waste glass powder as a partial cement replacement at dosages ranging from 0 to 40%. The durability assessment includes accelerated carbonation, total water immersion absorption, capillary water absorption, freeze-thaw cycling, wetting-drying cycling, resistance to hydrochloric acid attack, and scan-

ning electron microscopy (SEM) analysis. This comprehensive investigation provides new insights into the long-term performance of glass-powder-based sand concrete and establishes a complete characterization framework complementing the previously reported mechanical properties.

2. Materials Description and Testing Procedures

2.1. Materials description

The fine aggregates employed in this investigation consist of two locally sourced sands: a dune sand (DS), extracted from the southern area of El Oued city (Algeria), and a river sand (RS), obtained from the southeastern zone of El M'Ghair city (Algeria). The particle size of DS does not exceed 0.63 mm, whereas RS has a maximum grain diameter of 5 mm. To achieve an adequate

particle size distribution, both sands were blended to produce a mixed sand (RDS) following a grain size correction approach, in which the fine fraction of RS was adjusted by the addition of DS. The sands were blended at an RS-to-DS mass ratio of 1.7:1. This ratio was selected based on previous studies, which demonstrated that it provides an appropriate particle size distribution by combining the coarse fraction of river sand with the fine fraction of dune sand. This optimized grading contributes to a denser granular skeleton, which is considered advantageous for sand concrete production (Bederina et al. 2005; Ammari et al. 2021). The mineralogical characterization of the sands, carried out by X-ray diffraction (XRD) analysis (Figs. 1 and 2), confirmed their predominantly siliceous nature, with minor traces of calcium carbonate (CaCO_3) also detected. Moreover, the physical characterization results, summarized in Table 1, indicate that the mixed sand RDS meets the cleanliness requirements specified by standard NF P18-598 (1991).

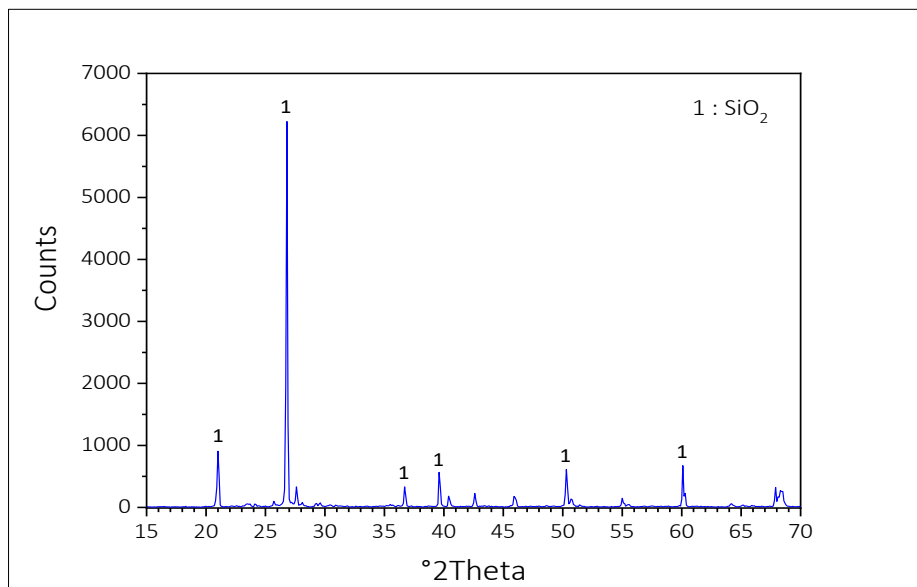


Fig. 1. X-ray diffraction (XRD) pattern of the utilized dune sand (DS).

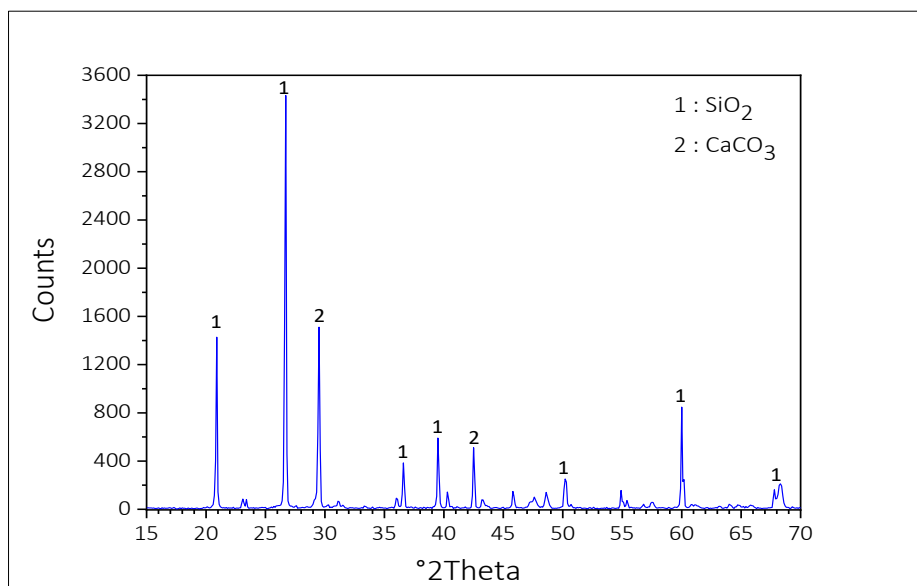


Fig. 2. X-ray diffraction (XRD) pattern of the utilized river sand (RS).

Table 1. Physical characteristics of the used sand (RDS).

Maximum diameter (mm)	5
Apparent density (kg/m ³)	1577
Absolute density (kg/m ³)	2570
Fineness modulus	2.2
Compactness (%)	61.36
Porosity (%)	38.64
Visual sand equivalent (%)	92.02
Piston sand equivalent (%)	77.13

The binding material adopted in this study is a Portland composite cement, designated as CEM II/B-L 42.5N, conforming to the Algerian standard NA 442 (2013). This cement type incorporates limestone as a secondary constituent and belongs to the normal early strength class (42.5N). The measured absolute density and Blaine specific surface area of the cement are 3080 kg/m³ and

449 m²/kg, respectively, and its detailed chemical composition is provided in Table 2. Given the inherently high porosity of sand concrete resulting from the absence of coarse aggregates, it is essential to optimize the particle packing density by filling the intergranular voids within the fine fraction of the sand. For this purpose, a limestone filler was incorporated as a fine mineral addition. This filler plays a fundamental role in the formulation of sand concrete by completing the grain size distribution curve and reducing the overall porosity of the mixture, as highlighted by Chauvin and Grimaldi (1988).

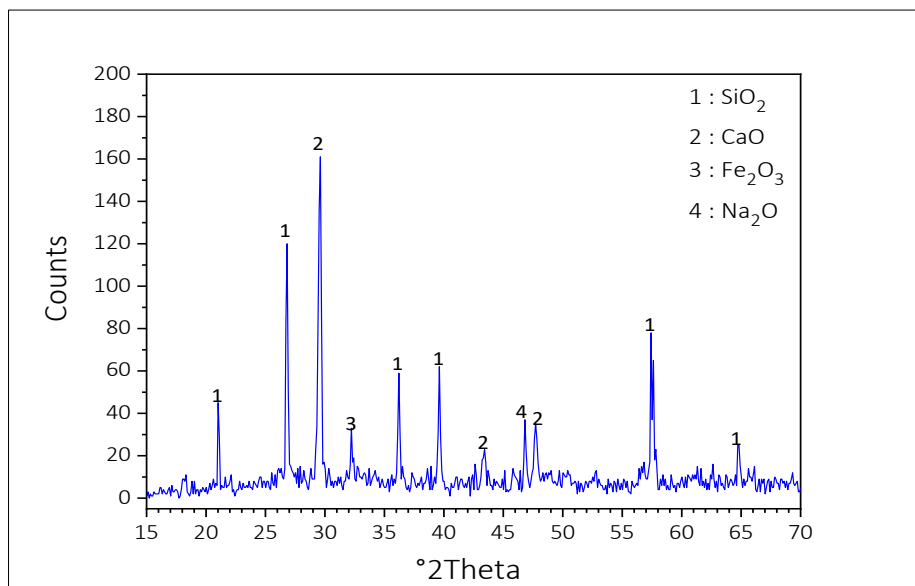
The limestone filler utilized in this research was obtained from crushing waste sourced from a quarry situated in the northern vicinity of Hassi Messaoud city (Algeria). The filler was produced by sieving the fine fraction of this crushing waste through an 80 µm mesh sieve. The physical characterization of this filler revealed absolute and apparent density values of 2500 kg/m³ and 981 kg/m³, respectively. The mineralogical analysis confirmed that the filler is entirely calcareous in nature, composed predominantly of calcium carbonate (CaCO₃), as reported by Ammari et al. (2023).

Table 2. Chemical composition of the cement used in this study.

Element	SiO ₂	CaO	MgO	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	K ₂ O	Cl-	Na ₂ O	Free CaO	LOI	Insoluble Residues
Quantity (%)	18.84	60.03	1.81	4.90	3.21	2.65	0.68	0.017	0.09	0.67	8.49	1.13

The supplementary cementitious material investigated in this study is a glass powder derived from white industrial glass waste. The preparation process involved crushing the collected glass fragments into fine particles, followed by sieving through an 80 µm mesh to obtain a uniform powder with a controlled fineness. This powder was incorporated into the sand concrete mixtures as a partial mass substitute for cement at varying replacement levels. The measured physical properties of the glass powder include an absolute density

of 2570 kg/m³ and a Blaine specific surface area of 288 m²/kg. The mineralogical composition, determined through XRD analysis (Fig. 3), revealed the presence of silica (SiO₂) as the dominant constituent, along with calcium oxide (CaO), iron oxide (Fe₂O₃), and sodium oxide (Na₂O). The high silica content (SiO₂ ≥ 70%) confirms the siliceous nature of the glass powder, which is a key prerequisite for potential pozzolanic reactivity when used as a cement replacement in cementitious materials.

**Fig. 3.** X-ray diffraction (XRD) pattern of the utilized glass powder.

Due to the specific granular composition of sand concrete, the incorporation of a chemical admixture is considered indispensable to ensure adequate workability of the fresh mix, as emphasized by Chauvin and Grimaldi (1988). In this regard, a high-range water-reducing superplasticizer, commercially known as MEDAPLAST-SP 40, was selected for all concrete mixtures. This admixture is supplied in liquid form, allowing for easy dispersion in the mixing water, and its properties comply with the requirements of the European standard EN 934-2 (2012).

2.2. Testing procedures

2.2.1. Preparation of the investigated concrete

The various sand concrete mixture compositions investigated in this study are summarized in Table 3. Glass powder was incorporated as a partial replacement of cement at mass percentages ranging from 10% to 40%, with increments of 10%. For ease of identification throughout this study, the different sand concrete mixtures were designated as follows:

- SC-WGP: Reference sand concrete without glass powder (control mix);
- SC-GP10%: Sand concrete incorporating 10% glass powder;
- SC-GP20%: Sand concrete incorporating 20% glass powder;
- SC-GP30%: Sand concrete incorporating 30% glass powder;
- SC-GP40%: Sand concrete incorporating 40% glass powder.

2.2.2. Mixing process and storage of specimens

To ensure thorough homogeneity of the mixture and thereby enhance the overall quality of the concrete, the mixing process was performed at a low speed following a specific sequential procedure:

- Step 1: Cement and glass powder were first dry-mixed together for 2.5 minutes to ensure uniform blending of the binding materials;
- Step 2: Limestone filler and sand were then introduced in a dry state, and mixing was continued for an additional 2.5 minutes;
- Step 3: Once a homogeneous dry blend was achieved, 70% of the total mixing water was gradually incorporated into the mixture over a period of 1.5 minutes without interruption;
- Step 4: The remaining 30% of the mixing water, pre-mixed with the chemical admixture, was finally added and mixed for 1 minute without interruption.

This mixing protocol was adopted based on several previous studies conducted on sand concrete (Bederina et al. 2016; Ammari et al. 2020a; Ammari et al. 2020b). After mixing, the fresh concrete was cast into molds, with each mold filled in two equal layers. Each layer was vibrated and compacted using 30 manual strokes to ensure adequate compaction and to minimize entrapped air voids. The molded specimens were then kept in their molds for 24 hours before being demolded. Subsequently, the specimens were stored under controlled laboratory conditions (temperature: $25 \pm 3 \text{ }^{\circ}\text{C}$; relative humidity: $50\% \pm 8\%$) until the designated testing date.

Table 3. Concrete mix designs considered in this study.

Composition	Cement (kg/m ³)	Glass powder (kg/m ³)	Total binder (kg/m ³)	Sand (RDS) (kg/m ³)	Limestone filler (kg/m ³)	Mixing water (l/m ³)	Water-to- binder ratio	Super-plasticizer *	
								(%)	(kg/m ³)
SC-WGP	400	0	400	1296	150	235	0.59	1.5	6
SC-GP10%	360	40	400	1296	150	235	0.59	1.5	6
SC-GP20%	320	80	400	1296	150	235	0.59	1.5	6
SC-GP30%	280	120	400	1296	150	235	0.59	1.5	6
SC-GP40%	240	160	400	1296	150	235	0.59	1.5	6

* The super-plasticizer dosage is expressed as a mass percentage of the total binder content (cement + GP).

2.2.3. Experimental techniques

a. Accelerated carbonation

The resistance of sand concrete to carbonation was assessed through an accelerated carbonation protocol conducted in accordance with the AFPC-AFREM procedure described in XP P18-458 (2008). The principle of this test involves exposing concrete specimens to a controlled gaseous environment composed of 50% CO₂ and 50% air inside a dedicated carbonation chamber (Fig. 4(a,b)), while maintaining the relative humidity within the range of 40% to 80%, which is considered the most favorable range for carbonation progression. For each mixture composition, four cubic specimens measuring

10 × 10 × 10 cm were prepared: three designated for carbonation depth measurements, and one dedicated to tracking the mass evolution throughout the testing period. Two additional reference specimens per mix were stored under ambient laboratory conditions (temperature of $20 \pm 5 \text{ }^{\circ}\text{C}$ and relative humidity of $65\% \pm 7\%$) to monitor the natural carbonation progression for comparative purposes.

The specimen pre-conditioning protocol comprised the following sequential steps. Initially, all specimens underwent a 28-day curing period in a humid environment with a relative humidity exceeding 95%, or alternatively were submerged in water. Upon completion of the curing phase, each specimen was weighed to establish its reference mass. Subsequently, the specimens

were transferred to an oven maintained at $40 \pm 2^\circ\text{C}$ for 48 hours, after which they were weighed again to record their conditioned mass. Prior to placement in the carbonation chamber, the two square faces of each specimen were sealed with adhesive aluminum foil to ensure

unidirectional CO_2 diffusion through the four exposed lateral faces (Fig. 4(c)). The specimens were then positioned inside the chamber with a minimum spacing of 2 cm between adjacent samples to guarantee uniform gas exposure on all unsealed surfaces

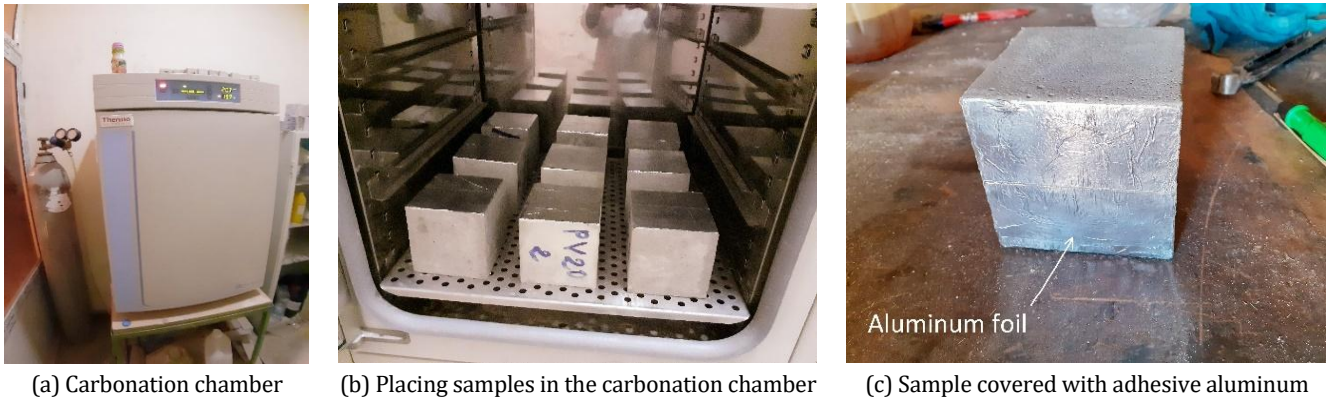


Fig. 4. Accelerated carbonation test.

The carbonation depth was evaluated at three exposure ages: 7, 14, and 28 days. At each designated age, the specimens were removed from the chamber and weighed to record any mass change. To determine the carbonation front, each specimen was split into two halves, and the freshly fractured surfaces were immediately sprayed with a phenolphthalein indicator solution (1% concentration dissolved in alcohol). This colorimetric technique relies on the pH sensitivity of phenolphthalein: the non-carbonated zone, characterized by a high pH close to 13, turns pink upon contact with the indicator, whereas the carbonated zone, where the pH has dropped to approximately 8.5 due to the consumption of calcium hydroxide by CO_2 , remains colorless. The carbonation depth on each exposed face was measured using a graduated ruler, with five readings recorded per face, comprising the minimum distance, the maximum distance, and three intermediate distances. The final reported carbonation depth for each specimen corresponds to the arithmetic mean of all measured values across the exposed faces.

b. Water absorption by total immersion

The water absorption by total immersion was evaluated on cubic specimens with dimensions of $5 \times 5 \times 5$ cm, in accordance with the Belgian standard NBN B 15-215 (1989). For each mixture composition, three specimens were prepared and tested to ensure the reproducibility of results. Prior to testing, the specimens were oven-dried at $105 \pm 5^\circ\text{C}$ until a constant mass was achieved, and then fully immersed in water at $20 \pm 2^\circ\text{C}$ until saturation, as prescribed by the standard. The reported values represent the arithmetic mean of three measurements for each mix.

c. Capillary water absorption

Capillary water absorption was evaluated on prismatic specimens with dimensions of $4 \times 4 \times 16$ cm. For each mixture composition, three specimens were pre-

pared and tested to ensure the reproducibility of results. Before the capillary absorption measurements, the test specimens were pre-conditioned according to the recommendations of the AFPC-AFREM procedure. The test consisted of placing each specimen vertically with its lower face in contact with a thin layer of water (approximately 5 mm deep), while the lateral surfaces were sealed to ensure unidirectional water uptake. The mass gain due to capillary absorption was recorded at predetermined time intervals. The capillary absorption coefficient (C_A) was calculated as the cumulative mass of absorbed water per unit exposed surface area according to Eq. (1):

$$C_A = \frac{M_t - M_0}{A} \quad (1)$$

where (M_t) is the mass of the specimen at time (t) (kg), (M_0) is the initial dry mass of the specimen (kg), and (A) is the exposed cross-sectional area in contact with water (m^2). In this study, the exposed surface area was 4×4 cm (0.0016 m^2). The reported values represent the arithmetic mean of three measurements for each mixture.

d. Freeze-thaw and wetting-drying

In the present study, the durability of sand concrete was evaluated through wetting-drying and freeze-thaw cyclic tests following ASTM D559 (2015) and ASTM D560 (2016), respectively. Although these standards were originally developed for compacted soil-cement mixtures, their use for sand concrete is well justified. Unlike ordinary concrete, sand concrete contains no coarse aggregates and relies exclusively on fine sand as the primary aggregate combined with cement and filler (Bederina et al. 2005; Chauvin and Grimaldi 1988), making its granular composition and matrix structure significantly closer to those of soil-cement mixtures than to that of conventional concrete. Moreover, the standard freeze-thaw test for ordinary concrete, as described in ASTM C666/C666M (2015), involves rapid cycles under water-saturated conditions with temperatures down to -18°C , a protocol specifically designed for concrete containing

coarse aggregates and therefore not directly applicable to sand concrete given its distinct pore structure and transport properties. Furthermore, several previous studies on sand concrete and similar fine-aggregate cementitious composites have successfully adopted ASTM D559 (2015) and ASTM D560 (2016) as appropriate durability testing protocols (Bederina et al. 2016; Aoual-Benslafa et al. 2011), confirming their suitability for this type of material. Finally, in the absence of a dedicated international standard for evaluating the cyclic durability of sand concrete, the selection of ASTM D559 and ASTM D560 is deemed technically appropriate, given the compositional analogy between sand concrete and soil-cement mixtures, and is consistent with the established testing methodology reported in the literature for similar fine-aggregate cementitious systems.

The freeze-thaw test was performed on cubic specimens measuring $10 \times 10 \times 10$ cm, in accordance with the testing protocol adopted in this study. For each mixture composition, three specimens were prepared to ensure the reproducibility of results. A total of twelve accelerated aging cycles were applied, starting at a curing age of 28 days. Each cycle consisted of freezing in air at -5°C for four hours, followed by complete immersion in water at 23°C until full thawing was achieved (approximately four hours). A temperature-controlled chamber was used to regulate the thermal cycles. The mass and compressive strength of each specimen were measured before and after the completion of all freeze-thaw cycles to evaluate both the weight loss and the strength degradation induced by the cyclic exposure. The reported values represent the arithmetic mean of three measurements obtained for each mix.

To assess the durability of sand concrete under alternating moisture conditions, the wetting-drying test was performed on cubic specimens measuring $10 \times 10 \times 10$ cm, in accordance with the testing protocol adopted in this study. Specimens were cast for all mixture compositions (0%, 10%, 20%, 30%, and 40% GP), with three replicates per mix to guarantee the reliability of the experimental data. At the age of 28 days, the specimens were subjected to twelve accelerated aging cycles. Each cycle involved immersion in water for five hours, followed by oven drying at 70°C for 42 hours. The mass and compressive strength of each specimen were determined both prior to and after the completion of the wetting-drying program, allowing the quantification of weight loss and strength degradation as indicators of durability performance. All reported results correspond to the mean value of three tested specimens per mixture.

e. Resistance to acid attack

The resistance of sand concrete to acid attack was evaluated by monitoring the mass variation and conducting chemical analyses on specimens immersed in a hydrochloric acid (HCl) solution, following the general guidelines of ASTM C267 (2020). Prismatic sand concrete specimens with dimensions of $4 \times 4 \times 16$ cm were used for this test. For each mixture composition (0%, 10%, 20%, 30%, and 40% GP), three specimens were prepared and tested to ensure reliable and reproducible measurements. After 28 days of water curing, the speci-

mens were removed from water and exposed to ambient conditions at a temperature of 23°C for 30 minutes to remove excess surface water. The initial dry mass of each specimen was then recorded before immersion in the acid solution (Bassuoni and Nehdi 2007). A hydrochloric acid solution with a concentration of 5% was prepared in acid-resistant containers and maintained at an ambient temperature of 23°C . The specimens were positioned with a spacing of 2 cm apart, ensuring that all surfaces were covered with approximately 2 cm of acid solution. The pH level of the solution was monitored every two days using pH indicator strips, and the recorded pH remained below 4 throughout the testing period. The durability performance was evaluated macroscopically through mass variation measurements, and microstructurally through X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses. The reported mass variation values represent the average of three specimens per mixture.

f. Microstructural analysis

The microstructural characteristics of sand concrete specimens were investigated using scanning electron microscopy (SEM) and X-ray diffraction (XRD) to gain a deeper understanding of the effect of glass powder incorporation on the cementitious matrix. For each mixture composition, representative samples were carefully selected and examined to ensure that the observations reflected the overall microstructural behavior of the material. SEM analysis was performed using a Phenom ProX scanning electron microscope to examine the surface morphology, identify micro-cracks, and detect any microstructural changes induced by the different testing conditions. Multiple micrographs were captured at various magnifications and from different locations on each specimen to ensure representative imaging of the microstructure. For XRD analysis, the cement matrices of the studied sand concrete mixtures were first crushed and sieved through an $80\ \mu\text{m}$ mesh to obtain a fine powder suitable for diffraction measurements. The prepared samples were then analyzed using a PROTO AXRD diffractometer to identify the crystalline phases and assess the mineralogical changes resulting from glass powder addition and exposure to aggressive environments.

3. Results and Analysis

3.1. Accelerated carbonation

3.1.1. Carbonation depth

The visual examination of the specimens after exposure to accelerated carbonation is illustrated in Fig. 5. A clear distinction between two zones can be observed on the fractured surfaces: the outer carbonated region, which retains the natural grey color of concrete due to the consumption of calcium hydroxide and the associated pH reduction to approximately 8.5, and the inner non-carbonated core, which turns pink upon spraying with the phenolphthalein indicator, confirming that the alkalinity of the pore solution remains intact in this zone ($\text{pH} \approx 13$).

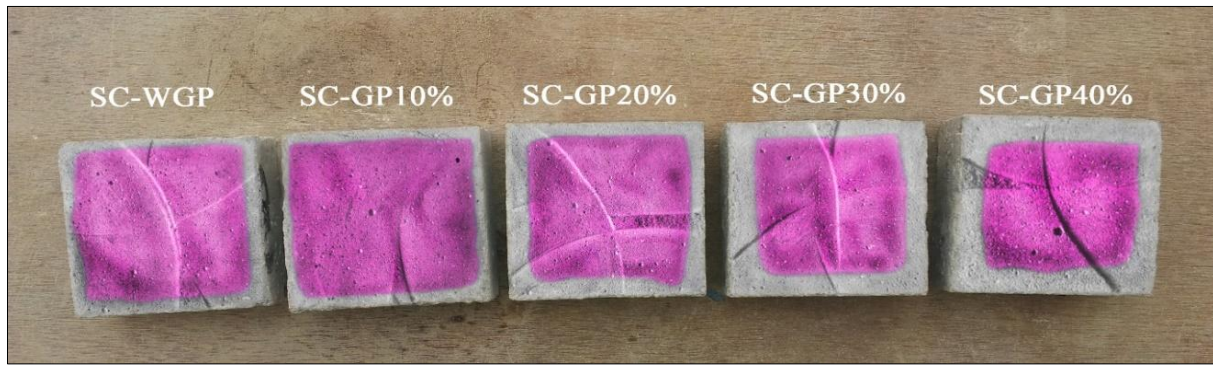


Fig. 5. Carbonation front detection using phenolphthalein indicator on the studied concretes at 28 days.

The carbonation front separating these two regions appears well-defined and regular across all tested sand concrete compositions, indicating a relatively uniform CO_2 diffusion pattern through the matrix. Regarding the influence of glass powder content, the results reveal that the incorporation of 10% GP produced the most favorable performance, exhibiting a reduced carbonation depth compared to the reference mix (SC-WGP). This improvement can be attributed to the pozzolanic reaction of the glass powder at this dosage, which generates ad-

ditional C-S-H gel that refines the pore structure and hinders CO_2 penetration into the matrix. However, at replacement levels exceeding 10%, a progressive increase in carbonation depth was observed, suggesting that the dilution of the cementitious matrix at higher GP dosages creates a more porous and permeable microstructure that facilitates the inward diffusion of carbon dioxide.

The evolution of carbonation depth as a function of exposure time at 7, 14, and 28 days for all sand concrete compositions is presented in Fig. 6.

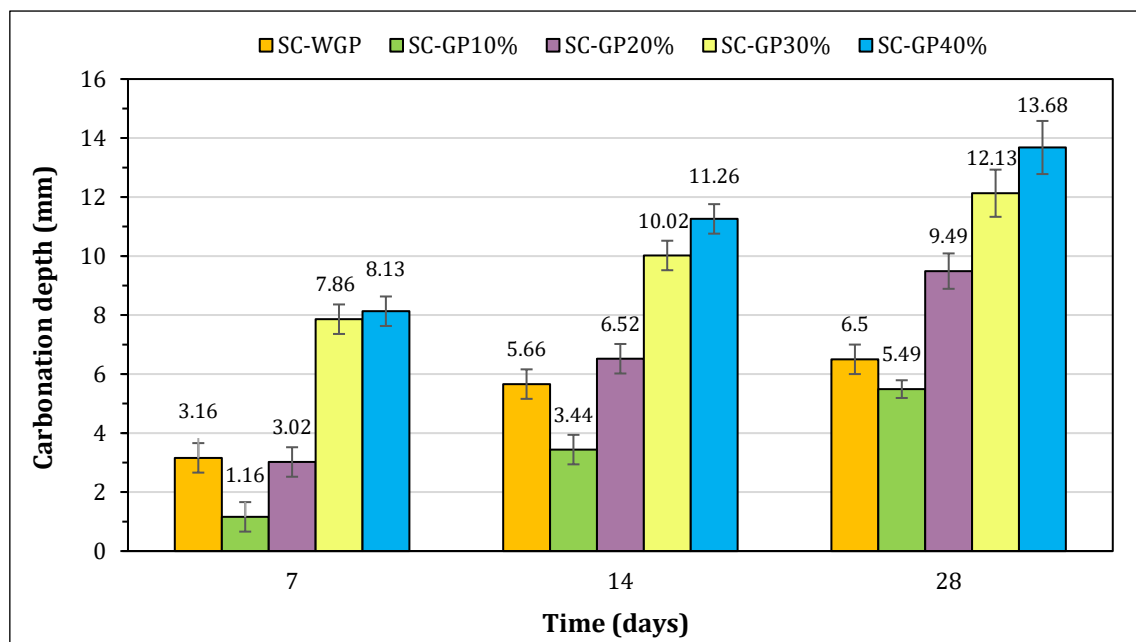


Fig. 6. Evolution of carbonation depth over time.

The results reveal a clear dependence of carbonation depth on the glass powder replacement level, with distinctly different behaviors observed below and above the 10% GP threshold. At 28 days of accelerated carbonation exposure, the reference mix (SC-WGP) recorded a carbonation depth of 6.49 mm, while the SC-GP10% mix exhibited the shallowest carbonation front among all tested compositions, reaching only 5.49 mm, which corresponds to a reduction of approximately 15.41% in carbonation depth compared to the reference mix. This enhanced resistance to carbonation penetration at 10% GP can be attributed to the effective pozzolanic reaction at this dosage, which consumes a portion of the available calcium

hydroxide ($\text{Ca}(\text{OH})_2$) to form additional C-S-H gel. While this reaction theoretically reduces the amount of $\text{Ca}(\text{OH})_2$ available for carbonation, the resulting densification of the pore structure at 10% GP appears to outweigh this effect by significantly hindering the inward diffusion of CO_2 through the matrix. Schwarz et al. (2008) reported a comparable pore-refining effect at moderate glass powder replacement levels, which effectively reduced the transport properties of the cementitious matrix. Similarly, Matos and Sousa-Coutinho (2012) observed that glass powder at low replacement dosages contributed to an acceptable carbonation performance due to the balance between pore refinement and $\text{Ca}(\text{OH})_2$ consumption.

In contrast, replacement levels exceeding 10% GP led to a progressive and substantial increase in carbonation depth. At 28 days, the carbonation depth rose sharply to 9.49 mm, 12.13 mm, and 13.68 mm for SC-GP20%, SC-GP30%, and SC-GP40%, respectively, corresponding to increases of 46.22%, 86.90%, and 110.79% in carbonation depth relative to the reference mix. Notably, the most pronounced increase in carbonation depth occurred between SC-GP10% and SC-GP20%, where it nearly doubled from 5.49 mm to 9.49 mm (a difference of 4.00 mm), indicating the existence of a critical threshold between 10% and 20% GP beyond which the carbonation resistance deteriorates rapidly. This pronounced increase in carbonation depth can be explained by two concurrent mechanisms. First, the excessive replacement of cement by glass powder significantly reduces the total quantity of $\text{Ca}(\text{OH})_2$ produced during hydration, thereby lowering the carbonation buffering capacity of the matrix, as the carbonation process fundamentally relies on the reaction between atmospheric CO_2 and $\text{Ca}(\text{OH})_2$ to form calcium carbonate (CaCO_3). Second, the dilution effect at higher dosages results in an insufficiently densified microstructure with greater pore connectivity, which facilitates the penetration of CO_2 into deeper layers of the concrete. Islam et al. (2017) emphasized that beyond an optimal glass powder threshold, the beneficial pozzolanic contribution is outweighed by the detrimental reduction in cement content, leading to a decline in overall performance. These findings are also consistent with those of Salim and Mosaberpanah (2021), who reported that carbonation resistance of glass-powder-modified cementitious materials deteriorated significantly at high replacement levels due to the combined effect of reduced portlandite availability and increased porosity. Consequently, the SC-GP10% composition exhibited the lowest measured carbonation depth among all tested compositions.

In addition to the accelerated carbonation test, an attempt was made to evaluate the natural carbonation be-

havior of the studied sand concrete compositions. It is widely recognized that natural carbonation provides more realistic results compared to accelerated testing, as it reflects the actual service conditions of the material under atmospheric CO_2 concentrations of approximately 0.04%. However, the practical implementation of natural carbonation tests presents significant challenges, primarily due to the difficulty of maintaining constant ambient conditions over extended periods and the inherently slow rate of CO_2 diffusion at such low concentrations. In the present study, companion specimens for each mix were stored under ambient laboratory conditions (temperature of $20 \pm 5^\circ\text{C}$ and relative humidity of $65\% \pm 7\%$) throughout the experimental program. The results indicated that none of the tested sand concrete compositions exhibited any measurable carbonation depth under natural exposure conditions during the monitoring period. This absence of detectable carbonation depth can be attributed to the relatively short exposure duration, which was insufficient for atmospheric CO_2 at low concentrations to penetrate to a measurable depth within the concrete matrix. Siad et al. (2016) noted that the carbonation process under natural conditions is extremely slow, particularly for well-cured concrete specimens, and that measurable carbonation depths typically require exposure periods of several months to years, depending on the environmental conditions and concrete permeability. This observation further confirms that accelerated carbonation testing remains the most practical and reliable method for evaluating the carbonation resistance of sand concrete within a reasonable experimental timeframe.

3.1.2. Variation of mass gain

Alongside the carbonation depth measurements, the mass evolution of all sand concrete specimens was monitored at 7, 14, and 28 days of accelerated carbonation exposure, and the results are presented in Fig. 7.

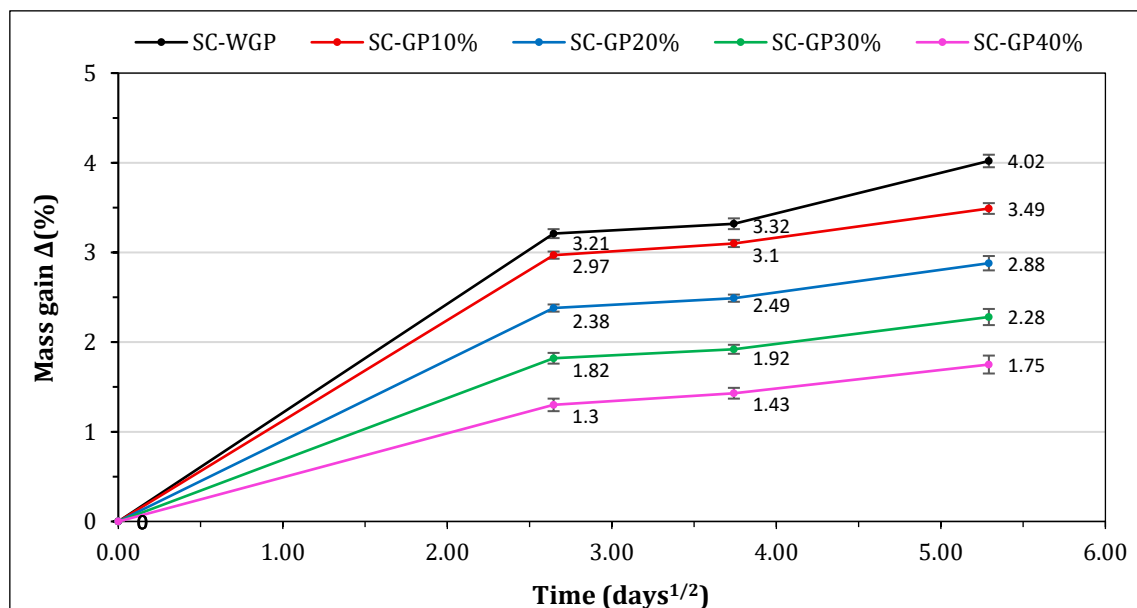


Fig. 7. Evolution of mass gain over time for the studied concretes.

During the carbonation process, the reaction between the diffused CO_2 and the calcium hydroxide ($\text{Ca}(\text{OH})_2$) present in the pore solution produces calcium carbonate (CaCO_3), which has a higher molar mass than the original portlandite, resulting in a net mass gain of the specimens. Therefore, the magnitude of mass gain serves as an indirect indicator of the extent of the carbonation reaction within the cementitious matrix.

The results demonstrate that the incorporation of glass powder into sand concrete progressively reduced the mass gain across all replacement levels compared to the reference mix (SC-WGP). At 28 days, the reference mix recorded the highest mass gain of 4.02%, which decreased to 3.49%, 2.88%, 2.28%, and 1.75% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. These values correspond to reductions of approximately 13.18%, 28.36%, 43.28%, and 56.47% in mass gain relative to the reference mix, with the SC-GP40% composition exhibiting the lowest mass gain among all tested compositions. Regarding the temporal evolution, a rapid increase in mass gain was observed during the first 7 days for all compositions, reflecting the initial stage of carbonation where the CO_2 reacts readily with the $\text{Ca}(\text{OH})_2$ accessible in the surface-connected pores. Beyond this period and up to 28 days, the mass gain evolved at a considerably slower rate, with all compositions following a nearly parallel trend, indicating that the carbonation front had progressed into deeper and less accessible pore regions where the CO_2 diffusion rate is considerably reduced.

The progressive reduction in mass gain with increasing glass powder content is directly related to the decreasing availability of $\text{Ca}(\text{OH})_2$ within the matrix. As the cement content is reduced through glass powder substitution, the total amount of $\text{Ca}(\text{OH})_2$ generated during hydration diminishes proportionally, leaving less portlandite available to react with the diffused CO_2 and consequently producing less CaCO_3 . This mechanism explains why the SC-GP40% mix, having the lowest cement content among all compositions, recorded the lowest mass gain. Shi et al. (2005) confirmed that the pozzolanic reaction of glass powder further consumes the available $\text{Ca}(\text{OH})_2$ to

produce C-S-H gel, thereby additionally reducing the portlandite reservoir available for carbonation. Matos and Sousa-Coutinho (2012) reported analogous observations in mortar containing glass powder, where the mass gain during carbonation decreased with increasing glass powder dosage due to the reduced $\text{Ca}(\text{OH})_2$ content.

It is essential, however, to interpret these mass gain results in conjunction with the carbonation depth measurements discussed above, as the two indicators convey complementary but distinct information about the carbonation process. While a lower mass gain may appear to indicate better carbonation resistance, it actually reflects a reduced $\text{Ca}(\text{OH})_2$ content rather than an inherently superior resistance to CO_2 penetration. This is clearly evidenced by comparing the SC-GP10% and SC-GP40% compositions: although SC-GP40% exhibited the lowest mass gain (1.75% vs. 3.49% for SC-GP10%), it recorded the deepest carbonation front (13.68 mm vs. 5.49 mm for SC-GP10%). This apparent contradiction confirms that the lower mass gain at higher GP dosages is not an indicator of improved durability, but rather a consequence of the depleted $\text{Ca}(\text{OH})_2$ reserve, which consequently allows CO_2 to penetrate more rapidly through the poorly buffered matrix. In contrast, the SC-GP10% composition achieved both a moderate reduction in mass gain (13.18%) and the shallowest carbonation depth (5.49 mm), confirming that at this dosage, the pozzolanic reaction refines the pore structure sufficiently to impede CO_2 diffusion while maintaining an adequate $\text{Ca}(\text{OH})_2$ buffering capacity to resist carbonation progression.

3.2. Water absorption by total immersion

This property provides a direct indication of the behavior of glass powder-based concrete when exposed to water. Water absorption capacity is a key indicator of the porosity of concrete, as it directly reflects the presence and volume of internal pores. The water absorption coefficients obtained by total immersion for the various concrete mixtures investigated in this study are presented in Fig. 8.

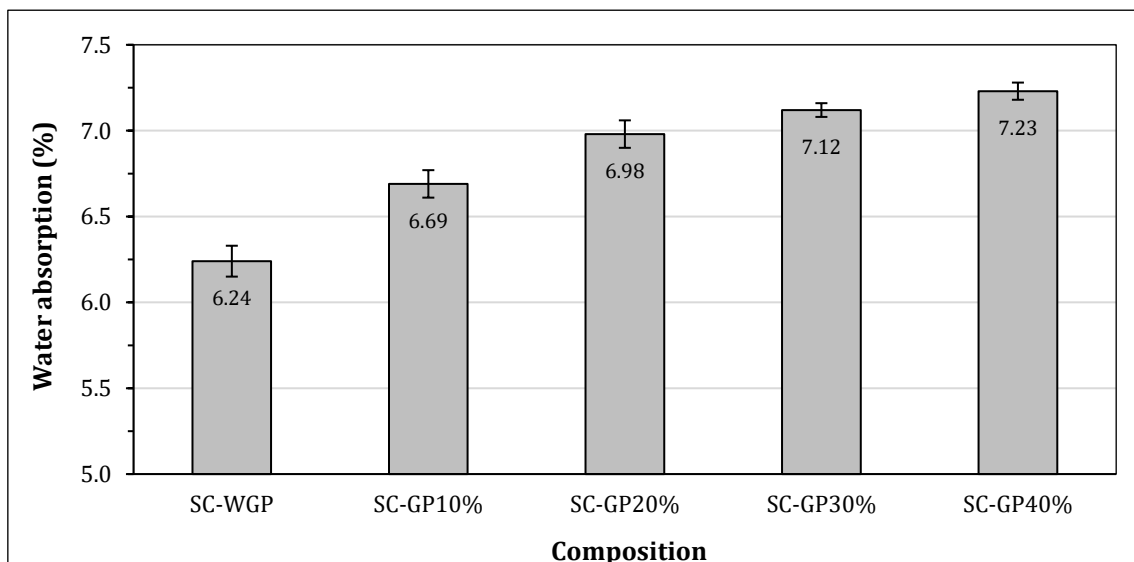


Fig. 8. Influence of glass powder proportion on water absorption by immersion.

The total water absorption results reveal an unfavorable effect of glass powder incorporation on the porosity-related properties of sand concrete. The water absorption coefficient increased progressively with increasing GP content across all replacement levels. The reference mix (SC-WGP) recorded a water absorption value of 6.24%, which increased to 6.69%, 6.98%, 7.12%, and 7.23% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. These values correspond to increases of approximately 7.21%, 11.86%, 14.10%, and 15.87% relative to the reference mix. This systematic increase suggests that glass powder incorporation adversely affects the pore structure of sand concrete, a trend that requires further analysis in light of the underlying microstructural mechanisms.

The primary explanation for this behavior lies in the modification of the pore network within the cementitious matrix. At higher glass powder replacement levels, the reduction in cement content leads to a decrease in the volume of hydration products, particularly C-S-H gel, which is primarily responsible for filling the capillary pores and densifying the microstructure. This creates additional interconnected voids within the matrix, facilitating greater water ingress and retention. Furthermore, the smooth and non-reactive surface of unreacted glass particles, especially at dosages above 20%, may weaken the bond at the particle-paste interface, generating micro-gaps that contribute to increased porosity and water accessibility. Adesina and Das (2020) observed a similar increase in water absorption with increasing glass powder content in cementitious composites, attributing it to the reduced hydration activity at higher replacement levels that leaves more unfilled pore space within the matrix. Letelier et al. (2019) also reported comparable findings in mortars containing waste glass, noting that the absorption increase was directly related to the higher porosity resulting from cement dilution. Moreover, Jain et al. (2020) demonstrated that incorporating 25% glass powder into concrete increased the water absorption coefficient by approximately 8% compared to the control concrete, which closely aligns with the 7.21% increase observed in the present study at 10% GP. Ramakrishnan et al. (2017) further confirmed this trend, showing that increasing the glass powder replacement level to 20% resulted in a measurable rise in the water absorption coefficient.

It is worth noting, however, that the rate of absorption increase is not uniform across all replacement levels, exhibiting a clear decelerating pattern. The most notable increment occurred between the reference mix and SC-GP10%, with the absorption rising from 6.24% to 6.69% (a difference of 0.45%). This increment progressively diminished to 0.29% between SC-GP10% and SC-GP20%, then to 0.14% between SC-GP20% and SC-GP30%, and finally to only 0.11% between SC-GP30% and SC-GP40%. This plateau-like behavior at higher dosages suggests that beyond a certain replacement threshold, the pore network reaches a near-saturation state where additional glass powder no longer substantially alters the overall porosity. At low replacement levels such as 10%, the pozzolanic activity of the glass powder partially compensates for the porosity increase by producing secondary C-S-H gel that fills a portion of the newly formed

voids. Schwarz et al. (2008) reported a similar observation, noting that fine glass powder at moderate replacement levels provided a degree of pore refinement that partially mitigated the negative effects of cement reduction. At higher dosages, however, the limited availability of calcium hydroxide restricts the extent of the pozzolanic reaction, leaving a greater volume of unreacted glass particles that do not contribute to pore filling, thereby amplifying the absorption increase. Matos and Sousa-Coutinho (2012) confirmed this mechanism, showing that excessive glass powder replacement led to a dilution effect that progressively increased the porosity of cementitious materials.

This finding highlights the importance of carefully selecting the glass powder replacement level to minimize the adverse impact on water absorption. While the absorption increase at 10% GP remains within an acceptable range (7.21% increase, from 6.24% to 6.69%), the progressive deterioration at higher dosages raises concerns about the long-term performance of sand concrete in water-saturated environments, where elevated absorption can accelerate the ingress of aggressive agents and compromise the overall durability of the material. The implications of this porosity increase on other durability indicators, such as resistance to cyclic environmental exposure and chemical attack, will be examined in the subsequent sections.

3.3. Capillary water absorption

In addition to total water absorption, the capillary water absorption test provides further insight into the pore connectivity and transport properties of sand concrete, as it specifically reflects the ability of the material to absorb water through its capillary pore network under the effect of surface tension. Fig. 9 presents the average values of the capillary absorption coefficients over 24 hours for all studied compositions.

The results indicate that the capillary absorption of sand concrete is considerably and adversely affected by the incorporation of glass powder at all replacement levels. The reference mix (SC-WGP) recorded a capillary absorption value of 7.68 kg/m², which increased progressively to 8.85, 10.02, 10.94, and 12.76 kg/m² for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. These values correspond to increases of approximately 15.23%, 30.47%, 42.45%, and 66.14% relative to the reference mix. Notably, the capillary absorption increase is considerably more pronounced than the total immersion absorption increase discussed previously (which ranged from 7.21% to 15.87%), suggesting that glass powder incorporation predominantly affects the capillary pore structure rather than the overall porosity of the matrix.

This amplified capillary absorption can be attributed to several microstructural factors. First, the progressive replacement of cement by glass powder reduces the quantity of hydration products available to fill and segment the capillary pore network, resulting in a more interconnected and continuous capillary system that facilitates faster water transport. Second, at higher replacement levels (30–40%), the excess of unreacted glass particles may create preferential pathways at the particle-paste interface, acting as channels that enhance capillary

suction. Matos and Sousa-Coutinho (2012) investigated the capillary absorption of mortar containing 10% and 20% glass powder as cement replacement and reported a measurable increase in the capillary absorption coefficient at both dosages, attributing this to the coarsening of the pore structure caused by the reduced cement hydration. Adesina and Das (2020) observed a similar trend in cementitious composites incorporating glass powder, confirming that the capillary pore connectivity

increases with higher glass powder content due to the insufficient formation of pore-blocking hydration products. Furthermore, Schwarz et al. (2008) compared the microstructural effects of glass powder and fly ash in concrete and noted that while both materials exhibited pozzolanic activity, glass powder at higher dosages was less effective in refining the capillary pore structure, which is consistent with the progressive capillary absorption increase observed in the present study.

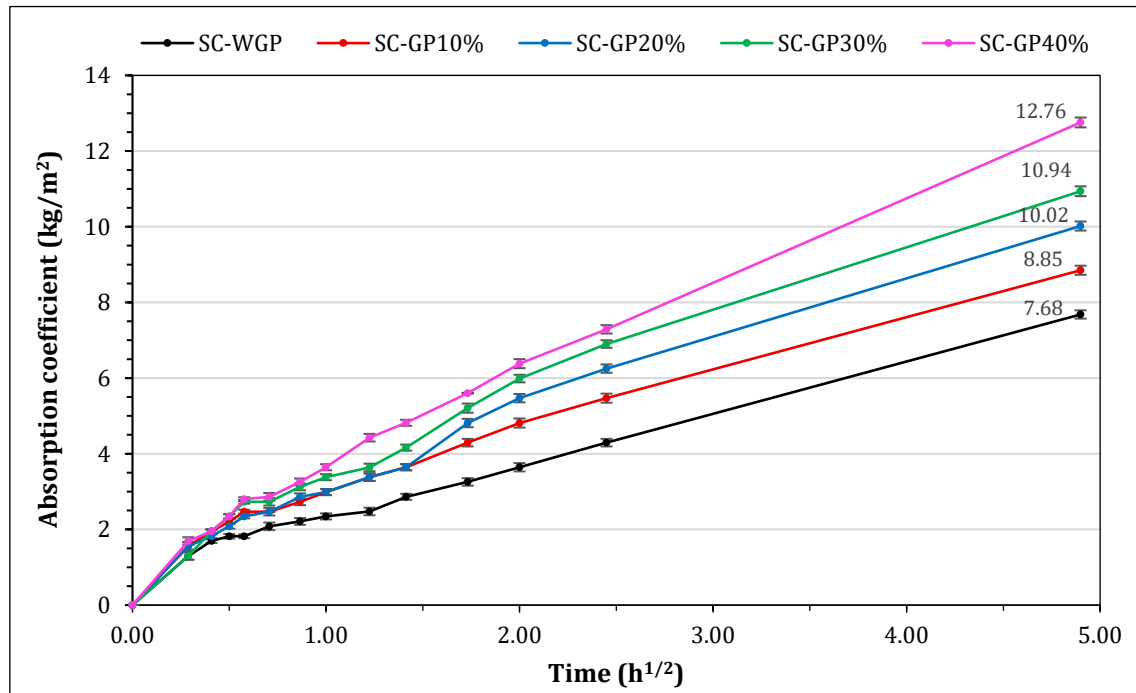


Fig. 9. Evolution of capillary absorption of the studied concretes as a function of time.

An examination of the differences between successive mixtures shows that the cumulative capillary water absorption increased by 1.17 kg/m² between SC-WGP and SC-GP10%, by 1.17 kg/m² between SC-GP10% and SC-GP20%, by 0.92 kg/m² between SC-GP20% and SC-GP30%, and by 1.82 kg/m² between SC-GP30% and SC-GP40%. Therefore, the increase was not uniform across the investigated replacement levels, and the largest increment occurred between 30% and 40% GP. However, without additional statistical or microstructural evidence, this change should not be interpreted as proof of a critical threshold or a transition in the capillary pore network. Islam et al. (2017) emphasized the existence of such threshold effects in glass powder modified concrete, where the benefits of glass powder diminish beyond an optimal level, giving way to accelerated deterioration of the microstructural properties.

When compared to the total immersion absorption results, the capillary absorption data reveal a more severe impact of glass powder on sand concrete properties. While total immersion absorption showed a decelerating increase that plateaued at higher GP dosages, capillary absorption exhibited an accelerating trend, particularly at 40% GP. This discrepancy can be explained by the different mechanisms governing each test: total immersion absorption captures the overall accessible pore volume, whereas capillary absorption is governed by the connec-

tivity and diameter distribution of the capillary pores. The glass powder incorporation, while not dramatically increasing the total pore volume at higher dosages, appears to significantly enhance the continuity and connectivity of the capillary network, thereby amplifying the capillary suction forces. This adverse effect on capillary absorption represents an important consideration for the practical application of glass-powder-based sand concrete, particularly in environments where capillary rise may facilitate the transport of aggressive agents such as chlorides and sulfates into the concrete matrix. However, at 10% GP, the capillary absorption increase remains the most moderate among all replacement levels (15.23%), reinforcing the importance of limiting the glass powder dosage to preserve the transport properties of sand concrete.

3.4. Freeze-thaw test

The resistance of concrete to freeze-thaw cycles is a fundamental durability characteristic for construction elements exposed to cold climates. This resistance is closely related to several material properties, including porosity, permeability, pore structure, and aggregate characteristics. To quantify the strength and mass loss induced by the freeze-thaw cycles for all studied compositions, the variations were recorded and the results are presented in Fig. 10.

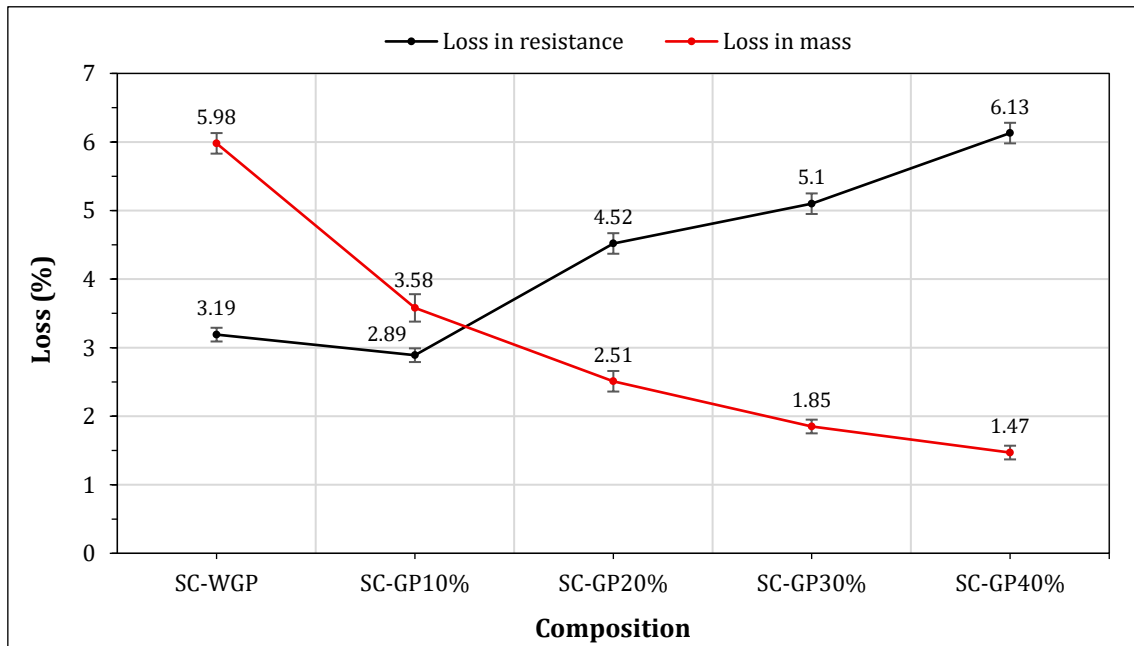


Fig. 10. Impact of freeze–thaw cycles on the durability of the studied concretes.

The freeze-thaw test results reveal that the impact of glass powder incorporation on the durability of sand concrete varies depending on the performance indicator considered. In terms of compressive strength loss, a reduction in compressive strength was observed for all compositions after twelve freeze-thaw cycles, which is consistent with the well-established phenomenon of internal micro-crack propagation induced by repeated freezing and thawing of pore water within the cementitious matrix. Ammari et al. (2020a) reported a similar trend when studying the durability of sand concrete containing barley straw fibers, where freeze-thaw cycles caused measurable strength degradation across all tested compositions. Among all tested mixtures in the present study, the 10% GP mix (SC-GP10%) exhibited the lowest compressive strength loss of 2.89%, compared to 3.19% for the reference mix (SC-WGP). However, beyond this dosage, the compressive strength loss increased progressively, reaching 4.52%, 5.10%, and 6.13% for SC-GP20%, SC-GP30%, and SC-GP40%, respectively. This superior strength retention at 10% GP can be attributed to the pozzolanic reaction of the fine glass powder with calcium hydroxide ($\text{Ca}(\text{OH})_2$). Supporting this observation, Shi et al. (2005) demonstrated that glass powder possesses significant pozzolanic reactivity due to its high amorphous silica content, which reacts with $\text{Ca}(\text{OH})_2$ to produce additional calcium silicate hydrate (C-S-H) gel. Shayan and Xu (2006) confirmed this pozzolanic behavior through field trials on concrete slabs, showing that glass powder effectively contributed to pore structure refinement and matrix densification. Similarly, Idir et al. (2011) investigated the pozzolanicity of glass cullet fines and reported that finely ground glass powder exhibited a clear pozzolanic potential comparable to conventional supplementary cementitious materials. This denser microstructure limits the penetration and accumulation of water within the pores, thus reducing the internal stresses generated during ice formation and consequently minimizing the strength degradation.

At higher replacement levels (20–40%), the dilution effect of excessive glass powder replacement progressively weakens the binding capacity of the cementitious matrix, resulting in increased internal damage under cyclic freezing and thawing stresses.

This finding is in agreement with the observations of Schwarz et al. (2008), who observed that while fine glass powder improved the durability characteristics of concrete at low replacement levels, the beneficial effect diminished at higher dosages. Matos and Sousa-Coutinho (2012) also reported that excessive cement replacement by glass powder led to a dilution effect that negatively impacted the overall performance of cementitious materials. Furthermore, Islam et al. (2017) emphasized the existence of an optimal replacement level, beyond which the mechanical and durability properties begin to decline. However, when mass loss is considered as the performance criterion, a distinctly opposite trend emerges. The results show that increasing the glass powder content progressively reduced the mass loss rates across all compositions. The reference mix (SC-WGP) recorded the highest mass loss of 5.98%, while the incorporation of glass powder reduced this value to 3.58%, 2.51%, 1.85%, and 1.47% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. Notably, the 40% GP mix exhibited the lowest mass loss, representing a reduction of approximately 75.42% compared to the reference mix. This behavior can be explained by the presence of unreacted glass particles within the matrix at higher replacement levels. Sobolev et al. (2007) highlighted that glass is a material that can be recycled without loss of quality, indicating its inherent chemical stability and resistance to degradation. Shi et al. (2005) further confirmed the high chemical durability of glass particles, noting that their low solubility and inert nature allow them to act as physically stable inclusions that resist surface erosion and scaling during aggressive exposure conditions. Furthermore, the smooth and non-porous surface of glass particles may contribute to reducing water absorption at

the surface level, which limits the physical deterioration caused by ice crystallization at the outer layers.

This apparent divergence between the two performance indicators highlights the necessity of adopting a multi-criteria evaluation approach when assessing the freeze-thaw durability of sand concrete. Jain et al. (2020) adopted a similar multi-criteria approach when evaluating the durability of concrete containing waste glass powder, assessing both water absorption and acid resistance to obtain a comprehensive durability characterization. Likewise, Ramakrishnan et al. (2017) conducted multiple durability tests on concrete incorporating glass powder as a supplementary cementitious material and emphasized that no single test can fully capture the overall durability behavior. Mass loss predominantly reflects surface deterioration and physical erosion of the outer layers, whereas compressive strength loss captures the extent of internal microstructural damage, including the propagation of micro-cracks and the degradation of the interfacial transition zone between the cement paste and aggregate. In the case of higher GP contents (30% and 40%), although the surface integrity was better preserved as evidenced by lower mass loss values of 1.85% and 1.47% respectively, the excessive cement replacement led to a dilution effect that weakened the overall cementitious matrix, making it more susceptible to internal damage. This explains why the 40% GP mix, despite exhibiting the lowest mass loss (1.47%), showed the

highest compressive strength loss (6.13%) among all tested compositions.

Therefore, considering the overall balance between both durability indicators, the 10% GP mix offers the most favorable compromise under freeze-thaw conditions. While it does not achieve the absolute lowest mass loss (3.58% vs. 1.47% for SC-GP40%), it provides the best compressive strength retention (2.89%), which is considered the more critical parameter for structural performance, as internal microstructural integrity directly governs the load-bearing capacity and long-term serviceability of sand concrete in real construction applications. This observation is consistent with the findings of Ammari et al. (2023), who identified 10% GP as the optimal replacement level for mechanical properties of sand concrete in their previous study.

3.5. Wetting-drying test

The wetting-drying test is commonly employed to evaluate the long-term durability of concrete exposed to cyclic moisture conditions, such as those encountered in humid or coastal environments. This test allows the assessment of both strength and mass variations after repeated wetting-drying cycles, providing a comprehensive indication of the material's resistance to moisture-induced degradation. The results obtained for all studied compositions are presented in Fig. 11.

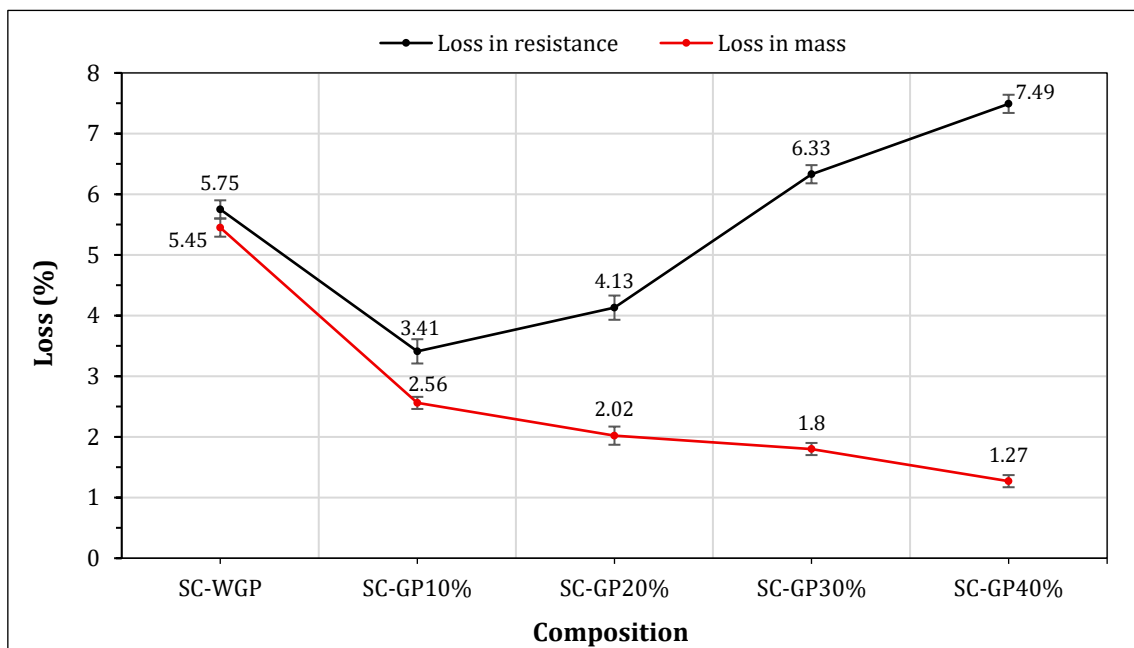


Fig. 11. Impact of wetting-drying cycles on the durability of the studied concretes.

An analysis of the compressive strength loss and mass loss results presented in Fig. 11 reveals two contrasting trends that merit careful discussion. Regarding compressive strength, the incorporation of 10% GP (SC-GP10%) led to the lowest strength loss of 3.41%, representing a substantial reduction of approximately 40.70% compared to the reference mix (SC-WGP), which recorded a loss of 5.75%. The 20% GP mix also showed a moderate improvement with a strength loss of 4.13%. In contrast,

higher dosages of glass powder proved detrimental to strength retention, with SC-GP30% and SC-GP40% recording strength losses of 6.33% and 7.49%, respectively, both exceeding the reference mix. This non-linear behavior suggests that at a low replacement level of 10%, the glass powder effectively participates in the pozzolanic reaction, generating secondary C-S-H gel that strengthens the interfacial transition zone (ITZ) between the paste and sand grains. Schwarz et al. (2008)

reported comparable findings, demonstrating that fine glass powder at moderate replacement levels improved the microstructure of concrete and enhanced its resistance to aggressive environments. Adesina and Das (2020) further confirmed that glass powder incorporation enhanced the durability properties of cementitious composites by densifying the matrix and reducing porosity, which corroborates the improved wetting-drying resistance observed at 10% GP in the present study. Beyond 20% replacement, however, the insufficient availability of calcium hydroxide to react with the excess glass powder results in a progressively weaker and more porous matrix that becomes increasingly vulnerable to moisture-induced internal damage. This is consistent with the observations of Matos and Sousa-Coutinho (2012), who found that high dosages of glass powder as cement replacement compromised the durability performance of mortar, and with Islam et al. (2017), who reported that the benefits of glass powder incorporation diminish beyond an optimal threshold.

Conversely, the mass loss results exhibit a consistent and monotonic decreasing trend with increasing glass powder content, irrespective of the observed strength behavior. The reference mix (SC-WGP) showed the highest mass loss of 5.45%, which was progressively reduced to 2.56%, 2.02%, 1.80%, and 1.27% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. The 40% GP mix thus achieved a considerable reduction of approximately 76.70% in mass loss compared to the reference mix. Unlike the strength loss trend, the continuous improvement in mass stability with increasing GP content can be attributed to the progressive filling of surface-accessible pores by unreacted glass particles. Jain and Neithalath (2010) demonstrated that glass-powder-modified concretes exhibited lower diffusion coefficients, attributing this improvement to the physical pore-blocking effect of fine glass particles, which is consistent with the reduced mass loss observed in the present study. Similarly, Letelier et al. (2019) found that waste glass incorporation in mortars contributed to reducing permeability, supporting the hypothesis that the impermeable and smooth surface texture of glass particles creates a barrier effect that limits water ingress and egress during wetting-drying cycles, thereby preserving the surface integrity and reducing material detachment from the outer layers.

This divergence between compressive strength loss and mass loss trends under wetting-drying conditions confirms that a single performance indicator is insufficient to fully characterize the durability of sand concrete, as previously observed in the freeze-thaw results. However, a notable distinction exists between the two tests: while the freeze-thaw results showed relatively modest differences in strength loss across compositions (ranging from 2.89% to 6.13%), the wetting-drying test produced a wider dispersion (from 3.41% to 7.49%), indicating that sand concrete is more sensitive to wetting-drying cycles than to freeze-thaw cycles, particularly at higher glass powder dosages. Ammari et al. (2020a) and Bederina et al. (2016) reported similar observations regarding the sensitivity of sand concrete to cyclic moisture exposure, attributing it to the inherently porous microstructure of this type of concrete. This heightened

sensitivity can be explained by the fact that the alternating shrinkage and swelling stresses generated during drying and wetting phases create differential moisture gradients between the surface and the core of the specimens, which are more damaging to the weakened matrix at high GP replacement levels than the volumetric expansion caused by ice crystallization during freeze-thaw cycling.

In light of these findings, the 10% GP mix once again demonstrates the best overall durability performance under wetting-drying conditions. It is the only composition that simultaneously improved both performance indicators relative to the reference mix, achieving the lowest strength loss (3.41%) and a substantial reduction in mass loss (2.56%, representing a 53.03% decrease compared to the reference mix). Although higher GP dosages provided superior mass stability, this benefit was offset by a considerable deterioration in mechanical performance. This conclusion is in agreement with the findings of Ammari et al. (2023), who identified 10% GP as the optimal dosage for mechanical performance of sand concrete. Salim and Mosaberpanah (2021) also reported that low glass powder replacement levels yielded the best durability performance in high-performance mortar, while Ghrici et al. (2007) demonstrated that low replacement levels of pozzolanic materials achieved the best balance between durability and mechanical strength, further reinforcing the conclusion that 10% GP represents the optimal compromise for sand concrete.

3.6. Resistance to acidic environments

This section focuses on evaluating the resistance of sand concrete incorporating glass powder to chemical degradation induced by hydrochloric acid (HCl) exposure. The assessment was conducted on specimens immersed in a 5% HCl solution, and the durability performance was characterized through two complementary approaches: a physical evaluation based on monitoring the mass variation over the immersion period, and a microstructural investigation employing X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM) observations to identify the mineralogical and morphological changes occurring within the cementitious matrix as a result of acid-induced deterioration.

3.6.1. Mass variation

The mass variation results of all sand concrete compositions after 90 days of immersion in the HCl acid solution are presented in Fig. 12.

The temporal evolution of mass loss reveals a continuous and progressive degradation pattern for all tested compositions throughout the entire immersion period, from the first week up to 90 days, with no stabilization observed, indicating that the acid attack is an ongoing and persistent process that progressively deteriorates the cementitious matrix over time. This observation is consistent with findings reported in the literature, where prolonged HCl exposure was shown to cause continuous mass loss in cementitious materials due to the sustained dissolution of hydration products (Huang et al. 2005).

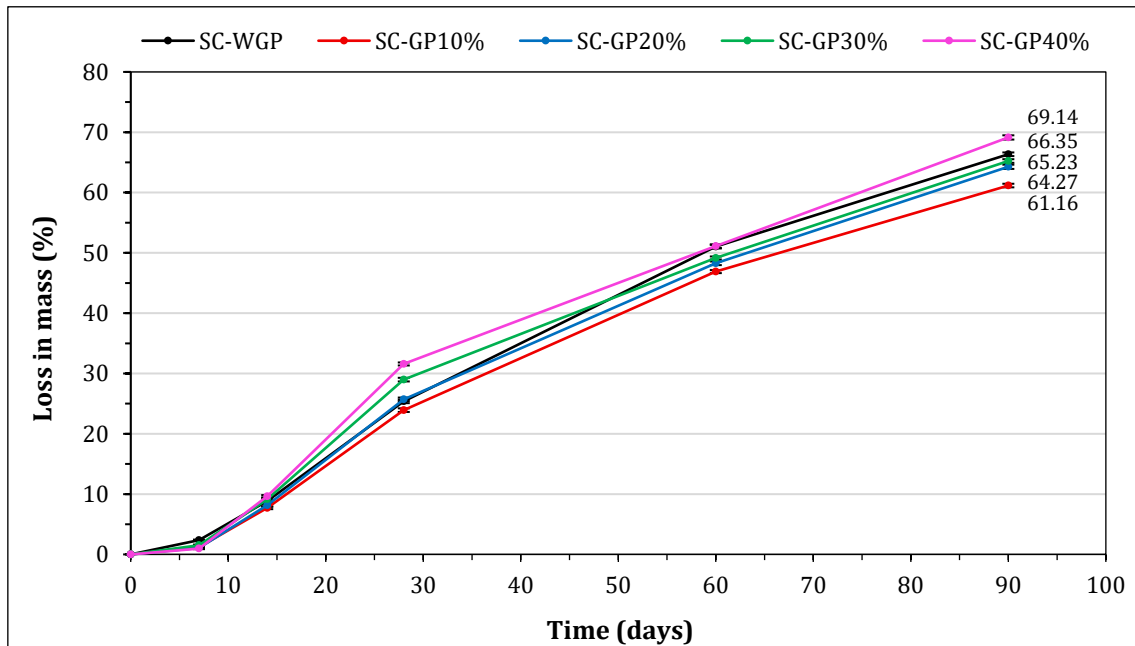


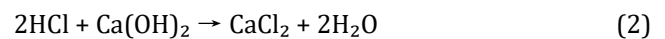
Fig. 12. Evolution of mass changes of the studied concretes with immersion time in acid solution.

At 90 days, the mass loss values for all compositions were notably high, ranging from 61.16% to 69.14%, reflecting the severe aggressiveness of the 5% HCl solution on the sand concrete matrix. The reference mix (SC-WGP) recorded a mass loss of 66.35%, while the incorporation of glass powder at 10%, 20%, and 30% reduced this value to 61.16%, 64.27%, and 65.23%, respectively, corresponding to reductions of approximately 7.82%, 3.13%, and 1.69% relative to the reference mix. Among all tested compositions, the SC-GP10% mix demonstrated the highest resistance to acid-induced mass loss, achieving the lowest value of 61.16%. This improved performance can be attributed to the effective pozzolanic reaction at this dosage, which produces additional C-S-H gel that densifies the microstructure and reduces the permeability of the matrix, thereby decelerating the rate of acid penetration into the inner layers of the concrete. Salim and Mosaberpanah (2021) reported a comparable improvement in acid resistance at low glass powder replacement levels, attributing it to the enhanced pore refinement that limits the ingress of aggressive agents into the cementitious matrix. The SC-GP20% and SC-GP30% compositions also exhibited improved acid resistance compared to the reference, although the beneficial effect diminished progressively with increasing GP content, suggesting that the pore-refining capacity of the pozzolanic reaction weakens as the cement content decreases.

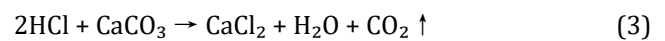
However, a critical reversal in this trend was observed at 40% GP, where the mass loss increased to 69.14%, exceeding the reference mix by 4.21%. This finding is particularly noteworthy as it demonstrates that the SC-GP40% composition is the only mix that performed worse than the reference concrete under acid exposure. At this high replacement level, the severe dilution of the cementitious matrix results in a substantially reduced $\text{Ca}(\text{OH})_2$ content and an insufficiently densified microstructure with elevated porosity and enhanced pore connectivity, which accelerates the penetration of

the HCl solution into deeper regions of the concrete. Jain et al. (2020) observed a similar behavior, reporting that while glass powder incorporation at moderate levels improved the chemical resistance of concrete, excessive dosages compromised the matrix density and consequently reduced the overall acid resistance.

The deterioration mechanism governing the mass loss under HCl exposure involves two principal chemical reactions. The first reaction occurs between the hydrochloric acid and the calcium hydroxide ($\text{Ca}(\text{OH})_2$) present in the pore solution, as expressed in Eq. (2):



The second reaction involves the attack of HCl on the calcium carbonate (CaCO_3) present in the matrix, as expressed in Eq. (3):



Both reactions generate calcium chloride (CaCl_2), a highly soluble salt that crystallizes within the pore network of the concrete. The continuous formation and accumulation of this salt induces expansive internal stresses within the matrix, leading to the initiation and propagation of micro-cracks that progressively disintegrate the composite structure and cause material detachment (Barbhuiya and Kumala 2017). As the exposure duration increases, these cracks create preferential pathways that further facilitate the penetration and propagation of the acid solution into deeper regions of the cementitious matrix, creating a self-accelerating degradation cycle that amplifies the mass loss over time (Huang et al. 2005).

Therefore, the acid resistance results confirm that the glass powder effect on sand concrete durability is dosage-dependent and not uniformly beneficial. The incorporation of GP at 10%, 20%, and 30% improved acid resistance compared to the reference mix, with the best performance observed at 10% replacement. However, at

40% GP, the excessive cement replacement led to a net deterioration in acid resistance, with a mass loss exceeding even that of the reference concrete. This dual behavior reinforces the importance of limiting the glass powder replacement level to preserve both the matrix density and the chemical buffering capacity, and further confirms that 10% GP offers the most favorable balance between microstructural enhancement and acid durability for sand concrete.

3.6.2. Visual examination

The physical state of all sand concrete specimens after 90 days of exposure to the 5% HCl solution is documented in Fig. 13. A visual comparison between the acid-exposed specimens and the unexposed reference speci-

mens revealed several characteristic signs of deterioration common to all tested compositions. The most prominent feature observed was the formation of a brownish layer deposited on the external surfaces of all exposed specimens. This discoloration is attributed to the precipitation of calcium chloride (CaCl_2) crystals on the concrete surface, generated by the chemical reactions between HCl and the calcium-bearing phases (Ca(OH)_2 and CaCO_3) within the cementitious matrix, as previously reported by Ghrici et al. (2007) and Aoual-Benslafa et al. (2011) for cementitious materials exposed to similar acidic environments. Additionally, a noticeable deterioration was observed at the corners and edges of the specimens, which represent the most vulnerable zones due to their higher surface-to-volume ratio that exposes them to multi-directional acid penetration.



Fig. 13. Visual examination of concretes exposed to acid solution at 90 days.

Despite this visible degradation, the specimens generally retained their overall geometric integrity and surface texture, although a measurable dimensional reduction was observed. The reported dimensions represent the average values obtained from three specimens for each mixture after acid exposure, with the average final dimensions of approximately $30 \times 30 \times 145$ mm compared to the original $40 \times 40 \times 160$ mm. This dimensional reduction corresponds to an approximately 43.75% decrease in the cross-sectional area and an approximately 49% reduction in specimen volume, quantitatively confirming the severity of the acid-induced material dissolution over the 90-day exposure period. Siad et al. (2016) documented comparable physical deterioration patterns on the surfaces of concrete specimens containing glass powder after prolonged immersion in aggressive acid

solutions, confirming that surface erosion and material loss are inevitable consequences of acid exposure for all concrete compositions, although the extent of damage varies with the matrix density and pore structure.

3.6.3. X-ray diffraction (XRD) analysis

The XRD diffractograms of the surface samples collected from the sand concrete specimens after 90 days of exposure to a 5% HCl solution are presented in Figs. 14 and 15 for the reference concrete (SC-WGP) and the SC-GP40% mixture, respectively. The SC-GP40% specimen was selected as a representative glass-powder-modified concrete because all glass-powder mixtures exhibited essentially the same crystalline phases after acid exposure, with only slight variations in peak intensities.

Therefore, presenting a single representative diffractogram is sufficient to illustrate the mineralogical characteristics of the glass-powder-modified concretes and to

facilitate comparison with the reference concrete in order to evaluate the influence of glass powder on the mineralogical evolution under hydrochloric acid attack.

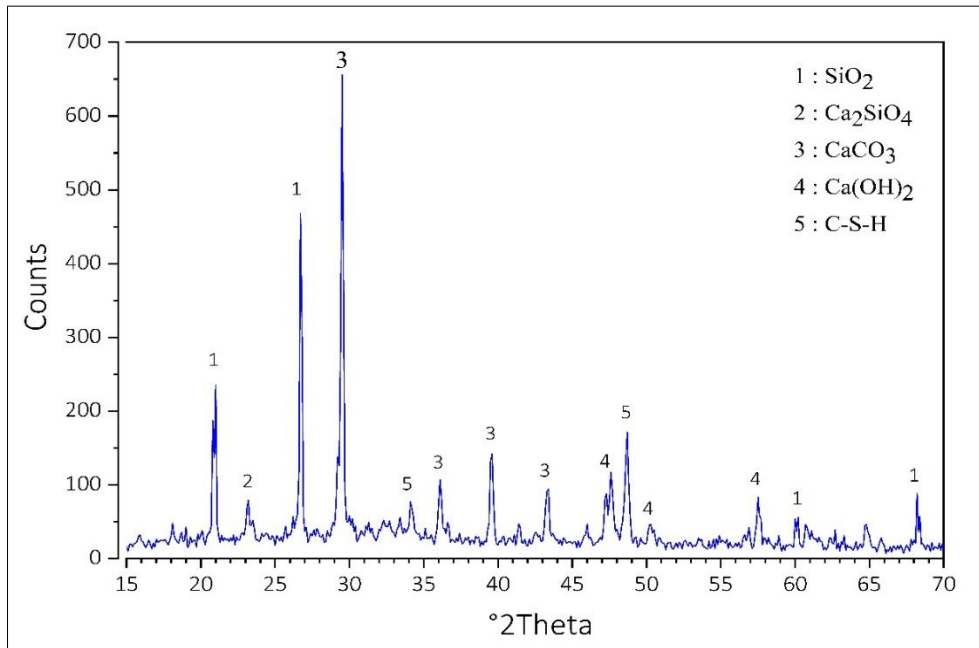


Fig. 14. X-ray diffraction analysis of the control concrete (SC-WGP) after hydrochloric acid attack.

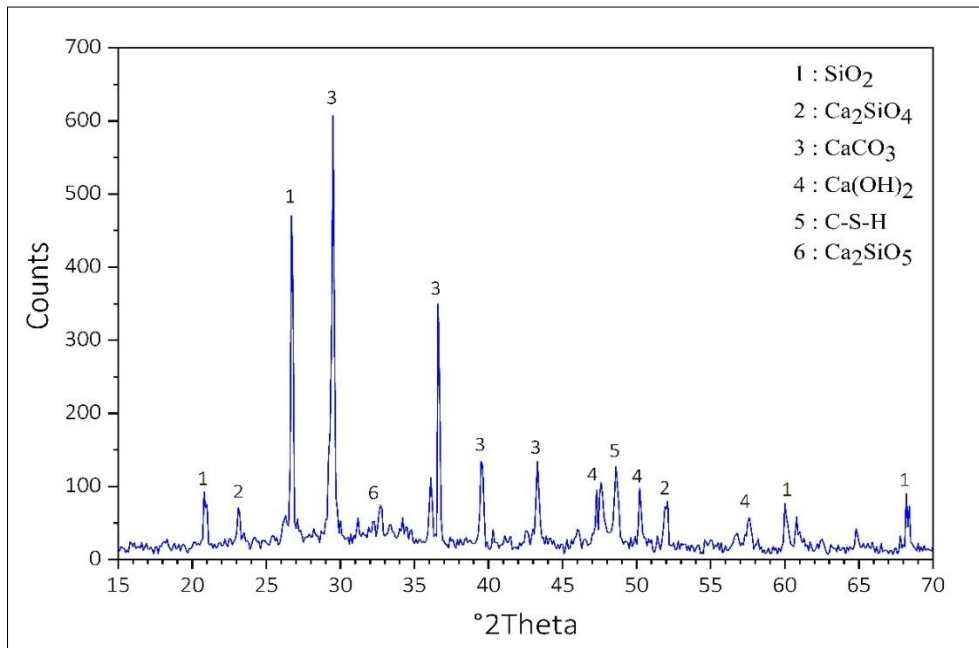


Fig. 15. X-ray diffraction analysis of concrete containing glass powder (SC-GP40%) after hydrochloric acid attack.

The mineralogical analysis of the reference mix (Fig. 14) identified the following crystalline phases: quartz (SiO_2), originating from the siliceous sand aggregate; dicalcium silicate (Ca_2SiO_4), corresponding to residual unhydrated cement; calcium carbonate (CaCO_3), associated with the limestone filler and its reaction products; portlandite ($\text{Ca}(\text{OH})_2$), the principal hydration product of cement; and calcium silicate hydrate (C-S-H), the main binding phase of the cementitious matrix.

The diffractogram of the SC-GP40% specimen (Fig.

15) revealed the same crystalline phases identified in the reference mix, with the notable detection of an additional calcium silicate phase (Ca_2SiO_5). The exclusive presence of this supplementary phase in the glass-powder-modified specimen provides direct mineralogical evidence of the pozzolanic reaction between the amorphous silica content of the glass powder and the available calcium hydroxide, leading to the formation of additional calcium silicate compounds that contribute to densifying the cementitious matrix and refining the pore structure.

Furthermore, the detection of CaCO_3 and Ca(OH)_2 peaks in both diffractograms, despite the prolonged acid exposure, indicates that the acid attack did not completely consume these calcium-bearing phases, suggesting that remnants of these compounds persisted within the inner regions of the specimens where the acid penetration was limited. Nevertheless, the partial dissolution of Ca(OH)_2 and CaCO_3 through their reaction with HCl, as described in Eqs. (2) and (3), remains the primary mechanism responsible for the mass loss and structural degradation observed across all tested compositions.

3.6.4. Scanning electron microscopy (SEM) analysis

The microstructural characteristics of the SC-GP10% sand concrete specimens before and after 90 days of exposure to a 5% HCl solution were examined using scanning electron microscopy (SEM), and the representative micrographs are presented in Figs. 16 and 17, respectively. The analyzed samples were extracted from the surface region of the specimens, which was directly exposed to the acid solution and therefore represented the most severely deteriorated zone.

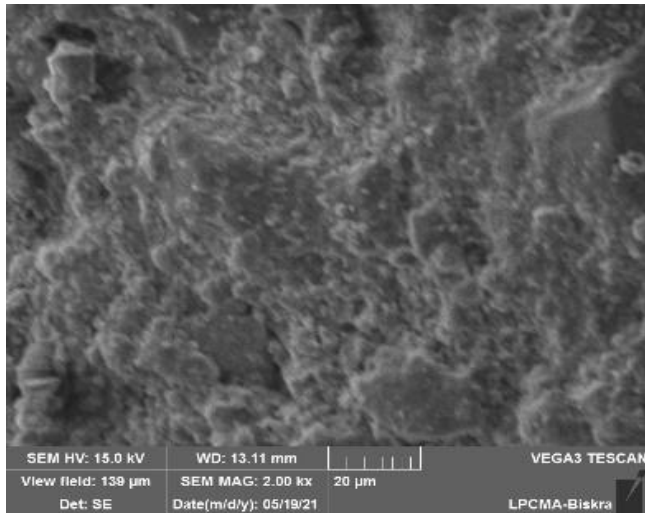


Fig. 16. SEM micrograph of the SC-GP10% specimen before exposure to the 5% HCl solution (after 28 days of curing), showing the surface region (magnification $\times 2000$).

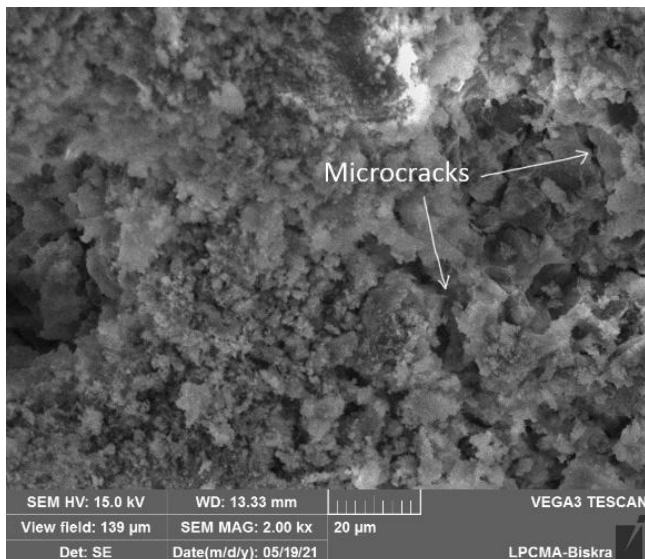
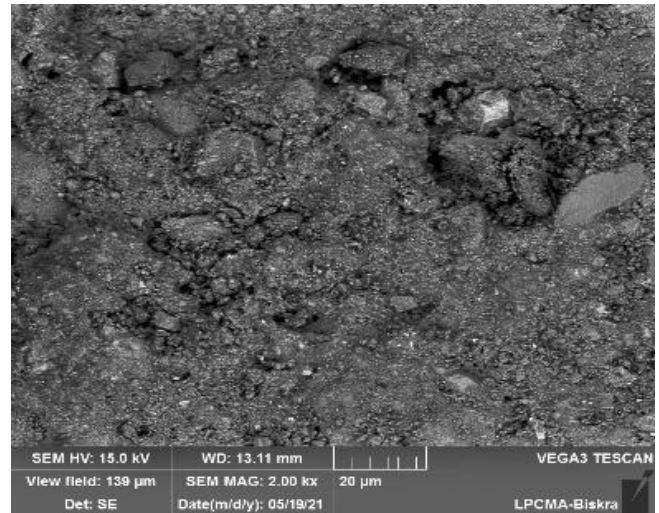
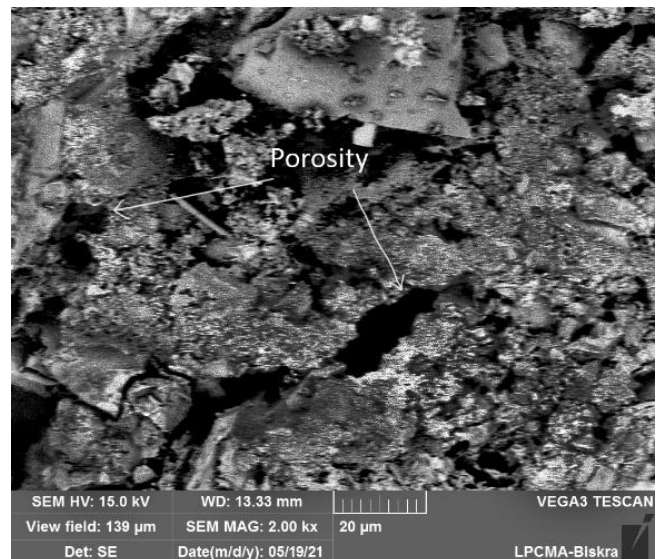


Fig. 17. SEM micrograph of the SC-GP10% specimen after 90 days of exposure to the 5% HCl solution, showing the surface region (magnification $\times 2000$).



The SC-GP10% mixture was selected as a representative glass-powder-modified concrete because all mixtures containing glass powder exhibited similar surface deterioration and comparable microstructural features after acid exposure, with only minor differences in the extent of damage. Therefore, the selected SEM micrographs are representative of the microstructural re-

sponse of the glass-powder-modified concretes under hydrochloric acid attack. The SEM micrograph of the SC-GP10% specimen before acid exposure (Fig. 16) reveals a relatively dense and compact cementitious matrix, characterized by a well-developed microstructure with identifiable C-S-H gel phases and a coherent interfacial transition zone (ITZ) between the cement paste and the

sand grains. The overall morphology indicates adequate hydration and satisfactory pore filling under normal curing conditions.

In contrast, the SEM micrograph of the same SC-GP10% specimen after 90 days of immersion in the 5% HCl solution (Fig. 17) reveals pronounced microstructural degradation. The exposed surface exhibits a considerably more porous and disrupted matrix, with the formation of numerous micro-cracks and an increase in the volume and size of voids compared with the specimen before acid exposure. This deterioration is attributed to the progressive dissolution of the calcium-bearing hydration products, primarily $\text{Ca}(\text{OH})_2$ and CaCO_3 , through their chemical reaction with HCl, as described in Eqs. (2) and (3). The dissolution of these phases creates additional void spaces within the matrix, while the crystallization of the reaction product CaCl_2 within the existing pores generates expansive internal stresses that initiate and propagate micro-cracks, further weakening the structural integrity of the cementitious matrix.

4. Conclusions

This study investigated the influence of glass powder incorporation at varying replacement levels (0%, 10%, 20%, 30%, and 40%) on the durability properties of sand concrete, including water absorption, capillary absorption, accelerated carbonation, freeze-thaw resistance, wetting-drying resistance, and resistance to hydrochloric acid attack. The experimental findings revealed that the effect of glass powder on sand concrete durability is dosage-dependent and not uniformly beneficial, with both favorable and unfavorable trends observed depending on the property considered and the replacement level adopted. The principal conclusions drawn from this investigation are summarized as follows:

- The incorporation of glass powder adversely affected both the total water absorption and capillary absorption of sand concrete at all replacement levels. The total immersion absorption increased from 6.24% for the reference mix to 7.23% for the 40% GP mix (an increase of 15.87%). The cumulative capillary water absorption after 24 hours increased from 7.68 kg/m² for the reference mixture to 12.76 kg/m² for the SC-GP40% mixture, corresponding to an increase of approximately 66.1%. This progressive deterioration in transport properties represents a notable limitation of glass powder incorporation, particularly at dosages exceeding 20%, and should be carefully considered in the design of sand concrete intended for water-exposed environments.
- Regarding accelerated carbonation resistance, the 10% GP mix achieved the shallowest carbonation depth of 5.49 mm at 28 days, representing a reduction of 15.41% compared to the reference mix (6.49 mm). However, higher replacement levels led to a pronounced increase in carbonation depth, reaching 13.68 mm at 40% GP (an increase of 110.79%), due to the combined effect of reduced $\text{Ca}(\text{OH})_2$ availability and increased matrix porosity.
- Under freeze-thaw cycling, the 10% GP mix exhibited the lowest compressive strength loss of 2.89%, while higher GP dosages led to progressively greater strength deterioration, reaching 6.13% at 40% GP. Conversely, mass loss decreased consistently with increasing GP content, with the 40% GP mix recording the lowest mass loss of 1.47%. A similar divergence between strength loss and mass loss indicators was observed under wetting-drying conditions, where the 10% GP mix achieved the lowest strength loss of 3.41% and was the only composition that simultaneously improved both performance indicators relative to the reference mix.
- The acid resistance results demonstrated that glass powder incorporation at 10%, 20%, and 30% improved the resistance of sand concrete to HCl attack, with the 10% GP mix recording the lowest mass loss of 61.16% after 90 days. However, the 40% GP mix exhibited a mass loss of 69.14%, exceeding even the reference mix (66.35%), confirming that excessive glass powder replacement compromises the chemical resistance of the matrix.
- SEM analyses revealed that the acid-exposed specimens exhibited pronounced microstructural degradation, characterized by increased porosity and micro-crack propagation resulting from the dissolution of calcium-bearing phases and the crystallization of CaCl_2 within the pore network. XRD analysis confirmed these observations and further identified an additional calcium silicate phase (Ca_2SiO_5) exclusively in the glass-powder-containing specimens, suggesting that the observed phase assemblage may be associated with reactions involving the glass powder; however, further verification is required to confirm the occurrence and extent of the pozzolanic reaction. This additional phase formation may contribute to matrix densification and could partly explain the enhanced acid resistance observed at low GP replacement levels.

Overall, this study demonstrates that 10% glass powder represents the optimal replacement level for sand concrete durability, not because it is uniformly superior under every criterion, but because it offers the most favorable compromise between mechanical integrity, carbonation resistance, cyclic durability, and acid resistance, with only a moderate and acceptable increase in absorption properties. This behavior can be attributed to the balance between the beneficial pozzolanic contribution of glass powder at moderate replacement levels and the adverse dilution effect occurring at higher dosages. At 10% GP, the pozzolanic reaction promotes the formation of additional calcium silicate hydrate (C-S-H) phases, contributing to matrix refinement and reducing the penetration of aggressive agents. In contrast, excessive glass powder incorporation reduces the available cementitious phase and calcium hydroxide content, limiting hydration and pozzolanic reactions and resulting in a less compact microstructure with increased pore connectivity. Consequently, the durability performance of sand concrete progressively declines at higher GP replacement levels, confirming the existence of an optimum glass powder content beyond which the negative

effects outweigh the beneficial contributions. These findings provide practical guidelines for the valorization of glass waste in sand concrete production. Future research should investigate the long-term natural carbonation behavior over extended exposure periods, evaluate the performance under combined aggressive environments, and explore the potential use of glass powder in conjunction with other supplementary cementitious materials to mitigate the observed increase in absorption properties.

Acknowledgements

The authors would like to thank the General Directorate of Scientific Research and Technological Development of Algeria (DGRSDT) for their support and contribution to this study.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- Adesina A, Das S (2020). Influence of glass powder on the durability properties of engineered cementitious composites. *Construction and Building Materials*, 242, 118199.
- Aly M, Hashmi MSJ, Olabi AG, Messeiry M, Abadir EF, Hussain AI (2012). Effect of colloidal nano-silica on the mechanical and physical behaviour of waste-glass cement mortar. *Materials & Design*, 33, 127-135.
- Ammari MS, Bederina M, Belhadj B, Merrah A (2020a). Effect of steel fibers on the durability properties of sand concrete with barley straws. *Construction and Building Materials*, 264, 120689.
- Ammari MS, Belhadj B, Bederina M, Ferhat A, Quéneudec M (2020b). Contribution of hybrid fibers on the improvement of sand concrete properties: barley straws treated with hot water and steel fibers. *Construction and Building Materials*, 233, 117374.
- Ammari MS, Bederina M, Belhadj B, Quéneudec M (2021). Effect of barley straw treatments on desiccation shrinkage and thermal properties of lightweight sand concrete. *Algerian Journal of Environmental Science and Technology*, 7(3), 2037-2044.
- Ammari MS, Tobchi MB, Amrani Y, Mim A, Bederina M, Ferhat A (2023). Influence of glass powder incorporation on the physical-mechanical properties of sand concrete. *World Journal of Engineering*, 20(2), 314-324.
- Aoual-Benslafa FK, Maarouf H, Semcha A, Mekerta B (2011). Durabilité des mortiers à base de sédiments de dragage du port d'Oran. In: *Conférence Méditerranéenne Côtière et Maritime*, Tanger, Morocco, pp. 195-198.
- ASTM C267-20 (2020). *Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymer Concretes*. ASTM International, West Conshohocken, PA, USA.
- ASTM C666/C666M-15 (2015). *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*. ASTM International, West Conshohocken, PA, USA.
- ASTM D559/D559M-15 (2015). *Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures*. ASTM International, West Conshohocken, PA, USA.
- ASTM D560/D560M-16 (2016). *Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures*. ASTM International, West Conshohocken, PA, USA.
- Barbhuiya S, Kumala D (2017). Behaviour of a sustainable concrete in acidic environment. *Sustainability*, 9(9), 1556.
- Bassuoni MT, Nehdi ML (2007). Resistance of self-consolidating concrete to sulfuric acid attack with consecutive pH reduction. *Cement and Concrete Research*, 37(7), 1070-1084.
- Bederina M, Khenfer MM, Dheilily RM, Quéneudec M (2005). Reuse of local sand: effect of limestone filler proportion on the rheological and mechanical properties of different sand concretes. *Cement and Concrete Research*, 35(6), 1172-1179.
- Bederina M, Belhadj B, Ammari MS, Gouilleux A, Makhloufi Z, Montreilay N, Quéneudec M (2016). Improvement of the properties of a sand concrete containing barley straws - treatment of the barley straws. *Construction and Building Materials*, 115, 464-477.
- Bulut HA (2024). A different approach for green concrete production: determination of the effect of e-waste and waste rubber powder on durability properties of concrete. *Challenge Journal of Concrete Research Letters*, 15(3), 69-81.
- Chauvin J, Grimaldi G (1988). Les bétons de sable. *Bulletin de Liaison des Laboratoires des Ponts et Chaussées*, 157, 9-15.
- Chen G, Lee H, Young KL, Yue PL, Wong A, Tao T, Choi KK (2002). Glass recycling in cement production-an innovative approach. *Waste Management*, 22(7), 747-753.
- EN 934-2:2009+A1:2012 (2012). *Admixtures for Concrete, Mortar and Grout - Part 2: Concrete Admixtures - Definitions, Requirements, Conformity, Marking and Labelling*. European Committee for Standardization, Brussels, Belgium.
- Ghrici M, Kenai S, Said-Mansour M (2007). Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements. *Cement and Concrete Composites*, 29(7), 542-549.
- Huang P, Bao Y, Yao Y (2005). Influence of HCl corrosion on the mechanical properties of concrete. *Cement and Concrete Research*, 35(3), 584-589.
- Idir R, Cyr M, Tagnit-Hamou A (2010). Use of fine glass as ASR inhibitor in glass aggregate mortars. *Construction and Building Materials*, 24(7), 1309-1312.
- Idir R, Cyr M, Tagnit-Hamou A (2011). Potential pozzolanicity of glass cullet fines and aggregates. *Annales du Bâtiment et des Travaux Publics*, 1, 28-34.
- Islam GS, Rahman M, Kazi N (2017). Waste glass powder as partial replacement of cement for sustainable concrete practice. *International Journal of Sustainable Built Environment*, 6(1), 37-44.
- Jain JA, Neithalath N (2010). Chloride transport in fly ash and glass powder modified concretes-influence of test methods on microstructure. *Cement and Concrete Composites*, 32(2), 148-156.
- Jain KL, Sancheti G, Gupta LK (2020). Durability performance of waste granite and glass powder added concrete. *Construction and Building Materials*, 252, 119075.
- Letelier V, Henríquez-Jara BI, Manosalva M, Parodi C, Ortega JM (2019). Use of waste glass as a replacement for raw materials in mortars with a lower environmental impact. *Energies*, 12(10), 1974.
- Mahmud H, Ahmed T, Islam MS (2025). Combined effect of rice husk ash and animal bone powder on strength and permeability of concrete. *Challenge Journal of Structural Mechanics*, 11(1), 1-13.
- Mathur VK (2006). Composite materials from local resources. *Construction and Building Materials*, 20(7), 470-477.
- Matos AM, Sousa-Coutinho J (2012). Durability of mortar using waste glass powder as cement replacement. *Construction and Building Materials*, 36, 205-215.

- Meyer C, Egosi N, Andela C (2001). Concrete with waste glass as aggregate. In: Dhir RK, Limbachiya MC, Dyer TD, editors. *Recycling and Reuse of Glass Cullet*. Thomas Telford, London, UK, pp. 179-188.
- NA 442 (2013). *Ciment - Composition, spécifications et critères de conformité des ciments courants*. Algerian Institute of Standardization (IANOR), Algiers, Algeria.
- Nassar RUD, Soroushian P (2012). Green and durable mortar produced with milled waste glass. *Magazine of Concrete Research*, 64(7), 605-615.
- NBN B 15-215 (1989). *Concrete Testing - Absorption of Water by Immersion*. Belgian Institute for Standardization, Brussels, Belgium.
- NF P18-598 (1991). *Aggregates - Sand Equivalent*. Association Française de Normalisation (AFNOR), Paris, France.
- Park SB, Lee BC, Kim JH (2004). Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and Concrete Research*, 34(12), 2181-2189.
- Rakshvir M, Barai SV (2006). Studies on recycled aggregates-based concrete. *Waste Management & Research*, 24(3), 225-233.
- Ramakrishnan K, Pugazhmani G, Sripragadeesh R, Muthu D, Venkatasubramanian C (2017). Experimental study on the mechanical and durability properties of concrete with waste glass powder and ground granulated blast furnace slag as supplementary cementitious materials. *Construction and Building Materials*, 156, 739-749.
- Salim MU, Mosaberpanah MA (2021). Mechanical and durability properties of high-performance mortar containing binary mixes of cenosphere and waste glass powder under different curing regimes. *Journal of Materials Research and Technology*, 13, 602-617.
- Sangha CM, Alani AM, Walden PJ (2004). Relative strength of green glass cullet concrete. *Magazine of Concrete Research*, 56(5), 293-297.
- Schwarz N, Cam H, Neithalath N (2008). Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash. *Cement and Concrete Composites*, 30(6), 486-496.
- Shao Y, Lefort T, Moras S, Rodriguez D (2000). Studies on concrete containing ground waste glass. *Cement and Concrete Research*, 30(1), 91-100.
- Shayan A, Xu A (2006). Performance of glass powder as a pozzolanic material in concrete: a field trial on concrete slabs. *Cement and Concrete Research*, 36(3), 457-468.
- Shi C, Wu Y, Riefler C, Wang H (2005). Characteristics and pozzolanic reactivity of glass powders. *Cement and Concrete Research*, 35(5), 987-993.
- Shi C, Zheng K (2007). A review on the use of waste glasses in the production of cement and concrete. *Resources, Conservation and Recycling*, 52(2), 234-247.
- Siad H, Lachemi M, Sahmaran M, Hossain KMA (2016). Effect of glass powder on sulfuric acid resistance of cementitious materials. *Construction and Building Materials*, 113, 163-173.
- Sobolev K, Türker P, Soboleva S, Iscioglu G (2007). Utilization of waste glass in ECO-cement: strength properties and microstructural observations. *Waste Management*, 27(7), 971-976.
- Taha B, Nounu G (2008). Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. *Construction and Building Materials*, 22(5), 713-720.
- Topcu IB, Canbaz M (2004). Properties of concrete containing waste glass. *Cement and Concrete Research*, 34(2), 267-274.
- Ünal S, Canbaz M (2025). Utilization of expired cement and aged roof tile powder in the production of sustainable geopolymers: mechanical and physical properties. *Challenge Journal of Structural Mechanics*, 11(2), 82-88.
- Ünal S, Canbaz M (2026). Development of a sustainable geopolymers structural element with waste glass powder: mechanical characteristics. *Challenge Journal of Structural Mechanics*, 12(1), 22-29.
- XP P18-458 (2008). *Tests for Hardened Concrete - Accelerated Carbonation Test - Measurement of the Thickness of Carbonated Concrete*. Association Française de Normalisation (AFNOR), Paris, France.
- Zeghichi L, Mezghiche B, Benghazi Z (2012). Contribution à l'étude des propriétés du ciment blanc et composé. *Communication Science & Technologie*, 10, 27-35.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

A field-exposure study on the effects of seasonal temperature variations and curing conditions on concrete strength and density

Rukiye Koçkar Tuğla ^{a,*}

^a Department of Construction, Abana Sabahat-Mesut Yılmaz Vocational School, Kastamonu University, 37970 Abana, Kastamonu, Türkiye

ABSTRACT

The performance of concrete is largely influenced by temperature and curing conditions during the early stages of hydration. While these effects have been extensively investigated under controlled laboratory conditions, field-based experimental evidence remains limited. Therefore, this study investigated the combined effects of seasonal temperature variations and curing conditions on the compressive strength of C30/37 concrete under field conditions. Concrete samples produced at a commercial ready-mix concrete plant were subjected to three curing conditions between March and July: water curing (WC), air curing (AC), and intermittent water curing (IWC). Monthly temperature data were recorded, and the effects of curing conditions and seasonal temperature variations on density and compressive strength were evaluated. The results showed that water curing produced the highest compressive strength (56.36 MPa) and density (2.40 g/cm³), whereas air curing yielded the lowest performance because of greater moisture loss. A negative correlation was observed between temperature and density ($R^2 = 0.87$ for AC and 0.81 for IWC), whereas only a weak relationship was found between density and compressive strength, indicating that density alone is not sufficient to explain concrete strength. In addition, variations in compressive strength under similar curing conditions suggest that early-age temperature exposure has a lasting influence on concrete performance. Overall, the results indicate that seasonal temperature variations influence concrete performance by altering hydration and moisture conditions. The findings provide field-based data that complement previous laboratory studies and contribute to a better understanding of concrete behaviour under practical construction-site conditions.

ARTICLE INFO

Article history:

Received – May 23, 2026
Revision requested – July 24, 2026
Revision received – July 28, 2026
Accepted – August 4, 2026

Keywords:

Curing conditions
Seasonal temperature variations
Compressive strength
Concrete density
Field exposure
Ready-mix concrete



This is an open access article distributed under the CC BY licence.

© 2026 by the Author.

Citation: Koçkar Tuğla R (2026). A field-exposure study on the effects of seasonal temperature variations and curing conditions on concrete strength and density. *Challenge Journal of Concrete Research Letters*, 17(3), 341–351.

1. Introduction

Concrete is a composite construction material generally produced using water, aggregate, and cement, and, where necessary, admixtures. It is initially workable and hardens after setting. Concrete is widely used worldwide due to its durability, workability, and cost-effectiveness (Barbhuiya et al. 2024; Emarah et al. 2025; Haigh and Ameri Sianaki 2025). The mechanical performance of concrete, particularly its compressive strength, is markedly influenced by curing conditions, environmental fac-

tors, and temperature variations (Barbhuiya et al. 2024; Haigh and Ameri Sianaki 2025; Chu et al. 2024; Lin et al. 2023). In addition, previous studies have shown that mixture composition, curing history, and production conditions also contribute to concrete performance (Wang et al. 2023a; Mohe et al. 2022; Mostofinejad et al. 2016; Akeed et al. 2022).

Curing conditions play a decisive role in the strength and durability of concrete (Haigh and Ameri Sianaki 2025; Xu et al. 2023). Proper curing reduces shrinkage and cracking by providing the moisture necessary for hy-

* Corresponding author. E-mail address: rkockar@kastamonu.edu.tr (R. Koçkar Tuğla)

dration (Haigh and Ameri Sianaki 2025; Chu et al. 2024). Traditional curing techniques primarily encompass practices such as water and air curing (Haigh and Ameri Sianaki 2025), which have long been utilized as conventional approaches to maintain the moisture levels necessary for hydration and strength development (Başyigit et al. 2011). In addition to these standard methods, advanced technologies such as steam and autoclave curing are used to significantly accelerate hydration (Xu et al. 2023). Furthermore, recent innovations have introduced high-efficiency thermal regimes, including microwave and electrical curing, to the precast industry (Dong et al. 2024). These specialised modern regimes, which often include dry-hot, steam and combined curing methods, are particularly effective for optimising the microstructure of high-performance construction materials (Wang et al. 2023a; Wang et al. 2023b).

Water curing is one of the most effective methods as it allows hydration to continue by maintaining moisture within the concrete (Emarah et al. 2025; Haigh and Ameri Sianaki 2025; Neville 2011). In contrast, with air curing, moisture loss increases, particularly under high-temperature conditions, leading to a loss of strength (Haigh and Ameri Sianaki 2025; Başyigit et al. 2011). Periodic curing (controlled moisture and periodic watering), however, lies between these two curing conditions, and partial moisture loss may occur (Emarah et al. 2025).

Cement hydration is highly sensitive to ambient and curing temperatures; indeed, the rate of hydration reactions is primarily controlled by temperature (Chu et al. 2024; Wang et al. 2023a; Kiernożycki and Błyszko 2021). At low temperatures, hydration reactions slow down considerably; this leads in particular to a delay in strength development during the early stages and the formation of a weaker or looser microstructure (Chu et al. 2024; Lin et al. 2023; Xu et al. 2023; Wang et al. 2023b). For example, when the casting temperature falls below the freezing point, the expansion of water within the concrete as it forms ice crystals (ice expansion pressure) can damage the internal structure of the cement paste whilst it is still in the setting stage, thereby reducing its ultimate strength (Wang et al. 2023a; Shi et al. 2019). Conversely, whilst high temperatures accelerate hydration thereby providing high early-age strength, increased evaporation and uncontrolled moisture loss result in a more porous and coarse void distribution within the concrete's internal structure; this situation adversely affects the mechanical properties and durability in the long term (Haigh and Ameri Sianaki 2025; Chu et al. 2024; Wang et al. 2023b; Dong et al. 2024). Consequently, both the slowing of hydration caused by low temperatures and the structural irregularities and porosity triggered by high temperatures can adversely affect concrete performance (Haigh and Ameri Sianaki 2025; Lin et al. 2023; Xu et al. 2023; Başyigit et al. 2011).

Density is an important indicator of the internal structure and quality of concrete (Emarah et al. 2025). High density generally implies a compact structure containing fewer voids, and this is associated with higher mechanical performance (Barbhuiya et al. 2024; Emarah et al. 2025; Haigh and Ameri Sianaki 2025). However, the relationship between density and compressive strength is

not always direct; it is influenced by numerous parameters, such as curing conditions, temperature history, and degree of hydration (Emarah et al. 2025; Lin et al. 2023; Xu et al. 2023).

Much of the research on the effects of temperature and curing on concrete is limited to laboratory conditions, where variables can be precisely controlled (Chu et al. 2024; Wang et al. 2023a). However, in field conditions, concrete is exposed to various seasonal and regional factors, particularly from the moment of pouring through the curing period. These uncontrolled environmental factors can directly affect the internal homogeneity, hydration process and safety of the concrete (Wang et al. 2023a; Başyigit et al. 2011). Particularly in high-altitude regions or areas subject to substantial temperature fluctuations, concrete is exposed to accelerated moisture loss and temperature fluctuations during its early stages of curing. This can lead to a phenomenon known as 'ageing' in the microstructure or to permanent damage to the pore structure, thereby markedly reducing its mechanical performance (Chu et al. 2024; Huang et al. 2025). Although several studies have investigated the effects of temperature and curing under laboratory conditions, relatively few have evaluated concrete performance under actual field conditions (Chu et al. 2024; Wang et al. 2023a). Existing field studies have mainly focused on specific harsh environmental conditions, such as high-altitude exposure (Chu et al. 2024), whereas the combined influence of seasonal temperature variations and practical curing conditions under typical construction-site environments remains insufficiently investigated.

On construction sites, the neglect of concrete curing during building inspections, together with seasonal temperature variations, is a critical factor contributing to deviations from the concrete's design strength (Emarah et al. 2025; Kiernożycki and Błyszko 2021). According to the standard, the strength of properly produced and formed concrete will decrease by approximately 30–40% if it is not cured in accordance with the environmental conditions after reaching its initial strength (Başyigit et al. 2011). In particular, it is difficult to standardise the manual sprinkling method used under site conditions. However, this situation prevents the concrete's microstructure from improving. On construction sites, concrete samples inspected by building inspectors are stored in unsupervised locations, under unsuitable weather, and without ideal curing conditions (Başyigit et al. 2011; Yılmaz et al. 2019). As factors such as ambient temperature and humidity vary when construction inspectors take samples, considerable deviations from the concrete's actual performance are observed (Chu et al. 2024; Yılmaz et al. 2019).

A clear gap still exists in the literature between results obtained in laboratory conditions and the actual performance observed in field applications. In this study, unlike traditional laboratory studies, concrete samples were collected from a ready-mix concrete plant over 5 months and subjected to 3 different curing conditions. The concrete samples were evaluated at natural ambient temperatures and in the direct site environment. The primary objective of the study is to quantitatively demonstrate the combined effect of seasonal temperature variations and curing conditions on the compres-

sive strength and density of concrete under uncontrolled environmental conditions. Unlike previous field-exposure studies that focused on concrete performance under specific environmental scenarios, such as high-altitude exposure (Chu et al. 2024), the present study evaluates concrete produced at a commercial ready-mix concrete plant under naturally varying seasonal conditions. By monitoring concrete over five consecutive months under three practical curing conditions, the study provides field-exposure experimental evidence of the combined influence of seasonal temperature, curing condition, density, and compressive strength under typical construction-site conditions. The findings provide prac-

tical guidance for evaluating concrete quality under typical construction-site conditions and may help improve curing practices in construction.

2. Materials and Method

2.1. Materials

The type of cement used in this study was CEM II/A-M (V-L) 42,5 R. The chemical and physical characteristics of the cement, which comply with TS EN 197-1 (2012), are given in Tables 1 and 2, respectively.

Table 1. Chemical characteristics of cement.

	MgO (%)	SO ₃ (%)	Cl (%)	Na ₂ O (%)	K ₂ O (%)	Loss on ignition (%)	Undissolved residue (%)
Cement	1.98	3.07	0.01	0.24	0.76	9.18	1.67

Table 2. Physical characteristics of cement.

	Specific surface area* (cm ² /g)	Specific gravity (g/cm ³)	Fineness (32 micron) (%)	Fineness (40 micron) (%)	Initial set (minute)	Final set (minute)	Volumetric expansion (mm)
Cement	4004	3.04	7.8	4.2	211	292	1

*Blaine method

Crushed aggregate in three different sizes (0–5 mm, 5–11 mm and 11–22 mm) was used in the production of the concrete. The specific gravities of fine (0–5 mm) and coarse aggregates (5–11 mm and 11–22 mm) are 2.62 g/cm³ and 2.64 g/cm³; the water absorption values of the aggregates are 1.33%, 1.08%, and 0.86%, respectively. During concrete production, aggregate moisture was routinely monitored at the ready-mix concrete plant, and the mixing water was adjusted accordingly. The aggregate grading is shown in Fig. 1.

A commercial chemical admixture was used at a dosage of 1% by weight of cement. The technical properties of the chemical admixture, data taken from the

manufacturer's product data sheet, are presented in Table 3.

The target water/cement (w/c) ratio for all concrete mixtures was 0.53. However, during concrete production in July, an additional 5 L of water per m³ was added to maintain workability under elevated ambient temperatures. Consequently, the effective water/cement ratio of the July mixture increased from 0.53 to approximately 0.545. This modification should be considered when interpreting the July test results, as the increased water content may have influenced the mechanical properties in addition to the environmental exposure condition. Detailed mixture proportions are presented in Table 4.

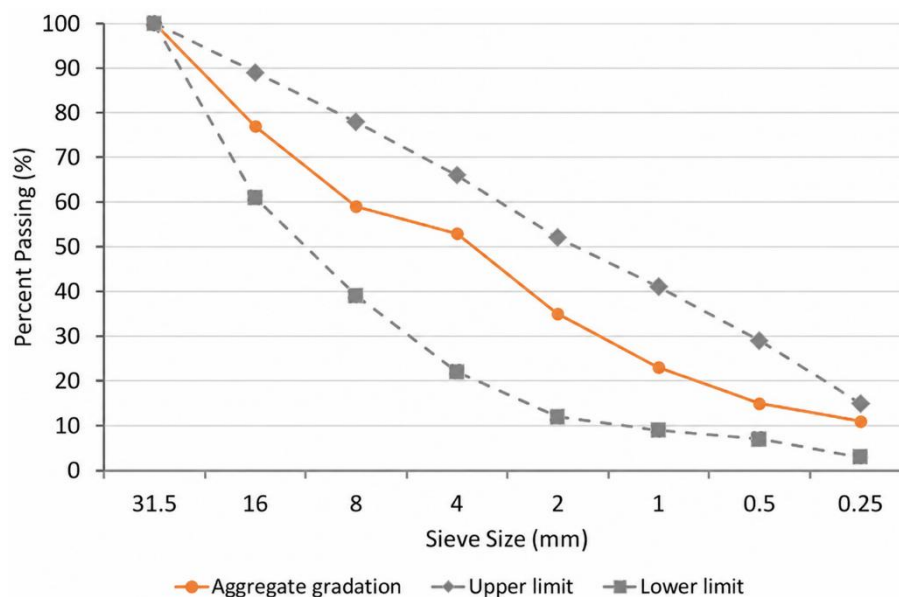


Fig. 1. Particle-size distribution of the combined aggregate, together with the specification limits.

Table 3. The technical properties of the chemical admixture (Sika Türkiye 2024).

Chemical admixture properties	Value
Admixture type	High-range water-reducing superplasticiser
Chemical base	Polycarboxylate-based
Standard classification	TS EN 934-2
Recommended dosage	0.8-1.5% by weight of cement
Density (20°C)	1.0602 g/cm ³
pH	4.82
Solid content	22.46%
Chloride content	0.0570%
Alkali content (Na ₂ O equivalent)	0.31%
Corrosion behaviour	No corrosion effect

Table 4. Mixing proportions and material amounts (kg/m³).

Mixture	Months	Cement	Sand	Crushed aggregate	Admixture	Water	W/C
The concrete samples	March-June	330	1006	830	3.3	175	0.530
	July	330	1006	830	3.3	180	0.545

2.2. Specimen preparation and curing conditions

The concrete mixes used in this study were prepared at a ready-mix concrete plant in Kastamonu. The batching, mixing, and production processes under real-world conditions were carefully executed to ensure precise composition and thorough homogenization of the concrete specimens at a ready-mix concrete plant (Fig. 2). The essential components of C30/37 concrete, including coarse crushed aggregate, sand, cement, a chemical admixture, and water, were systematically and automatically introduced into the mixer in accordance with the TS EN 206 +A2 standard. The mixing process followed a structured protocol to achieve a uniform, well-integrated mixture of all concretes each month. The concrete produced at the concrete plant was placed in 150 × 150 × 150 mm cube moulds in accordance with the TSE EN 12390-2 standard. The concrete in the formwork was compacted using a vibrating table to ensure a void-free and homogeneous structure. The concretes were placed in cube moulds under ambient conditions and demoulded after 24 hours; each specimen was then placed under the specified curing conditions. The concrete samples used in the study were produced over five periods in 2025—March, April, May, June, and July—to assess the effects of seasonal temperature variations. For each month, nine cube specimens were produced and divided into three different curing conditions (Fig. 3). Each curing group consisted of three specimens. The concrete specimens in each curing group were kept in the same place throughout 28 days. Compressive strength values are reported as the mean of three measurements.

To evaluate the variability and reliability of the experimental results, the standard deviation (SD) and coefficient of variation (CV) were calculated for each curing condition.

The different curing conditions used in this study:

- Water Curing (WC): The concrete samples were cured

by being fully immersed in water tanks under controlled conditions at approximately 20 ± 2°C for 28 days, in accordance with TS EN 12390-2. This method was considered the “reference curing condition”.

- Air Curing (AC): The concrete samples were stored in direct exposure to outdoor ambient conditions, without a moisture supply, and in fixed positions. They have been exposed to the normal weather conditions of the relevant month outdoors, including temperature, solar radiation, and wind, etc. This condition represented the actual environment on construction sites, which are typical conditions for construction.
- Intermittent Water Curing (IWC): The concrete samples were stored under natural ambient conditions and in fixed positions. Until every part of their surface was wet, they were sprayed with water (approx. 3 L) once daily in the evening, when there was no sun exposure. This method was chosen as a practical curing approach that can be easily implemented on a construction site.

The three curing methods were selected because they represent the most common curing conditions encountered during concrete production and quality control in construction practice in Türkiye. Water curing was used as the reference curing method, air curing represented the absence of curing under field conditions, and intermittent water curing simulated the manual water spraying practice commonly applied on construction sites.

All curing conditions were maintained for 28 days. Ambient air temperature (AT) data were recorded during the study period. However, relative humidity (RH) was not measured directly at the experimental site. RH values presented in this study were obtained from the Turkish State Meteorological Service database and used solely to describe the general environmental conditions during the testing period, March to July in 2025. Therefore, RH was not included in the quantitative regression analyses.



Fig. 2. Production of concrete samples in a ready-mix concrete plant.

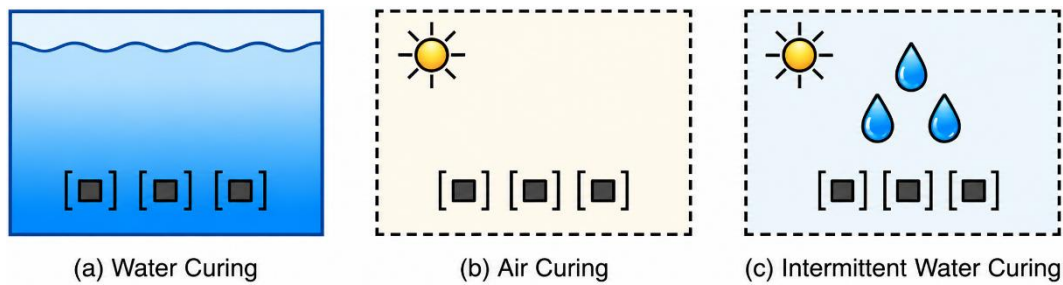


Fig. 3. The scheme of the different curing conditions.

2.3. Testing of fresh and hardened concrete

For each concrete sample, a slump test was carried out in accordance with TS EN 12350-2, and workability was checked to ensure consistency in the fresh concrete properties. The measured slump values were 20, 22, 23, 23 and 23 cm for March, April, May, June and July, respectively.

The density values were calculated at the age of 28 days using the specimen mass measured immediately before the compressive strength test. The apparent density was determined by dividing the specimen mass measured immediately before the compressive strength test by the nominal specimen volume.

At the end of the 28-day curing period, compressive strength tests were performed on all specimens in accordance with TS EN 12390-3. The tests were conducted on a calibrated hydraulic pressure press with a maximum capacity of 2000 kN (Fig. 4). The load was increased continuously at a constant rate until the specimen failed, and the maximum load was recorded. The compressive strength was calculated as the breaking load divided by the specimen's cross-sectional area. The average compressive strength and standard deviation values were determined for each curing group and casting period.

3. Results and Discussion

In this study, the compressive strength (CS) of concrete samples with a design CS of C30/37 was investigated under different curing conditions. The experimental data obtained have been analysed; compressive strength, density and ambient temperature conditions have been evaluated together. The parameters affecting concrete strength and their relationships are presented in detail in this section.

Concrete samples (AC and IWC) were exposed to outdoor curing conditions at the same location during March, April, May, June, and July. The recorded temperature data for each month are presented in Table 5. According to the first-day measurements, April was the coldest month, while July had the highest temperatures. Furthermore, the average temperature values calculated for 7-day and 28-day periods indicate a consistent increase from March to July, reflecting seasonal variations. The relative humidity in Kastamonu gradually decreases from approximately 70–75% in March to 55–60% in July, suggesting a higher potential for evaporation during the summer period. Since these RH values were obtained from meteorological records rather than direct field measurements, they are presented only to describe the general environmental conditions.



Fig. 4. The photograph of the compressive strength testing press.

Table 5. Variation of minimum ($T_{\min}$), maximum ($T_{\max}$), average temperatures (T_{avg}) ($^{\circ}\text{C}$) and relative humidity (RH) during the curing period.

Months	Curing period	First day for concrete			Average 7 day			Average 28-day			Relative humidity*
		$T_{\min}$	$T_{\max}$	T_{avg}	$T_{\min}$	$T_{\max}$	T_{avg}	$T_{\min}$	$T_{\max}$	T_{avg}	
March	28-day	2	13	7.5	-2.4	9.3	3.5	1.5	13	7.3	70–75
April	28-day	-1	8	3.5	3.7	10.7	7.2	2.9	17.8	10.4	65–70
May	28-day	8	25	16.5	6.7	20.7	13.7	7.5	23.1	15.3	65–70
June	28-day	7	23	15	10.1	27.1	18.6	13.3	30.7	22	60–65
July	28-day	21	37	29	19.0	35.1	27.1	18.9	34.7	26.8	55–60

*Data was taken from the Turkish State Meteorological Service.

The data on the weight, density and compressive strength of the concrete samples are presented in Table 6. The results show that curing conditions affect concrete performance. The variation of density values under different curing conditions is presented in Fig. 5. The results show that specimens subjected to water curing (WC) consistently exhibit higher density than those subjected to air curing (AC) or intermittent water curing (IWC). A general decrease in density with increasing temperature is observed, particularly under AC and IWC conditions. This behaviour is primarily attributed to increased evaporation and moisture loss under higher temperatures. Moisture loss limits the availability of water required for continued cement hydration and contributes to the formation of a less compact internal structure, particularly under insufficient curing conditions. However, a slight increase in density was observed for the AC specimens in July compared with June, despite the higher ambient temperature. This deviation may also be associated with the additional 5 L/m^3 of mixing water introduced in the July mixture, which slightly increased the effective water/cement ratio. Therefore, the July density values should be interpreted with caution, as they reflect the combined influence of environmental exposure and the slightly increased water/cement ratio. In contrast, water-cured specimens exhibited higher apparent density values. This may be attributed to both improved in-

ternal compactness resulting from continuous hydration and the higher moisture content of the specimens at the time of testing. Consequently, density changes observed under field conditions should be interpreted as the combined outcome of hydration progress, moisture condition at testing, and environmental exposure rather than solely as an indicator of internal compactness. These findings are in strong agreement with previous studies (Emarah et al. 2025; Haigh and Ameri Sianaki 2025; Chu et al. 2024; Başıyigit et al. 2011).

The compressive strength results under different curing conditions are shown in Fig. 6. The compressive strength of water-cured concrete was 56.36 MPa, and that of air-cured concrete was 53.22 MPa in April (Table 6). It is observed that the compressive strength data of the intermittent water curing (IWC) generally fall between the two types of curing (WC and AC). It is evident that water curing provides the highest strength values across all conditions, while air curing results in the lowest. A general decrease in strength is observed at higher temperatures, particularly under insufficient curing conditions. However, slight deviations are observed in March, where lower temperatures may have slowed hydration and delayed strength development (Fig. 6). These findings highlight the critical role of curing conditions in controlling strength development under varying environmental conditions.

Table 6. Data on the weight, density and compressive strength of concrete samples under different curing conditions by months.

Months	Water curing (WC)			Air curing (AC)			Intermittent water curing (IWC)		
	Weight (g)	Density (g/cm ³)	Compressive strength* (MPa)	Weight (g)	Density (g/cm ³)	Compressive strength* (MPa)	Weight (g)	Density (g/cm ³)	Compressive strength* (MPa)
March	8047	2.38	48.51±1.50	7926	2.35	37.10±0.36	7914	2.34	40.77±2.17
April	8107	2.40	56.36±1.90	7936	2.35	53.22±2.76	7905	2.34	52.06±1.57
May	7930	2.35	53.85±1.43	7851	2.33	50.16±1.87	7810	2.31	49.88±2.98
June	7822	2.32	47.36±1.62	7631	2.26	42.97±1.02	7604	2.25	44.19±1.84
July	7952	2.36	48.42±1.82	7671	2.27	42.82±1.93	7690	2.28	45.19±0.99

*Values are presented as mean ± standard deviation.

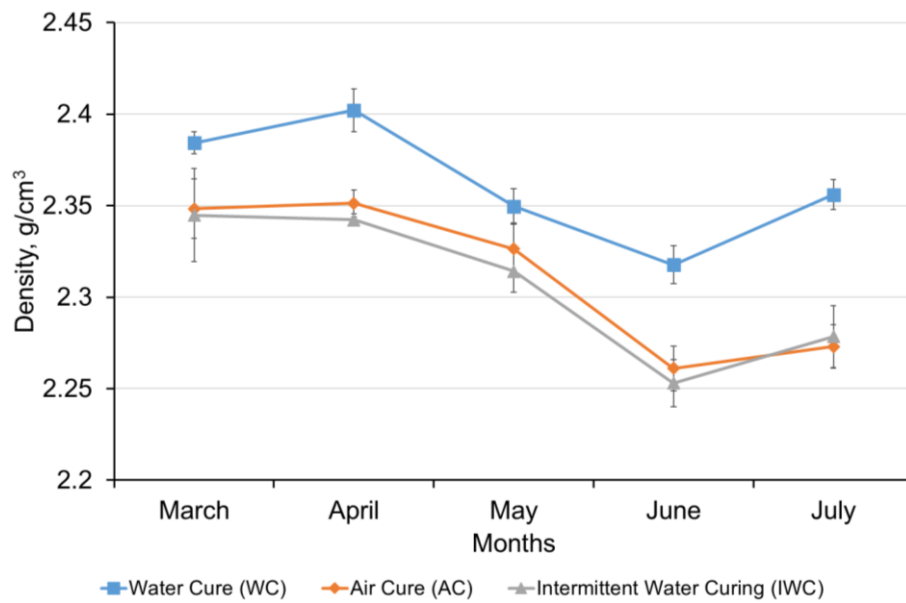


Fig. 5. Variation of density values under different curing conditions (WC, AC, and IWC) across months.

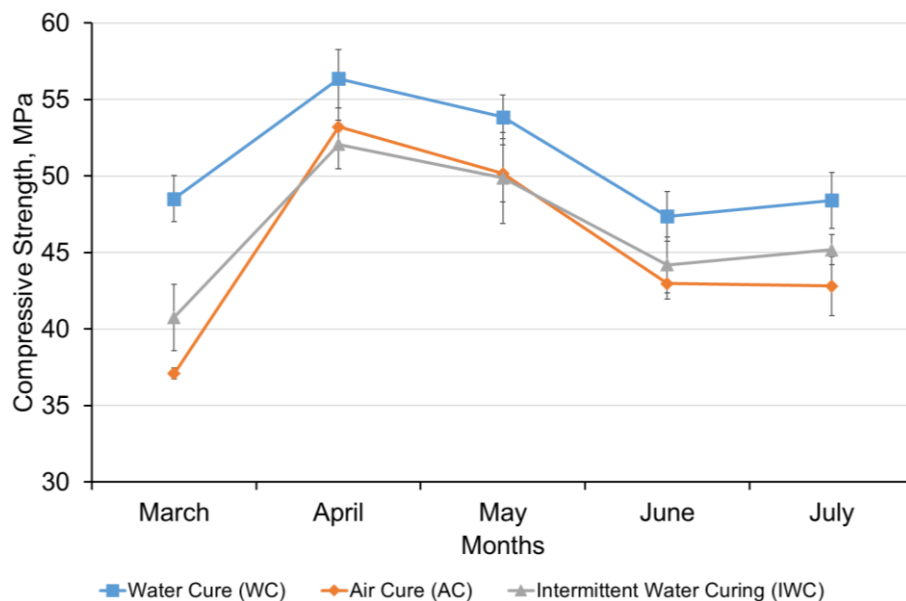


Fig. 6. Compressive strength variation of concrete samples under different curing conditions.

Since the WC specimens were cured under a constant water temperature ($20 \pm 2^\circ\text{C}$) throughout the study, only the AC and IWC specimens were considered when evaluating the relationship between ambient temperature and compressive strength (Fig. 7). The highest compressive strength values were observed under the average curing temperatures recorded in April (10.4°C) and May (15.3°C), whereas lower strengths were obtained at both lower and higher temperatures. The present results suggest that the moderate ambient temperatures recorded during April and May provided favorable conditions for compressive strength development, which is consistent with previous studies reporting improved hydration under moderate curing temperatures (Huang et al. 2025; Yilmaz et al. 2019). As expected, WC specimens consistently exhibited higher compressive strength than AC and

IWC specimens because continuous moisture availability allowed cement hydration to proceed uninterrupted and likely promoted a denser microstructure (Emarah et al. 2025). Lower compressive strength values were observed in March because the low ambient temperatures slowed the hydration process, whereas a partial increase was observed in July despite the elevated ambient temperatures (Fig. 7). The partial strength increase observed in July, despite the high temperatures, may be attributed to accelerated early-age hydration (Xu et al. 2023; Wang et al. 2023b). However, considering the increased evaporation and porosity associated with high temperatures, this trend may also have been influenced by early-age curing conditions and mixture parameters (Haigh and Ameri Sianaki 2025; Chu et al. 2024; Wang et al. 2023b).

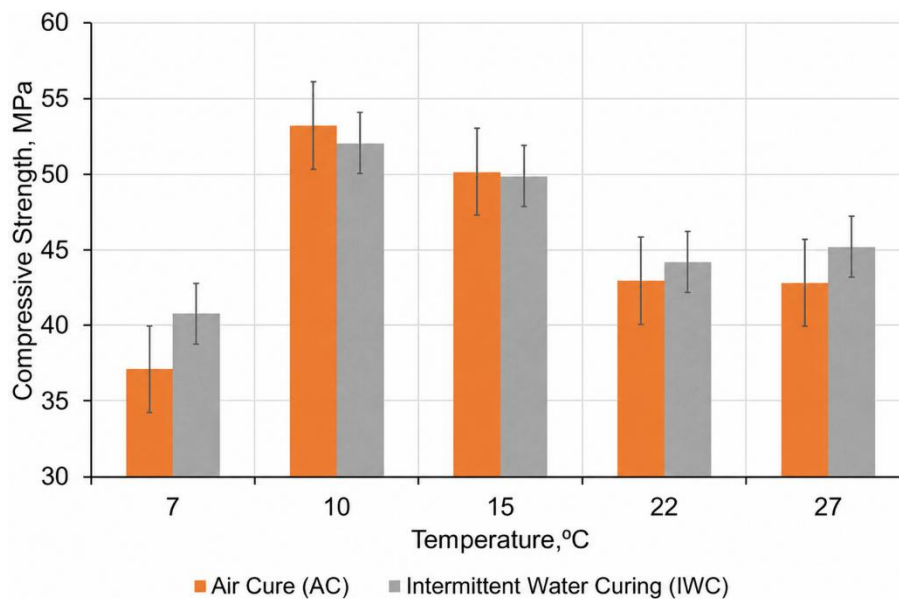


Fig. 7. Relationship between compressive strength and the measured average 28-day ambient temperature for air-cured (AC) and intermittent water-cured (IWC) specimens.

Although an additional 5 L of water per m^3 was introduced during concrete production in July to compensate for the increased water demand associated with elevated ambient temperatures, this amount represented only a minor fraction of the total mixing water. Moreover, the slump value measured in July (23 cm) was identical to those recorded in May and June, suggesting that the additional water mainly contributed to maintaining workability rather than substantially modifying the fresh concrete characteristics. The July results should be interpreted with caution because the additional 5 L of water increased the effective water/cement ratio from 0.53 to approximately 0.545. Consequently, the observed behaviour cannot be attributed solely to elevated ambient temperature and curing conditions. The modified mixture proportion may also have contributed to the measured density and compressive strength values. Therefore, the July results reflect the combined influence of environmental exposure and a slightly increased water/cement ratio.

The coefficients of variation obtained for the compressive strength results ranged from 0.98% to 5.98%,

indicating good consistency among replicate specimens. These relatively low values suggest that the observed differences in compressive strength are predominantly related to curing conditions and environmental exposure rather than experimental variability.

When the relationships among temperature, density, and compressive strength are considered together, it is evident that concrete behaviour is governed by a complex interaction mechanism.

To better understand the influence of temperature, a regression analysis was conducted between temperature and density. The results are presented in Fig. 8. Regression analysis indicated a negative relationship between temperature and density for AC ($R^2 = 0.8696$) and IWC ($R^2 = 0.8075$) (Fig. 8). These results suggest that temperature primarily affects concrete through increased evaporation and moisture loss.

In contrast, the relationship between density and compressive strength was found to be relatively weak. The relationship between density and compressive strength is shown in Fig. 9. Very low correlation coefficients were obtained for air curing ($R^2 = 0.0749$) and in-

termittent water curing ($R^2 = 0.0516$), while a relatively higher, yet still limited, relationship was observed for water curing ($R^2 = 0.3377$). These results suggest that the compressive strength of concrete cannot be explained solely by density and that factors such as curing conditions, ambient temperature, and water content also play important roles. In particular, the fact that different

strength results are obtained for specimens with similar density values indicates that concrete behaviour has a multi-parameter structure. These findings suggest that approaches based on a single parameter may be insufficient when evaluating concrete performance under field conditions, and that multiple parameters must be considered together.

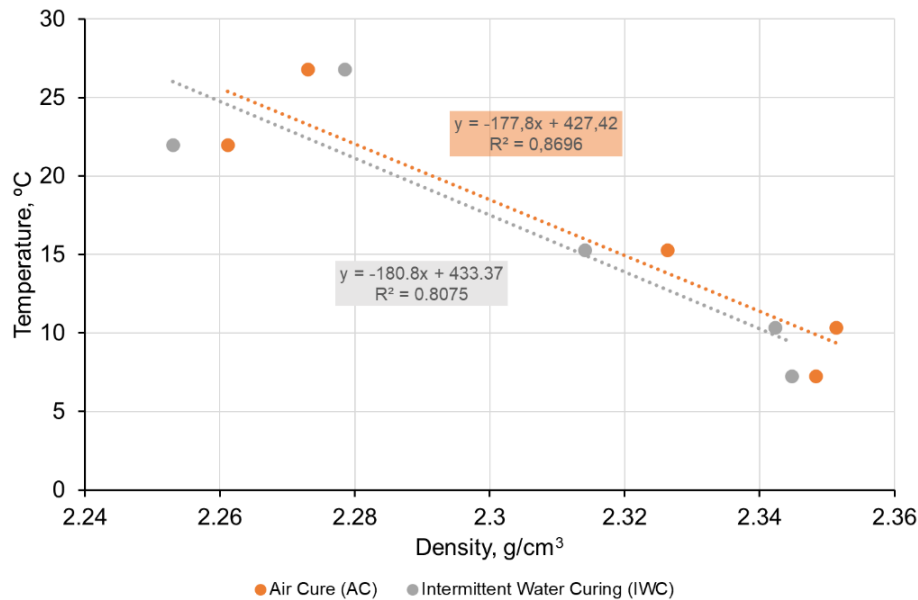


Fig. 8. Relationship between temperature and density for AC and IWC conditions.

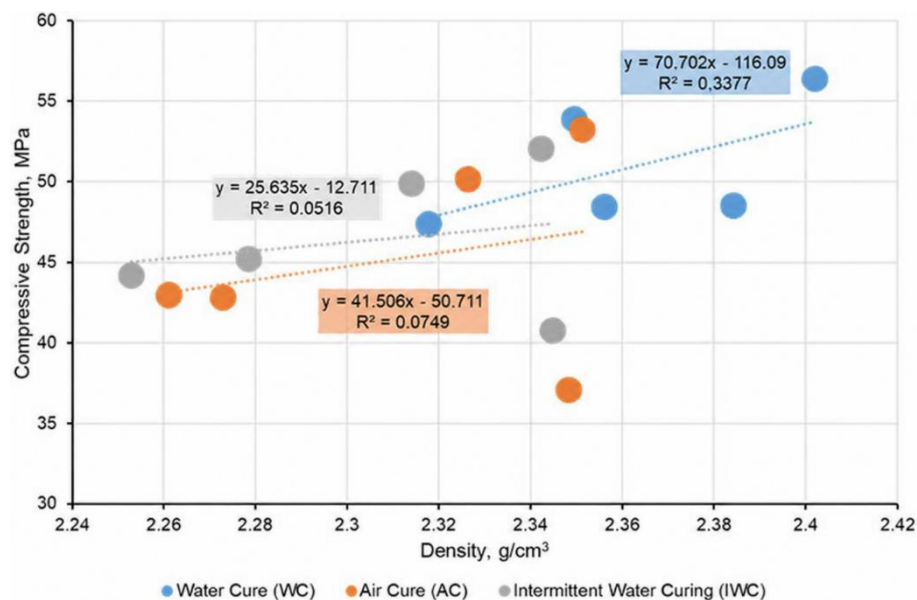


Fig. 9. Relationship between density and compressive strength under different curing conditions.

Overall, the findings demonstrate that the effect of temperature on concrete performance occurs through both direct and indirect mechanisms. Temperature alters the microstructure (represented by density) indirectly, while simultaneously influencing strength development directly through hydration kinetics and moisture loss. Furthermore, when temperature and compressive strength are considered together, a decrease in strength is observed at high temperatures, particularly when curing is insufficient. This indicates

that temperature not only affects density indirectly but also directly influences hydration and moisture loss, thereby affecting the development of strength. These results clearly indicate that concrete performance cannot be explained by a single parameter and that temperature, curing conditions, and microstructural characteristics must be evaluated together. This is particularly critical in field conditions, where the combined influence of these parameters governs concrete's overall behaviour.

4. Conclusions

This study investigated the combined effects of temperature, curing conditions, and density on the compressive strength of concrete under field conditions. Based on the experimental results, the following conclusions can be drawn:

- Curing conditions play a dominant role in concrete performance. Water curing (WC) consistently provided the highest compressive strength and density, while air curing (AC) yielded the lowest performance due to insufficient moisture retention.
- Ambient temperature substantially affects concrete behaviour. Low temperatures, as observed in March, reduced compressive strength due to slower hydration, whereas high temperatures increased moisture loss, negatively affecting both density and strength.
- The comparison between the March and April results suggests that the average temperature during the 28-day curing period may have had a greater influence on compressive strength development than the temperature on the day of casting under the conditions of the present study.
- A negative correlation was found between temperature and density ($R^2 = 0.8696$ for AC and $R^2 = 0.8075$ for IWC), indicating that increasing temperature leads to increased evaporation and reduced density.
- The relationship between density and compressive strength was found to be weak (low R^2 values), demonstrating that compressive strength cannot be explained by density alone.
- The coefficients of variation ranged from 0.98% to 5.98%, indicating good repeatability and consistency of the experimental results.
- Despite identical curing conditions, variations in compressive strength highlight the critical role of early-age temperature conditions prior to curing, indicating that initial environmental exposure has a lasting impact on concrete performance.
- The July results should be interpreted cautiously because the additional mixing water slightly increased the effective water/cement ratio from 0.53 to approximately 0.545. Therefore, the observed performance reflects the combined effects of curing conditions, environmental exposure, and a minor variation in mixture proportion, rather than temperature alone.

Overall, the results show that temperature influences concrete performance both directly (through hydration kinetics) and indirectly (through density changes), and that these effects should be evaluated together rather than independently. This study has several limitations. The experimental program was conducted using a single cement type, a single concrete strength class (C30/37), and concrete produced at one ready-mix concrete plant under local environmental conditions. In addition, the number of specimens was limited, and no microstructural analyses were performed. Therefore, the findings should be interpreted within the scope of the present study and should not be generalised to other concrete types, mixture proportions, or environmental conditions. It is recommended that further research investigate the effects of different field-curing conditions on the compressive strength of concrete, particularly in cold weather, and evaluate other practical curing techniques,

including membrane curing, wet coverings, plastic sheet curing, and sealed curing, to further extend the applicability of the present findings.

Acknowledgements

The author would like to thank Tonbullar Ready-Mix Concrete Company in Kastamonu, Türkiye and its team, especially Mr. Emre Capulcuoglu, for their support and contribution to this study.

Funding

The author received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

During the preparation of this manuscript, Deeply was used exclusively for language editing and stylistic refinement. The authors take full responsibility for the content, interpretation, and conclusions of the published article.

Author Contributions

The author declares sole responsibility for all aspects of the study, including conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing of the original draft, and writing, review, and editing of the manuscript.

REFERENCES

- Akeed MH, Qaidi S, Ahmed HU, Faraj RH, Majeed SS, Mohammed AS, Emad W, Tayeh BA, Azevedo ARG (2022). Ultra-high-performance fiber-reinforced concrete. Part V: mixture design, preparation, mixing, casting, and curing. *Case Studies in Construction Materials*, 17, e01363.
- Barbhuiya S, Das BB, Idrees M (2024). Thermal energy storage in concrete: a comprehensive review on fundamentals, technology and sustainability. *Journal of Building Engineering*, 82, 108302.
- Başıyigit C, Akkaş A, Serin E, Kartlı Mİ (2011). Investigation effects of different curing conditions on pumice aggregate lightweight concrete properties. *e-Journal of New World Sciences Academy Engineering Sciences*, 6(4), 1540-1546.
- Chu Y, Guo LP, Dai GZ, Wu JD, Lyu BC, Fei XP, Chen HT, Chen B (2024). Effects of the early curing regime on the properties and pore structure of concrete in an environment with high altitudes and low atmospheric pressures. *Journal of Building Engineering*, 82, 108195.
- Dong S, Ouyang X, Yoo DY, Han B (2024). Influence of early thermal curing regimes on properties of ultra-high performance concrete: a review. *Journal of Building Engineering*, 96, 110494.
- Emarah DA, Mostafa MA, Anwar M (2025). Effect of curing procedure on mechanical properties and pore structure characteristics of three different concrete types. *Results in Materials*, 27, 100732.
- Haigh R, Ameri Sianaki O (2025). Traditional and advanced curing strategies for concrete materials: a systematic review of mechanical performance, sustainability, and future directions. *Applied Sciences*, 15(20), 11055.
- Huang W, He J, Jin Y, Lei D (2025). Study on the influence of large temperature difference curing on mechanical, thermal and pore structure characteristics of foamed concrete. *Construction and Building Materials*, 494, 143512.
- Kiernozyczyk W, Błyszko J (2021). The influence of temperature on the hydration rate of cements based on calorimetric measurements. *Materials*, 14(11), 3025.

- Lin L, Wang S, Zhang P, Li J, Wang S, Zhong J, Zeng L, Qiu X (2023). Effect of curing regime on the strength development and microstructure evolution of high strength concrete. *Journal of Building Engineering*, 78, 107750.
- Mohe NS, Shewalul YW, Agon EC (2022). Experimental investigation on mechanical properties of concrete using different sources of water for mixing and curing concrete. *Case Studies in Construction Materials*, 16, e00959.
- Mostofinejad D, Nikoo MR, Hosseini SA (2016). Determination of optimized mix design and curing conditions of reactive powder concrete (RPC). *Construction and Building Materials*, 123, 754-767.
- Neville AM (2011). *Properties of Concrete*. 5th ed., Pearson Education Limited, Harlow, UK.
- Shi Y, Long G, Ma C, Xie Y, He J (2019). Design and preparation of ultra-high performance concrete with low environmental impact. *Journal of Cleaner Production*, 214, 633-643.
- Sika Türkiye (2024). *Sika® ViscoCrete® Hi-Tech 2928 Ürün Teknik Bilgi Föyü*. <https://tur.sika.com/dms/getdocument.get/477c2234-c599-4afd-8c4d-e068e1133ff7/sika-viscocrete-hi-tech2928.pdf> [accessed 28-07-2026].
- TS EN 197-1 (2012). *Cement - Part 1: Composition, Specifications and Conformity Criteria for Common Cements*. Turkish Standards Institution, Ankara, Türkiye.
- TS EN 206+A2 (2021). *Concrete - Specification, Performance, Production and Conformity*. Turkish Standards Institution, Ankara, Türkiye.
- TS EN 12390-2 (2019). *Testing Hardened Concrete - Part 2: Making and Curing Specimens for Strength Tests*. Turkish Standards Institution, Ankara, Türkiye.
- TS EN 12390-3 (2019). *Testing Hardened Concrete - Part 3: Compressive Strength of Test Specimens*. Turkish Standards Institution, Ankara, Türkiye.
- Turkish State Meteorological Service (n.d.). *Weather Forecast Data for Kastamonu*. <http://www.mgm.gov.tr/tahmin/il-ve-ilceler.aspx?il=Kastamonu> [accessed 04-01-2026].
- Wang S, Wang B, Zhu H, Chen G, Li Z, Yang L, Zhang Y, Zhou X (2023a). Ultra-high performance concrete: mix design, raw materials and curing regimes-a review. *Materials Today Communications*, 35, 105468.
- Wang L, Wei W, Zhang J, Hu Y, Zhang L (2023b). Effect of curing regime on the mechanical properties and durability of steam cured-concrete. *Buildings*, 13(7), 1697.
- Xu D, Tang J, Hu X, Yu C, Han F, Sun S, Deng W, Liu J (2023). The influence of curing regimes on hydration, microstructure and compressive strength of ultra-high performance concrete: a review. *Journal of Building Engineering*, 76, 107401.
- Yılmaz E, Nazlıkol D, Özcan İ (2019). Effects of environmental conditions on concrete compressive strength. *Hazır Beton*, 156, 73-77.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Mechanical performance of concrete using rice husk ash–plastic artificial aggregates with varying particle sizes

Dwi Nurtanto ^{a,*} , Ketut Aswatama Wiswamitra ^a ,
Mohamad Fikri Nurhidayat ^a , Bagas Rahmandita Subchan ^a , Imam Junaidi ^a

^a Department of Civil Engineering, Universitas Jember, Jember 68121, Indonesia

ABSTRACT

The increasing consumption of plastic and its long decomposition period necessitate innovative strategies for utilizing Polyethylene Terephthalate (PET) plastic waste in civil engineering applications, particularly through its conversion into artificial coarse aggregates for concrete. This study investigates the effect of Rice Husk Ash (RHA) fineness used as a filler in PET-based artificial aggregates on the mechanical properties of concrete. Three RHA particle size ranges were considered: ASP50 (RHA passing sieve No. 50 and retained on sieve No. 100), ASP100 (RHA passing sieve No. 100 and retained on sieve No. 200), and ASP200 (RHA passing sieve No. 200). PET plastic waste and RHA were mixed at a ratio of 1:4, melted, cast, and crushed to produce artificial coarse aggregates with particle sizes ranging from 5 to 10 mm. A conventional concrete mixture with natural coarse aggregate was prepared as the control specimen for comparison. Concrete specimens were cast in cylindrical molds and tested for compressive strength and splitting tensile strength at 28 days. The results showed that concrete incorporating ASP200–PET aggregates achieved the highest compressive strength (17.42 MPa) and splitting tensile strength (1.58 MPa) among the modified mixtures. A consistent improvement in mechanical performance was observed with decreasing RHA particle size, attributed to better particle packing and denser concrete. However, the mechanical properties of concrete containing artificial PET aggregates remained lower than those of conventional concrete with natural aggregates. Despite this reduction in strength, the significant decrease in concrete density indicates the potential of RHA–PET artificial aggregates for lightweight and non-structural concrete applications.

ARTICLE INFO

Article history:

Received – January 15, 2026
Revision requested – April 7, 2026
Revision received – July 25, 2026
Accepted – August 4, 2026

Keywords:

Rice husk ash
PET waste
Artificial coarse aggregate
RHA fineness
Compressive strength
Lightweight concrete



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

Citation: Nurtanto D, Wiswamitra KA, Nurhidayat MF, Subchan BR, Junaidi I (2026). Mechanical performance of concrete using rice husk ash–plastic artificial aggregates with varying particle sizes. *Challenge Journal of Concrete Research Letters*, 17(3), 352–363.

1. Introduction

The development of sustainable concrete materials has attracted increasing attention due to the growing environmental concerns associated with plastic waste accumulation and the depletion of natural aggregate resources. Among various plastic wastes, Polyethylene Terephthalate (PET) is one of the most widely generated and persistent materials, creating serious disposal and environmental concerns (Soong et al. 2022; Wang et al. 2022; Bohre et al.

2023; Tladi et al. 2023). Consequently, the incorporation of PET waste into concrete has gained attention as a sustainable approach to reduce landfill disposal while decreasing the environmental footprint associated with conventional construction materials (Askar et al. 2023; Marvila et al. 2022; Sosoi et al. 2022; Qaidi et al. 2023). However, despite its environmental benefits, the incorporation of PET aggregates often leads to reductions in mechanical performance, highlighting the need for effective strategies to improve the properties of PET-based concrete.

* Corresponding author. E-mail address: dwinurtanto.teknik@unej.ac.id (D. Nurtanto)
ISSN: 2548-0928 / DOI: <https://doi.org/10.20528/cjcr.2026.1089>

In addition to environmental concerns related to plastic waste, the construction sector faces increasing pressure due to the extensive consumption of natural aggregates. Continuous extraction of natural aggregates has resulted in resource depletion and environmental degradation, motivating researchers to explore recycled and alternative aggregate materials (Zulkernain et al. 2021; AbdelMoti and Mustafaa 2019; Mousavimehr and Nematzadeh 2020; M. Correa et al. 2020). PET waste has therefore been investigated as a potential aggregate replacement because of its availability, low density, and contribution to circular economy principles.

Previous studies have demonstrated that PET can be used as a substitute aggregate in concrete, producing lighter concrete and providing an environmentally friendly solution for plastic waste utilization (Dawood et al. 2021; Qaidi et al. 2023; Almeshal et al. 2020; Jaskowska-Lemańska et al. 2022; Bachtiar et al. 2020). However, despite these environmental benefits, many researchers have reported reductions in mechanical properties, particularly compressive strength, due to the relatively smooth surface texture and lower stiffness of PET compared with conventional mineral aggregates (Dawood et al. 2021; Almeshal et al. 2020; Qaidi et al. 2023). These findings suggest that additional measures are required to improve the performance of concrete incorporating PET aggregates.

Rice Husk Ash (RHA), an abundant agro-industrial by-product in many developing countries, has emerged as a promising supplementary cementitious material because of its high silica content and pozzolanic reactivity (Endale et al. 2023; Kang et al. 2019; Jittin et al. 2020; Zareei et al. 2017; Amran et al. 2021; Siddika et al. 2018). Numerous studies have shown that RHA can enhance the mechanical and durability properties of concrete through both pozzolanic reactions and filler effects (Faried et al. 2021; Satwarnirat et al. 2023; Gencel et al. 2021; Abolhasani et al. 2022; Siddika et al. 2021). In particular, the fineness of RHA plays a critical role in determining its effectiveness. Finer RHA particles provide a larger specific surface area, resulting in greater pozzolanic activity, improved particle packing, and a denser concrete microstructure. Consequently, the use of finely ground RHA has been reported to improve compressive strength and long-term durability more effectively than coarser RHA (Sandhu and Siddique 2017; Farid and Zaheer 2023; Lin et al. 2023; Pu et al. 2024).

The combined utilization of PET waste and RHA offers a promising strategy for producing more sustainable concrete while simultaneously addressing plastic waste management and agricultural waste disposal (Awolusi et al. 2023; Hu et al. 2020; Tayeh et al. 2021; Hasan et al. 2022). Likewise, the development of lightweight and environmentally friendly cementitious materials has attracted increasing research interest as a means of reducing the environmental impact of the construction industry. For example, Paikara and Gyawali (2023) developed aerated lightweight mortar using aluminum powder to reduce material density and improve sustainability. Although their study employed a different lightweight mechanism and material system, it highlights the growing need to develop sustainable lightweight construction materials with acceptable mechanical performance. In

the context of PET-RHA artificial aggregates, recent studies have demonstrated their potential for sustainable concrete production; however, reductions in mechanical performance remain a major challenge. Moreover, limited attention has been given to the influence of RHA fineness on the quality of PET-based artificial aggregates and the resulting concrete performance. Therefore, further research is required to clarify the role of RHA particle size in enhancing the properties of concrete containing PET-based artificial aggregates.

This gap is particularly important because the mechanisms of the two materials may complement each other. While PET aggregates tend to reduce mechanical strength due to weaker aggregate–paste bonding, finer RHA particles can enhance matrix densification and improve the interfacial transition zone. Therefore, it is reasonable to hypothesize that increasing RHA fineness may compensate for the strength reduction commonly associated with PET aggregate utilization.

Accordingly, this study investigates the effect of RHA fineness on the mechanical performance of concrete containing PET-based artificial aggregates. Unlike previous PET-RHA studies that mainly examined material replacement levels, the present research systematically evaluates the influence of different RHA fineness levels on the strength development of PET aggregate concrete. This approach provides new insight into the interaction between PET aggregates and finely ground RHA and establishes whether RHA fineness can be used as an effective strategy to overcome the mechanical limitations of PET-based concrete. The PET waste utilized in this study was processed into artificial aggregates through the treatment procedure shown in Fig. 1, while the RHA was obtained and prepared following the process illustrated in Fig. 2. The findings are expected to contribute to the development of sustainable concrete materials that effectively utilize both plastic and agricultural wastes while maintaining adequate mechanical properties.

2. Methodology

2.1. Materials

Ordinary Portland Cement (OPC) Type I, manufactured by Semen Gresik (Indonesia), was used as the cementitious binder throughout this study. Potable tap water, free from visible impurities and suitable for concrete production, was used for both mixing and curing. Natural fine aggregate and natural coarse aggregate were obtained from local suppliers in Jember, East Java, Indonesia, and their physical properties are summarized in Table 1.

The rice husk ash (RHA) used for manufacturing the artificial coarse aggregates was obtained from CV. Pabrik Beras Rajawali, Rambipuji, Jember, East Java, Indonesia. The RHA was produced by controlled combustion of rice husks at approximately 450–500 °C for 4–6 h before being sieved into the designated particle-size ranges. Since the objective of this study was to investigate the effect of RHA particle fineness as a filler in PET-based artificial aggregates rather than its pozzolanic activity as a cement replacement material, chemical characterization of the RHA (e.g., SiO₂ content and loss on ignition) was not conducted.



Fig. 1. Treatment process of waste PET plastic:
(a) Raw waste PET plastic; (b) Cutting process of PET plastic; (c) Processed PET plastic after cutting.



Fig. 2. Production process of rice husk ash (RHA):
(a) Red brick firing process; (b) Produced RHA; (c) Sieving of RHA.

Table 1. Test results of natural aggregates.

Testing	Fine aggregate	Coarse aggregate
Sieve analysis	Zone 2	Pass 20 mm
Specific gravity	2.40	2.69
Bulk density (g/cm ³)	1.34	1.41
Water absorption (%)	3.99	2.46
Moisture content (%)	3.45	2.01

2.2. Artificial coarse aggregate

Artificial coarse aggregates were manufactured from waste PET plastic and rice husk ash (RHA). The RHA was used exclusively as a filler material within the PET matrix rather than as a supplementary cementitious material. Therefore, the primary experimental variable in this study was the particle fineness of the RHA. All RHA fractions were obtained from the same source and production batch, ensuring identical chemical composition while varying only the particle size through sieving. The artificial coarse aggregates were produced using a constant RHA-to-PET ratio of 1:4. For each production batch, 400 g of shredded PET plastic and 100 g of RHA were used, corresponding to an RHA-to-PET ratio of 1:4. The mixture was sufficient to produce approximately three cube specimens measuring 50 × 50 × 50 mm prior to crushing and sieving.

To evaluate the effect of RHA fineness, three different RHA particle size ranges were utilized. As summarized in Table 2, the artificial coarse aggregates were classified as

ASP50, ASP100, and ASP200, corresponding to RHA particles passing sieve No. 50 (300 μm) and retained on sieve No. 100 (150 μm), passing sieve No. 100 (150 μm) and retained on sieve No. 200 (75 μm), and passing sieve No. 200 (75 μm), respectively. The resulting artificial coarse aggregates were produced with particle sizes ranging from 5 to 10 mm.

Artificial coarse aggregates were produced by melting shredded PET plastic in a metal pan under continuous heating. The melting process was conducted in a well-ventilated area to minimize the accumulation of fumes generated during heating and to ensure operator safety. The PET was heated for approximately 1 h until complete melting was achieved. Subsequently, rice husk ash (RHA) was gradually added to the molten PET at the specified proportion, and the mixture was continuously stirred until a homogeneous blend was obtained. During the mixing process, the molten mixture gradually turned black. The homogeneous mixture was then poured into cube molds measuring 50 mm × 50 mm × 50 mm and allowed to cool at room temperature until fully solidified.

After hardening, the molded specimens were removed from the molds and crushed manually using a hammer. The crushed material was subsequently sieved to obtain

artificial coarse aggregates with particle sizes ranging from 5 to 10 mm. The detailed production process of the artificial coarse aggregate is illustrated in Fig. 4(a–j).

Table 2. Composition of artificial coarse aggregate.

Gravel code artificial	Proportion (RHA:PET)	Size of RHA
ASP50	1:4	Passing sieve No. 50 (300 μm) and retained on sieve no. 100 (150 μm)
ASP100	1:4	Passing sieve No. 100 (150 μm) and retained on sieve No. 200 (75 μm)
ASP200	1:4	Passing sieve No. 200 (75 μm)

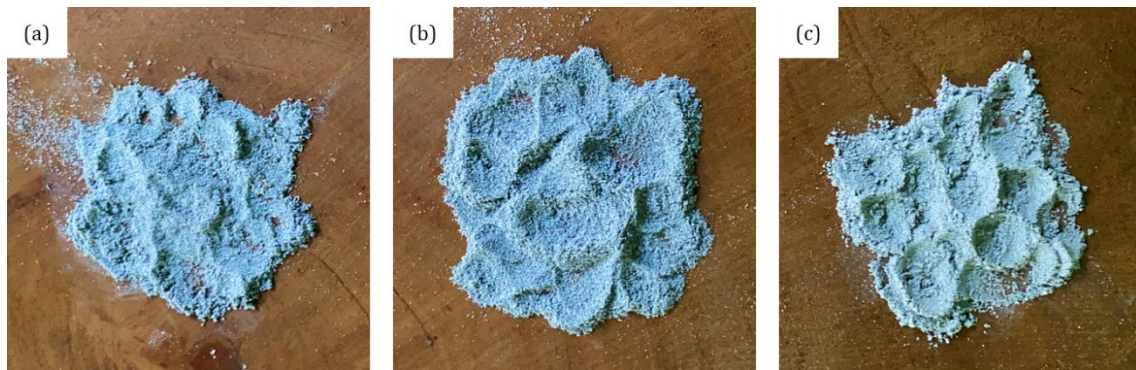


Fig. 3. Sieving results of rice husk ash (RHA): (a) ASP50; (b) ASP100; (c) ASP200.

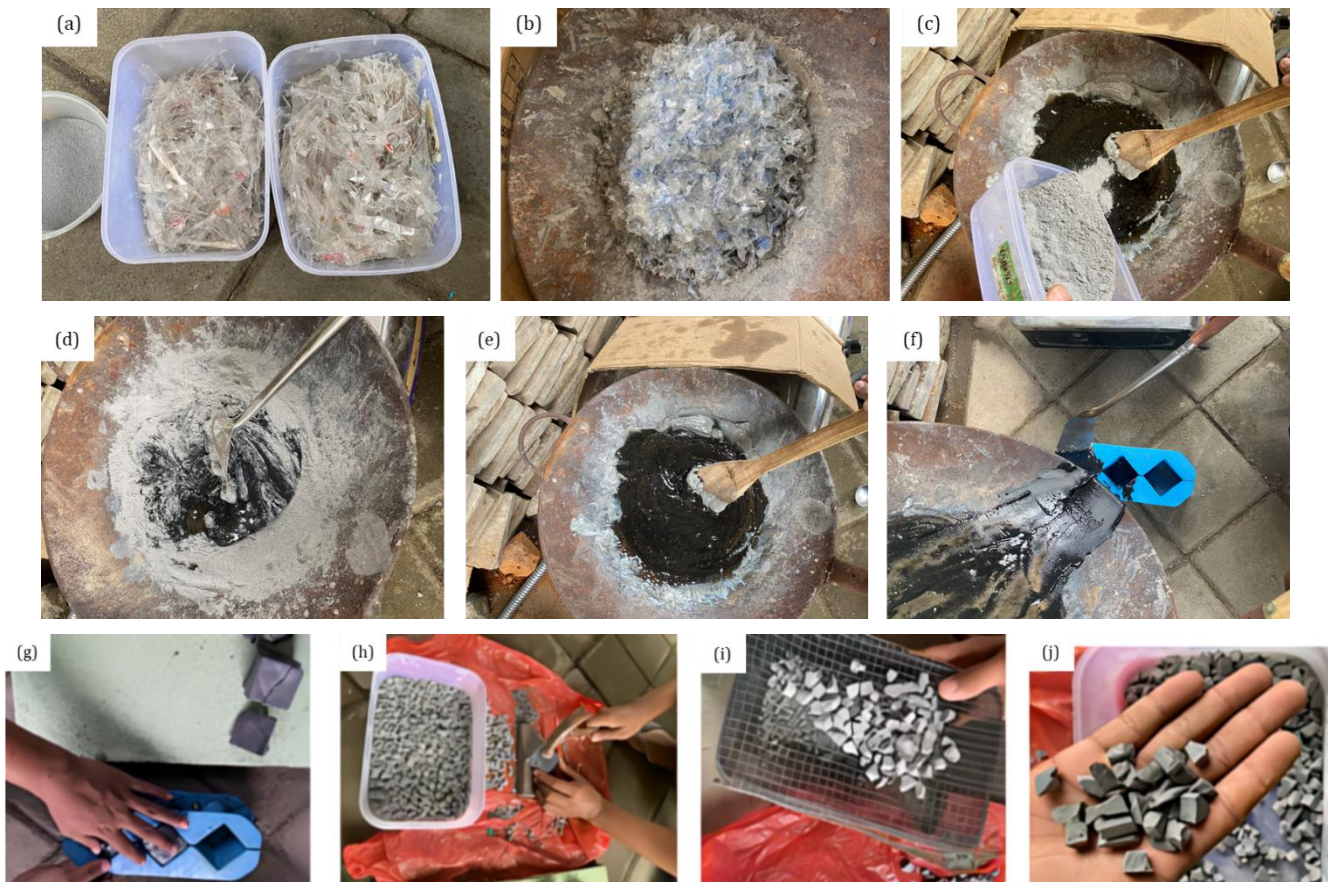


Fig. 4. Production process of artificial coarse aggregate: (a) Preparation of equipment and materials; (b) Melting of PET; (c) Mixing with rice husk ash (RHA); (d) Stirring PET and RHA until homogeneous; (e) Melt ready for casting; (f) Pouring into molds; (g) Demolding; (h) Crushing using a hammer; (i) Sieving; (j) Artificial coarse aggregate after sieving.

Fig. 5 illustrates the influence of RHA fineness on the physical characteristics of the produced artificial coarse aggregates. Finer particles may fill internal voids within the artificial aggregate, resulting in a denser structure, improved mechanical integrity, and enhanced bonding with the surrounding cementitious matrix (Al-Baghdadi et al. 2021; Stratoura et al. 2023).

Table 3 shows that ASP200-PET had the highest specific gravity (1.40) and bulk density (0.77 g/cm³), whereas ASP50-PET had the highest water absorption (1.40%) and moisture content (0.21%). According to the test results, the fineness of rice husk ash used as a filler for

plastic aggregate affects the properties of the artificial aggregate. The test results indicate that the fineness of the rice husk ash used as a filler in the PET-based artificial aggregates significantly influenced their physical properties. As the RHA fineness increased, both the specific gravity and bulk density of the artificial aggregates increased, indicating the formation of a denser aggregate structure (Al-Baghdadi et al. 2021; Kannur and Chore 2023; Shiringire et al. 2024). In contrast, water absorption and moisture content decreased with increasing RHA fineness, reflecting the reduction in pore volume within the artificial aggregates (Ganasen et al. 2023; Abellan-Garcia et al. 2023).



Fig. 5. Manufacturing results and material testing of artificial coarse aggregate.

Table 3. Test results of artificial lightweight coarse aggregate.

Testing	ASP50-PET	ASP100-PET	ASP200-PET	Condition	Control	Reference
Sieve analysis	Pass 20 mm	Pass 20 mm	Pass 20 mm	Max. 37.5mm	OK	ACI E1-07 (2007)
Specific gravity	1.35	1.38	1.40	Lightweight aggregate (1.0-1.8)	OK	SNI 03-2461-2002 (2002)
Bulk density (g/cm ³)	0.72	0.75	0.77	Lightweight aggregate < 0.88	OK	ASTM C29/C29M-97 (1997)
Water absorption (%)	1.40	1.04	0.92	0.5-4%	OK	ACI E1-07 (2007)
Moisture content (%)	0.21	0.19	0.10	Difference test max. 0.79%	OK	ASTM C566-04 (2004)

To further explain the physical and mechanical properties of the artificial aggregates, microscopic observations were conducted using a digital microscope. The microstructural characteristics of the aggregates are presented in Fig. 6(a-d). The ASP50-PET aggregate exhibited a rougher surface texture and a greater number of visible pores compared with ASP100-PET and ASP200-PET. In contrast, ASP200-PET displayed a denser and more homogeneous surface with fewer visible pores. These observations indicate that increasing the fineness of the rice husk ash filler contributed to a reduction in pore formation within the PET-RHA composite aggregate.

The observed microstructural differences are consistent with the measured physical properties of the aggregates. Aggregates containing a larger number of pores generally exhibit lower specific gravity and bulk density because a greater proportion of their volume consists of void spaces. Conversely, the presence of interconnected pores increases the capacity of the aggregate to absorb and retain water, resulting in higher water absorption and moisture content values (Bouarroudj et al. 2023; Duan et al. 2022; Rao et al. 2020; Théréné et al. 2020). Therefore, the denser microstructure observed in ASP200-PET is expected to contribute to higher density and lower water absorption compared with ASP50-PET.

Furthermore, the microstructure of the artificial aggregate directly influences its mechanical behavior and its interaction with the surrounding cementitious matrix. The finer RHA particles in ASP200-PET act as fillers that occupy void spaces within the PET matrix, producing a denser internal structure and reducing stress concentration points associated with pores. As a result, the aggregate becomes mechanically stronger and less susceptible to cracking under load. The denser aggregate structure also promotes improved contact and bonding with the sur-

rounding mortar, leading to a more effective transfer of stresses across the aggregate–paste interface. These mechanisms explain the higher compressive strength obtained for concrete containing ASP200-PET aggregates compared with ASP50-PET and ASP100-PET aggregates. Therefore, the improvement in concrete mechanical performance can be attributed not only to the increased density of the artificial aggregate but also to the enhancement of its microstructural quality and aggregate–mortar interfacial bonding (Rocha et al. 2023; Herrera Rosas et al. 2023).

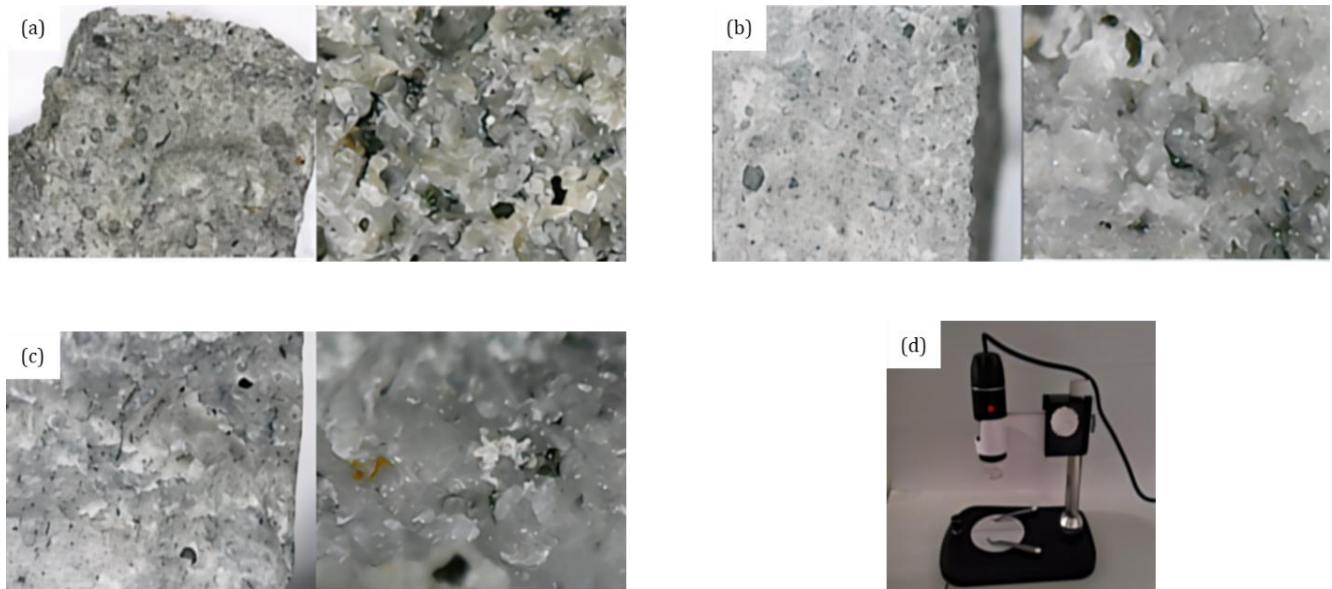


Fig. 6. Digital microscope observations of artificial coarse aggregates: (a) ASP50–PET; (b) ASP100–PET; (c) ASP200–PET; (d) Digital microscope.

2.3. Mix proportion

The concrete mixtures were prepared using Ordinary Portland Cement (OPC) Type I, manufactured by Semen Gresik, as the binder; potable tap water as the mixing water; natural fine aggregate; and either natural or artificial coarse aggregate. The target compressive strength was 25 MPa. The mix proportions, expressed on a per-cubic-meter basis (kg/m^3), are presented in Table 4. The constituent materials were proportioned on a 1 m^3 basis. The quantities of the artificial coarse aggregates were calculated based on their specific gravities to provide an equivalent coarse aggregate volume to that of the control mixture while maintaining the target concrete volume. For laboratory production, the mix proportions were proportionally scaled down to produce approximately 15 L of concrete per batch, which was sufficient to cast six cylindrical specimens ($100 \text{ mm} \times 200 \text{ mm}$) for compressive strength and splitting tensile strength testing.

Three types of artificial aggregates were produced using a mixture of PET plastic waste and rice husk ash (RHA), namely ASP50, ASP100, and ASP200. BN0 denotes the control mixture consisting of conventional concrete with natural gravel as the coarse aggregate. BN1 incorporates artificial coarse aggregate coded ASP50 with an RHA ratio of 1:4. The ASP50 aggregate was produced through a melting–mixing process using

RHA passing sieve No. 50 ($300 \mu\text{m}$) and retained on sieve No. 100 ($150 \mu\text{m}$), combined with PET plastic waste. BN2 incorporates artificial aggregate coded ASP100 with the same RHA ratio of 1:4. The ASP100 aggregate was manufactured using RHA passing sieve No. 100 ($150 \mu\text{m}$) and retained on sieve No. 200 ($75 \mu\text{m}$), mixed with PET plastic waste through the same process. BN3 contains artificial aggregate coded ASP200 with an RHA ratio of 1:4 and was produced by melting and mixing PET plastic waste with RHA passing sieve No. 200 ($75 \mu\text{m}$). The resulting artificial aggregates were subsequently used as coarse aggregate replacements in the concrete mixtures.

Concrete mixing was carried out using a 50 L capacity concrete mixer. Each laboratory batch consisted of approximately 15 L of fresh concrete, prepared by proportionally scaling the 1 m^3 mix design presented in Table 4. The constituent materials were weighed according to the required proportions. The mixing process began with the dry mixing of cement, fine aggregate, and coarse aggregate (natural or artificial aggregate) for approximately 2 min to ensure uniform distribution of the materials. Subsequently, water was gradually added while the mixer was in operation, and mixing was continued for an additional 3 min until a homogeneous concrete mixture was obtained. After mixing, the fresh concrete was immediately subjected to slump testing and then cast into cylindrical molds ($100 \text{ mm} \times 200 \text{ mm}$) for compressive strength and splitting tensile strength tests.

Table 4. Concrete mix design.

Code	Cement (kg/m ³)	Water (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	ASP50 (kg/m ³)	ASP100 (kg/m ³)	ASP200 (kg/m ³)
BN0	385	211	739.06	1039.74	–	–	–
BN1	385	211	739.06	–	521.80	–	–
BN2	385	211	739.06	–	–	533.40	–
BN3	385	211	739.06	–	–	–	541.13

2.4. Compressive strength and splitting tensile strength testing

The mechanical properties of the concrete were evaluated through compressive strength and splitting tensile strength tests using cylindrical specimens. The specimens had a diameter of 100 mm and a height of 200 mm. After casting, the specimens were cured under laboratory conditions until the designated testing age.

Compressive strength tests were conducted in accordance with ASTM C39/C39M (2021) using a compression testing machine with a maximum capacity of 1500 kN. The load was applied continuously at a rate of 2.5–6.0 kN/s until specimen failure occurred. The compressive strength was calculated by dividing the maximum applied load by the cross-sectional area of the specimen.

Splitting tensile strength tests were performed in accordance with ASTM C496/C496M (2017) using the same compression testing machine. The cylindrical specimens were positioned horizontally between the loading platens, and the load was applied continuously until splitting failure occurred. The splitting tensile strength was determined from the maximum load recorded during the test.

For each concrete mixture, three cylindrical specimens were tested for compressive strength and three cylindrical specimens were tested for splitting tensile strength at 28 days. The reported strength values represent the arithmetic mean of the three test results. To evaluate the variability of the experimental data, the standard deviation (SD) was calculated using the sample standard deviation ($n - 1$), while the coefficient of variation (COV) was calculated as the ratio of the sample standard deviation to the mean value and expressed as a percentage.

3. Results and Discussion

3.1. Workability

The slump test was conducted to evaluate the workability of fresh concrete. The test was performed using a standard slump cone with a top diameter of 100 mm, a bottom diameter of 200 mm, and a height of 300 mm. The slump values reported in Table 5 represent the results of a single slump test conducted for each concrete mixture.

Based on Table 5 and Fig. 7, the slump values of BN0, BN1, BN2, and BN3 were 110 mm, 100 mm, 95 mm, and 80 mm, respectively. All mixtures satisfied the target slump range of 60–180 mm, indicating acceptable workability for concrete placement. However, a gradual reduction in slump was observed as the fineness of the RHA used in the PET-based artificial aggregates increased.

**Fig. 7.** Slump test results.**Table 5.** Slump test results.

Test object code	Slump value	Unit
BN0	110	mm
BN1	100	mm
BN2	95	mm
BN3	80	mm

This reduction in workability can be attributed to the finer RHA particles incorporated into the artificial aggregates. Finer RHA possesses a larger specific surface area, which increases water demand and reduces the amount of free water available for lubrication within the concrete mixture. In addition, the denser microstructure of aggregates produced with finer RHA may contribute to greater internal friction among solid particles during mixing. As a result, BN3 concrete containing ASP200-PET aggregate exhibited the lowest slump value. Nevertheless, the measured slump values indicate that all mixtures maintained adequate workability despite the reduction associated with increasing RHA fineness (Liang et al. 2024; Mohsen et al. 2023; Shaheen 2025; Tanash et al. 2025; H. Wang et al. 2023)

The observed reduction in slump with increasing RHA fineness is consistent with findings reported by previous researchers. Liang et al. (2024) and Wang et al. (2023) reported that finer ash particles increase the specific surface area of the solid constituents, thereby increasing water demand and reducing the amount of free water available for flow. Similarly, Mohsen et al. (2023) and Tanash et al. (2025) observed that the incorporation of fine pozzolanic materials can decrease concrete workability due to enhanced particle packing and internal friction. The trend obtained in the present study therefore agrees with previous investigations, confirming that the use of finer RHA in PET-based artificial aggregates contributes to lower slump values while maintaining acceptable workability for concrete placement.

3.2. Compressive strength

Based on Fig. 8 and Table 6, the 28-day compressive strength results indicate that BN3 concrete incorporating ASP200–PET artificial coarse aggregate achieved the highest compressive strength among the modified mixtures, with an average value of 17.42 MPa. In comparison, BN1 concrete containing ASP50–PET aggregate and BN2 concrete containing ASP100–PET aggregate achieved average 28-day compressive strengths of 14.58

MPa and 15.52 MPa, respectively. The control concrete (BN0) incorporating natural coarse aggregate exhibited the highest 28-day compressive strength overall, with an average value of 27.50 MPa.

To evaluate the variability of the compressive strength results, the sample standard deviation (SD) and coefficient of variation (COV) were calculated from the three specimens tested for each concrete mixture. The control concrete (BN0) exhibited a low COV of 3.50%, indicating excellent test consistency. Similarly, BN2 and BN3 showed COV values of 6.82% and 9.13%, respectively, demonstrating acceptable repeatability of the compressive strength results. In contrast, BN1 exhibited a relatively high COV of approximately 23.20%, indicating greater variability among the test specimens. This higher variability is likely associated with the more porous and heterogeneous microstructure of the ASP50–PET artificial aggregate, which may have caused non-uniform stress distribution and specimen-to-specimen variation during testing. Therefore, the BN1 results should be interpreted with caution and represent a limitation of the present study. Nevertheless, despite the greater variability observed for BN1, the overall trend of increasing compressive strength with increasing RHA fineness (BN1 < BN2 < BN3) remained consistent across the experimental program.

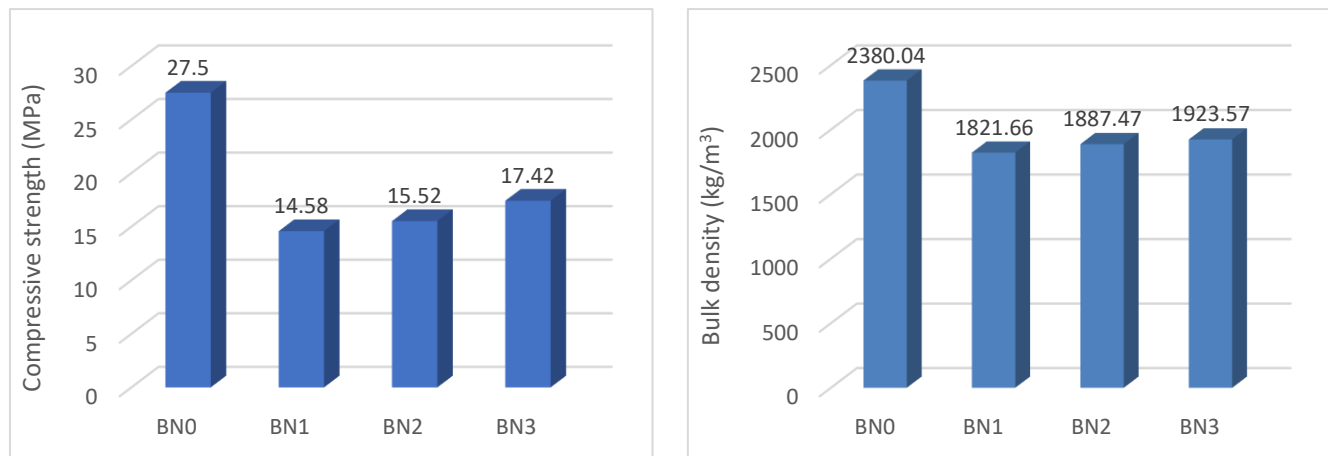


Fig. 8. Compressive strength and bulk density of concrete.

Although the target compressive strength of 25 MPa was not achieved by the PET-based artificial aggregate concretes, compressive strength increased consistently with increasing RHA fineness. BN3 reached 17.42 MPa (approximately 69.7% of the target strength), demonstrating that finer RHA improved the performance of PET-based artificial aggregates. This improvement can be attributed to the filler effect of fine RHA particles, which reduced pore volume within the PET matrix, produced denser artificial aggregates, and enhanced stress transfer between the aggregate and the surrounding mortar. Unlike conventional applications in which RHA acts as a supplementary cementitious material, the RHA in this study functioned primarily as a micro-filler during artificial aggregate production, improving aggregate quality through physical densification rather than pozzolanic reactions.

The compressive strength results were consistent with the density measurements. Concrete containing natural coarse aggregate exhibited the highest average density (2380.04 kg/m³), whereas BN1, BN2, and BN3 exhibited average densities of 1821.66, 1887.47, and 1923.57 kg/m³, respectively. The increase in density with increasing RHA fineness indicates that finer RHA particles reduced internal voids within the PET–RHA artificial aggregates, producing a denser and more homogeneous microstructure. Consequently, ASP200–PET exhibited the highest density and compressive strength among the modified mixtures.

The observed improvement in compressive strength with increasing RHA fineness agrees with previous studies reporting that finer RHA enhances particle packing and reduces porosity, resulting in a denser microstructure. Although the PET-based aggregate concrete exhib-

ited lower strengths than conventional concrete because of the lower stiffness of PET and its weaker bond with the cementitious matrix, BN3 provided the most favorable balance between mechanical performance and reduced density. These results demonstrate the potential of PET–RHA artificial aggregates for lower-density, non-

structural and semi-structural concrete applications, including partition walls, paving blocks, pedestrian walkways, and landscape elements. Further optimization of the aggregate production process and concrete mixture design is recommended to improve mechanical performance for broader engineering applications.

Table 6. Density and compressive strength of all specimens.

Specimen code	Coarse aggregate type	Density (kg/m ³)	Density average	Compressive strength (MPa)	Compressive strength average (MPa)	SD (MPa)	COV (%)
BN0	Normal concrete	2,528.66		28.32			
BN0	Normal concrete	2,254.78	2380.04	26.44	27.50	0.96	3.50
BN0	Normal concrete	2,356.69		27.74			
BN1	ASP50-PET	1,840.76		18.04			
BN1	ASP50-PET	1,796.18	1821.66	11.28	14.58	3.38	23.20
BN1	ASP50-PET	1,828.03		14.42			
BN2	ASP100-PET	1,859.87		16.00			
BN2	ASP100-PET	1,847.13	1887.47	16.26	15.52	1.06	6.82
BN2	ASP100-PET	1,955.41		14.31			
BN3	ASP200-PET	1,993.63		16.38			
BN3	ASP200-PET	1,808.92	1923.57	16.62	17.42	1.59	9.13
BN3	ASP200-PET	1,968.15		19.25			

3.3. Splitting tensile strength

Based on Fig. 9 and Table 7, the 28-day splitting tensile strength results indicate that BN3 concrete incorporating ASP200-PET artificial coarse aggregate achieved the highest splitting tensile strength among the modified mixtures, with an average value of 1.58 MPa. In comparison, BN1 concrete containing ASP50-PET aggregate and BN2 concrete containing ASP100-PET aggregate achieved average splitting tensile strengths of 1.35 MPa and 1.53 MPa, respectively. The control concrete (BN0) incorporating natural coarse aggregate exhibited the highest splitting tensile strength overall, with an average value of 2.67 MPa.

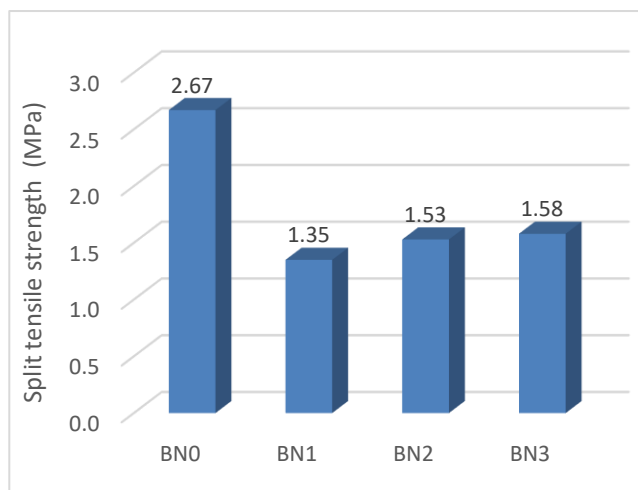


Fig. 9. Splitting tensile strength of concrete.

To evaluate the reliability of the splitting tensile strength results, the standard deviation (SD) and coefficient of variation (COV) were calculated from the three specimens tested for each mixture. The control concrete (BN0) exhibited an SD of 0.055 MPa and a COV of 2.07%, while BN1, BN2, and BN3 exhibited SD values of 0.044 MPa, 0.046 MPa, and 0.156 MPa, respectively, corresponding to COV values of 3.23%, 3.01%, and 9.89%. These relatively low COV values indicate good repeatability of the splitting tensile strength tests and demonstrate that the observed strength trends are consistent among the tested specimens.

Although the incorporation of PET-based artificial aggregates reduced the splitting tensile strength compared with natural coarse aggregate concrete, a clear improvement was observed with increasing RHA fineness. The lower tensile strength of the PET-based mixtures can be attributed to the relatively smooth surface texture and lower stiffness of PET aggregates, which may weaken the interfacial bond between the aggregate and the surrounding cementitious matrix (Zahid et al. 2024; Xiong et al. 2023; Badache et al. 2025). However, the use of finer RHA particles improved the internal structure of the artificial aggregates by reducing pore content and producing a denser aggregate matrix. Consequently, BN3 containing ASP200-PET aggregate achieved the highest splitting tensile strength among the PET-based mixtures.

The results further indicate that increasing RHA fineness increased the density of the PET-RHA artificial aggregates and improved their mechanical performance. The denser aggregate structure likely enhanced the aggregate–mortar bond and facilitated more effective stress transfer under tensile loading, thereby contributing to the observed increase in splitting tensile strength.

Table 7. Density and splitting tensile strength of all specimens.

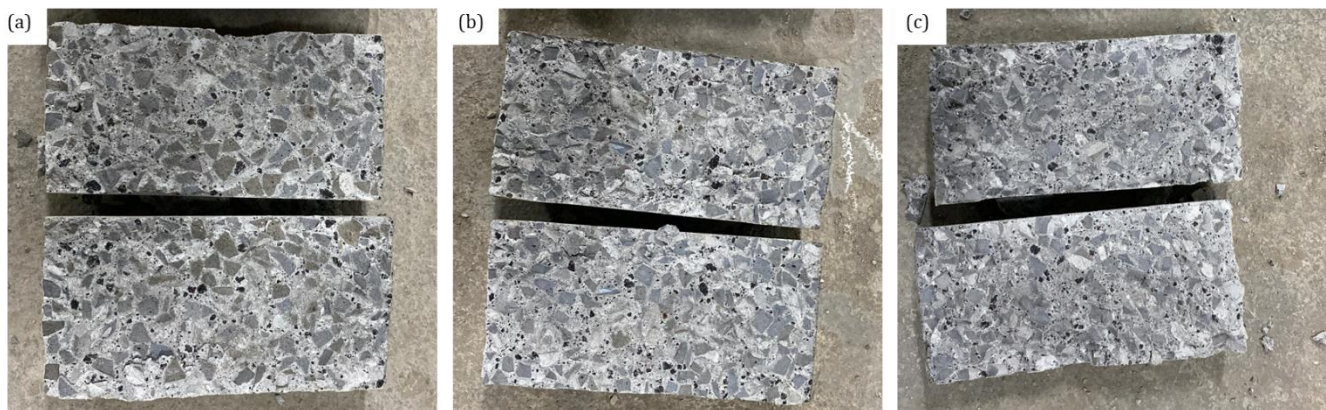
Specimen code	Coarse aggregate type	Density (kg/m ³)	Density average	Splitting tensile Strength (MPa)	Splitting tensile strength average (MPa)	SD (MPa)	COV (%)
BN0	Normal concrete	2,452.23		2.73			
BN0	Normal concrete	2,509.55	2460.72	2.63	2.67	0.055	2.07
BN0	Normal concrete	2,420.38		2.64			
BN1	ASP50-PET	1,834.39		1.30			
BN1	ASP50-PET	1,783.44	1821.66	1.38	1.35	0.044	3.23
BN1	ASP50-PET	1,847.13		1.37			
BN2	ASP100-PET	1,955.41		1.48			
BN2	ASP100-PET	1,828.03	1893.84	1.56	1.53	0.046	3.01
BN2	ASP100-PET	1,898.09		1.56			
BN3	ASP200-PET	1,923.57		1.76			
BN3	ASP200-PET	1,898.09	1895.97	1.50	1.58	0.156	9.89
BN3	ASP200-PET	1,866.24		1.48			

The splitting tensile strength results are also consistent with previous studies investigating plastic-based aggregates and supplementary cementitious materials. Previous researchers have reported that concretes containing PET aggregates generally exhibit lower tensile strength than conventional concrete because of the relatively smooth surface texture and weaker interfacial transition zone between the aggregate and cement matrix. Nevertheless, improvements in tensile strength have been observed when finer pozzolanic materials are incorporated, owing to their ability to refine the microstructure and enhance aggregate–matrix bonding. The increase in splitting tensile strength from 1.35 MPa for BN1 to 1.58 MPa for BN3 obtained in this study supports

these observations and confirms the positive influence of finer RHA on the mechanical performance of PET-based artificial aggregate concrete.

Fig. 10(a–c) presents the fracture patterns of concrete specimens after the splitting tensile strength test. The BN3 concrete incorporating ASP200-PET exhibits the roughest fracture surface, followed by BN2 concrete with ASP100-PET, while the smoothest fracture surface is observed in BN1 concrete with ASP50-PET.

These observations indicate that concretes with higher compressive strength and splitting tensile strength tend to produce rougher fracture surfaces, reflecting improved internal bonding and crack propagation resistance within the concrete matrix.

**Fig. 10.** Fracture patterns of concrete specimens: (a) BN1; (b) BN2; (c) BN3.

4. Conclusions

This study investigated the mechanical properties of concrete incorporating rice husk ash (RHA)–PET artificial coarse aggregates produced using different RHA particle sizes. The control concrete (BN0) achieved a 28-day compressive strength of 27.50 MPa, exceeding the target strength of 25 MPa and confirming the adequacy of the reference mixture. In contrast, the incorporation of PET-based artificial aggregates reduced the compressive

strength to 14.58–17.42 MPa. Nevertheless, compressive strength increased with increasing RHA fineness, with BN3 (ASP200–PET) exhibiting the highest compressive strength among the modified mixtures (17.42 MPa), followed by BN2 (15.52 MPa) and BN1 (14.58 MPa).

The density measurements obtained from the compressive-strength specimens (Table 6) indicate that the incorporation of PET-based artificial aggregates substantially reduced concrete density. While the control concrete exhibited an average density of 2380.04 kg/m³,

the average densities of BN1, BN2, and BN3 were 1821.66 kg/m³, 1887.47 kg/m³, and 1923.57 kg/m³, respectively. The density measurements obtained from the splitting tensile-strength specimens (Table 7) showed similar trends, with minor differences attributable to normal specimen-to-specimen variability because separate sets of cylinders were used for each mechanical test. Overall, increasing the fineness of the RHA produced denser artificial aggregates, resulting in a gradual increase in concrete density. These results demonstrate that the incorporation of PET–RHA artificial aggregates produced lower-density concrete compared with conventional concrete.

The splitting tensile strength followed a trend similar to that of compressive strength. The control concrete achieved the highest tensile strength (2.67 MPa), whereas BN1, BN2, and BN3 achieved average values of 1.35 MPa, 1.53 MPa, and 1.58 MPa, respectively. The improvement observed with increasing RHA fineness suggests that finer RHA particles enhanced the internal structure of the PET-based aggregates and improved stress transfer within the concrete matrix.

Overall, the incorporation of RHA–PET artificial aggregates reduced the mechanical properties of concrete compared with conventional natural aggregate concrete but substantially decreased its density. Among the investigated mixtures, BN3 (ASP200–PET) exhibited the most favorable combination of compressive strength (17.42 MPa), splitting tensile strength (1.58 MPa), and density (1923.57 kg/m³). Therefore, BN3 is considered the optimum mixture in this study and shows potential for use in lightweight partition walls, non-load-bearing masonry blocks, paving blocks, pedestrian walkways, landscape elements, and other lightweight precast products where reduced self-weight and sustainable material utilization are desirable. Further optimization of the aggregate production process and concrete mixture design is required to achieve higher strength levels suitable for broader structural applications.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- AbdelMoti HM, Mustafaa MA (2019). Use of polypropylene waste plastic pellets as partial replacement for fine aggregate in concrete. *University of Khartoum Engineering Journal*, 9(1), 37–43.
- Abellán-García J, Martínez DM, Khan MI, Abbas YM, Pellicer-Martínez F (2023). Environmentally friendly use of rice husk ash and recycled glass waste to produce ultra-high-performance concrete. *Journal of Materials Research and Technology*, 25, 1869–1881.
- Abolhasani A, Samali B, Aslani F (2022). Rice husk ash incorporation in calcium aluminate cement concrete: life cycle assessment, hydration and strength development. *Sustainability*, 14(2), 1012.
- ACI E1-07 (2007). *Aggregates for Concrete*. American Concrete Institute, Farmington Hills, MI, USA.
- Al-Baghdadi HM, Shubbar AA, Al-Khafaji ZS (2021). The impact of rice husk ash on mechanical properties of reactive powder concrete. *International Review of Civil Engineering*, 12(4), 248–254.
- Almeshal I, Tayeh BA, Alyousef R, Alabduljabbar H, Mohamed AM (2020). Eco-friendly concrete containing recycled plastic as partial replacement for sand. *Journal of Materials Research and Technology*, 9(3), 4631–4643.
- Amran M, Fediuk R, Murali G, Vatin N, Karelina M, Ozbakkaloglu T, Krishna RS, Sahoo AK, Das SK, Mishra J (2021). Rice husk ash-based concrete composites: a critical review of their properties and applications. *Crystals*, 11(2), 168.
- Askar MK, Al-Kamaki YSS, Hassan A (2023). Utilizing polyethylene terephthalate (PET) in concrete: a review. *Polymers*, 15(15), 3320.
- ASTM C29/C29M-97 (1997). *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*. ASTM International, West Conshohocken, PA, USA.
- ASTM C39/C39M-21 (2021). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA, USA.
- ASTM C496/C496M-17 (2017). *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA, USA.
- ASTM C566-04 (2004). *Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying*. ASTM International, West Conshohocken, PA, USA.
- Awolusi TF, Oguntayo DO, Aladeboye OJ, Azab M, Deifalla AF (2023). Optimization of concrete containing polyethylene terephthalate powder and rice husk ash using response surface methodology. *Journal of Engineering*, 2023(1), 6237122.
- Bachtar E, Jumawan F, Tahang T, Setiawan A (2020). Examining polyethylene terephthalate (PET) as artificial coarse aggregates in concrete. *Civil Engineering Journal*, 6(12), 2416–2424.
- Badache A, Latroch N, Hacini M, Benosman AS, Mouli M, Senhadji Y, Maherzi W (2025). Innovative composite aggregates from thermoplastic waste for circular economy mortars. *Construction Materials*, 5(3), 58.
- Bohre A, Jadhao P, Tripathi K, Pant KK, Likozar B, Saha B (2023). Chemical recycling of PET waste. *ChemSusChem*, 16(14), e202300142.
- Bouarroudj ME, Rémond S, Cazacliu B, Potier G, Courard L, Bulteel D (2023). Effects of crushing and grinding on the porosity of hardened cement paste. *Buildings*, 13(9), 2319.
- Correa PM, Santana RMC, Guimarães D, Graeff AG (2020). Post-consumer PP as partial substitute of sand: effect of surface treatment PP with surfactant on concrete properties. *Composite Interfaces*, 27(9), 815–828.
- Dawood AO, Al-Khazraji H, Fali RS (2021). Physical and mechanical properties of concrete containing PET wastes as a partial replacement for fine aggregates. *Case Studies in Construction Materials*, 14, e00482.
- Duan Z, Zhao W, Ye T, Zhang Y, Zhang C (2022). Measurement of water absorption of recycled aggregate. *Materials*, 15(15), 5141.
- Endale SA, Taffese WZ, Vo DH, Yehualaw MD (2023). Rice husk ash in concrete. *Sustainability*, 15(1), 137.
- Farid SA, Zaheer MM (2023). Production of new generation and sustainable concrete using rice husk ash (RHA): a review. *Materials Today: Proceedings*, in press.
- Faried AS, Mostafa SA, Tayeh BA, Tawfik TA (2021). Nano rice husk ash in ultra-high-performance concrete. *Construction and Building Materials*, 290, 123279.

- Ganasen N, Krishnaraj L, Onyelowo KC, Alaneme GU, Otu ON (2023). Soft computing techniques for predicting the properties of raw rice husk concrete bricks using regression-based machine learning approaches. *Scientific Reports*, 13, 14503.
- Gencil O, Benli A, Bayraktar OY, Kaplan G, Sutcu M, Elabade WAT (2021). Effect of waste marble powder and rice husk ash on the microstructural, physico-mechanical and transport properties of foam concretes exposed to high temperatures and freeze-thaw cycles. *Construction and Building Materials*, 291, 123374.
- Hasan NMS, Sobuz MHR, Khan MMH, Mim NJ, Meraz MM, Datta SD, Rana MJ, Saha A, Akid ASM, Mehedi MT, Houda M, Sutan NM (2022). Integration of rice husk ash as supplementary cementitious material in the production of sustainable high-strength concrete. *Materials*, 15(22), 8171.
- Hu L, He Z, Zhang S (2020). Sustainable use of rice husk ash in cement-based materials: environmental evaluation and performance improvement. *Journal of Cleaner Production*, 264, 121744.
- Jaskowska-Lemańska J, Kucharska M, Matuszak J, Nowak P, Łukaszczyk W (2022). Selected properties of self-compacting concrete with recycled PET aggregate. *Materials*, 15(7), 2566.
- Jittin V, Bahurudeen A, Ajinkya SD (2020). Utilisation of rice husk ash for cleaner production of different construction products. *Journal of Cleaner Production*, 263, 121578.
- Kang S, Hong S, Moon J (2019). The use of rice husk ash as reactive filler in ultra-high performance concrete. *Cement and Concrete Research*, 115, 389-400.
- Kannur B, Chore HS (2023). Low-fines self-consolidating concrete using rice husk ash for road pavement: an environment-friendly and sustainable approach. *Construction and Building Materials*, 365, 130036.
- Liang C, Chen H, Li R, Chi W, Wang S, Hou S, Gao Y, Zhang P (2024). Effect of additional water content and adding methods on the performance of recycled aggregate concrete. *Construction and Building Materials*, 423, 135868.
- Lin Y, Alengaram J, Ibrahim Z (2023). Effect of treated and untreated rice husk ash, palm oil fuel ash, and sugarcane bagasse ash on the mechanical, durability, and microstructure characteristics of blended concrete - a comprehensive review. *Journal of Building Engineering*, 78, 107500.
- Marvila MT, de Matos P, Rodríguez E, Monteiro SN, de Azevedo ARG (2022). Recycled aggregate: a viable solution for sustainable concrete production. *Materials*, 15(15), 5276.
- Mohsen MO, Aburumman MO, Al Diseet MM, Taha R, Abdel-Jaber M, Senouci A, Abu Taqa A (2023). Fly ash and natural pozzolana impacts on sustainable concrete permeability and mechanical properties. *Buildings*, 13(8), 1927.
- Mousavimehr M, Nematzadeh M (2020). Post-heating flexural behavior and durability of hybrid PET-rubber aggregate concrete. *Construction and Building Materials*, 265, 120359.
- Paikara RK, Gyawali TR (2023). Influence of aluminum powder content and powder-to-sand ratio on the physical and mechanical properties of aerated lightweight mortar. *Cleaner Materials*, 10, 100213.
- Pu B, Liu B, Li L, Jiang L, Zhou J, Ding P (2024). Using rice husk ash in alkali-activated ultra-high-performance concrete: flowability, early age strength and elasticity modulus. *Construction and Building Materials*, 443, 137771.
- Qaidi S, Al-Kamaki Y, Hakeem I, Dulaimi AF, Özkılıç Y, Sabri M, Sergeev V (2023). Investigation of the physical-mechanical properties and durability of high-strength concrete with recycled PET as a partial replacement for fine aggregates. *Frontiers in Materials*, 10, 1101146.
- Rao Y, Ding Y, Sarmah AK, Liu D, Pan B (2020). Vertical distribution of pore-aggregate-cement paste in statically compacted pervious concrete. *Construction and Building Materials*, 237, 117605.
- Rocha JHA, Tinoco MP, Toledo Filho RD (2023). The effect of recycled concrete powder (RCP) from precast concrete plant on fresh and mechanical properties of cementitious pastes. *Materiales de Construcción*, 73(352), e325.
- Herrera Rosas M, Cayo Chileno NG, Araoz Campos A, Aquino Rocha JH (2023). Analysis of concrete mechanical properties when adding type-E glass fibers. *Journal of Building Pathology and Rehabilitation*, 8, 40.
- Sandhu RK, Siddique R (2017). Influence of rice husk ash (RHA) on the properties of self-compacting concrete: a review. *Construction and Building Materials*, 153, 751-764.
- Satwarnirat A, Archenita D, Eldiswari Z, Silvianengsih, Yuliet R (2023). The influence of cement substitution with rice husk ash on high-strength concrete. *E3S Web of Conferences*, 464, 09008.
- Shaheen YBI, Etman ZA, Sabiha HL (2025). Design of reactive powder concrete mortar mixes through high strength and durability. *Challenge Journal of Concrete Research Letters*, 16(3), 142-154.
- Shirgire A, Thenmozhi S, Jesuraj VP, Shelar A, Chavhan VS, Javanjal V (2024). Experimental study on high performance concrete using rice husk ash. *Materials Today: Proceedings*, 103, 594-600.
- Siddika A, Mamun MAA, Ali MH (2018). Study on concrete with rice husk ash. *Innovative Infrastructure Solutions*, 3, 18.
- Siddika A, Mamun MAA, Alyousef R, Mohammadhosseini H (2021). State-of-the-art-review on rice husk ash: a supplementary cementitious material in concrete. *Journal of King Saud University - Engineering Sciences*, 33(5), 294-307.
- SNI 03-2461-2002 (2002). *Specification of Lightweight Aggregate for Structural Lightweight Concrete*. Badan Standardisasi Nasional, Jakarta, Indonesia.
- Soong YHV, Sobkowicz MJ, Xie D (2022). Recent advances in biological recycling of polyethylene terephthalate (PET) plastic wastes. *Bio-engineering*, 9(3), 98.
- Sosoi G, Abid C, Barbuta M, Burlacu A, Balan MC, Branoaea M, Vizitiu RS, Rigollet F (2022). Experimental investigation on mechanical and thermal properties of concrete using waste materials as an aggregate substitution. *Materials*, 15(5), 1728.
- Stratoura MC, Lazari GED, Badogiannis EG, Papadakis VG (2023). Perlite and rice husk ash re-use as fine aggregates in lightweight aggregate structural concrete-durability assessment. *Sustainability*, 15(5), 4217.
- Tanash AO, Budiea AMA, Md Jaafar MF, Muthusamy K, Zulkarnain F (2025). Experimental study on the mechanical performance of polypropylene fiber-reinforced concrete incorporating palm oil fuel ash as partial cement replacement. *Challenge Journal of Concrete Research Letters*, 16(3), 115-124.
- Tayeh BA, Alyousef R, Alabduljabbar H, Alaskar A (2021). Recycling of rice husk waste for a sustainable concrete: a critical review. *Journal of Cleaner Production*, 312, 127734.
- Théréné F, Keita E, Naël-Redolfi J, Boustingorry P, Bonafous L, Roussel N (2020). Water absorption of recycled aggregates: measurements, influence of temperature and practical consequences. *Cement and Concrete Research*, 137, 106196.
- Tladi M, Mashifana T, Sithole NT (2023). Utilization of plastic waste and waste rubber tyres to modify bitumen binder in road construction. *Key Engineering Materials*, 947, 131-138.
- Wang H, Chen D, Guo R, Tian J, Li B (2023). A preliminary study on the improvement of gangue/tailing cemented fill by bentonite: flow properties, mechanical properties and permeability. *Materials*, 16(20), 6802.
- Wang J, Li X, Zhang T, Chen Y, Wang T, Zhao Y (2022). Electro-reforming polyethylene terephthalate plastic to co-produce valued chemicals and green hydrogen. *The Journal of Physical Chemistry Letters*, 13(2), 622-627.
- Xiong B, Falliano D, Restuccia L, Di Trapani F, Demartino C, Marano GC (2023). Mortar with substituted recycled PET powder: experimental characterization and data-driven strength predictive models. *Journal of Materials in Civil Engineering*, 35(9), 04023312.
- Zahid M, Abbas YM, Shafiq N, Khan MI, Ismail FI (2024). Sustainable engineered geopolymer composites utilizing gamma-irradiated PET and graphene nanoplatelets: optimization and performance enhancement. *Sustainability*, 16(17), 7455.
- Zareei SA, Ameri F, Dorostkar F, Ahmadi M (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: evaluating durability and mechanical properties. *Case Studies in Construction Materials*, 7, 73-81.
- Zulkarnain NH, Gani P, Ng CC, Uvarajan T (2021). Utilisation of plastic waste as aggregate in construction materials: a review. *Construction and Building Materials*, 296, 123669.



Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Evaluation of shear strength prediction models for polypropylene fiber-reinforced concrete beams without stirrups: Influence of residual tensile strength estimation on fib-MC2010 code predictions

Kadir Sengun ^{a,*} , Hasan Cem Akkaya ^b 

^a Department of Civil Engineering, Istanbul Aydin University, 34295 İstanbul, Türkiye

^b Department of Civil Engineering, Kırklareli University, 39100 Kırklareli, Türkiye

ABSTRACT

Predicting the shear strength of polypropylene fiber-reinforced concrete (PFRC) beams remains challenging because most formulations were calibrated using steel fiber-reinforced concrete (SFRC) data, while post-cracking tensile properties required by design models are rarely reported for PFRC members. This study evaluates analytical and code-based models using a database of 98 PFRC beams without transverse reinforcement. The evaluated formulations included analytical models and the RILEM TC 162-TDF, DAFStB, and fib Model Code 2010 approaches. Particular attention is given to fib Model Code 2010, which requires residual tensile strength parameters unavailable for most specimens. Therefore, three alternative procedures were used specifically within the fib Model Code 2010 framework to estimate these parameters. The resulting estimates were incorporated separately into the same shear resistance equation to quantify their influence on predicted capacity. Performance was assessed using the mean experimental-to-predicted shear strength ratio, coefficient of variation, root mean square error, coefficient of determination, mean absolute error, and distributions of safe and unsafe predictions. Considerable differences were observed among the models. Among the analytical formulations, the model proposed by Arslan et al. provided the most balanced performance, whereas DAFStB exhibited the weakest predictive capability. The three fib Model Code 2010 implementations produced substantially different results despite using the same shear resistance equation. The findings show that fib Model Code 2010 predictions are highly sensitive to the residual tensile strength estimation procedure. Reliable PFRC-specific characterization of post-cracking tensile behavior is therefore essential for improving design-oriented shear strength predictions.

Citation: Sengun K, Akkaya HC (2026). Evaluation of shear strength prediction models for polypropylene fiber-reinforced concrete beams without stirrups: Influence of residual tensile strength estimation on fib-MC2010 code predictions. *Challenge Journal of Concrete Research Letters*, 17(3), 364–386.

ARTICLE INFO

Article history:

Received – August 1, 2026
Revision requested – August 24, 2026
Revision received – August 29, 2026
Accepted – September 7, 2026

Keywords:

Polypropylene fiber-reinforced concrete
Shear strength
PFRC beams
fib Model Code 2010
Residual tensile strength



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

1. Introduction

The shear performance of reinforced concrete (RC) beams has received considerable attention due to the brittle behavior associated with shear failure and its sudden occurrence. While flexural failure normally occurs

along with yielding of longitudinal steel and plastic deformation, shear failure normally involves the fast formation and spread of diagonal cracks. Therefore, the increase of shear strength, restraint of crack propagation, and increase of load-bearing capability after the formation of cracks have been some of the challenges that

* Corresponding author. E-mail address: kadir sengun@aydin.edu.tr (K. Sengun)

ISSN: 2548-0928 / DOI: <https://doi.org/10.20528/cjcr.2026.1288>

civil engineers face in the analysis and design of RC structures. Among the different methods developed to meet these challenges, the use of fibers in concrete has proven to be an effective method for increasing the tensile properties of concrete (Majdzadeh et al. 2006; Greenough and Nehdi 2008; Jongvivatsakul et al. 2013; Sahoo et al. 2015; Campione et al. 1999; Parmentier et al. 2012).

Fiber reinforced concrete (FRC) has proven itself highly promising in improving the structural behavior of reinforced concrete members. The presence of fibers across cracks helps in transferring tensile stresses, arresting crack opening, increasing aggregate interlocking and improving the residual load carrying capacity of the member post cracking. FRC members generally show higher ductility, energy dissipation capacity, crack distribution and shear strength when compared to ordinary reinforced concrete members (Majdzadeh et al. 2006; Greenough and Nehdi 2008; Jongvivatsakul et al. 2013; Sahoo et al. 2015; Campione et al. 1999; Parmentier et al. 2012). Such promising results have paved the way for investigating and using FRC in structural members that are subjected to shear loading. Of all the fibers that have been studied, steel fiber reinforced concrete (SFRC) has attracted more research interest than any other fiber type both experimentally and analytically. Steel fibers' mechanical properties like high tensile strength, high stiffness and effective bonding properties make them highly useful in bridging shear cracks. Experimental studies have shown that steel fibers help in increasing shear strength of the member and also partly replace transverse reinforcing steel bars (Greenough and Nehdi 2008; Sahoo et al. 2015; Parmentier et al. 2012). Hence, many of the shear strength equations that have been proposed were based on SFRC data (Majdzadeh et al. 2006; Jongvivatsakul et al. 2013; Parmentier et al. 2012). However, their applicability to other fiber types might be questioned since contribution of fibers to the shear resistance depends not only on amount of fibers but also on such factors as fiber stiffness, tensile strength, aspect ratio, bond properties, anchoring process and interaction with concrete matrix. These parameters differ between various fibers which results in decreased efficiency of prediction based on the models created for SFRC. The importance of fiber characteristics, reinforcement distribution, and fiber-matrix interaction mechanisms has also been highlighted in recent theoretical studies on short-fiber-reinforced composite systems. Advanced continuum formulations incorporating non-local elasticity, strain-gradient effects, stress-driven constitutive models, and doublet mechanics have shown that reinforcement configuration, constituent interaction, and scale-dependent effects can considerably influence the mechanical response of fiber-reinforced structures (Akpınar et al. 2025a, 2025b, 2026a, 2026b). This problem is particularly significant for polypropylene fiber-reinforced concrete (PFRC) and other macro synthetic fiber systems. Compared to steel fibers, polypropylene fibers usually demonstrate such characteristics as lower elastic modulus, specific bond properties and pull out behavior. This makes contribution of polypropylene fibers to crack bridging and post cracking properties different from steel fibers. At the same time, there

are several advantages provided by use of polypropylene fibers, including corrosion resistance, low density, easy processing and durability (Conforti et al. 2015; Ababneh et al. 2017; Arslan et al. 2017; Yang et al. 2021; Sahoo et al. 2015).

Recent experiments have shown that polypropylene fibers could significantly affect the shear properties of RC beams. Studies show that crack control, ductility, toughness, and shear resistance were improved, especially for beams with no transverse reinforcements or beams with low stirrup ratios (Conforti et al. 2015; Xiang et al. 2022; Ababneh et al. 2017; Arslan et al. 2017; Yang et al. 2021; Zhang et al. 2020; Ünal et al. 2021). Additionally, the application of polypropylene fibers was also found to positively affect the structural performance of lightweight concrete beams, wide shallow beams, and other types of special structural sections (Conforti et al. 2015; Xiang et al. 2022; Ababneh et al. 2017; Yang et al. 2021). The positive effects of macro-synthetic fibers on the post-cracking properties have also been shown in different studies (Lakavath et al. 2021; Ababneh et al. 2017). However, despite these promising findings, the behavior of polypropylene fibers has proven to be inconsistent among different experimental studies. While in some cases significant improvements in the shear properties of polypropylene fibers were noticed, in others there were no significant changes, especially for lower amounts of polypropylene fibers (Lakavath et al. 2021). On the other hand, many factors such as the compressive strength of concrete, fiber volume fraction, fiber shape, longitudinal reinforcement ratio, beam depth, shear span-to-depth ratio, and many others affect the shear performance of PFRC members (Lakavath et al. 2021; Xiang et al. 2022; Ababneh et al. 2017; Shaaban et al. 2021; Said et al. 2021; Hossain et al. 2023; Al Ghali et al. 2023; Atea 2017). These issues lead to the difficulty in designing reliable and universally acceptable shear strength prediction models. The second significant factor to consider is the variety of experimental data collected so far concerning the elements of PFRCs. In particular, the previously conducted research on various beam types, types of concrete, loading conditions, reinforcement arrangement, and the use of different materials, including lightweight concrete, pre-stressed concrete, recycled aggregate concrete, hybrid fiber systems, and sustainable concrete mixes has been carried out (Lakavath et al. 2021; Xiang et al. 2022; Ababneh et al. 2017; Shaaban et al. 2021; Said et al. 2021; Hossain et al. 2023; Al Ghali et al. 2023; Atea 2017). While these studies yield valuable data concerning specific cases, the variety of the test conditions creates problems in assessing their general applicability.

This diversity of experimental conditions creates additional challenges in developing reliable shear strength prediction models for PFRC members. Various studies have been performed on different beam types, concrete classes, loading scenarios, reinforcement configurations, and material combinations, including lightweight concrete, prestressed concrete, recycled aggregate concrete, hybrid fiber systems, and sustainable concrete mixes (Lakavath et al. 2021; Xiang et al. 2022; Ababneh et al. 2017; Shaaban et al. 2021; Said et al. 2021; Hossain et al.

2023; Al Ghali et al. 2023; Atea 2017). While these studies have considerably improved the current understanding of PFRC shear behavior, the applicability and reliability of existing shear strength prediction models across such a diverse range of structural configurations remain insufficiently established. Furthermore, most available analytical and code-based formulations have been developed and calibrated using steel fiber-reinforced concrete (SFRC) databases, whereas their predictive performance for PFRC beams has not yet been comprehensively evaluated.

An additional challenge arises from the implementation of design-oriented approaches such as fib Model Code 2010 (fib 2010), which require residual tensile strength parameters to represent the post-cracking behavior of fiber-reinforced concrete. These parameters are unavailable for most PFRC beam specimens reported in the literature, introducing considerable uncertainty into model implementation and limiting the direct evaluation of such approaches. Moreover, most available analytical and code-based shear strength formulations were originally developed or calibrated using steel fiber-reinforced concrete databases, and their predictive performance for PFRC beams has not yet been comprehensively established. Therefore, a systematic assessment based on a sufficiently broad PFRC database is required to clarify the applicability, accuracy, and limitations of the available prediction models.

Accordingly, the primary objective of this study is to evaluate the predictive performance of existing analytical, semi-empirical, and code-based shear strength models using a database of 98 PFRC beams without transverse reinforcement collected from published experimental studies. The evaluated formulations include the models proposed by Said et al. (2021), Zhang et al. (2020), Arslan et al. (2017), and Albidah and Abbas (2024), together with the fib Model Code 2010, DAFStB, and RILEM TC 162-TDF approaches. Particular attention is given to fib Model Code 2010 because the residual tensile strength parameters required for its implementation were unavailable for most specimens. To address this limitation, three alternative residual tensile strength estimation procedures were applied separately within the same fib Model Code 2010 shear resistance formulation, allowing the influence of residual tensile strength characterization on predicted shear capacity to be isolated. Model performance was evaluated using multiple statistical indicators and the distributions of safe and unsafe predictions. Through this framework, the study clarifies the applicability and limitations of existing shear strength models for PFRC beams and demonstrates the importance of PFRC-specific residual tensile strength characterization in design-oriented prediction procedures.

2. Experimental Database

2.1. Database compilation

An extensive database for polypropylene fiber reinforced concrete (PFRC) beams without transverse reinforcement has been prepared based on published experimental tests available in literature. The database con-

tains only those PFRC beams that were subjected to monotonic loading and failed in shear. Beam specimens that failed in any other mode besides shear failure have been omitted from the database. In addition, beams containing conventional transverse reinforcement within the investigated shear span were not considered in order to isolate the contribution of polypropylene fibers to shear resistance. The adopted selection criteria were intended to ensure a consistent database focused specifically on the assessment of fiber contribution to shear resistance in PFRC beams. The compiled database consists of 98 beam specimens collected from 28 independent experimental investigations (Altoubat et al. 2009; Navas et al. 2018; Al-Alawi and Mashrei 2022; Xiang et al. 2022; Altoubat et al. 2020; Uğur and Ünal 2022; Zhang et al. 2014; Ababneh et al. 2017; Arslan et al. 2017; Majdazadeh et al. 2006; Sahoo et al. 2015; Shaaban et al. 2021; Bastami 2019; Murad and Abdel-Jabbar 2022; Altoubat et al. 2012; Parmentier et al. 2012; Furlan Jr and de Hanai 1997; Hossain et al. 2023; Shoeib et al. 2023; Mori et al. 2017; Bajaj and Shrivastava 2011; Al-Khafaji and Harba 2023; Kamal et al. 2014; Al Ghali et al. 2023; Atea 2017; Rao 2011; Ozturk et al. 2017; Ketenci 2022). To ensure database consistency, duplicate inclusion of specimens reported in multiple publications was avoided whenever overlapping experimental datasets were identified. The collected specimens cover a wide range of concrete compressive strengths (f_c), fiber volume fractions (V_f), fiber aspect ratios (l_f/d_f), longitudinal reinforcement ratios (ρ), effective depths (d), and shear span-to-effective depth ratios (a/d). The wide range of material, geometric, reinforcement-related, and fiber parameters represented in the database provides a suitable basis for evaluating both the robustness and general applicability of existing shear strength prediction models for PFRC beams. For each specimen, the value of the compressive strength of concrete (f_c), effective depth (d), ratio of longitudinal steel reinforcement (ρ), ratio of shear span to effective depth (a/d), volume fraction of fibers (V_f), fiber aspect ratio (l_f/d_f), and shear strength (V_{exp}) were documented if they were available. This selection of parameters was based on their importance as influential factors of the shear performance of fiber-reinforced concrete members. Table 1 presents a summary of the experimental works used in the database along with the number of specimens per source.

Concrete compressive strength values stated in the original literature were not reported using the same type of specimens. Some reports were using cylinder compressive strengths while others were using cube compressive strengths. In order to unify all the reported compressive strength values, all were converted to the equivalent cylinder compressive strengths. In case of reports stating the cube compressive strength values, $f_c' = 0.80f_{cu}$ was adopted. Hence, the f_c' parameter used in this study denotes the equivalent cylinder compressive strength for all specimens. It is acknowledged that the relationship between cube and cylinder compressive strengths may vary depending on concrete strength level, aggregate characteristics, specimen geometry, and testing procedures. Nevertheless, the conversion factor $f_c' = 0.80f_{cu}$ was adopted as a practical standardization

approach to ensure a consistent compressive-strength parameter across the compiled database and facilitate a uniform comparison of the investigated prediction models. For sake of clarity, the full specimen-based database is provided in Appendix B. The database consists of specimen number, reference source, geometric information, reinforcement information, fiber information, equivalent

cylinder compressive strengths, failure modes and experimental shear strengths. All specimens were subjected to monotonic loading by either three point or four point bending schemes. In case where experimental shear strength values were not stated, they were calculated from ultimate load values based on the static equilibrium equations for the given loading and support condition.

Table 1. Experimental studies included in the database and corresponding number of specimens.

Reference	Number of Specimens
Altoubat et al. (2009)	11
Navas et al. (2018)	4
Al-Alawi and Mashrei (2022)	9
Xiang et al. (2022)	3
Altoubat et al. (2020)	1
Uğur and Ünal (2022)	1
Zhang et al. (2014)	1
Ababneh et al. (2017)	3
Arslan et al. (2017)	6
Majdzadeh et al. (2006)	6
Sahoo et al. (2015)	1
Shaaban et al. (2021)	3
Bastami (2019)	3
Murad and Abdel-Jabbar (2022)	3
Altoubat et al. (2012)	2
Parmentier et al. (2012)	4
Furlan Jr. and de Hanai (1997)	1
Hossain et al. (2023)	2
Shoeib et al. (2023)	3
Mori et al. (2017)	2
Bajaj and Shrivastava (2011)	12
Al-Khafaji and Harba (2023)	2
Kamal et al. (2014)	2
Al Ghali et al. (2023)	2
Atea (2017)	2
Rao et al. (2011)	6
Ozturk et al. (2017)	1
Ketenci (2022)	2
Total	98

2.2. Characteristics of the database

The developed database includes various types of geometrical, material, reinforcement, and fiber properties which affect the shear capacity of PFRC members. The value of the equivalent cylinder compressive strength (f_c) is between 13.85 MPa and 150 MPa, which shows that a variety of concrete strength grades are taken into account in the developed database. The values of the effective depth are varied from 85.25 mm up to 600 mm, whereas the values of the volume fraction of fibers vary from 0.10% to 3.00%. Besides, a great variability can be found in such parameters as the longitudinal reinforcement

ratio (ρ), shear span-to-depth ratio (a/d), and fiber aspect ratio. Such variability provides a good basis to test the validity of the existing shear capacity prediction models for PFRC beams. The ranges of the main parameters used in this study are listed in Table 2.

3. Shear Strength Prediction Models

This research investigates the predictability of available analytical and code-based shear strength prediction equations for PFRC beams without transverse reinforcement. The considered equations cover different method-

ologies for predicting shear resistance and involve different parameters that are related to the strength of concrete, the properties of fibers, the ratio of reinforcement, geometrical properties of the members, size effects, and post-cracking behavior. An important difference between the considered equations is the consideration of the contribution of the fibers. Whereas the analytical equations take into account the properties of the fibers through direct parameters like the volume fraction of fibers and as-

pect ratio of the fibers, the code-based equations use the residual tensile strength parameters, which try to capture the post-cracking behavior of the fiber-reinforced concrete. Attention is paid to fib Model Code 2010 (fib 2010). Three different residual tensile strength estimations were used since there are few reported experimental data about post-cracking tensile properties. The investigated models and the corresponding implementation procedures are described in the following sections.

Table 2. Summary of database parameter ranges.

Parameters	Minimum–Maximum Values
Concrete compressive strength, f'_c (MPa)	13.850 – 150.000
Effective depth, d (mm)	85.250 – 600.000
Shear span-to-depth ratio, a/d	0.580 – 4.870
Longitudinal reinforcement ratio, ρ	0.0020 – 0.0464
Fiber volume fraction, V_f (%)	0.100 – 3.000
Fiber aspect ratio, l_f/d_f	12.500 – 840.000
Fiber tensile strength, f_{tenf} (MPa)	375.000 – 685.000
Fiber elastic modulus, E_f (MPa)	3450.000 – 10500.000
Experimental shear capacity, V_{exp} (kN)	13.720 – 500.000

3.1. Overview of the evaluated models

The investigated models differ considerably in terms of their theoretical assumptions, required input parameters, and implementation procedures. The evaluated formulations include empirical, semi-empirical, and code-based approaches that have been proposed for different types of fiber-reinforced concrete (FRC) structures. Although some of the models were originally developed for steel fiber-reinforced concrete (SFRC), polyvinyl alcohol fiber-reinforced concrete (PVA-FRC), or FRC members in general, they were included in the present study to assess their applicability to PFRC beams without transverse reinforcement. For example, the model proposed by Said et al. (2021) was developed for PVA fiber-reinforced members, whereas the Albidah and Abbas (2024) formulation was calibrated using an SFRC database. Differences in fiber stiffness, bond characteristics, pull-out behavior, and post-cracking tensile response may therefore limit the direct transferability of these formulations to PFRC beams. Nevertheless, both models were included to evaluate their predictive performance when extended beyond their original calibration domains. The principal characteristics, required input parameters, and implementation requirements of the investigated models are summarized in Table 3. As shown in Table 3, the investigated formulations differ not only in their theoretical background but also in the way fiber contribution is incorporated into shear resistance predictions. While empirical and semi-empirical models generally utilize directly reported material, geometric, reinforcement-related, and fiber parameters, the code-based approaches rely on residual tensile strength parameters intended to represent the post-cracking be-

havior of fiber-reinforced concrete. This distinction is particularly important in the present study because residual tensile properties were unavailable for a large proportion of the specimens included in the compiled database. Consequently, additional estimation procedures were required for the implementation of the code-based formulations. The adopted procedures and associated assumptions are described in the following section.

It should be noted that the applicability information available from the original studies is summarized in Tables 2 and 3 through the reported parameter ranges of the present PFRC database and the original fiber types used during model development. However, explicit applicability limits were not consistently defined in several of the original formulations. Consequently, all selected models were evaluated using the same PFRC beam database in order to provide a consistent basis for comparison. In particular, the residual strength equations adopted in fib Model Code 2010 Approach I were originally developed using hook-end steel-fiber-reinforced concrete specimens with low fiber volume fractions. Since the objective of this study was to evaluate the predictive performance of existing models for PFRC beams, these original calibration ranges were not used as exclusion criteria during database compilation.

3.2. Model implementation and assumptions

Several of the investigated formulations require input parameters that were unavailable for a considerable portion of the experimental studies included in the database. In particular, residual flexural tensile strength parameters (f_{R1} and f_{R3}) and residual tensile strength parameters required by the code-based approaches (e.g.,

f_{Ftuk} , $f_{fctR,u}$, and $f_{Rk,A}$) were generally not reported in the original experimental publications. As a result, additional implementation procedures and assumptions were required to ensure the consistent application of all investigated models across the compiled database. Whenever sufficient information was available, the original formulations were implemented without modification. When required parameters were missing, they were estimated using procedures proposed in the corresponding references or commonly adopted in the literature. Consequently, the predictive performance of some

models reflects not only the accuracy of the shear resistance formulation itself but also the reliability of the adopted parameter-estimation procedure. This issue is particularly relevant for the code-based approaches, namely fib Model Code 2010 (fib 2010), DAfStB (2012), and RILEM TC 162-TDF (2003), whose implementation depends on residual tensile strength parameters used to represent the post-cracking behavior of fiber-reinforced concrete. The implementation procedures and assumptions adopted for these formulations are described in the following sections.

Table 3. Characteristics and implementation requirements of the evaluated shear strength prediction models.

Model	Original Fiber Type	Model Category	Main Parameters	Required Residual Parameter	Implementation Procedure	Additional Assumptions
Said et al. (2021)	PVA-FRC	Empirical	$f_c, V_f/\text{Fiber factor}$	No	Direct	None
Zhang et al. (2020)	PP-FRC	Empirical	$f_c, V_f/\text{Fiber factor}$	No	Direct	None
Arslan et al. (2017)	FRC	Semi-empirical	$f_c, V_f, \rho, a/d, d$	No	Direct	None
Albidah and Abbas (2024)	SFRC	Empirical	$f_c, V_f, \rho, a/d$	No	Direct	None
fib Model Code 2010 (fib 2010)	FRC	Code-based	f_c, ρ, d, f_{Ftuk}	f_{Ftuk}	Indirect residual strength characterization (3 approaches)	Residual strength estimation required
DAfStB (2012)	SFRC	Code-based	$f_c, d, f_{fctR,u}$	$f_{fctR,u}$	Indirect residual strength characterization	Residual strength estimation required
RILEM TC 162-TDF (2003)	SFRC	Code-based	$f_c, d, f_{Rk,A}$	$f_{Rk,A}$	Indirect residual strength characterization	$f_{Rk,A} = f_{spfc}$ assumption

3.2.1. fib Model Code 2010 (fib 2010)

The shear resistance of PFRC beams without transverse reinforcement was evaluated using the provisions of fib Model Code 2010 (fib 2010). The model accounts for the contribution of fibers through the post-cracking tensile behavior of fiber-reinforced concrete, represented by the characteristic ultimate residual tensile strength parameter, f_{Ftuk} . In fib Model Code 2010, f_{Ftuk} is derived from the residual flexural tensile strength parameters f_{R1} and f_{R3} obtained from standardized bending tests and therefore plays a central role in the prediction of shear resistance. Although fib Model Code 2010 (fib 2010) was originally developed and calibrated for steel fiber-reinforced concrete (SFRC), it was included in the present study to evaluate its applicability to PFRC beams. However, the residual strength parameters required for its implementation were unavailable for the majority of the specimens included in the compiled database. Consequently, the post-cracking tensile properties could not be determined directly from the original experimental studies. To overcome this limitation, three alternative residual tensile strength estimation procedures were adopted. These approaches were incorporated into the same fib Model Code 2010 formulation in order to systematically investigate the influence of residual tensile strength characterization on shear strength predictions. In Approaches I and II, the residual flexural tensile strengths f_{R1} and f_{R3}

were first estimated and subsequently converted into the characteristic ultimate residual tensile strength f_{Ftuk} according to fib Model Code 2010 provisions. In Approach III, the implementation procedure adopted by Lantsoght (2019) was followed. The adopted approaches are described in the following sections.

Approach I: Residual strength estimation using the model of Nzambi et al. (2022)

In the first approach, the residual flexural tensile strengths were estimated using the empirical model proposed by Nzambi et al. (2022). The model predicts the residual strength parameters based on fiber characteristics and pull-out behavior. The estimated residual flexural tensile strengths f_{R1} and f_{R3} were subsequently used to determine the characteristic ultimate residual tensile strength f_{Ftuk} according to the fib Model Code 2010 (fib 2010) procedure, as expressed in Eq. (1). The equations proposed by Nzambi et al. (2022) are provided in Appendix A.

$$f_{Ftuk} = f_{Fts} - \frac{w_u}{CMOD_3} (f_{Fts} - 0.5f_{R3} + 0.2f_{R1}) \quad (1)$$

where f_{Fts} is the serviceability residual tensile strength, f_{R1} and f_{R3} are residual flexural tensile strengths obtained at CMOD values of 0.5 mm and 2.5 mm, respectively, and w_u is the crack width at ultimate. Detailed definitions of all parameters are provided in Appendix A.

The calculated f_{Ftuk} values were then incorporated into the fib Model Code 2010 (fib 2010) shear resistance formulation to determine the predicted shear capacities of the specimens included in the database.

Approach II: Residual strength estimation using the model of Moraes-Neto et al. (2013)

In the second approach, the empirical equations proposed by Moraes-Neto et al. (2013) were used to estimate the residual flexural tensile strengths f_{R1} and f_{R3} . The corresponding equations are presented in Appendix A. The estimated residual flexural tensile strengths were subsequently converted into the characteristic ultimate residual tensile strength f_{Ftuk} according to the fib Model Code 2010 (fib 2010) procedure, as expressed in Eq. (1). The calculated f_{Ftuk} values were then incorporated into the fib Model Code 2010 (fib 2010) shear resistance formulation to determine the predicted shear capacities of the specimens included in the database.

Approach III: implementation based on the procedure adopted by Lantsoght (2019)

The third approach followed the implementation procedure adopted by Lantsoght (2019) for the evaluation of fiber-reinforced concrete beam databases. In this procedure, the splitting tensile strength of fiber-reinforced concrete was first estimated using the empirical relationship proposed by Thomas and Ramaswamy (2007). The corresponding equation is presented in Appendix A as Eq. (A13). The estimated splitting tensile strength was subsequently used to determine the residual tensile strength parameter $f_{fctR,u}$ according to the DAfStB (2012) procedure. Consistent with the methodology adopted by Lantsoght (2019), the calculated $f_{fctR,u}$ values were directly used as the f_{Ftuk} parameter required for the implementation of fib Model Code 2010 (fib 2010). The resulting f_{Ftuk} values were then incorporated into the fib Model Code 2010 shear resistance formulation to determine the predicted shear capacities of the specimens included in the database.

3.2.2. DAfStB (2012)

The DAfStB (2012) formulation evaluates the contribution of fibers to shear resistance through the residual tensile strength parameter $f_{fctR,u}$. Since direct measurements of the required residual tensile properties were unavailable for most specimens included in the database, the implementation procedure adopted by Lantsoght (2019) was followed. In this procedure, the splitting tensile strength of fiber-reinforced concrete was first estimated using the empirical relationship proposed by Thomas and Ramaswamy (2007). The corresponding splitting tensile strength equation proposed by Thomas and Ramaswamy (2007) is presented in Appendix A as Eq. (A13). The estimated splitting tensile strength was subsequently used to determine the residual tensile strength parameter $f_{fctR,u}$ according to the DAfStB (2012) procedure. The calculated $f_{fctR,u}$ values were then incorporated into the DAfStB shear resistance formulation to predict the shear capacities of the specimens included in the database. Consequently, the predictive

performance obtained for the DAfStB model reflects both the accuracy of the shear resistance formulation and the reliability of the adopted residual tensile strength estimation procedure.

3.2.3. RILEM TC 162-TDF (2003)

The RILEM TC 162-TDF (2003) recommendations evaluate the contribution of fibers to shear resistance through the residual flexural tensile strength parameter $f_{Rk,4}$. Since direct measurements of this parameter were unavailable for most specimens included in the database, the implementation procedure adopted by Lantsoght (2019) was followed. In this procedure, the splitting tensile strength of fiber-reinforced concrete was first estimated using the empirical relationship proposed by Thomas and Ramaswamy (2007). The corresponding splitting tensile strength equation proposed by Thomas and Ramaswamy (2007) is presented in Appendix A as Eq. (A13). Following the methodology adopted by Lantsoght (2019), the residual flexural tensile strength required by the RILEM formulation was assumed equal to the estimated splitting tensile strength, i.e., $f_{Rk,4} = f_{spfc}$. The resulting $f_{Rk,4}$ values were subsequently incorporated into the RILEM TC 162-TDF (2003) shear resistance formulation to determine the predicted shear capacities of the specimens included in the database. Consequently, the predictive performance obtained for the RILEM model reflects both the accuracy of the RILEM shear resistance formulation and the reliability of the adopted residual tensile strength estimation procedure.

The code-based formulations were implemented following the procedures and parameter values reported in their original recommendations and in the implementation framework adopted by Lantsoght (2019), as detailed in Appendix A. Accordingly, the prescribed partial safety factors were retained and were not uniformly set equal to 1.0. This implementation was adopted to evaluate each code-based formulation in accordance with its published framework rather than to derive uniformly unfactored nominal capacities. Therefore, the comparison with the empirical and semi-empirical models should be interpreted as an assessment of the predictive performance of the formulations under their respective implementation frameworks.

4. Statistical Evaluation Methodology

The predictive performance of the investigated shear strength models was evaluated by comparing the experimentally measured shear capacities (V_{exp}) with the corresponding predicted values (V_{pred}). For each specimen, the experimental-to-predicted shear strength ratio (V_{exp}/V_{pred}) was calculated and used as the primary indicator of model performance. A ratio equal to unity indicates perfect agreement between experimental and predicted values, whereas values greater than and less than unity indicate conservative and unconservative predictions, respectively. Since unconservative predictions may lead to unsafe structural assessments, particular attention was given to cases where $V_{exp}/V_{pred} < 1.0$.

To provide a comprehensive evaluation of model performance, the mean value (μ), standard deviation (σ), coefficient of variation (COV), mean absolute error (MAE), root mean square error ($RMSE$), and coefficient of determination (R^2) were calculated. These statistical indicators were used to assess prediction accuracy, consistency, scatter, and overall reliability.

The mean value was determined as:

$$\mu = \frac{1}{n} \sum_{i=1}^n \left(\frac{V_{exp}}{V_{pred}} \right)_i \quad (2)$$

where n denotes the total number of specimens included in the database.

The standard deviation was calculated using:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n \left[\left(\frac{V_{exp}}{V_{pred}} \right)_i - \mu \right]^2}{n-1}} \quad (3)$$

The coefficient of variation was obtained from:

$$COV = \frac{\sigma}{\mu} \quad (4)$$

The mean absolute error was calculated as:

$$MAE = \frac{1}{n} \sum_{i=1}^n |V_{exp,i} - V_{pred,i}| \quad (5)$$

The root mean square error was determined from:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (V_{exp,i} - V_{pred,i})^2} \quad (6)$$

The coefficient of determination (R^2) was obtained as the square of the Pearson correlation coefficient (r) between the experimental and predicted shear strengths:

$$R^2 = r^2 \quad (7)$$

where r denotes the Pearson correlation coefficient.

Models exhibiting mean values close to unity, low coefficients of variation, low prediction errors (MAE and $RMSE$), high coefficients of determination (R^2), and a limited proportion of unconservative predictions were considered to provide more accurate and reliable shear strength estimates. The investigated formulations were subsequently compared based on the collective interpretation of these statistical indicators.

5. Results and Discussion

The predictive capabilities of the selected shear strength models were evaluated using the assembled database of polypropylene fiber-reinforced concrete (PFRC) beams without transverse reinforcement. The investigated models included empirical, semi-empirical, mechanics-based, and code-based formulations available in the literature. In addition to the analytical models proposed by previous researchers (Arslan et al. (2017); Albidah and Abbas (2024); Said et al. (2021); Zhang et al. (2020)), the RILEM TC 162-TDF (2003), DAfStB (2012),

and fib Model Code 2010 (fib 2010) approaches were also assessed. For the latter models, several assumptions and parameter estimation procedures were adopted owing to the limited availability of residual tensile strength data in the collected experimental database.

5.1. Statistical evaluation of existing shear strength models

The statistical performance of the investigated shear strength prediction models is summarized in Table 4, while the corresponding MAE values are illustrated in Fig. 1. The results reveal substantial differences among the evaluated formulations in terms of prediction accuracy, consistency, and overall reliability. As shown in Table 4 and Fig. 1, the MAE values vary considerably, ranging from 31.53 kN to 140.23 kN, indicating that the predictive capability of existing shear strength models for PFRC beams without transverse reinforcement differs significantly.

Among the directly applicable analytical and semi-empirical formulations, the model proposed by Arslan et al. (2017) provided the most balanced overall performance. The model achieved a mean experimental-to-predicted shear strength ratio close to unity (1.029), together with relatively low prediction errors ($MAE = 32.22$ kN and $RMSE = 61.22$ kN). These results indicate a good balance between prediction accuracy and consistency over a wide range of PFRC beam configurations. The satisfactory performance of the model may be attributed to its consideration of several parameters known to influence shear behavior, including concrete compressive strength, longitudinal reinforcement ratio, shear span-to-depth ratio, size effect, and fiber contribution.

The formulation proposed by Albidah and Abbas (2024) achieved the highest coefficient of determination ($R^2 = 0.784$) and the lowest coefficient of variation ($COV = 0.337$) among all investigated models, demonstrating a strong ability to capture the overall trend of the experimental database. However, the corresponding mean value of 0.828 indicates a tendency toward unconservative predictions. Although the prediction scatter remained relatively low, the observed bias suggests that the model may overestimate the shear capacity of some PFRC beams.

In contrast, the models proposed by Zhang et al. (2020) and Said et al. (2021) exhibited less satisfactory predictive performance. The formulation of Zhang et al. (2020) produced a mean value of 0.711 and relatively high prediction errors, whereas the model proposed by Said et al. (2021) yielded highly conservative predictions with a mean value of 1.999 and the lowest coefficient of determination ($R^2 = 0.225$) among the directly applicable formulations. These results indicate a limited ability of both models to consistently predict the shear strength of the PFRC beams included in the database.

Different trends were observed for the code-based formulations. In general, the predictive performance of these approaches was strongly influenced by the procedures adopted to characterize the residual tensile properties of fiber-reinforced concrete. The RILEM TC 162-

TDF (2003) formulation produced relatively low prediction errors and a competitive level of accuracy, whereas the DAFStB (2012) model exhibited the largest prediction errors among all investigated formulations. The performance of the fib Model Code 2010 (fib 2010) implementations also varied considerably depending on the adopted residual tensile strength estimation procedure. A more detailed discussion of the code-based approaches is presented in Sections 5.2 and 5.3.

Overall, the results presented in Table 4 and Fig. 1 indicate that the predictive performance of existing shear strength models for PFRC beams varies substantially. Models incorporating the combined effects of concrete strength, reinforcement ratio, member geometry, and fiber contribution generally provided more accurate and

consistent predictions. Furthermore, the observed variability among the code-based formulations suggests that the characterization of post-cracking tensile behavior plays a critical role in the reliability of shear strength predictions for PFRC members.

In addition to the statistical indicators presented in Table 4, the distribution of experimental-to-predicted shear strength ratios was also examined to assess model reliability. Table 5 summarizes the distribution of safe and unsafe predictions based on the $V_{exp}/V_{pred} = 1.00$ criterion for the investigated models, while Fig. 2 illustrates the relationships between experimental and predicted shear strengths. Together, these results provide additional insight into prediction accuracy, bias, and overall model reliability.

Table 4. Statistical performance of the investigated shear strength prediction models.

Model	Mean	COV	RMSE (kN)	R ²	MAE (kN)
Arslan et al. (2017)	1.029	0.367	61.220	0.592	32.220
Albidah and Abbas (2024)	0.828	0.337	58.110	0.784	39.730
Said et al. (2021)	1.999	0.574	93.670	0.225	54.840
Zhang et al. (2020)	0.711	0.537	86.070	0.536	63.330
RILEM TC 162-TDF (2003)	1.281	0.584	76.380	0.400	32.600
DAFStB (2012)	0.458	0.561	202.470	0.333	140.230
FibMC2010 Approach I	0.713	0.608	110.000	0.390	73.540
FibMC2010 Approach II	1.046	0.608	75.470	0.389	37.560
FibMC2010 Approach III	1.139	0.566	72.460	0.430	31.530

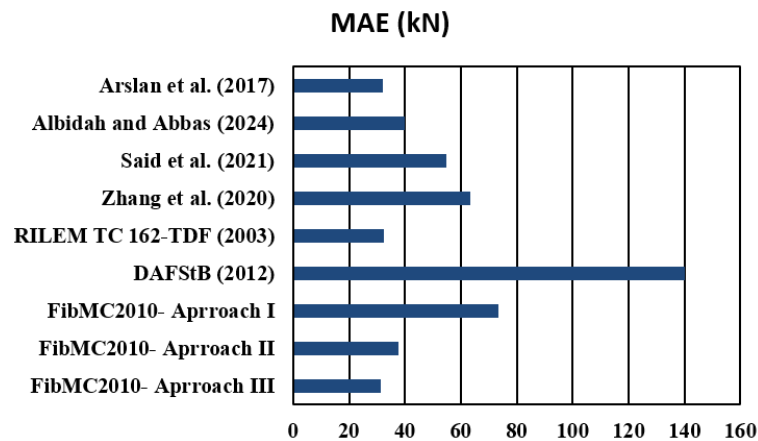


Fig. 1. Comparison of MAE values obtained from the investigated shear strength prediction models.

Table 5. Distribution of experimental-to-predicted shear strength ratios (V_{exp}/V_{pred}) for the investigated models.

Model	V_{exp}/V_{pred}		Unsafe (%)	Safe (%)
	< 1.00	≥ 1.00		
Arslan et al. (2017)	53	45	54	46
Albidah and Abbas (2024)	78	20	80	20
Said et al. (2021)	14	84	14	86
Zhang et al. (2020)	85	13	87	13
RILEM TC 162-TDF (2003)	29	69	30	70
DAFStB (2012)	93	5	95	5
FibMC2010-Approach I	86	12	88	12
FibMC2010-Approach II	68	30	69	31
FibMC2010-Approach III	60	38	61	39

The columns “< 1.00” and “≥ 1.00” represent the number of unsafe and safe predictions, respectively.

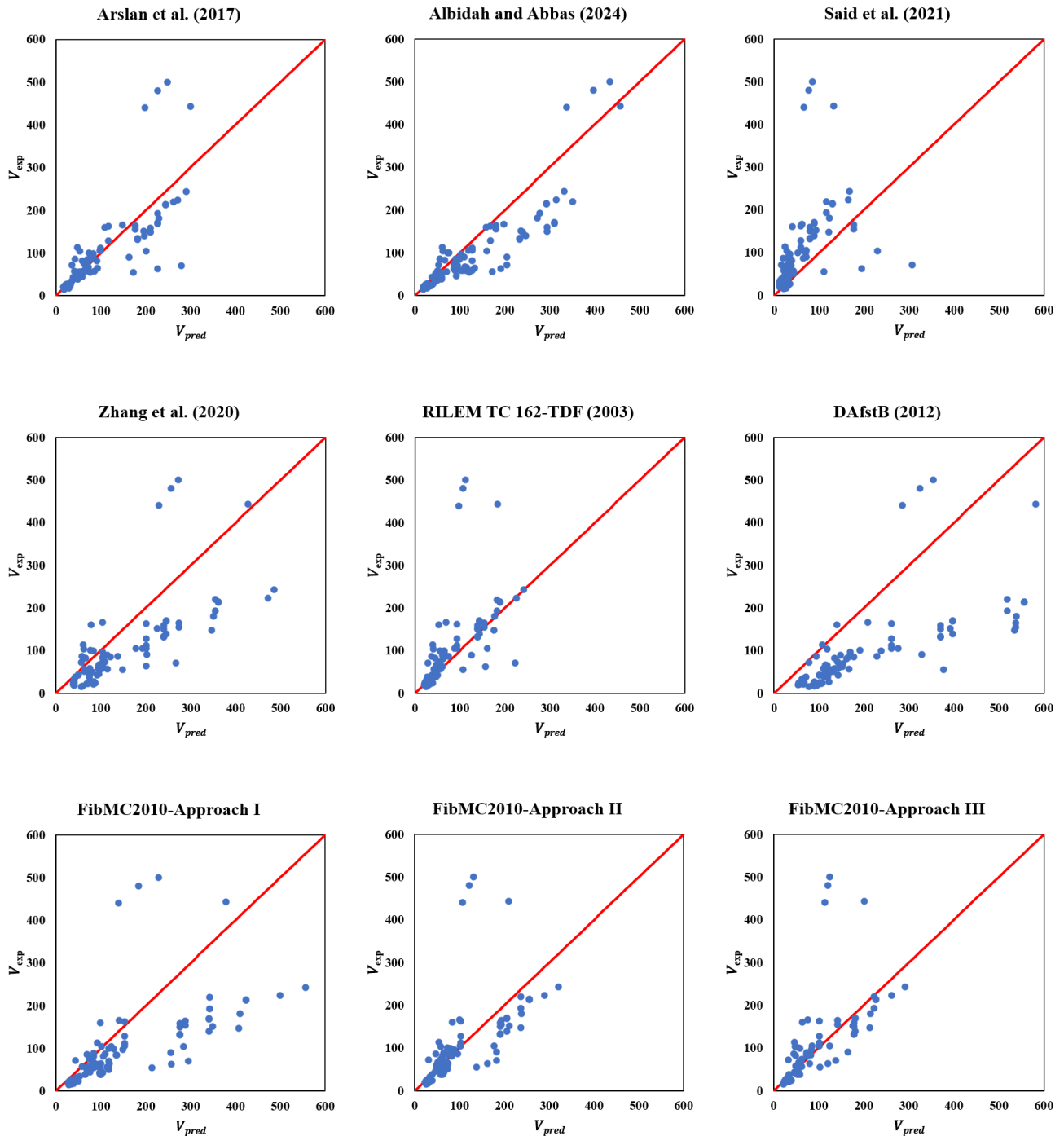


Fig. 2. Experimental-versus-predicted shear strength relationships for the investigated shear strength prediction models.

The scatter plots presented in Fig. 2 further highlight the differences among the investigated formulations. Models exhibiting lower prediction errors and mean V_{exp}/V_{pred} ratios close to unity generally produced data points more closely distributed around the line of perfect agreement. In contrast, models with larger prediction errors showed greater scatter and more pronounced deviations from the experimental results.

Inspection of the experimental-versus-predicted shear strength relationships shown in Fig. 2 also provides insight into possible prediction bias. The Said et al. (2021) model generally produced conservative pre-

dictions, with deviations becoming more pronounced for specimens with relatively high experimental shear capacities. In contrast, the DAfStB (2012) model exhibited a strong tendency to overestimate shear strength, consistent with its low mean experimental-to-predicted ratio and high proportion of unsafe predictions. The formulations proposed by Arslan et al. (2017) and fib Model Code 2010 Approach III showed a comparatively more balanced distribution of predictions across the investigated shear-strength range. These observations complement the statistical indicators presented in Table 4.

5.2. Performance of the code-based shear models

The code-based formulations exhibited markedly different levels of predictive performance when applied to the compiled PFRC beam database. Since the implementation of both RILEM TC 162-TDF (2003) and DAFStB (2012) required estimated residual tensile strength parameters, the obtained results reflect not only the accuracy of the underlying shear resistance formulations but also the reliability of the adopted parameter-estimation procedures. Among the investigated code-based approaches, the RILEM TC 162-TDF (2003) model demonstrated a relatively balanced predictive performance. Although a certain degree of prediction scatter was observed, the overall error levels remained comparable to those obtained from the better-performing analytical formulations. As shown in Table 5, the RILEM formulation produced a substantially lower percentage of unsafe predictions than the DAFStB model, suggesting that the adopted implementation procedure can provide reasonable estimates of PFRC beam shear strength despite the absence of experimentally determined residual flexural tensile strength parameters. In contrast, the DAFStB (2012) formulation consistently exhibited the weakest performance among the investigated code-based approaches. As indicated by the safety classification results presented in Table 5, the DAFStB model produced the highest proportion of unsafe predictions (95%) among the investigated formulations. This behaviour indicates a strong tendency to overestimate the shear resistance of PFRC beams and may be attributed to both the characteristics of the DAFStB shear resistance formulation and the residual tensile strength estimation procedure adopted for its implementation. Since neither the shear formulation nor the parameter-estimation framework was originally developed for PFRC members, additional uncertainty may have been introduced when the approach was applied to the present database. It is difficult to isolate the contribution of individual parameters within the DAFStB procedure. However, part of the observed discrepancy may stem from the estimation of the splitting tensile strength using the Thomas and Ramaswamy model, which was originally calibrated using steel-fiber-reinforced concrete data. In addition, the orientation and residual-strength factors embedded in the DAFStB formulation were developed for SFRC systems and may not fully represent the fiber–matrix interaction, pull-out behavior, and post-cracking response of polypropylene fibers. Consequently, both the residual tensile strength estimation procedure and the original DAFStB parameter calibration are likely contributors to the high proportion of unsafe predictions observed for PFRC beams. The contrasting performances of the RILEM TC 162-TDF (2003) and DAFStB (2012) approaches highlight the importance of residual tensile strength characterization in code-based shear strength prediction. Although both formulations attempt to incorporate the post-cracking contribution of fibers through residual strength parameters, their predictive capabilities differed substantially when applied to the PFRC beam database considered in this study. These findings suggest that the reliability of code-based shear strength

predictions depends not only on the shear resistance formulation itself but also on the procedure used to characterize the residual tensile behaviour of the material. Owing to its particular relevance to this issue, the performance of fib Model Code 2010 (fib 2010) is discussed separately in the following section.

5.3. Sensitivity of fib Model Code 2010 to residual strength estimation procedures

The statistics for the three fib Model Code 2010 (fib 2010) approaches are reported in Table 6 below. While the same shear resistance equation was utilized in all cases, there were noticeable disparities in the results produced through the three different methods of estimating residual tensile strength. Given that the key factor that distinguishes between the considered approaches is their representation of tensile behavior after cracking, the comparison will be beneficial in demonstrating the influence of residual tensile strength estimations on the accuracy of the predictions under fib Model Code 2010. The fib approach relying on the Nzambi et al. (2022) model (Approach I) was the least accurate one among the three approaches. According to Table 6, the model had the lowest mean experimental-to-predicted ratio of 0.713 as well as the highest RMSE (110.00 kN) and MAE (73.54 kN) values out of all the fib-based approaches. Moreover, the coefficient of variation (COV = 0.608) was quite high. These results suggest that the adopted residual tensile strength estimation procedure was less compatible with the PFRC beam database considered in this study. Part of this discrepancy may be attributed to the fact that the residual-strength relationships proposed by Nzambi et al. (2022) were originally calibrated using hook-end steel-fiber-reinforced concrete specimens. Differences in elastic modulus, fiber–matrix bond characteristics, pull-out mechanisms, and crack-bridging behavior between steel fibers and polypropylene fibers may therefore contribute to the reduced compatibility of the resulting residual tensile strength estimates when applied to PFRC beams.

Significant improvement was made possible through the use of the approach described by Moraes-Neto et al. (2013) (Approach II). In this case, the accuracy of prediction of shear strength was greatly improved, which allowed for the attainment of the mean ratio equal to 1.046, which is rather close to unity. In addition, RMSE and MAE were significantly reduced when compared to Approach I. This implies that the values of residual tensile properties estimated through the application of the Moraes-Neto et al. (2013) approach can be considered as being more appropriate for the utilization of the fib Model Code 2010 in the analysis of the given PFRC specimens. The most successful implementation of the fib Model Code 2010 was attained through the application of the procedure suggested by Lantsoght (2019) (Approach III). According to Table 6, this approach allowed for the reduction of MAE to 31.53 kN, RMSE to 72.46 kN, COV to 0.566 and provided R^2 of 0.430, which was higher than for other approaches. These results indicate a more accurate and consistent representation of the post-cracking tensile contribution incorporated into the fib Model Code 2010 framework.

The results of the safety classifications provided in Table 5 confirm these findings. The percentage of the unsafe predictions ($V_{exp}/V_{pred} < 1.00$) was reduced from 88% in Approach I to 69% in Approach II and 61% in Approach III, thus reflecting the progressively improving reliability of predictions with the change of the applied residual tensile strength estimation procedure. Among all considered approaches, the lowest percentage of unsafe predictions and the highest percentage of safe predictions were obtained for Approach III. This confirms the significant impact of the residual tensile strength estimation procedure on the reliability of fib Model Code 2010 shear strength predictions. A particularly important finding is that considerable differences were obtained between the three approaches even though the same shear resistance formula of the fib Model Code 2010 (fib 2010) was used. The main difference between the three approaches being in the method used to estimate the residual tensile behavior of fiber reinforced concrete, the discrepancies in terms of prediction accu-

racy could be largely attributed to the method chosen to characterize the residual tensile strength. This implies that the prediction capabilities of the fib Model Code 2010 are extremely dependent on the method used to estimate the post cracking behavior of fiber reinforced concrete especially where no experimental residual strength is available. It must be acknowledged that the residual strength estimation procedures employed in Approaches I, II and III were initially developed through databases not identical to the one used in this experiment for polypropylene fiber reinforced concrete beams. Some of the discrepancies in terms of prediction accuracy therefore can be explained by differences in fiber type, bond behavior and post cracking behavior. However, it is clear from the results obtained that a good method to characterize residual tensile properties is important in achieving accurate fib Model Code 2010 predictions. The findings further highlight the need for residual tensile strength estimation procedures specifically calibrated for polypropylene fiber-reinforced concrete.

Table 6. Statistical comparison of fib Model Code 2010 implementations.

Approach	Mean	COV	RMSE (kN)	R ²	MAE (kN)
Approach I (Nzambi et al. (2022))	0.713	0.608	110.000	0.390	73.540
Approach II (Moraes-Neto et al. (2013))	1.046	0.608	75.470	0.389	37.560
Approach III (Lantsoght (2019))	1.139	0.566	72.460	0.430	31.530

5.4. Influence of shear span-to-depth ratio and concrete strength

To further examine the influence of database heterogeneity on model performance, additional subgroup analyses were conducted based on the shear span-to-effective depth ratio (a/d) and concrete compressive strength. The specimens were classified into two groups according to a/d (< 2.5 and ≥ 2.5) and cylinder compressive strength ($f'_c < 50$ MPa and $f'_c \geq 50$ MPa). The corresponding statistical results are presented in Table 7. Particular attention was given to the performance of the three fib Model Code 2010 implementations, since the primary objective of this study was to investigate the influence of alternative residual tensile strength estimation procedures on shear strength prediction accuracy.

It can be observed from the results above that the predictive performance of fib Model Code 2010 is affected by the ratio between shear span and depth of the member. Where $a/d \geq 2.5$, Approach III gave the best prediction out of the three approaches under consideration, having a V_{exp}/V_{pred} of 1.006 and MAE of 19.60 kN. Approach II and I had MAE of 27.26 kN and 77.16 kN, respectively. However, where $a/d < 2.5$, the prediction performance of all three approaches worsened with an increase in MAE to 45.03 kN, 49.20 kN, and 69.44 kN, respectively. From the results, it is clear that the predictive performance of fib Model Code 2010 decreases in cases where the a/d ratio is relatively low.

A comparison of the three residual tensile strength estimation procedures reveals that the relative ranking of

the fib Model Code 2010 implementations remains essentially unchanged across both a/d categories. Approach III consistently exhibited the lowest prediction errors and mean values closest to unity, whereas Approach I produced the largest deviations from the experimental results. Approach II generally provided intermediate performance between the other two procedures. This observation confirms that the procedure adopted for residual tensile strength characterization has a substantial effect on fib Model Code 2010 predictions regardless of member geometry.

The influence of concrete compressive strength was also investigated by separating the database into specimens with $f'_c < 50$ MPa and $f'_c \geq 50$ MPa. Although the effect of concrete strength was less pronounced than that of the a/d ratio, the prediction accuracy of the fib Model Code 2010 implementations generally decreased for higher-strength concretes. For Approach III, the MAE increased from 24.83 kN for specimens with $f'_c < 50$ MPa to 56.10 kN for specimens with $f'_c \geq 50$ MPa. Similarly, the mean V_{exp}/V_{pred} ratio increased from 1.075 to 1.375. Comparable trends were observed for Approaches I and II, indicating that the investigated residual tensile strength estimation procedures tend to produce increasingly conservative predictions as concrete compressive strength increases.

Similar tendencies were also observed for several of the other investigated models. In particular, the Arslan et al. and RILEM formulations generally exhibited lower prediction errors for specimens with $a/d \geq 2.5$ than for those with $a/d < 2.5$. Nevertheless, the subgroup anal-

yses consistently demonstrated that the conclusions obtained from the full database remained unchanged. Among the three fib Model Code 2010 implementations, the procedure adopted from Lantsoght (Approach III) provided the most reliable and consistent predictions, whereas the implementation based on the residual

strength equations proposed by Nzambi et al. (Approach I) exhibited the weakest overall predictive performance. These findings further demonstrate the critical importance of residual tensile strength characterization in the implementation of fib Model Code 2010 for PFRC beams.

Table 7. Statistical performance of the investigated models for different a/d ratios and concrete-strength ranges.

Model	Arslan et al. (2017)	Albidah and Abbas (2024)	Said et al. (2021)	Zhang et al. (2020)	RILEM TC 162-TDF (2003)	DAFStb (2012)	FibMC2010 Approach I	FibMC2010 Approach II	FibMC2010 Approach III
$a/d \geq 2.5$									
Mean	1.045	0.901	1.794	0.696	1.158	0.415	0.594	0.887	1.006
COV	0.326	0.316	0.421	0.447	0.378	0.380	0.348	0.355	0.378
RMSE (kN)	31.859	49.692	45.411	85.099	22.682	194.465	112.509	37.187	28.185
R^2	0.885	0.891	0.691	0.872	0.877	0.832	0.884	0.878	0.877
MAE (kN)	21.517	32.541	35.600	59.224	14.343	138.600	77.164	27.259	19.595
$a/d < 2.5$									
Mean	1.012	0.746	2.230	0.727	1.420	0.506	0.847	1.226	1.289
COV	0.414	0.336	0.648	0.621	0.687	0.653	0.669	0.681	0.644
RMSE (kN)	82.694	66.358	127.910	87.162	108.839	211.147	107.092	102.809	101.432
R^2	0.528	0.789	0.102	0.543	0.286	0.193	0.321	0.305	0.389
MAE (kN)	44.313	47.863	76.580	67.961	53.245	142.063	69.436	49.201	45.031
$f'_c < 50$									
Mean	1.019	0.856	1.830	0.710	1.210	0.431	0.668	0.950	1.075
COV	0.368	0.335	0.575	0.529	0.527	0.538	0.588	0.545	0.494
RMSE (kN)	52.826	61.269	71.381	86.204	51.827	222.247	113.805	54.983	48.309
R^2	0.632	0.768	0.278	0.614	0.530	0.416	0.538	0.571	0.601
MAE (kN)	29.665	40.263	46.219	62.766	24.640	152.915	77.961	32.674	24.834
$f'_c \geq 50$									
Mean	1.066	0.727	2.618	0.712	1.540	0.556	0.876	1.398	1.375
COV	0.369	0.312	0.492	0.579	0.674	0.575	0.614	0.630	0.680
RMSE (kN)	85.208	44.673	149.203	85.592	131.809	100.941	94.750	124.467	126.280
R^2	0.928	0.958	0.749	0.751	0.683	0.718	0.674	0.698	0.702
MAE (kN)	41.574	37.789	86.429	65.375	61.801	93.697	57.315	55.468	56.104

5.5. Implications for PFRC shear strength prediction

It can be clearly seen from the results of the current investigation that the performance of the shear strength prediction of existing models of PFRC beams highly depends on the parameters that describe the role of fibers in providing resistance to shear forces. In general, the models, which take into account the influence of various factors such as concrete strength, reinforcement ratio, geometrical dimensions of members and the influence of fibers, provided better predictions than models using fewer parameters. These results mean that an accurate evaluation of the shear strength of PFRC beams cannot be done by means of simplified descriptions of fiber contribution. In particular, an important point is the use of code-based approaches. While these models attempt to capture the post-cracking behavior of fiber reinforced concrete based on the parameters of the residual tensile strength of fibers, it has been shown that the accuracy of such prediction heavily relies on the methodology used to define the above properties. Such an influence was seen to be the strongest for the case of fib Model Code

2010 (fib 2010), with a considerable variation in the accuracy of prediction being achieved even while using the same shear resistance equation. This means that the way of estimating the residual tensile strength plays a decisive role in the accuracy of code-based prediction of shear strength. In view of the design practice, this can be considered to mean that currently available formulations for the steel fiber reinforced concrete could be employed to provide reasonably accurate estimation of PFRC shear resistance if proper methodology is applied to estimate the post-cracking behavior of tensile strength. Yet, the difference between the methods evaluated suggests that one should be careful when applying residual tensile strength estimation techniques based on the SFRC database to the PFRC members. This limitation is largely associated with the fundamental differences between polypropylene and steel fibers. Compared with steel fibers, polypropylene fibers generally exhibit a lower elastic modulus, different pull-out behavior, reduced bond stiffness, and distinct crack-bridging mechanisms. As a result, residual tensile strength relationships calibrated using SFRC databases may not accurately rep-

resent the post-cracking behavior of PFRC members. Overall, the results emphasize that improvements in the characterization of post-cracking tensile properties may have a greater influence on prediction reliability than modifications to the shear resistance equations themselves. Future research should therefore focus on developing PFRC-specific residual tensile strength characterization procedures and design-oriented prediction frameworks capable of more accurately representing the contribution of polypropylene fibers to shear resistance.

6. Conclusions

This study evaluated the predictive performance of existing analytical and code-based shear strength prediction models using a database of 98 polypropylene fiber-reinforced concrete (PFRC) beams without transverse reinforcement collected from the literature. Particular attention was given to the implementation of fib Model Code 2010 (fib 2010) and the influence of different residual tensile strength estimation procedures on prediction accuracy. Based on the results obtained, the following conclusions can be drawn:

- Important distinctions have been found between the analyzed models of shear strength prediction, suggesting that the choice of the model used is an important factor in estimating the shear strength of PFRC.
- Among the applicable forms of analysis or semi-empirical equations, the model suggested by Arslan et al. (2017) performed relatively evenly across all aspects of predictions, whereas the model suggested by Albidah and Abbas (2024) showed a good capability to represent the trend of the experimental database.
- Performance of the code-based methods was quite variable. The RILEM TC 162-TDF (2003) model per-

formed reasonably well in terms of prediction accuracy while the DAfStB (2012) method performed worst among all for the constructed PFRC dataset.

- The examination of the distribution of the ratio of experimentally determined to predicted shear strengths demonstrated considerable variability in the reliability of the model predictions, particularly in terms of the percentage of unsafe predictions.
- The predictive capability of fib Model Code 2010 (fib 2010) was found to be highly sensitive to the adopted residual tensile strength estimation procedure. Despite the use of the same underlying shear resistance formulation, substantial variations in prediction accuracy were observed among the investigated implementations.
- The results demonstrate that reliable characterization of post-cracking tensile behavior is essential for accurate code-based shear strength prediction. Among the investigated alternatives, the implementation based on the procedure adopted by Lantsoght provided the most consistent overall performance.
- Additional subgroup analyses indicated that the predictive performance of most investigated models was affected by the shear span-to-depth ratio. Lower prediction errors were generally observed for specimens with $a/d \geq 2.5$, while prediction accuracy tended to decrease for members with smaller a/d ratios.

Overall, the findings highlight the importance of residual tensile strength characterization in the assessment of PFRC shear resistance and demonstrate the need for PFRC-specific material characterization procedures and design-oriented prediction approaches. Future research should focus on developing residual tensile strength estimation methods specifically calibrated for polypropylene fiber-reinforced concrete and on expanding the available database of experimentally determined post-cracking tensile properties.

Appendix A. Prediction procedures for shear resistance of FRC beams

A.1. fib Model Code 2010 (fib 2010)

For the purposes of this study, the shear resistance was evaluated using the provisions of fib Model Code 2010 (fib 2010). The corresponding shear resistance was determined as:

$$V_{Rd,F} = \frac{0.18}{\gamma_c} k \left[100\rho \left(1 + 7.5 \frac{f_{Ftuk}}{f_{ctk}} \right) f_{ck} \right]^{1/3} b_w d \quad (A1)$$

The size effect factor was determined from:

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \quad (A2)$$

The residual tensile strength corresponding to the serviceability limit state was obtained as:

$$f_{Fts} = 0.45 f_{R1} \quad (A3)$$

The residual tensile strength corresponding to the ultimate limit state was calculated as:

$$f_{Ftuk}(w_u) = f_{Fts} - \frac{w_u}{2.5} [f_{Fts} - (0.5 f_{R3} + 0.2 f_{R1})] \quad (A4)$$

In accordance with fib Model Code 2010, the crack width at ultimate was taken as $w_u = 1.5$ mm.

The mean tensile strength of concrete was determined from:

$$f_{ctm} = 0.3f_{ck}^{2/3} \quad (A5)$$

For the purpose of the present comparative assessment, the characteristic tensile strength was assumed equal to the mean tensile strength ($f_{ctk} = f_{ctm}$) in all implementations. This assumption was adopted uniformly for all specimens and all fib Model Code 2010 implementations in order to ensure consistency among the investigated residual tensile strength estimation procedures and to isolate their influence on the resulting shear strength predictions.

In these equations, $V_{Rd,F}$ denotes the shear resistance provided by SFRC; k is the size-effect factor; ρ is the longitudinal reinforcement ratio; f_{Ftuk} is the characteristic ultimate residual tensile strength; f_{ctm} and f_{ctk} are the mean and characteristic tensile strengths of concrete, respectively; f_{ck} is the characteristic compressive strength of concrete; b_w is the web width; and d is the effective depth. The parameters f_{Fts} and f_{Ftu} represent the residual tensile strengths associated with the serviceability and ultimate limit states, respectively.

The residual flexural tensile strengths f_{R1} and f_{R3} , required in Eqs. (A3) and (A4), were determined using the procedures described in Appendices A.2 and A.3. Alternatively, the procedure presented in Appendix A.4 was used to estimate the residual tensile strength parameter required for the fib Model Code 2010 method.

A.2. Residual strength equations proposed by Nzambi et al. (2022)

The residual flexural tensile strengths f_{R1} and f_{R3} were estimated using the empirical equations proposed by Nzambi et al. (2022). The maximum fiber tensile stress was first calculated as:

$$\sigma_{f,max} = 4\lambda f_{ct} \left(\frac{l_f \phi}{d_f} \right) \quad (A6)$$

The residual flexural tensile strength corresponding to CMOD = 0.5 mm was determined from:

$$f_{\{R1\}} = 1.121(\sigma_{f,max} V_f)^{\{0.91\}} \quad (A7)$$

The residual flexural tensile strength corresponding to CMOD = 2.5 mm was determined from:

$$f_{\{R3\}} = 1.150(\sigma_{f,max} V_f)^{\{0.76\}} \quad (A8)$$

In this equation, $\sigma_{f,max}$ represents the tensile strength of the fiber, λ is the coefficient relating to the pull out strength of the fiber, ϕ represents the coefficient due to the fiber matrix interaction, f_{ct} is the tensile strength of the concrete, V_f represents the fiber volume fraction, l_f is the fiber length and d_f is the fiber diameter. The resulting values of f_{R1} and f_{R3} were subsequently used in Eqs. (A3) and (A4).

A.3. Residual strength equations proposed by Moraes-Neto et al. (2013)

The residual flexural tensile strengths f_{R1} and f_{R3} were also estimated using the equations proposed by Moraes-Neto et al. (2013). The fiber reinforcement index was calculated as:

$$RI = V_f \left(\frac{l_f}{d_f} \right) \quad (A9)$$

The residual flexural tensile strength corresponding to CMOD = 0.5 mm was calculated as:

$$f_{R1} = 7.5(RI)^{0.8} \quad (A10)$$

The residual flexural tensile strength corresponding to CMOD = 2.5 mm was calculated as:

$$f_{R3} = 6.0(RI)^{0.7} \quad (A11)$$

where RI is the fiber reinforcement index, V_f is the fiber volume fraction, l_f is the fiber length, and d_f is the fiber diameter. The resulting values of f_{R1} and f_{R3} were subsequently used in Eqs. (A3) and (A4).

A.4. Thomas model and Lantsoght-based procedure

A third approach was adopted following the methodology proposed by Lantsoght. First, the fiber factor was calculated as:

$$F = V_f \left(\frac{l_f}{d_f} \right) r_f \quad (\text{A12})$$

The splitting tensile strength of fiber-reinforced concrete was estimated as:

$$f_{spfc} = 0.63\sqrt{f_{cu}} + 0.288F\sqrt{f_{cu}} + 0.052F \quad (\text{A13})$$

where F is the fiber factor, V_f is the fiber volume fraction, l_f is the fiber length, d_f is the fiber diameter, r_f is the fiber bond factor, f_{spfc} is the splitting tensile strength of steel fiber-reinforced concrete, and f_{cu} is the cube compressive strength of fiber-reinforced concrete.

Since all database compressive strengths were standardized to equivalent cylinder compressive strengths, the corresponding cube compressive strengths required by Eq. (A13) were obtained using the inverse of the adopted conversion relationship ($f_{cu} = f'_c/0.80$). Therefore, Eq. (A13) was implemented using the compressive strength definition originally required by the Thomas and Ramaswamy formulation.

The splitting tensile strength obtained from Eq. (A13) was subsequently employed in the DAfStB procedure described in Appendix A.5. Following the approach proposed by Lantsoght, the residual tensile strength obtained from the DAfStB model was assumed to represent the characteristic ultimate residual tensile strength required by the fib Model Code 2010 procedure.

A.5. DAfStB (2012)

The DAfStB (2012) formulation was implemented using the residual tensile strength parameter $f_{fctR,u}$. The total shear resistance was calculated as:

$$V_{f,Rd,c} = V_{Rd,c} + V_{Rd,cf} \quad (\text{A14})$$

The concrete contribution was determined from:

$$V_{Rd,c} = C_{Rd,c} \frac{k(100\rho_l f_{ck})^{1/3} b_w d}{\gamma_c} \quad (\text{A15})$$

The fiber contribution was calculated as:

$$V_{Rd,cf} = \alpha_{fc} \frac{f_{fctR,u} b_w h}{\gamma_{fct}} \quad (\text{A16})$$

The residual tensile strength parameter was obtained from:

$$f_{fctR,u} = k_{fF} k_{fG} (0.37) f_{cf1k,L2} \quad (\text{A17})$$

The size factor was determined as:

$$k_{fG} = 1 + 0.5 A_{fct} \leq 1.7 \quad (\text{A18})$$

where

$$A_{fct} = b_w \min(d, 1.5 \text{ m}) \quad (\text{A19})$$

and the size effect factor was calculated from:

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \quad (\text{A20})$$

In these equations, $V_{f,Rd,c}$, $V_{Rd,c}$, and $V_{Rd,cf}$ refer to the total shear resistance, the resistance due to the concrete material and the resistance due to the fibers respectively. Additionally, $f_{fctR,u}$ represents the tensile strength residual parameter, b_w , h and d are the dimensions of the member. k_{fF} and k_{fG} represent fiber orientation effect parameter and size effect parameter respectively while A_{fct} represents tensile effective area.

Based on the recommendations by Lantsoght, the following values were chosen during calculations:

$$k_{fF} = 0.50, \alpha_{fc} = 0.85, \gamma_{fct} = 1.25 \quad (A21)$$

The resulting value of $f_{fctR,u}$ was subsequently used as the residual tensile strength parameter required by the fib Model Code 2010 procedure.

A.6. RILEM TC 162-TDF (2003)

The shear resistance was evaluated according to the recommendations of RILEM TC 162-TDF (2003). The total shear resistance was calculated as:

$$V_{Rd} = V_{cd} + V_{fd} \quad (A22)$$

The concrete contribution was determined from:

$$V_{cd} = 0.12k(100\rho_l f_{ck})^{1/3} b_w d \quad (A23)$$

The fiber contribution was calculated as:

$$V_{fd} = 0.7k_f k \tau_{fd} b_w d \quad (A24)$$

where the flange factor was determined as:

$$k_f = 1 + n \left(\frac{h_f}{b_w} \right) \left(\frac{h_f}{d} \right) \leq 1.5 \quad (A25)$$

and

$$n = \frac{b_f}{b_w} - 1 \leq 3 \quad (A26)$$

The design bond strength parameter was obtained from:

$$\tau_{fd} = 0.12 f_{Rk,4} \quad (A27)$$

Following the methodology adopted by Lantsoght, the characteristic residual flexural tensile strength required by the RILEM procedure was assumed equal to the splitting tensile strength predicted by the Thomas model:

$$f_{Rk,4} = f_{spfc} \quad (A28)$$

In Eqs. (A22)–(A28), V_{Rd} represents total shear resistance, V_{cd} represents the concrete contribution, V_{fd} represents the fiber contribution, k is the size effect factor, ρ_l is the longitudinal reinforcement ratio, f_{ck} represents the characteristic compressive strength of concrete, b_w is the web width, d is the effective depth, k_f is the flange factor, h_f is the flange depth, b_f is the flange width, τ_{fd} represents the design bond strength parameter, $f_{Rk,4}$ is the characteristic residual flexural tensile strength corresponding to a CMOD of 3.5 mm and f_{spfc} is the splitting tensile strength determined using the Thomas model.

For rectangular beam specimens, $k_f = 1.0$. The splitting tensile strength f_{spfc} computed using Eq. (A13) was then used in Eq. (A28) for calculation of the fiber contribution to shear resistance using the RILEM method.

A.7. Zhang et al. (2020)

Zhang et al. proposed a modified compression field theory (MCFT)-based shear model for polypropylene fiber reinforced concrete beams. In the original formulation, the principal tensile stress consists of the sum of aggregate interlock stress and fiber-induced tensile stress. In the present study, only the fiber-induced tensile stress component was considered and directly adopted as the principal tensile stress.

The crack inclination angle was determined according to:

$$\theta = 29^\circ + 7000\varepsilon_x \quad (A29)$$

where ε_x is the longitudinal strain. Following the recommendation of Zhang et al.,

$$\varepsilon_x = 0.002 \quad (A30)$$

was assumed, resulting in a crack inclination angle of $\theta = 43^\circ$.

The principal tensile stress was then calculated directly from the fiber-induced tensile stress expression proposed by Zhang et al.:

$$\sigma_f = \left(1 + \eta_0 \eta_1 \eta_2 V_f \frac{l_f}{d_f}\right) f_t \quad (\text{A31})$$

where V_f is the fiber volume fraction, l_f/d_f is the fiber aspect ratio, and f_t is the tensile strength of concrete. Here, η_0 , η_1 , and η_2 denote the fiber orientation factor, fiber length efficiency factor, and bond coefficient, respectively. Zhang et al. suggested using the values $\eta_0=0.20$, $\eta_1=0.50$, and $\eta_2=1.0$ for a 3-D random fiber orientation.

In the current analysis, the interlock effect which forms part of the original equation was ignored, and the maximum tensile stress was taken to be the same as the tensile stress due to the fibers, $f_t = \sigma_f$. This was then used to estimate the residual tensile effect of the PFRC.

A.8. Said et al. (2021)

Said et al. proposed a modified shear strength model based on the Canadian Standards Association (CSA) provisions to account for the contribution of polyvinyl alcohol (PVA) fibers to beam shear resistance. The total shear resistance is expressed as the sum of the concrete, fiber, and stirrup contributions:

$$V_u = V_c + V_f + V_s \quad (\text{A32})$$

where V_c , V_f , and V_s represent the contribution of the concrete, fibers, and transverse reinforcement, respectively.

The concrete contribution is calculated by the CSA model formula:

$$V_c = \phi_c k \beta \sqrt{f'_c} b d_v \quad (\text{A33})$$

where $\phi_c = 0.65$, $k = 1.0$, and $\beta = 0.21$. The effective shear depth, d_v , is determined as follows:

$$d_v = \max(0.9d, 0.75h) \quad (\text{A34})$$

where d is the effective depth and h is the overall section depth.

The fiber contribution is given by:

$$V_f = F_f \beta_0 \tau b d_v \quad (\text{A35})$$

in which F_f is the fiber factor, β_0 is the fiber orientation factor, and τ is the fiber-matrix interface bond strength.

The fiber factor is given by:

$$F_f = V_f \left(\frac{l_f}{d_f}\right) k_f \quad (\text{A36})$$

in which V_f stands for volume fraction of fibers, l_f represents length of fibers, d_f is diameter of fibers, and k_f represents shape factor of fibers.

For PVA fibers, Said et al. adopted the following parameters:

$$\beta_0 = 0.41 \text{ and } k_f = 0.50 \quad (\text{A37})$$

$$\tau = 2.93 \text{ MPa} \quad (\text{A38})$$

Although the original model includes the contribution of transverse reinforcement, all specimens in the present database were tested without stirrups. Therefore, the contribution of transverse reinforcement was neglected:

$$V_s = 0 \quad (\text{A39})$$

Consequently, the predicted shear resistance was calculated as:

$$V_u = V_c + V_f \quad (\text{A40})$$

In the present study, the coefficients suggested by Said et al. were used as such without any change; however, the effect of transverse reinforcement was not included due to lack of any stirrup in the tested specimens.

A.9. Arslan et al. (2017)

Arslan et al. proposed a shear strength model for polypropylene fiber-reinforced concrete (PFRC) beams without stirrups. The model was derived from a previously developed formulation for steel fiber reinforced concrete beams and modified by introducing a polypropylene-to-steel ratio (PSR) to account for the lower efficiency of polypropylene fibers. The model incorporates the effects of concrete strength, longitudinal reinforcement ratio, fiber contribution, and shear span-to-depth ratio.

The nominal shear strength is calculated as:

$$v_n = \frac{0.2f_c^{\frac{2}{3}}}{\left(\frac{c}{d}\right)} + PSR \left(\frac{\sqrt{\rho(1+4F)}f_c}{3\left(\frac{a}{d}\right)} \right)^{\frac{1}{3}} \quad (\text{A41})$$

where f_c is the concrete cylinder compressive strength in MPa, ρ is the longitudinal steel ratio, a/d is the shear span to effective depth ratio, PSR is the polypropylene to steel fiber ratio, and F is the fiber factor.

The depth of the compression zone is obtained from:

$$\left(\frac{c}{d}\right)^2 + 600 \left(\frac{\rho}{f_c}\right) \left(\frac{c}{d}\right) - 600 \left(\frac{\rho}{f_c}\right) = 0 \quad (\text{A42})$$

where c is the depth of the compression zone and d is the effective depth.

The fiber factor is defined as:

$$F = \frac{1}{4} \left(\frac{\psi l_f}{A_f} \right) V_f d_f \quad (\text{A43})$$

where ψ is the fiber perimeter, l_f is the fiber length, A_f is the fiber cross-sectional area, V_f is the fiber volume fraction, and d_f is the fiber shape and bond factor.

In this formulation, d_f denotes the fiber shape and bond factor, which differs from the notation adopted in some of the other models where d_f represents the fiber diameter.

For non-circular fibers, Arslan et al. adopted the fiber intrinsic efficiency ratio proposed by Naaman and incorporated it into the fiber factor expression to better represent the bond characteristics of polypropylene fibers.

To account for the reduced bond and stiffness characteristics of polypropylene fibers relative to steel fibers, the polypropylene-to-steel ratio was taken as:

$$PSR = 0.70 \quad (\text{A44})$$

as recommended by the authors.

The fiber shape bond factor depends on fiber geometry. According to Narayanan and Darwish, values of 0.50, 0.75, and 1.00 may be used for round, crimped, and indented fibers, respectively.

In the present study, the original formulation proposed by Arslan et al. was adopted without modification. All specimens in the database were tested without transverse reinforcement; therefore, no stirrup contribution was considered. The nominal shear strength predicted was used directly for comparison with the experimentally measured shear strengths.

A.10. Albidah and Abbas (2024)

The authors, Albidah and Abbas, came up with a simpler design-oriented model based on a stacked ensemble machine learning model using a database consisting of 394 SFRC beams without stirrups. The sensitivity analysis revealed that the most important factors influencing the shear capacity of the beam were the shear span to depth ratio, the ratio of longitudinal reinforcement, the compressive strength of the concrete, and the fiber factor. Using these results, an empirical equation was formulated by the researchers.

The predicted shear strength is calculated as:

$$v_u = \alpha F^\beta \sqrt{f'_c} \left(\frac{\rho d}{a} \right)^\gamma \quad (\text{A45})$$

where v_u = Shear strength in MPa, f'_c = Concrete compressive strength in MPa, ρ = Longitudinal reinforcement ratio, d = Effective depth, a = Shear span length and F = Fiber Factor. The formula for the fiber factor is:

$$F = V_f \left(\frac{l_f}{d_f} \right) \quad (\text{A46})$$

where V_f is the fiber volume fraction, l_f is the fiber length, and d_f is the fiber diameter.

Using the Gauss-Newton iterative calibration technique, the parameters of the model were obtained as follows:

$$\alpha = 6.588 \quad (\text{A47})$$

$$\beta = 0.134 \quad (\text{A48})$$

$$\gamma = 0.537 \quad (\text{A49})$$

Appendix B. Complete specimen-level database

The complete specimen-level database used in the present study is provided in Table B. The database contains the geometric, material, reinforcement-related, fiber-related, and experimental properties of all specimens included in the assessment of shear strength prediction models.

Table B. The complete specimen-level database

B.N.	Research	Beams	b (mm)	h (mm)	d (mm)	a/d	ρ_s	f_y (MPa)	V_f (%)	Aspect ratio	f'_c (MPa)	f_{sf} (MPa)	E_{sf} (MPa)	Failure mode	V_{exp} (kN)
1	Altoubat et al. (2009)	L1-0.50-b	280	460	400	3.53	0.0215	420	0.50	90.00	41.90	620	9500	Shear	193.00
2	Altoubat et al. (2009)	L2-0.50-a	230	390	330	3.50	0.0318	420	0.50	90.00	41.90	620	9500	Shear	131.50
3	Altoubat et al. (2009)	L2-0.50-b	230	390	330	3.50	0.0318	420	0.50	90.00	41.90	620	9500	Shear	133.50
4	Altoubat et al. (2009)	L1-0.75-a	280	460	400	3.53	0.0215	420	0.75	90.00	41.90	620	9500	Shear	214.50
5	Altoubat et al. (2009)	L1-0.75-b	280	460	400	3.53	0.0215	420	0.75	90.00	41.90	620	9500	Shear	213.00
6	Altoubat et al. (2009)	L2-0.75-b	230	390	330	3.50	0.0318	420	0.75	90.00	41.90	620	9500	Shear	139.50
7	Altoubat et al. (2009)	L2-1.0-b	230	390	330	3.50	0.0318	420	1.00	90.00	35.60	620	9500	Shear	151.50
8	Altoubat et al. (2009)	Sh1-0.50-a	280	460	400	2.28	0.0215	420	0.50	90.00	41.90	620	9500	Shear	219.50
9	Altoubat et al. (2009)	Sh2-0.50-b	230	390	330	2.27	0.0318	420	0.50	90.00	41.90	620	9500	Shear	150.00
10	Altoubat et al. (2009)	Sh2-0.75-a	230	390	330	2.27	0.0318	420	0.75	90.00	41.90	620	9500	Shear	168.50
11	Altoubat et al. (2009)	Sh2-0.75-b	230	390	330	2.27	0.0318	420	0.75	90.00	41.90	620	9500	Shear	170.50
12	Navas et al. (2018)	OAP1	305	552	472.9	3.87	0.0167	579	1.10	56.50	43.12	400	4700	Shear	223.34
13	Navas et al. (2018)	OAP2	305	552	472.5	4.84	0.0223	579	1.10	56.50	44.91	400	4700	Shear	243.13
14	Navas et al. (2018)	OBP1	229	552	470.6	3.89	0.0224	579	1.10	56.50	42.67	400	4700	Shear	180.87
15	Navas et al. (2018)	OBP2	229	552	469.2	4.87	0.0225	579	1.10	56.50	42.00	400	4700	Shear	147.80
16	Al-Alawi and Mashrei (2022)	B-Sy M PF1–6.4	100	150	130	2.31	0.0464	500	0.69	64.00	150.00	685	10500	Shear	65.26
17	Al-Alawi and Mashrei (2022)	B-Sy M PF1–4.8	100	150	130	2.31	0.0464	500	0.52	64.00	150.00	685	10500	Shear	58.84
18	Al-Alawi and Mashrei (2022)	B-Sy M PF1–3.2	100	150	130	2.31	0.0464	500	0.34	64.00	150.00	685	10500	Shear	57.77
19	Al-Alawi and Mashrei (2022)	B-Sy M PF2–6.4	100	150	130	2.31	0.0464	500	0.69	180.00	150.00	620	6600	Shear	64.72
20	Al-Alawi and Mashrei (2022)	B-Sy M PF2–4.8	100	150	130	2.31	0.0464	500	0.52	180.00	150.00	620	6600	Shear	57.77
21	Al-Alawi and Mashrei (2022)	B-Sy M PF2–3.2	100	150	130	2.31	0.0464	500	0.34	180.00	150.00	620	6600	Shear	54.56
22	Al-Alawi and Mashrei (2022)	B-Sy M PF1–4.8 -p3	100	150	130	2.31	0.0464	500	0.52	64.00	150.00	685	10500	Shear	66.86
23	Al-Alawi and Mashrei (2022)	B-Sy M PF1–4.8 -p2	100	150	130	2.31	0.0396	500	0.52	64.00	150.00	685	10500	Shear	58.84
24	Al-Alawi and Mashrei (2022)	B-Sy M PF1–4.8 -p1	100	150	130	2.31	0.0329	500	0.52	64.00	150.00	685	10500	Shear	44.93
25	Xiang et al. (2022)	F3-A-3	150	300	241.5	2.98	0.0281	542	0.32	37.50	34.50	543	8200	Shear	62.86
26	Xiang et al. (2022)	F6-A-3	150	300	241.5	2.98	0.0281	542	0.63	37.50	37.50	543	8200	Shear	83.89
27	Xiang et al. (2022)	F9-A-3	150	300	241.5	2.98	0.0281	542	0.95	37.50	36.90	543	8200	Shear	96.72
28	Altoubat et al. (2020)	VB-0L-0.50	230	390	330	3.48	0.0318	420	0.50	90.00	32.30	620	9500	Shear	90.00
29	Uğur and Ünal (2022)	SCC-F2-S1	125	250	240	2.50	0.0052	366	0.28	77.14	38.61	550	7060	Shear	23.35
30	Zhang et al. (2014)	RE-00	150	300	250	2.80	0.0270	400	3.00	333.33	32.80	482	5000	Shear	104.38
31	Ababneh et al. (2017)	B1V3S0	100	150	125	2.40	0.0322	470	0.33	90.00	44.40	620	9500	Shear	32.00
32	Ababneh et al. (2017)	B1V5S0	100	150	125	2.40	0.0322	470	0.54	90.00	45.10	620	9500	Shear	35.00
33	Ababneh et al. (2017)	B1V7S0	100	150	125	2.40	0.0322	470	0.76	90.00	45.90	620	9500	Shear	38.50

34	Arslan et al. (2017)	B2.5P1.0	150	240	210	2.50	0.0128	492	1.00	50.00	27.00	470	3600	Shear	47.92
35	Arslan et al. (2017)	B2.5P2.0	150	240	210	2.50	0.0128	492	2.00	50.00	13.85	470	3600	Shear	42.94
36	Arslan et al. (2017)	B2.5P3.0	150	240	210	2.50	0.0128	492	3.00	50.00	18.45	470	3600	Shear	56.06
37	Arslan et al. (2017)	B3.5P1.0	150	240	210	3.50	0.0128	492	1.00	50.00	27.00	470	3600	Shear	46.75
38	Arslan et al. (2017)	B3.5P2.0	150	240	210	3.50	0.0128	492	2.00	50.00	13.85	470	3600	Shear	42.50
39	Arslan et al. (2017)	B3.5P3.0	150	240	210	3.50	0.0128	492	3.00	50.00	18.45	470	3600	Shear	50.72
40	Majdzadeh et al. (2006)	B6	150	150	120	3.02	0.0262	500	0.50	85.00	43.90	620	9500	Shear	86.00
41	Majdzadeh et al. (2006)	B7	150	150	120	3.02	0.0262	500	1.00	85.00	44.20	620	9500	Shear	113.00
42	Majdzadeh et al. (2006)	B8	150	150	120	3.02	0.0262	500	1.50	85.00	43.10	620	9500	Shear	104.00
43	Majdzadeh et al. (2006)	B9	150	150	120	3.02	0.0262	500	0.50	360.00	43.40	375	3500	Shear	82.00
44	Majdzadeh et al. (2006)	B10	150	150	120	3.02	0.0262	500	1.00	360.00	44.80	375	3500	Shear	100.00
45	Majdzadeh et al. (2006)	B11	150	150	120	3.02	0.0262	500	1.50	360.00	42.00	375	3500	Shear	99.00
46	Sahoo et al. (2015)	PFRC	150	200	172	3.49	0.0234	500	1.00	25.00	37.60	460	5000	Shear	38.40
47	Shaaban et al. (2021)	B5	120	300	260	2.35	0.0326	700	1.50	666.67	45.90	400	3450	Shear	63.00
48	Shaaban et al. (2021)	B6	120	300	260	2.35	0.0326	700	2.50	666.67	45.90	400	3450	Shear	70.80
49	Shaaban et al. (2021)	B7	120	300	260	2.35	0.0326	700	0.75	666.67	45.05	400	3450	Shear	55.00
50	Bastami (2019)	SCC-0.75%S1-15M-0	125	250	201	3.69	0.0160	434	0.75	74.00	51.60	625	9500	Shear	42.85
51	Bastami (2019)	HSC-0.75%S1-15M-0	125	250	201	3.69	0.0160	434	0.75	74.00	71.40	625	9500	Shear	56.10
52	Bastami (2019)	HSC-0.75%S1-20M-0	125	250	201	3.69	0.0238	426	0.75	74.00	78.30	625	9500	Shear	85.00
53	Murad and Abdel-Jabbar (2022)	P2	150	250	225	1.56	0.0119	420	0.22	76.50	45.30	585	6600	Shear	73.90
54	Murad and Abdel-Jabbar (2022)	P4	150	250	225	1.56	0.0119	420	0.44	76.50	40.80	585	6600	Shear	57.85
55	Murad and Abdel-Jabbar (2022)	P8	150	250	225	1.56	0.0119	420	0.88	76.50	37.70	585	6600	Shear	69.75
56	Altoubat et al. (2012)	L-F	230	390	330	3.50	0.0318	420	0.50	90.00	42.00	620	9500	Shear	132.50
57	Altoubat et al. (2012)	Sh-F	230	390	330	2.27	0.0318	420	0.50	90.00	42.00	620	9500	Shear	159.00
58	Parmentier et al. (2012)	Sy4.5-1-1	200	300	270	1.50	0.0116	500	0.50	70.00	54.50	600	5000	Shear	128.10
59	Parmentier et al. (2012)	Sy4.5-1-2	200	300	270	1.50	0.0116	500	0.50	70.00	54.50	600	5000	Shear	162.60
60	Parmentier et al. (2012)	Sy4.5-2-1	200	300	270	2.50	0.0116	500	0.50	70.00	54.50	600	5000	Shear	105.50
61	Parmentier et al. (2012)	Sy4.5-2-2	200	300	270	2.50	0.0116	500	0.50	70.00	54.50	600	5000	Shear	111.70
62	Furlan Jr. and de Hanai (1997)	P2B	100	100	85.25	3.52	0.0166	500	0.50	840.00	48.00	400	3500	Shear	17.50
63	Hossain et al. (2023)	R0C5F1	200	300	268	1.85	0.0075	496	0.15	666.67	28.30	400	4010	Shear	86.70
64	Hossain et al. (2023)	R0C10F1	200	300	268	1.85	0.0075	496	0.15	666.67	41.90	400	4010	Shear	105.10
65	Shoeib et al. (2023)	B2	120	650	600	0.58	0.0141	400	0.30	56.47	44.20	400	4700	Shear	440.00
66	Shoeib et al. (2023)	B3	120	650	600	0.58	0.0141	400	0.60	56.47	51.00	400	4700	Shear	480.00
67	Shoeib et al. (2023)	B4	120	650	600	0.58	0.0141	400	0.90	56.47	54.40	400	4700	Shear	500.00
68	Mori et al. (2017)	C-P12	100	200	164	1.22	0.0130	500	0.40	42.86	49.10	500	9500	Shear	71.45
69	Mori et al. (2017)	D-P12	250	500	434	1.15	0.0136	500	1.20	42.86	57.60	500	9500	Shear	443.15
70	Bajaj and Shrivastava (2011)	1-B2	100	150	130	3.85	0.0121	428	0.10	158.80	40.12	680	5800	Shear	19.95
71	Bajaj and Shrivastava (2011)	2-B2	100	150	130	3.85	0.0174	423	0.10	158.80	40.12	680	5800	Shear	24.30
72	Bajaj and Shrivastava (2011)	1-B3	100	150	130	3.85	0.0121	428	0.20	158.80	40.97	680	5800	Shear	21.00
73	Bajaj and Shrivastava (2011)	2-B3	100	150	130	3.85	0.0174	423	0.20	158.80	40.97	680	5800	Shear	25.35
74	Bajaj and Shrivastava (2011)	1-B4	100	150	130	3.85	0.0121	428	0.30	158.80	39.78	680	5800	Shear	22.20
75	Bajaj and Shrivastava (2011)	2-B4	100	150	130	3.85	0.0174	423	0.30	158.80	39.78	680	5800	Shear	26.40
76	Bajaj and Shrivastava (2011)	1-B5	100	150	130	3.85	0.0121	428	0.40	158.80	39.53	680	5800	Shear	22.80
77	Bajaj and Shrivastava (2011)	2-B5	100	150	130	3.85	0.0174	423	0.40	158.80	39.53	680	5800	Shear	27.15
78	Bajaj and Shrivastava (2011)	1-B6	100	150	130	3.85	0.0121	428	0.50	158.80	38.25	680	5800	Shear	21.75
79	Bajaj and Shrivastava (2011)	2-B6	100	150	130	3.85	0.0174	423	0.50	158.80	38.25	680	5800	Shear	26.25
80	Bajaj and Shrivastava (2011)	1-B7	100	150	130	3.85	0.0121	428	0.60	158.80	36.55	680	5800	Shear	21.45

81	Bajaj and Shrivastava (2011)	2-B7	100	150	130	3.85	0.0174	423	0.60	158.80	36.55	680	5800	Shear	25.05
82	Al-Khafaji and Harba (2023)	BS2	150	200	175	2.86	0.0129	678	0.10	666.67	37.20	400	3500	Shear	57.27
83	Al-Khafaji and Harba (2023)	BS3	150	200	175	2.86	0.0129	678	0.20	666.67	39.26	400	3500	Shear	49.32
84	Kamal et al. (2014)	B10P	100	150	130	2.31	0.0121	550	0.11	12.50	130.00	400	3500	Shear	20.95
85	Kamal et al. (2014)	B12P	100	150	130	2.31	0.0174	550	0.11	12.50	130.00	400	3500	Shear	27.00
86	Al Ghali et al. (2023)	PP-42	150	250	225	1.48	0.0186	565	0.25	42.00	49.20	600	9500	Shear	89.15
87	Al Ghali et al. (2023)	PP-270	150	250	225	1.48	0.0186	565	0.25	270.00	40.10	570	3500	Shear	81.30
88	Atea (2017)	BM(30)	100	300	280	1.00	0.0287	500	0.50	667.00	31.00	400	3500	Shear	160.00
89	Atea (2017)	BM(40)	100	300	280	1.00	0.0287	500	1.00	667.00	40.00	400	3500	Shear	166.00
90	Rao et al. (2011)	0,5-MixA	100	300	280	0.71	0.0020	500	0.12	300.00	18.47	600	3500	Shear	13.72
91	Rao et al. (2011)	0,5-MixB	100	300	280	0.71	0.0020	500	0.12	300.00	24.36	600	3500	Shear	20.16
92	Rao et al. (2011)	0,5-MixC	100	300	280	0.71	0.0020	500	0.12	300.00	29.78	600	3500	Shear	24.08
93	Rao et al. (2011)	1-MixA	100	300	280	0.71	0.0020	500	0.23	300.00	19.07	600	3500	Shear	15.12
94	Rao et al. (2011)	1-MixB	100	300	280	0.71	0.0020	500	0.23	300.00	24.60	600	3500	Shear	20.44
95	Rao et al. (2011)	1-MixC	100	300	280	0.71	0.0020	500	0.23	300.00	31.47	600	3500	Shear	24.64
96	Ozturk et al. (2017)	B2.5P1.0	150	240	210	2.50	0.0128	492	1.00	50.00	27.00	470	3600	Shear	38.34
97	Ketenci (2022)	C30PP1	250	400	367	2.45	0.0088	420	0.66	350.00	30.00	630	8000	Shear	164.34
98	Ketenci (2022)	C30PP2	250	400	367	2.45	0.0088	420	0.66	350.00	30.00	630	8000	Shear	154.92

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

During the preparation of this manuscript, AI models were used exclusively for language editing and stylistic refinement. The authors take full responsibility for the content, interpretation, and conclusions of the published article.

REFERENCES

- Ababneh A, Al-Rousan R, Alhassan M, Alqadami M (2017). Influence of synthetic fibers on the shear behavior of lightweight concrete beams. *Advances in Structural Engineering*, 20(11), 1671-1683.
- Akpınar M, Uzun B, Kadioğlu HG, Yaylı MÖ (2025a). Dynamic analysis of restrained short-fiber-reinforced and functionally graded nano-beams via stress-driven model. *ZAMM - Journal of Applied Mathematics and Mechanics*, 105(7), e70133.
- Akpınar M, Uzun B, Kadioğlu HG, Yaylı MÖ (2025b). Dynamics of a short-fiber-reinforced nanorod via hardening nonlocal approach. *Mechanics of Solids*, 60(3), 1738-1760.
- Akpınar M, Kadioğlu HG, Yaylı MÖ (2026a). Free vibration of a short-fiber-reinforced viscoelastic nanotube with non-local strain gradient theory. *Acta Mechanica*, online first.
- Akpınar M, Kadioğlu HG, Yaylı MÖ (2026b). A doublet mechanics approach to torsional vibration in viscoelastic short fiber-reinforced nanotubes. *The European Physical Journal Plus*, 141(7), 798.
- Al Ghali AE, El Ezz NE, Hamad B, Assaad J, Yehya A (2023). Comparative study on shear strength and life cycle assessment of reinforced concrete beams containing different types of fibers. *Case Studies in Construction Materials*, 19, e02497.
- Al-Alawi AR, Mashrei MA (2022). Shear capacity of sustainable ultra-high performance concrete beam reinforced with macro synthetic fiber as a sustainable alternative for stirrups and steel fiber. *Case Studies in Construction Materials*, 17, e01443.
- Al-Khafaji NH, Harba IS (2023). Shear and flexural behavior of lightweight concrete beams containing hybrid fibers. *Civil and Environmental Engineering*, 19(1), 206-217.
- Albidah AS, Abbas YM (2024). Improving shear strength prediction in steel fiber reinforced concrete beams: stacked ensemble machine learning modeling and practical applications. *Buildings*, 14(7), 2169.
- Altoubat S, Yazdanbakhsh A, Rieder KA (2009). Shear behavior of macro-synthetic fiber-reinforced concrete beams without stirrups. *ACI Materials Journal*, 106(4), 381-389.
- Altoubat S, Yazdanbakhsh A, Rieder KA (2012). Shear strength of beams reinforced with synthetic macro-fibers and stirrups. In: *8th RILEM International Symposium on Fibre Reinforced Concrete: Challenges and Opportunities (BEFIB 2012)*, Guimarães, Portugal, pp. 1108-1119.
- Altoubat S, Karzad AS, Maalej M, Barakat S, Junaid T (2020). Experimental study of the steel/CFRP interaction in shear-strengthened RC beams incorporating macro-synthetic fibers. *Structures*, 25, 88-98.
- Arslan G, Keskin RSO, Öztürk M (2017). Shear behaviour of polypropylene fibre-reinforced-concrete beams without stirrups. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 170(3), 190-198.
- Atea RS (2017). Improvement of structural properties for reinforced concrete deep beam using silica fume with polypropylene fibers. *Muthanna Journal of Engineering and Technology*, 5(1), 1-9.
- Bajaj K, Shrivastava Y (2011). Performance of fibre based concrete in shear. *International Journal of Earth Sciences and Engineering*, 4(6 SPL), 619-622.
- Bastami R (2019). *Structural Performance of High-Strength Reinforced Concrete Beams Built with Synthetic Fibers*. Ph.D. dissertation, University of Ottawa, Ottawa, Canada.

- Campione G, La Mendola L, Zingone G (1999). Shear resistant mechanisms of high strength fibre reinforced concrete beams. *WIT Transactions on the Built Environment*, 41, 23-32.
- Conforti A, Minelli F, Tinini A, Plizzari GA (2015). Influence of polypropylene fibre reinforcement and width-to-effective depth ratio in wide-shallow beams. *Engineering Structures*, 88, 12-21.
- DAfStB (2012). *DAfStB-Richtlinie Stahlfaserbeton*. Deutscher Ausschuss für Stahlbeton, Berlin, Germany.
- fib (2013). *fib Model Code for Concrete Structures 2010*. Ernst & Sohn, Berlin, Germany.
- Furlan Jr S, de Hanai JB (1997). Shear behaviour of fiber reinforced concrete beams. *Cement and Concrete Composites*, 19(4), 359-366.
- Greenough T, Nehdi M (2008). Shear behavior of fiber-reinforced self-consolidating concrete slender beams. *ACI Materials Journal*, 105(5), 468-477.
- Hossain FZ, Pal A, Ahmed KS, Bediwy A, Alam MS (2023). Shear behavior of polypropylene fiber-reinforced concrete beams containing recycled aggregate and crumb rubber. *Journal of Cleaner Production*, 412, 137370.
- Jongvivatsakul P, Matsumoto K, Niwa J (2013). Shear capacity of fiber reinforced concrete beams with various types and combinations of fibers. *Journal of JSCE*, 1(1), 228-241.
- Kamal MM, Safan MA, Etman ZA, Salama RA (2014). Behavior and strength of beams cast with ultra high strength concrete containing different types of fibers. *HBRC Journal*, 10(1), 55-63.
- Ketenci MO (2022). *Kesme donatısız polipropilen ve çelik lifli betonarme kirişlerin eğilme ve kesme kuvveti altında davranışlarının deneysel olarak incelenmesi*. M.Sc. thesis, Ege University, İzmir, Türkiye. (in Turkish)
- Lakavath C, Prakash SS, Dirar S (2021). Experimental and numerical studies on shear behaviour of macro-synthetic fibre reinforced prestressed concrete beams. *Construction and Building Materials*, 291, 123313.
- Lantsoght EOL (2019). Database of shear experiments on steel fiber reinforced concrete beams without stirrups. *Materials*, 12(6), 917.
- Majdzadeh F, Soleimani SM, Banthia N (2006). Shear strength of reinforced concrete beams with a fiber concrete matrix. *Canadian Journal of Civil Engineering*, 33(6), 726-734.
- Mori K, Sato Y, Kaneko Y (2017). Flexural and shear behavior of RC beams reinforced by polypropylene fiber. *Journal of Structural and Construction Engineering (Transactions of AIJ)*, 82(737), 1081-1090.
- Murad Y, Abdel-Jabbar H (2022). Shear behavior of RC beams prepared with basalt and polypropylene fibers. *Case Studies in Construction Materials*, 16, e00835.
- Navas FO, Navarro-Gregori J, Herdocia GL, Serna P, Cuenca E (2018). An experimental study on the shear behaviour of reinforced concrete beams with macro-synthetic fibres. *Construction and Building Materials*, 169, 888-899.
- Neto BNM, Barros JAO, Melo GSA (2013). A model for the prediction of the punching resistance of steel fibre reinforced concrete slabs centrally loaded. *Construction and Building Materials*, 46, 211-223.
- Nzambi AKLL, Ntuku JB, de Oliveira DRC (2022). Empirical equations for flexural residual strengths in concrete with low volumetric fractions of hook-end steel fiber. *Engineering Reports*, 4(5), e12490.
- Öztürk M, Keskin RSO, Arslan G (2017). The behavior of PFRC beams with and without web reinforcement. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics*, 1, 347-352.
- Parmentier B, Cauberg N, Vandewalle L (2012). Shear resistance of macro-synthetic and steel fibre reinforced concrete beams without stirrups. In: *8th RILEM International Symposium on Fibre Reinforced Concrete: Challenges and Opportunities (BEFIB 2012)*, Guimarães, Portugal.
- Rao MVK, Dakshina Murthy NR, Santhosh Kumar V (2011). Behaviour of polypropylene fibre reinforced fly ash concrete deep beams in flexure and shear. *Asian Journal of Civil Engineering (Building and Housing)*, 12(2), 143-154.
- RILEM TC 162-TDF (2003). Test and design methods for steel fibre reinforced concrete: σ - ϵ design method-final recommendation. *Materials and Structures*, 36(262), 560-567.
- Sahoo DR, Maran K, Kumar A (2015). Effect of steel and synthetic fibers on shear strength of RC beams without shear stirrups. *Construction and Building Materials*, 83, 150-158.
- Said M, Montaser W, Elgammal AS, Zahir AH, Shaaban IG (2021). Shear strength of reinforced mortar beams containing polyvinyl alcohol fibre (PVA). *International Journal of Civil Engineering*, 19, 1155-1178.
- Shaaban IG, Said M, Khan SU, Eissa M, Elrashidy K (2021). Experimental and theoretical behaviour of reinforced concrete beams containing hybrid fibres. *Structures*, 32, 2143-2160.
- Shoeib AEK, Abdelghaffar MS, Ibrahim AH, Badawy MS (2023). Behavior of self-compacted concrete deep beams reinforced with polypropylene fibers. *Engineering Research Journal - Faculty of Engineering (Shoubra)*, 52(1), 114-124.
- Thomas J, Ramaswamy A (2007). Mechanical properties of steel fiber-reinforced concrete. *Journal of Materials in Civil Engineering*, 19(5), 385-392.
- Uğur AE, Ünal A (2022). Assessing the structural behavior of reinforced concrete beams produced with macro synthetic fiber reinforced self-compacting concrete. *Structures*, 38, 1226-1243.
- Ünal A, Cengiz S, Kamanlı M (2021). Effect of stirrup spacing and polypropylene fiber ratio on behavior of reinforced concrete beams. *Periodica Polytechnica Civil Engineering*, 65(2), 522-536.
- Xiang Z, Zhou J, Niu J, Feng X, Wang J (2022). Study on shear behavior of high-performance polypropylene fiber-reinforced lightweight aggregate concrete beams. *Case Studies in Construction Materials*, 17, e01594.
- Yang X, Liang N, Hu Y, Feng R (2021). An experimental study of shear resistance for multisize polypropylene fiber concrete beams. *International Journal of Concrete Structures and Materials*, 15, 52.
- Zhang G, Zhang L, Xing G, Wei F, Lu D (2020). Experimental study on shear capacity of polypropylene fiber concrete beams. *Journal of Hunan University (Natural Sciences)*, 47(5), 70-77.
- Zhang R, Matsumoto K, Hirata T, Ishizeki Y, Niwa J (2014). Shear behavior of polypropylene fiber reinforced ECC beams with varying shear reinforcement ratios. *Journal of JSCE*, 2(1), 39-53.



Challenge Journal of CONCRETE RESEARCH LETTERS

Review Article

Sugarcane bagasse ash in cementitious systems: A review of fresh, mechanical, and durability properties

Sachin Kumar Verma ^{a,*} , Anil Kumar Sachan ^a , Rama Shanker ^a

^a Department of Civil Engineering, Motilal Nehru National Institute of Technology Allahabad, Prayagraj 211004, Uttar Pradesh, India

ABSTRACT

Currently, research is being conducted to investigate the potential of industrial and agricultural waste as raw materials in the construction industry. Integrating such materials into concrete diminishes cement consumption and CO₂ emissions from cement manufacturing. Sugarcane bagasse is a by-product of the sugar extraction process, and a significant portion of it is used as boiler fuel for electricity generation. This process releases a considerable amount of waste sugarcane bagasse ash (SCBA), which is frequently disposed of in the environment. Incorporating this waste can be both cost-effective and ecologically advantageous, fostering sustainable development. This review critically synthesizes published studies on the physical and chemical characteristics of SCBA, fresh-state behaviour, mechanical properties, durability indicators, and CO₂ reduction potential in cementitious materials, including mortar and concrete. Particular attention is given to the effects of ash processing, fineness, silica content, burning condition, and loss on ignition on reported performance. The reviewed evidence indicates that low-to-moderate SCBA contents can enhance compressive and split tensile strength, while durability improvements are commonly reflected in reduced water absorption, lower capillary absorption and chloride penetration, and higher electrical resistivity. The literature indicates that mechanical performance is most frequently optimized at about 10-15% replacement, whereas durability benefits are often reported within a broader range of 10-30%, depending on matrix type and ash quality. The findings also show that the environmental benefit of SCBA depends on processing intensity and transport burden. Overall, SCBA emerges as a promising but process-sensitive supplementary cementitious material for sustainable concrete production.

ARTICLE INFO

Article history:

Received – February 5, 2026
Revision requested – March 10, 2026
Revision received – April 12, 2026
Accepted – April 24, 2026

Keywords:

Sugarcane bagasse ash
Chemical properties
Durability
Mechanical properties
Physical properties



This is an open access article distributed under the CC BY licence.

© 2026 by the Authors.

Citation: Verma SK, Sachan AK, Shanker R (2026). Sugarcane bagasse ash in cementitious systems: A review of fresh, mechanical, and durability properties. *Challenge Journal of Concrete Research Letters*, 17(3), 387–404.

1. Introduction

The key strategies for sustainable cement manufacturing include energy conservation, reduction in CO₂ emissions, and the preservation of finite natural resources. However, the production of ordinary Portland cement (OPC) is highly unsustainable due to its extensive consumption of natural resources and high carbon emissions (Fairbairn et al. 2010). The global annual concrete production exceeds 30 billion metric tons (Ozmen

and Tanriverdi 2025), with the Indian construction industry using approximately 450 million cubic metres annually (IBEF 2025). Cement reacts chemically with water and other substances to form a hardened mass that binds components together. Various additives are often introduced to enhance the properties of fresh and hardened concrete (Jittin and Bahurudeen 2022; Miller et al. 2016).

Pozzolanic materials derived from agricultural waste have gained significant attention due to their ability to

* Corresponding author. E-mail address: sachin.2020rce15@mnit.ac.in (S. K. Verma)

improve the performance of blended cement concrete while mitigating environmental concerns (Agwa et al. 2022; Zeyad et al. 2016). SCBA is one such promising pozzolan, available in various regions worldwide. India alone produces over 300 million tons of sugarcane annually, generating approximately 10 million tons of SCBA as waste. The processing of sugarcane in mills results in about 0.62% residual ash and 26% bagasse per ton of sugarcane (Chindaprasirt et al. 2008; Dhengare et al. 2020; Juenger et al. 2019).

Bagasse is a fibrous residue generated after juice extraction from sugarcane and is widely used as a fuel source in the sugar industry. The ash produced from its combustion known as sugarcane bagasse ash (SCBA) has been increasingly utilized as a pozzolanic material in concrete or mortar mixtures as a partial replacement for cement and thus contribute to reducing disposal concerns. Several studies have investigated the chemical composition and pozzolanic activity of SCBA, concluding that it primarily consists of high silica content. However, unburned carbon particles in SCBA can adversely affect concrete reactivity and performance (Kumara et al. 2023; Praveenkumar et al. 2020).

Several studies on SCBA have provided useful background on its potential as a supplementary cementitious material. However, many of them remain largely descriptive or focus on isolated performance aspects without systematically linking ash processing quality to the variability observed across cementitious materials, including mortar and concrete. The present review seeks to address this gap by providing an integrated analysis of the physical and chemical characteristics of SCBA, fresh behaviour, mechanical response, durability performance, and CO₂ reduction potential within a unified framework. It further employs comparative tables and trend-based figures to identify practical optimum replacement ranges for key mechanical and durability indicators. Accordingly, this review aims to analyse the influence of SCBA on cement-based materials based on existing literature, with particular emphasis on its effects on mechanical and durability-related performance.

2. Literature Review Methodology

This review adopted a structured literature review methodology to synthesise the influence of sugarcane bagasse ash (SCBA) on cementitious materials. Relevant studies were retrieved from Scopus, Web of Science, ScienceDirect, and Google Scholar to ensure broad coverage of the peer-reviewed literature. The search was limited to articles published between 2008 and 2025, which corresponds to the main period during which SCBA has been systematically examined as a partial cement replacement material.

The search strategy was developed using combinations of SCBA-related and performance-related terms, including “sugarcane bagasse ash”, “SCBA concrete”, “SCBA mortar”, “SCBA supplementary cementitious material”, “SCBA mechanical properties”, “SCBA durability”, “SCBA workability”, “water absorption”, “capillary absorption”, “sorptivity”, “chloride penetration”, and “electrical resistivity”. These terms were combined using

Boolean operators such as AND and OR to capture studies addressing the physical and chemical characteristics of SCBA as well as its effects on fresh, mechanical, and durability properties.

The retrieved records were screened through title screening, abstract screening, and full-text eligibility assessment. Studies were included if they investigated SCBA in concrete or mortar and reported results on at least one of the following aspects, namely physical or chemical characteristics, fresh properties, mechanical performance, or durability behaviour; and provided sufficient quantitative information on mix proportion, replacement level, curing condition, and measured properties. Conference abstracts without full data, non-English publications, and studies lacking adequate methodological detail were excluded.

Approximately 120 studies were initially identified through database searching. After screening and eligibility assessment, around 65 studies were retained for detailed synthesis. To improve methodological rigour, the included studies were further appraised for reporting quality on the basis of the clarity of SCBA source and processing method, mix design details, curing regime, testing procedure, and completeness of quantitative results. Studies with sufficiently reported experimental data were prioritised for the comparative tables and trend-based figures used in this review.

This systematic approach is intended not only to summarise the available evidence, but also to provide a comparative and critical synthesis of how SCBA processing, replacement level, and matrix type jointly influence fresh, mechanical, durability, and environmental performance in cementitious systems.

3. Environmental Impact and CO₂ Reduction Potential of SCBA

Sugarcane bagasse ash (SCBA) is increasingly regarded as a low-carbon supplementary cementitious material because it can partially replace Portland cement, the production of which is highly emission intensive due to clinker burning and limestone calcination. The carbon footprint of conventional cement is generally reported to be around 0.8–0.9 kg CO₂ per kg cement, although the exact value varies with clinker factor, kiln efficiency, fuel type, electricity mix, and regional production conditions (Benhelal et al. 2013; Chen et al. 2010; Kajaste and Hurme 2016; Mohamad et al. 2022). The environmental benefit of SCBA lies in its capacity to valorise an agro-industrial residue while reducing clinker demand. However, the literature does not support a single universal carbon emission factor for sugarcane bagasse ash (SCBA). Reported carbon emission values for SCBA vary markedly with allocation assumptions and the system boundary adopted, particularly whether drying, sieving, grinding, calcination/activation, and transport are included (Fairbairn et al. 2010; Cordeiro et al. 2008, 2009; Kolawole et al. 2021; Francioso et al. 2024). Torres de Sande et al. (2023) quantified this variation, reporting 0.024 kg CO_{2e}/kg (carbon dioxide equivalent per kilogram) for untreated locally used SCBA and 0.46 kg CO_{2e}/kg for treated or activated imported SCBA, com-

pared with 0.912 kg CO_{2e}/kg for cement in the same study. Other studies have similarly adopted an SCBA emission factor of about 0.11 kg CO₂/kg (Ullah et al. 2025; Li et al. 2022; Chindaprasirt et al. 2020), confirming that although SCBA is generally far less carbon-intensive than Portland cement, its environmental benefit is strongly conditioned by processing intensity and transport burden.

Accordingly, the climate advantage of SCBA is best expressed as net CO₂ reduction. The net CO₂ reduction can be expressed as the difference between the carbon emissions avoided by replacing a given amount of cement and the carbon emissions generated from processing the equivalent amount of SCBA. The analysis was performed using the expression: Net CO₂ reduction = (cement replaced × 0.85) - (SCBA used × 0.46), assuming mass-equivalent replacement within 1 tonne of total binder, as shown in Table 1. The analysis adopted a cement emission factor of 0.85 kg CO₂/kg, which lies within the commonly reported range of 0.8–0.9 kg CO₂/kg for conventional cement production (Benhelal et al. 2013; Chen et

al. 2010; IEA 2023, as cited in Environmental Impact & CO₂ Reduction Potential of SCBA). An emission factor of 0.46 kg CO₂/kg was adopted for SCBA in the present analysis, as this value has been reported for treated or activated imported SCBA in the literature (Torres de Sande et al. 2023). Accordingly, it is taken to represent the cumulative influence of processing-related stages, including treatment or activation, on the embodied emissions of SCBA. The analysis shows a linear increase in net CO₂ savings with rising SCBA replacement levels under the adopted emission factors. At 5%, 10%, 20%, and 30% substitution, the estimated net CO₂ reductions are 19.5, 39, 78, and 117 kg CO₂/t binder, respectively. The consistently positive savings arise from the lower embodied emissions of SCBA (0.46 kg CO₂/kg) relative to cement (0.85 kg CO₂/kg). These results strengthen the environmental justification for SCBA as a supplementary cementitious material and highlight the need to evaluate net life-cycle benefits rather than relying solely on gross avoided emissions from cement replacement (Chindaprasirt et al. 2020; Li et al. 2022).

Table 1. Calculated net CO₂ reduction for different SCBA replacement levels.

SCBA replacing cement (%)	Cement avoided (kg/t binder)	Gross CO ₂ avoided from cement (kg/t binder)	CO ₂ burden of SCBA processing (kg/t binder)	Net CO ₂ reduction (kg/t binder)
5	50	42.5	23	19.5
10	100	85.0	46	39
20	200	170.0	92	78
30	300	255.0	138	117

Note: Calculations are based on 1 tonne of binder and assume one-to-one mass replacement of cement by SCBA.

4. Sugarcane Bagasse Ash Processing and Material Characteristics

Fig. 1 illustrates the process flow for sugar production and its byproducts. Bagasse, the fibrous residue after juice extraction, is burned in sugar mills, producing SCBA as waste. Fig. 2 presents images of raw sugarcane bagasse and SCBA. The SCBA has been widely investigated as a supplementary cementitious material. However, evidence from several studies indicates that performance depends not merely on its agricultural origin, but on the manner in which the ash is processed before incorporation into cementitious systems. The most influential processing variables include burning temperature, residence time, oxygen availability, grinding duration, fineness, carbon removal, and the resulting proportion of amorphous and crystalline silica (Cordeiro et al. 2011; Bahurudeen and Santhanam 2015; Embong et al. 2016; Gupta and Sachan 2019; Kolawole et al. 2021). A recurring finding across several studies is that untreated or poorly processed SCBA often contains fibrous residues, porous coarse particles, and substantial quantities of unburned carbon, all of which reduce pozzolanic reactivity and contribute to inconsistent material performance (Bahurudeen et al. 2016; Ouedraogo et al. 2022; Embong et al. 2016). Accordingly, SCBA should not be treated as a uniform material; rather, it should be understood as a process-dependent family of ashes whose engineering

value is governed by combustion history and post-treatment.

4.1. Physical characteristics of SCBA

Morphological observations generally describe irregularly shaped particles with rough and porous surfaces (as shown in Fig. 3), while Abdalla et al. (2022) and Bahurudeen and Santhanam (2015) also reported the co-existence of fine burned particles and unburned fibrous particles in raw ash. The physical characteristics of SCBA reported in several studies are summarized in Table 2. Studies indicate that the specific gravity of SCBA typically ranges from 1.65 to 2.42, while bulk density commonly varies between 410 and 610.6 kg/m³. Reported fineness values indicates substantial variation, ranging from 27.4 to 60320 m²/kg, reflecting differences in grinding and sieving procedures across studies (Abdalla et al. 2022; Bahurudeen and Santhanam 2015; Patil et al. 2021). Mello et al. (2020), Navaneetha et al. (2025) and Patil et al. (2021) reported that post-processing of SCBA resulted in higher fineness values. Treatments such as grinding, sieving, drying, or their combination was found to enhance the fineness of the ash. The high surface area can enhance filler action and pozzolanic reactivity. However, it can also increase water demand and affect fresh-state behaviour when accompanied by high porosity or carbonaceous impurities.

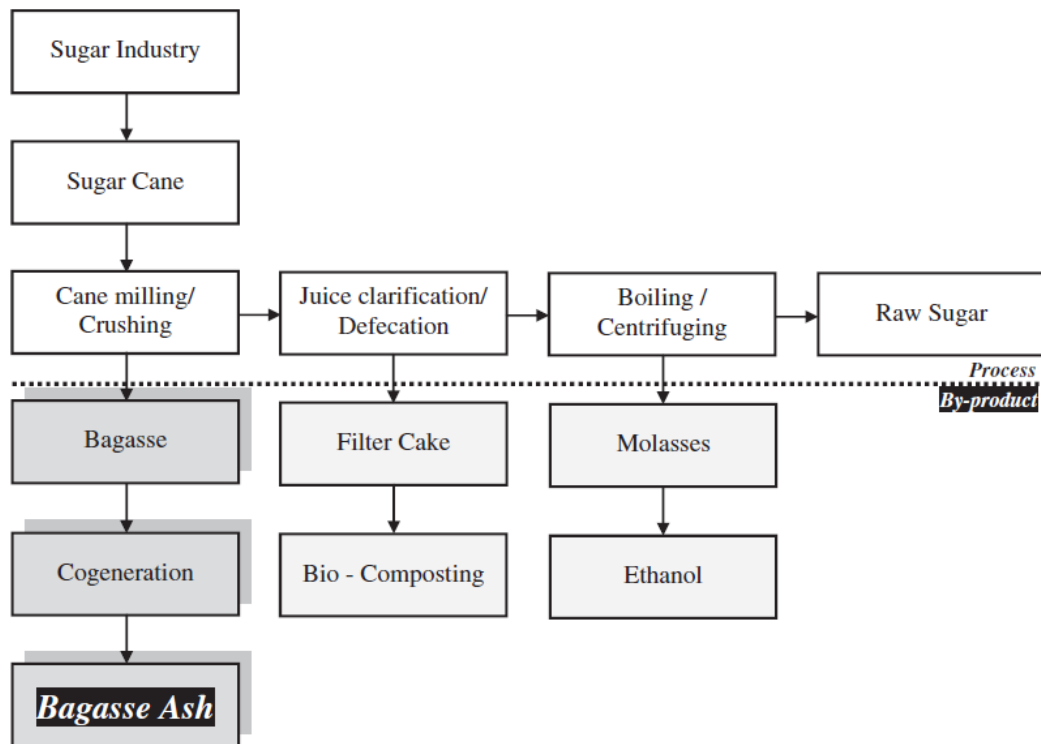


Fig. 1. Sugar production process (Sua-iam and Makul 2013).

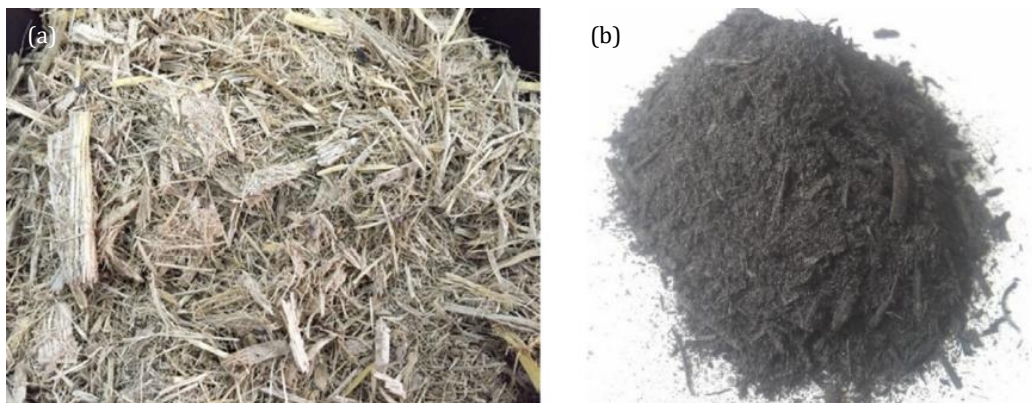


Fig. 2. a) Raw dry sugarcane; b) SCBA (Zareei et al. 2018).

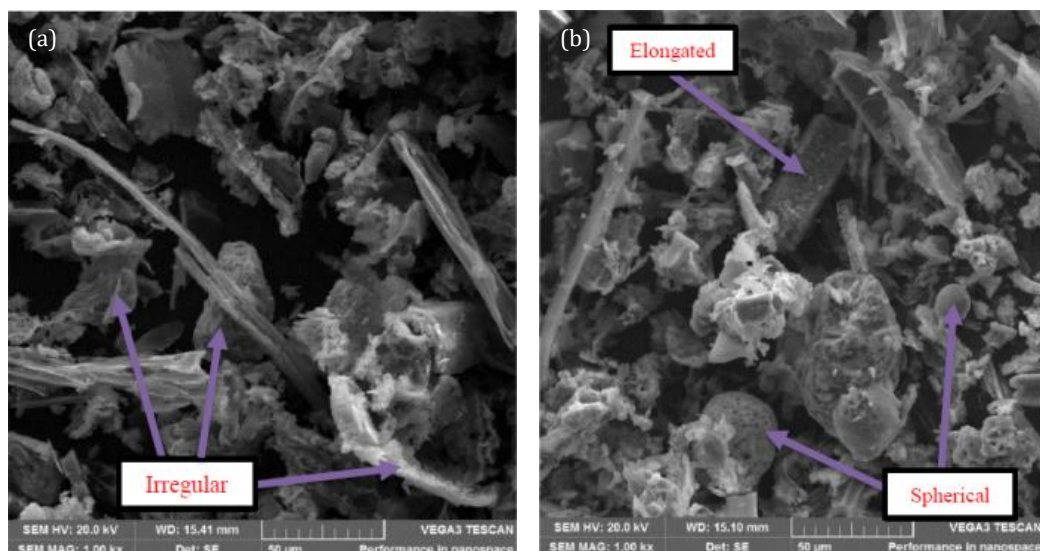


Fig. 3. SEM imaging of SCBA (a) Raw (b) Processed (Abdalla et al. 2022).

Table 2. Physical properties of SCBA reported in previous studies.

Authors	Specific gravity	Unit weight (kg/m ³)	Fineness (m ² /kg)	D ₅₀ (μm)	Sieve description and processing technique
Patil et al. (2021)	2.1	410	7832 ⁽¹⁾	–	Boiler ash (~850 °C), sieved through 90 μm
Kazmi et al. (2017)	2.12	610.6	453.2 ⁽¹⁾	–	Sieved through 300 μm and ball-milled to <45 μm
Ainomugisha et al. (2021)	1.81	474.33	–	–	Co-generation ash (~530 °C), sun-dried and sieved through 300 μm
Kumara et al. (2023)	1.65	–	225	–	Oven-dried at 110 °C for 24 h and sieved through 300 μm
Praveenkumar et al. (2020)	2.2	–	514	–	Raw bagasse burnt in open filed (110–120 °C), sieved through 300 μm and 75 μm, ball-milled (120 min), oven-dried at 600 °C for 3 h, and pulverized (1 h).
Mello et al. (2020)	2.0	–	60,320 ⁽¹⁾	–	Boiler-cleaning residue, oven-dried at 100 ± 5 °C for 24 h and rotary milled for ~3 h at 61.5 rpm
Sua-iam and Makul (2013)	2.35	–	27.4 ⁽¹⁾	107.9	Ash collected from an open dump, dried and homogenized. No sieving or grinding reported.
Andreão et al. (2020)	2.42	–	22,631	11.37	Wet-collected ash, water-washed for density separation, dried at 100 °C for 24 h, re-calcinated (< 800 °C, then 600 °C for 3 h), and Attritor-milled (1–2 h)
Joseph and Murugan (2024)	1.8	594	268 ⁽¹⁾	–	Sieved through 300 μm
Le and Sheen (2023)	2.165	–	444.9 ⁽¹⁾	–	Dried at 105–110 °C for 24 h and sieved through 149 μm (# 100 sieve)
Ashok et al. (2025)	2.18	–	290	–	Finely ground (abrasion machine) and sieved through 300 μm
Navaneetha et al. (2025)	2.0	–	39,070 ⁽¹⁾	19.58	Boiler ash (550–600 °C), dried at 105 ± 5 °C, sieved through 300 μm, and ball-milled for 180 min at 33 rpm

Note: The original values from the literature were converted to m²/kg for consistency.

4.2. Chemical properties of SCBA

The chemical composition of SCBA from previous research is summarized in Table 3. Silica is the most abundant oxide in SCBA, followed by alumina and iron oxide in smaller proportions. The silica content reported in the literature varies widely from 54.45% to 87.59%, reflecting significant differences in ash origin, combustion conditions, contamination levels, and post-processing history (Embong et al. 2016; Cordeiro et al. 2009; Ouedraogo et al. 2022; Gupta et al. 2021). Controlled combustion and recalcination generally yield ashes with higher reactive amorphous silica contents, whereas field burning, mixed ash contamination, or poorly regulated furnace conditions tend to produce higher crystalline content and larger quantities of inert impurities (Frías et al. 2011; Katare and Madurwar 2017; Morales et al. 2009).

4.3. Burning temperature and retention of amorphous silica

The burning temperature is the most extensively discussed processing parameters as it governs the removal of residual organic matter and the stability of the silica phase. Several studies identify an optimum calcination range of approximately 600–700 °C, within which carbonaceous matter is adequately removed while amorphous silica is largely retained (Gupta et al. 2021; Cordeiro et al. 2009; Bahurudeen and Santhanam 2015; Maldonado-García et al. 2017). Cordeiro et al. (2009) demonstrated

that controlled calcination significantly improved the reactivity of raw bagasse ash, while subsequent studies similarly reported that thermal upgrading can enhance the pozzolanic characteristics of high-carbon ash. However, the literature does not establish a universal optimum temperature, as the effectiveness of thermal treatment is also influenced by holding time, airflow, initial ash composition, and the origin of the material, whether raw bagasse, boiler ash, or previously burned residue (Soares et al. 2014; Kolawole et al. 2021). Moreover, excessive burning or prolonged overheating may induce silica crystallisation, thereby reducing reactivity despite improving apparent cleanliness of the ash (Arif et al. 2016; Ouedraogo et al. 2022; Bahurudeen and Santhanam 2015; Cordeiro et al. 2009).

4.4. Loss on ignition and the problem of unburned carbon

Loss on ignition (LOI) is one of the most critical indicators of SCBA quality because it reflects the extent of incomplete combustion and residual carbon content. Reported LOI values from previous studies range from 1.2% to 19.39% (Table 2). The higher values highlight the extent to which some ashes remain insufficiently processed for effective cementitious use. High LOI has been consistently identified as a major barrier to SCBA utilisation because unburned carbon dilutes the reactive fraction, increases water demand, interferes with chemical admixture efficiency, and undermines the consistency of both strength and durability performance

(Bahurudeen et al. 2016; Arif et al. 2016; Ganesan et al. 2007; Gupta et al. 2021). Comparative studies on processed and unprocessed SCBA further show that sieving, washing, removal of fibrous carbonaceous residues, and recalcination can significantly improve ash quality and

pozzolanic behavior (Lyra et al. 2021; Moraes et al. 2021; Bahurudeen and Santhanam 2015). Consequently, poor performance reported in some studies should not necessarily be interpreted as an inherent limitation of SCBA itself, but rather as evidence of inadequate pre-treatment.

Table 3. SCBA chemical oxides.

Authors	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	SO ₃	LOI (%)
Jha et al. (2020)	71.11	4.85	6.8	0.5	4.04	2.25	3.89	1.50	4.56
Kazmi et al. (2017)	85.17	1.69	2.73	0.69	2.59	0.29	0.36	0.17	3.55
Kumara et al. (2023)	73.18	3.85	1.96	1.11	3.78	0.96	0.98	0.27	14.78
Praveenkumar et al. (2020)	55.49	4.92	8.29	7.96	8.74	0.93	8.34	–	5.40
Chusilp et al. (2009)	54.45	6.06	3.23	1.37	15.41	–	–	0.04	19.39
Abdalla et al. (2022)	80.00	8.92	3.19	2.37	1.48	–	2.70	–	15.08
Ainomugisha et al. (2021)	63.59	5.66	3.39	0.75	3.19	0.62	–	1.30	–
Andreão et al. (2020)	63.9	7.00	3.40	–	7.90	–	6.4	4.20	3.80
Dhengare et al. (2020)	87.59	0.51	0.67	1.65	2.59	0.17	3.64	0.03	4.80
Gupta et al. (2021)	82.68	3.01	1.69	2.86	5.58	0.43	0.47	–	3.23
Kumara et al. (2023)	73.18	3.83	1.96	1.11	3.78	0.96	0.98	0.27	14.78
Zareei et al. (2018)	64.23	9.08	5.47	2.97	8.17	0.87	1.32	–	–
Hasnain et al. (2021)	74.34	5.55	3.40	0.67	2.15	0.12	1.46	–	11.42
Wagh and Waghe (2024)	74.40	1.10	1.15	2.1	2.80	0.14	4.70	1.60	–
Ashok et al. (2025)	75.90	1.55	2.32	1.77	6.25	–	–	–	4.00
Kirthiga and Elavenil (2023)	75.98	3.71	2.37	2.05	4.86	0.38	2.60	–	7.80
Tabish et al. (2025)	74.16	3.08	1.39	2.6	2.96	1.38	2.94	2.45	–
Khan et al. (2025)	63.78	8.32	1.68	4.76	10.54	1.32	2.60	–	4.21
Shaban et al. (2024)	81.30	2.50	1.60	2.3	4.10	0.40	3.30	1.00	2.50
Amjad et al. (2025)	62.44	6.74	5.77	2.97	6.16	3.15	6.87	0.72	–
Subedi et al. (2023)	76.90	7.50	3.00	1.30	4.30	0.70	4.30	0.20	1.20
Navaneetha et al. (2025)	71.11	5.26	7.72	–	11.92	–	–	3.66	3.00

4.5. Grinding, fineness, and surface-controlled reactivity

Grinding duration and resultant fineness are also fundamental to SCBA performance because its reactivity is strongly governed by surface area and particle refinement. Cordeiro et al. (2008) established that SCBA can contribute both as a pozzolanic material and as micro-filler, although these functions become more pronounced only when the ash is ground to a sufficiently fine state. Later studies confirmed that enhanced fineness increases surface area, improves packing density, promotes portlandite consumption, and facilitates the formation of secondary calcium silicate hydrate (C-S-H) (Bahurudeen and Santhanam 2015; Moraes et al. 2021; Jagadesh et al. 2020). Although finer SCBA may enhance later-age strength and durability, it may also increase fresh-state water demand when porosity and residual carbon content remain high (Klathae et al. 2020; Abdalla et al. 2022; Sakib et al. 2023; Ainomugisha et al. 2025; Yaseen 2024). In many cases, performance is governed

not merely by the replacement percentage, but by the extent to which grinding converts a porous, carbon-rich ash into a reactive ultrafine material. Accordingly, fineness and carbon content should be interpreted in conjunction rather than as independent variables (Jagadesh et al. 2015; Embong et al. 2016).

5. Workability Behaviour of SCBA in Cement-Based Materials

Several studies have reported that the incorporation of sugarcane bagasse ash (SCBA) generally reduces slump, workability, and flowability as the replacement level increases (Fig. 4). However, the magnitude of this reduction varies with ash source, fineness, particle morphology, and overall mix design. Abdalla et al. (2022) reported a progressive decline in slump with increasing SCBA dosage and attributed this response to the rough texture, flaky shape, and porous surface of SCBA particles, which increase internal friction and water demand.

Ainomugisha et al. (2021) similarly observed substantial slump loss at higher SCBA contents, explaining that the ash's high surface area, low specific gravity, angularity, porous structure, and residual unburnt carbon reduce the amount of free water available for lubrication. Zareei et al. (2018) linked lower fluidity to the irregular and fibrous morphology of SCBA particles, whereas Wagh and Waghe (2024) found in self-compacting concrete that higher bagasse ash contents reduced slump flow and increased both T_{500} time and V-funnel time, indicating a more viscous and less mobile fresh mix.

At the same time, the literature indicates that the adverse effect of SCBA on fresh properties can be moderated through appropriate ash processing and admixture optimization. Tabish et al. (2025) maintained the required slump range in SCBA-blended concrete through the use of a polycarboxylate-based superplasticizer, indicating the effectiveness of PCE-based admixtures in dispersing fine SCBA particles without increasing water content. Shaban et al. (2024) also employed a high-range water-reducing admixture in ultra-high-performance

concrete mixes, reinforcing the view that modern polycarboxylate systems are particularly important when SCBA is used at low water-binder ratios. In SCC mixtures, Wagh and Waghe (2024) used both a superplasticizer and a viscosity-modifying admixture to preserve self-compactability. Amjad et al. (2025) similarly suggested that milling or refining bagasse ash improves fresh behaviour by enhancing particle packing and reducing the detrimental rheological influence of coarse, porous particles. Interestingly, Kumara et al. (2023) reported a slight improvement in slump at lower SCBA replacement levels, indicating that fresh-state performance is not governed by replacement percentage alone, but also by ash quality, fineness, and carbon content. Overall, the evidence suggests that SCBA typically reduces workability because of its high surface area and porous particle structure, yet this limitation can be substantially mitigated through controlled replacement levels, ash refinement, ternary blending, and, most consistently, the use of polycarboxylate-based superplasticizers.

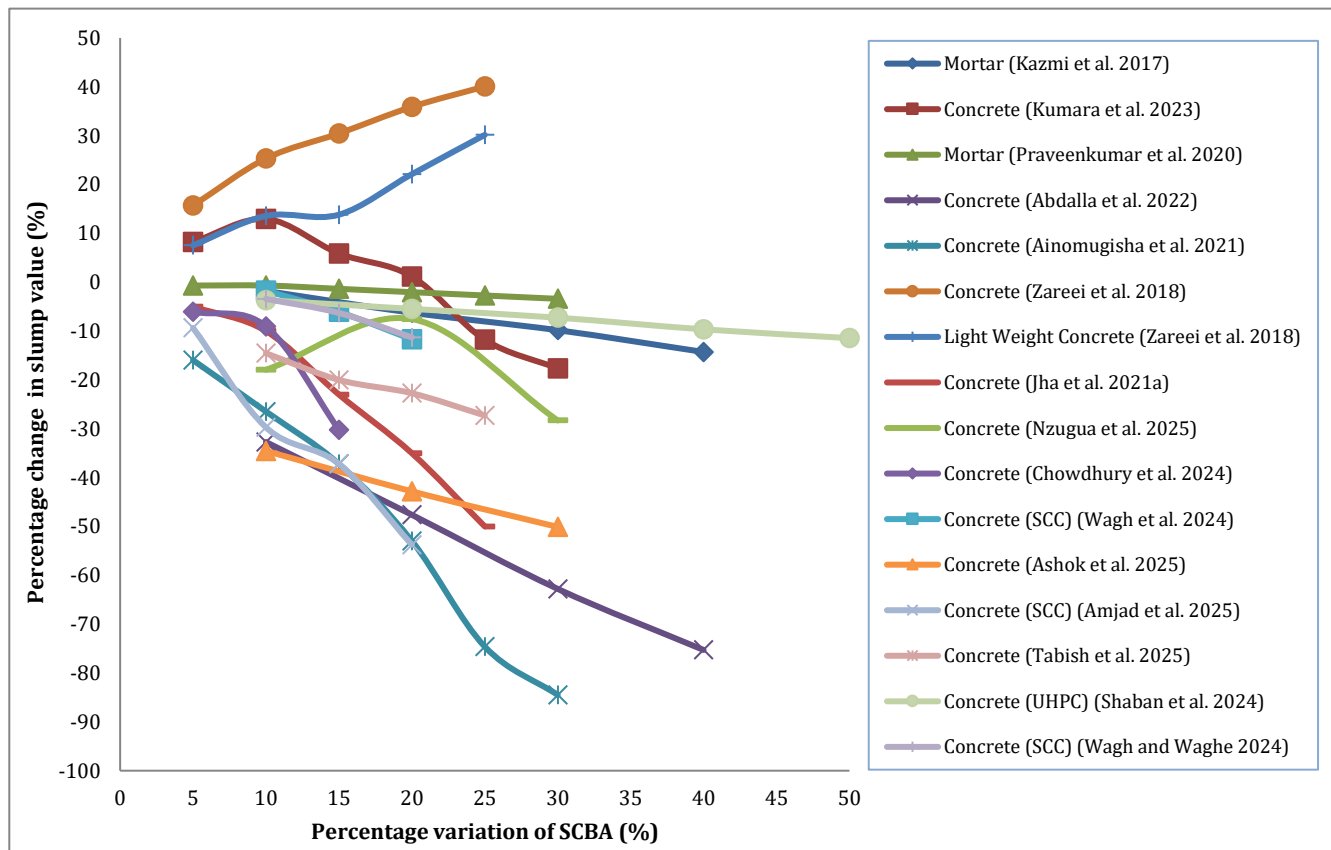


Fig. 4. Effect of SCBA on workability of cement-based materials.

6. Mechanical Properties

The mechanical properties of SCBA blended cementitious materials have been widely examined to determine the suitability of SCBA as a supplementary cementitious material in concrete and mortar. In the existing literature, mechanical performance is most commonly evaluated through strength development, as this provides a direct indication of the structural applicability of the material. The effect of SCBA on mechanical be-

haviour is influenced by several factors, including the replacement level, ash characteristics, fineness, burning conditions, curing regime, matrix type, and water-binder ratio. At low to moderate replacement levels, SCBA generally contributes to improved mechanical performance through filler action and pozzolanic reactivity, both of which promote a denser and more refined cementitious matrix (Ganesan et al. 2007; Khan et al. 2021; Kiran and Kishore 2017; Ramesh et al. 2017). Table 4 presents a comparative synthesis of quantitative

data from selected studies on SCBA blended cementitious materials. The table compiles key experimental variables, including cement type, matrix type, replacement levels, optimum replacement percentage, curing period, water–binder ratio, and percentage enhancement in 28-day strength. To ensure comparability, only

the optimum replacement level reported in each study and the corresponding improvement over the control mixture is presented. This format facilitates cross-study comparison and supports the identification of general trends in the mechanical behaviour of SCBA based systems.

Table 4. Optimum replacement of SCBA in cementitious materials and associated improvements in mechanical properties (%).

Reference	Cement type	Cementitious matrix	Replacement levels (% by weight)	Optimum replacement (%)	Curing period (days)	Water-Binder ratio	Enhancement in 28-day strength (%)	
							Compressive strength	Split tensile strength
Kumara et al. (2023)	OPC 53	Concrete	5, 10, 15, 20, 25, 30	15	7, 14, 28, 90	0.45	6.43	8.75
Praveenkumar et al. (2020)	OPC 53	Mortar	5, 10, 15, 20, 25, 30	5	3, 7, 28	0.5	3.99	–
Jha et al. (2021d)	OPC 43	Concrete	5, 10, 15, 20, 25	10	7, 28	0.45	2.14	–
Abdalla et al. (2022)	CEM I/42.5N	Concrete	10, 20, 30, 40	10	3, 7, 14, 28, 56	–	5.63	10.54
Gupta et al. (2021)	OPC 43	Mortar	5, 10, 15, 20, 25	10	3, 7, 28	–	9.21	–
Dhengare et al. (2020)	OPC 53	Concrete	5, 10, 15, 20, 25, 30	20	7, 28, 56, 90	–	7.66	–
Gupta et al. (2023a)	OPC 43	Concrete (SCC)	5, 10, 15, 20, 25	15	7, 28, 56, 90	0.4	19.57	55.73
Bheel et al. (2022)	Portland cement	Concrete	5, 10, 15, 20	10	28	0.5	9.70	8.77
Mittal and Varekar (2026)	Portland cement	Concrete	5, 10, 15, 20	5	3, 7, 28	0.5	10.29	2.76
Krishna et al. (2024)	OPC 53	Concrete	5, 10, 15, 20, 25	10	28	0.48	27.18	–
Sakib et al. (2023)	OPC	Mortar	5, 10, 15, 20, 25, 30	15	7, 14, 28, 56	0.56	10.10	–
Ullah et al. (2025)	OPC Type I	Concrete	5, 10, 15	10	14, 28, 56	0.4	19.20	22.82
Yaseen (2024)	OPC	Mortar	5, 10, 15, 20, 25, 30	5	7, 28	0.54	12.85	–
Sankeeth et al. (2025)	OPC	Concrete	5, 10, 15, 20	10	7, 28, 90	0.58	18.46	23.35
Kumar and Kumar (2023)	OPC 53	Concrete	5, 10, 15	10	7, 14, 28	0.58	21.02	–
Hasan et al. (2014)	OPC	Concrete	10, 15, 20	10	3, 7, 28	0.5	3.49	–
Jha et al. (2021a)	OPC 43	Concrete	5, 10, 15, 20, 25	10	7, 28, 90, 180	0.49	2.14	8.87
Srinivasan and Sathiya (2010)	OPC	Concrete	5, 10, 15, 20, 25	5	7, 28	–	37.40	30.67
Lourdu and Ali (2023)	OPC	Concrete	2.5, 5, 7.5, 10, 12.5, 15, 20	10	3, 7, 28	0.45	19.67	18.18
Tabish et al. (2025)	OPC43	Concrete	10, 15, 20, 25	15	7, 28, 90, 180, 365	0.48	11.42	11.15
Wagh et al. (2024)	OPC 43	Concrete (SCC)	10, 15, 20	10	7, 14, 28, 56	0.34	3.96	5.12
Chowdhury et al. (2024)	CEM I/42.5N	Concrete	5, 10, 15	5	1, 3, 7, 28	0.55	12.04	7.74

6.1. Compressive strength

The compressive strength behaviour of SCBA-blended mortar and concrete reported in the reviewed studies exhibits a broadly consistent, although not entirely uniform trend. Low-to-moderate replacement lev-

els generally preserve or enhance later-age strength, whereas higher replacement levels tend to reduce strength when the dilution of cement surpasses the pozzolanic contribution of SCBA. In mortar systems, strength enhancement is most frequently reported at about 10–15% replacement. Praveenkumar et al. (2020)

reported that the incorporation of bagasse ash improved mortar strength up to 15% replacement, which was attributed to its large surface area, enhanced pozzolanic reactivity, and filler action. Likewise, Sakib et al. (2023) found that 5–15% ground bagasse ash produced higher 56-day compressive strength than the control, with 15% replacement showing the best overall mechanical and durability performance. Yaseen (2024) similarly observed that 7-day strength decreased with increasing SCBA content because of early cement dilution and slow reaction kinetics, whereas 28-day strength increased at 5–15 wt% replacement, with the greatest increase recorded at 5 wt%. Concrete studies show the same broad pattern. Jha et al. (2021a) reported that compressive strength increased at 10% SCBA replacement and declined beyond that level, while Bheel et al. (2022) also identified 10% bagasse ash as the optimum replacement level for improving 28-day compressive strength. Moreover, Abdalla et al. (2022) concluded that bagasse ash can enhance long-term strength when used at low dosages, especially around 10%, although higher replacement levels generally produce strength reductions because of clinker dilution.

Evidence from several studies indicates that compressive strength development in SCBA-based systems is governed by the interaction of physical densification and pozzolanic reactivity. Several studies explicitly relate strength enhancement to the reaction of SCBA-derived silica and alumina with calcium hydroxide released during cement hydration. Abdalla et al. (2022) reported that these reactions produce secondary calcium silicate hydrate (C–S–H), calcium aluminate hydrate (C–A–H), and calcium aluminosilicate hydrate (C–A–S–H) phases, which contribute to strength development and microstructural refinement. In the same way, Yaseen (2024) explained that SCBA acts both as a micro-filler, which improves particle packing, and as a later-age pozzolana that forms secondary hydration products. Sakib et al. (2023) further noted that ground bagasse ash provides nucleation sites for hydration products, reduces porosity, and improves interfacial bonding. This interpretation is consistent with the microstructural observations reported by Praveenkumar et al. (2020), who attributed the increase in compressive strength at moderate replacement levels to the combined effects of fine particle filling and activated pozzolanic reaction. Likewise, Gupta et al. (2023b) identified SCBA as a pozzolanic material with good binder potential, although the benefit was confined to modest replacement levels. Overall, the literature indicates that SCBA improves compressive strength only when its filler effect and pozzolanic reactivity are sufficient to offset clinker dilution. Once the replacement level becomes excessive, however, reduced calcium availability, slower hydration, higher porosity, and weaker binder formation become dominant, resulting in strength loss (Bheel et al. 2022; Jha et al. 2021b; Kumara et al. 2023; Gupta et al. 2022; Ainomugisha et al. 2021; Kumar and Kumar 2023).

As shown in Table 4, the optimum replacement level of cement with SCBA for improving mechanical properties varies considerably across studies, reflecting the strong influence of ash processing, fineness, silica reactivity, loss on ignition, curing conditions, and mix com-

position. Although this variability prevents the identification of a universal optimum dosage, the compiled results still reveal a consistent performance range. Because compressive strength is the most widely reported mechanical property, its trends are further illustrated in Figs. 5 and 6. Fig. 5 compares the optimum SCBA contents reported in the literature and their corresponding percentage gains in compressive strength, while Fig. 6 shows the trend of average compressive strength across different replacement levels. Taken together, Table 4, Figs. 5 and 6 indicate that the most favourable mechanical performance is generally achieved at 10–15% SCBA replacement. This range likely reflects a balance between the pozzolanic contribution of reactive silica, which promotes additional C–S–H formation and matrix densification, and the dilution effect associated with higher cement replacement. However, the reported improvements are not universal, and performance declines beyond this range are common when ash quality or processing is inadequate. Thus, SCBA should be regarded as a processing-sensitive supplementary cementitious material, and 10–15% should be interpreted as a practical optimum range rather than a fixed dosage.

6.2. Split tensile strength

SCBA influences split tensile strength in a manner closely aligned with compressive strength, with improvements generally occurring only at low-to-moderate replacement levels. Across conventional and self-compacting concrete, most studies report that tensile strength rises up to an optimum SCBA content and then declines at higher dosages. Lourdu and Ali (2023) identified 10% SCBA as optimal, increasing split tensile strength from 3.3 MPa to 3.9 MPa, while Gupta et al. (2023a) reported improvement up to 15% SCBA in SCC before a reduction at higher contents. Kumara et al. (2023) similarly observed an increase from 2.97 MPa in the control mix to 3.23 MPa at 15% SCBA, followed by progressive decline beyond this level. Comparable trends were reported by Bheel et al. (2022), Chowdhury et al. (2024) and Ullah et al. (2025), indicating that the most consistent enhancement in tensile performance occurs within the 5–15% replacement range, although the precise optimum depends on ash fineness, curing age, concrete type, and mix design (Sankeeth et al. 2025).

The improvement in split tensile strength arises from the same mechanisms that govern compressive strength development, namely pozzolanic reactivity, filler action, and matrix densification. Gupta et al. (2023a) explained that silica-rich SCBA reacts with calcium hydroxide released during cement hydration to form additional C–S–H, thereby strengthening and densifying the matrix. Ullah et al. (2025) similarly linked higher tensile strength to secondary C–S–H formation, improved particle interlocking, and a denser internal structure, especially at later curing ages. Bheel et al. (2022) and Kumara et al. (2023) further emphasized that reactive silica refines the cementitious matrix and improves resistance to crack initiation and propagation. However, beyond the optimum dosage, the same adverse effects observed for compressive strength – cement dilution, reduced lime availability, unreacted ash particles, and higher poros-

ity—begin to dominate, leading to lower tensile performance (Bayapureddy et al. 2020; Srinivasan and Sathiya

2010; Abdalla et al. 2022; Ullah et al. 2025; Chowdhury et al. 2024; Kumara et al. 2023).

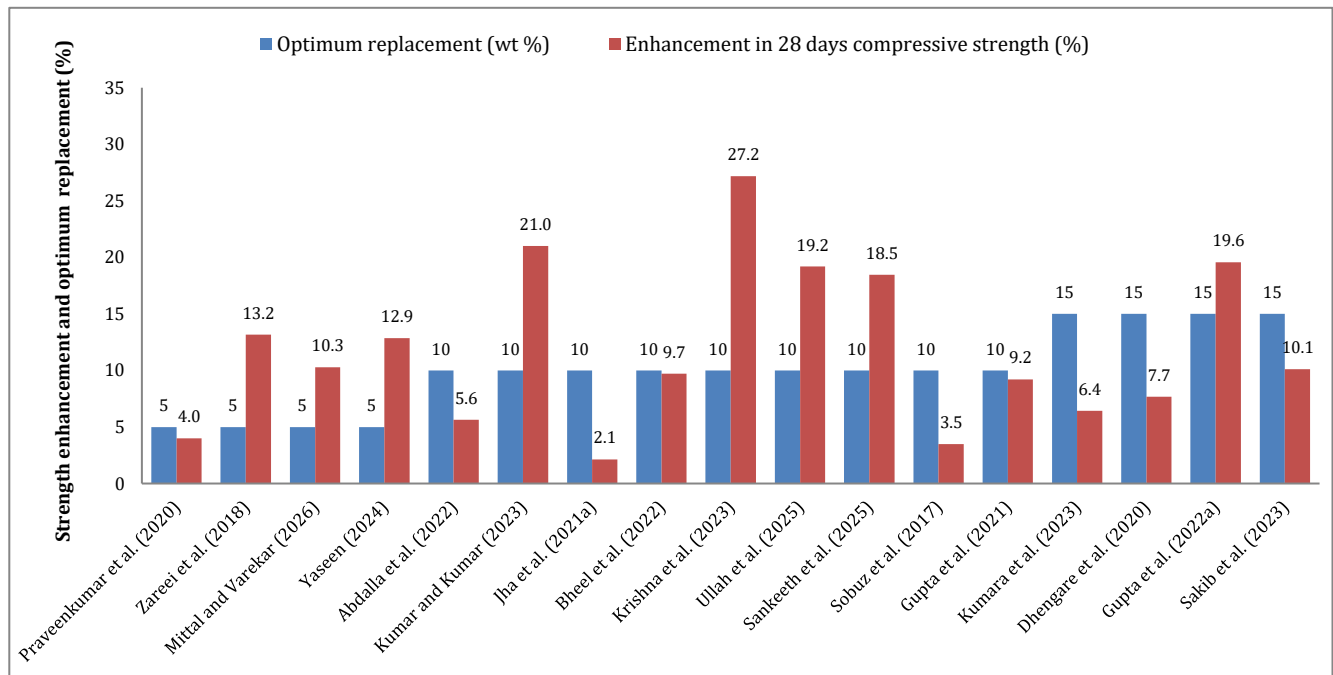


Fig. 5. Comparative representation of optimum SCBA content and corresponding percentage increase in compressive strength of cement-based materials.

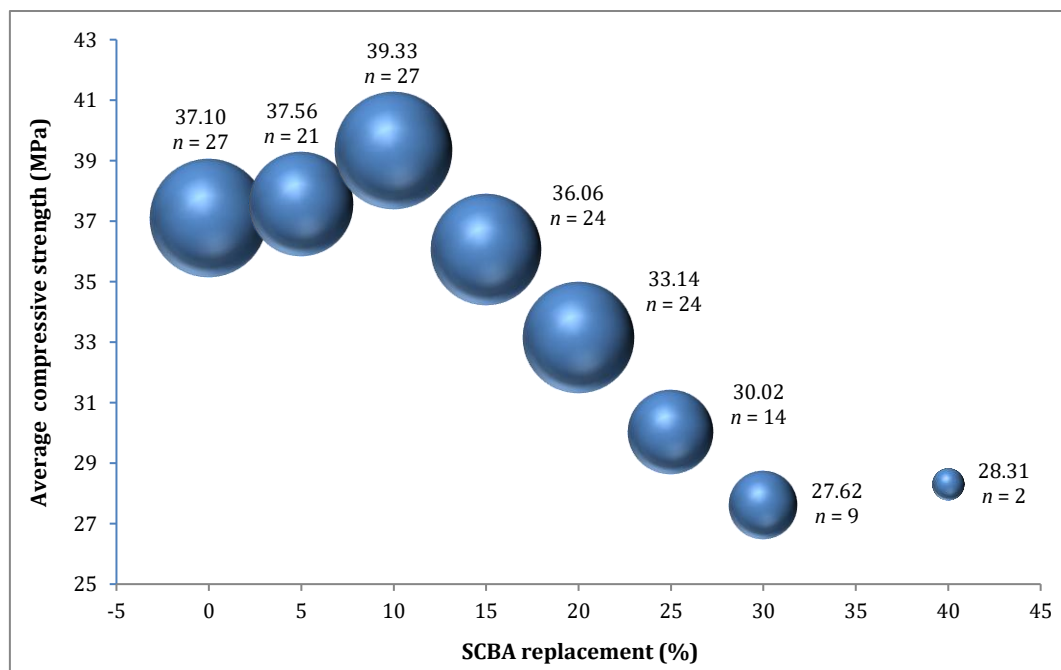


Fig. 6. Trend analysis average compressive strength value from various studies.

Similar to compressive strength, the results in Table 4 show that the optimum SCBA replacement level for improving split tensile strength generally lies within the 10–15% range, although some variation exists across studies. For comparison, the tensile strength data are presented in Figs. 7 and 8. Fig. 7 shows the reported optimum SCBA contents and the corresponding percentage increase in 28-day split tensile strength, while Fig. 8 presents the trend in average split tensile strength across

different replacement levels. Taken together, Table 4, Figs. 7 and 8 indicate that split tensile strength follows a trend broadly similar to that of compressive strength, with improvement at intermediate replacement levels and decline at higher dosages. Thus, the available evidence suggests that 10–15% SCBA is the most practical range for enhancing both compressive and split tensile strength, although the exact optimum remains study-specific.

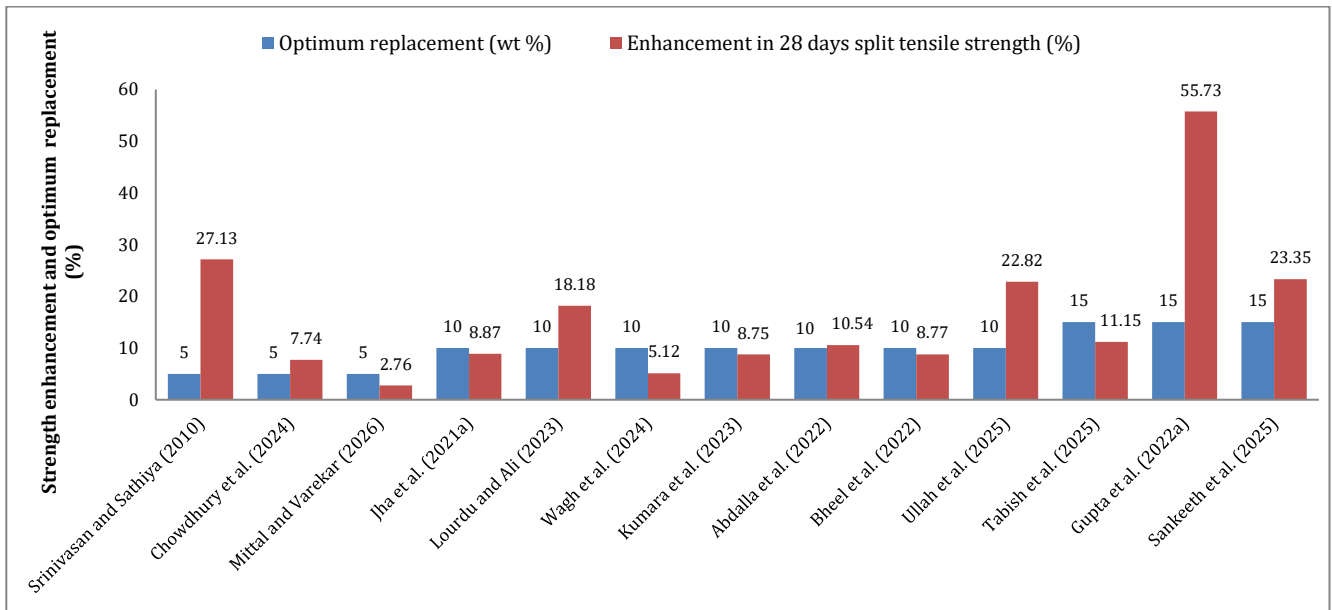


Fig. 7. Comparative representation of optimum SCBA content and corresponding percentage increase in split tensile of cement-based materials.

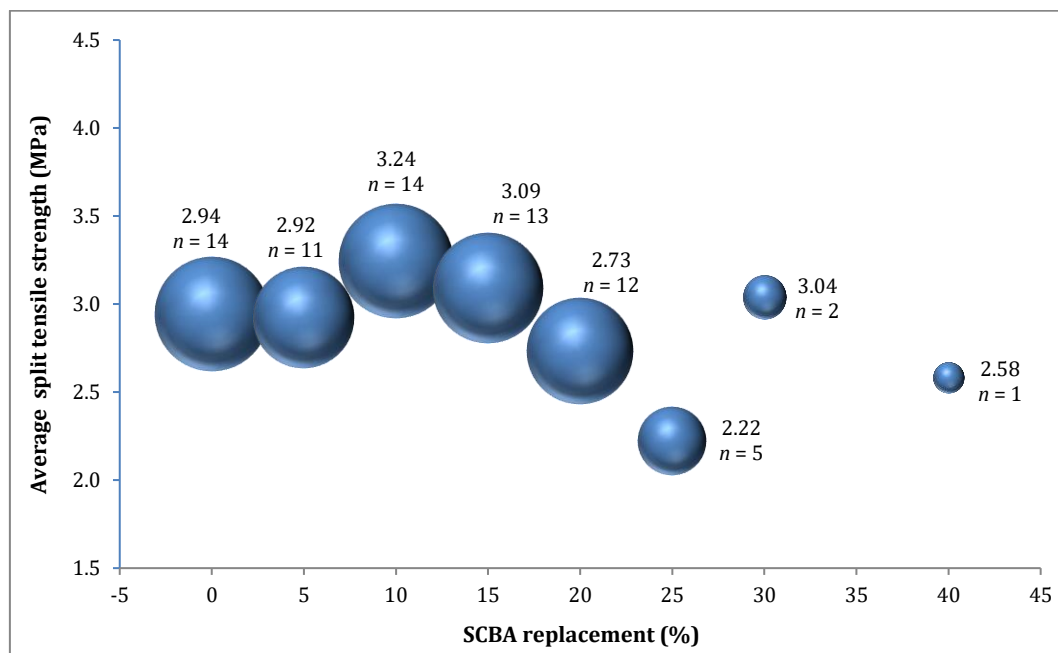


Fig. 8. Trend analysis average split tensile strength value from various studies.

7. Durability Performance

Sugarcane bagasse ash (SCBA) has been widely reported to improve the durability performance of cementitious materials when used at appropriate replacement levels, primarily through matrix densification and pore refinement, which reduce the ingress of water and aggressive ions. The literature indicates that durability has mainly been evaluated through transport-related parameters such as water absorption, capillary absorption, chloride penetration resistance, and electrical resistivity, with most studies showing improved performance at low to moderate SCBA contents. However, the extent of improvement varies with the physico-chemical characteristics of SCBA, particularly fineness, amorphous silica

content, calcination condition, and loss on ignition, as well as with the type of cementitious matrix and replacement level adopted (Ainomugisha et al. 2021; Zareei et al. 2018; Gupta et al. 2023b; Sakib et al. 2023; Yaseen 2024; Sankeeth et al. 2025). Therefore, in this section, the effect of SCBA on the durability of cement-based materials is evaluated through the key parameters most consistently reported in the uploaded studies, namely water absorption, capillary absorption, chloride resistance, and electrical resistivity.

Table 5 summarizes the studies on the durability performance of SCBA-blended cementitious materials, presenting the investigated replacement levels, the optimum SCBA content, and the corresponding changes in water absorption, capillary absorption, chloride pene-

tration, and electrical resistivity. The optimum replacement level generally ranges from 10% to 30%, although it varies with the durability parameter, matrix type, and ash characteristics. In several studies, the same optimum content applies to multiple durability indicators, whereas in others it differs across properties. Comparison of Table 4 and Table 5 further shows that the optimum SCBA content for durability does not always coincide with that for mechanical properties. Overall, low to

moderate SCBA replacement commonly reduces water absorption, capillary absorption, and chloride penetration while increasing electrical resistivity, indicating improved resistance to fluid and ion transport. The variability among studies nevertheless suggests that durability performance is influenced not only by replacement level, but also by SCBA fineness, processing condition, chemical composition, and the nature of the cementitious system.

Table 5. Optimum content of SCBA in cementitious materials for durability studies.

Reference	Replacement levels (% by weight)	Optimum replacement (%)	Decrease percentage (%)			Increase percentage (%) in electrical resistivity
			Water absorption	Capillary absorption	Chloride penetration	
Jittin and Bahurudeen (2022)	10,20,30	30	–	14.71	80.40	–
Joshaghani and Moeini (2018)	10,15,20,25	25	4.32	14.00	44.53	159.29
Praveenkumar et al. (2020)	5,10,15,20,25,30	30	–	86.26	–	–
Ainomugisha et al. (2021)	5,10,15,20,25,30	30	93.34	–	–	–
Arenas-Piedrahita et al. (2016)	10, 20	20	–	–	67.03	234.51
Cupim et al. (2025)	5,10,15,20	20	16.97	–	–	–
Allende et al. (2024)	10,20,30	30	–	–	23.01	–
Gupta et al. (2023b)	5,10,15,20,25	15	52.45	15.6	–	–
Sankeeth et al. (2025)	5,10,15,20	20	26.27	–	56.36	–
Yaseen (2024)	5,10,15,20,25,30	30	94.35	–	–	–
Jiménez-Quero et al. (2019)	10, 20	10	–	–	–	75.00
Reddy and Kumar (2026)	5,10,15,20	10	34.06	–	–	–
Nassar et al. (2022)	5,10,15	15	–	–	–	92.23
Le and Sheen (2023)	5,10,15,20	20	19.19	–	–	19.26

7.1. Water absorption

Water absorption is a key durability indicator in SCBA-based cementitious materials because it reflects pore structure, and resistance to water ingress. Fig. 9 depicts the variation of water absorption with different proportion of SCBA. The reviewed studies show that SCBA can reduce water absorption at low-to-moderate replacement levels when its filler effect and pozzolanic reactivity promote matrix densification and additional C-S-H formation. Abdalla et al. (2022) reported a reduction in water absorption from 1.21% in the control mix to 1.03% at 40% SCBA, attributing this improvement to the fine-particle filling effect of SCBA. Likewise, Joshaghani and Moeini (2017) found lower water absorption and capillary uptake in SCBA mortars than in the control, while Joshaghani and Moeini (2018) observed similar reductions in a binary SCBA-RHA (Rice Husk Ash) system due to filler action, pozzolanic activity, and secondary C-S-H formation. Comparable improvements were also reported in blended systems containing SCBA with metakaolin and polypropylene fibres (Althaqafi et al. 2024) and in self-curing concrete

incorporating copper slag and polyethylene glycol-400, particularly at 15-20% SCBA replacement (Reddy and Kumar 2026).

However, the literature also indicates that the effect of SCBA is highly dependent on ash quality, dosage, and curing conditions. Zareei et al. (2018) reported that higher SCBA contents increased water demand and water absorption because of the irregular and porous nature of the ash, with the most favourable response occurring at around 5% replacement. Similar trends were observed by Ainomugisha et al. (2021), who found increasing water absorption with higher contents of raw co-generation SCBA, and by Yaseen (2024), who reported a marked nonlinear increase at elevated replacement levels. Sankeeth et al. (2025) further confirms this threshold-dependent behaviour, showing an 8.5% reduction in water absorption at 5% SCBA but a 28% increase at 20%, although extended curing partially mitigated this adverse effect. Overall, the findings suggest that finely processed and optimally dosed SCBA can refine the pore structure and reduce water absorption, whereas excessive or poorly processed ash may increase absorption by introducing greater internal porosity.

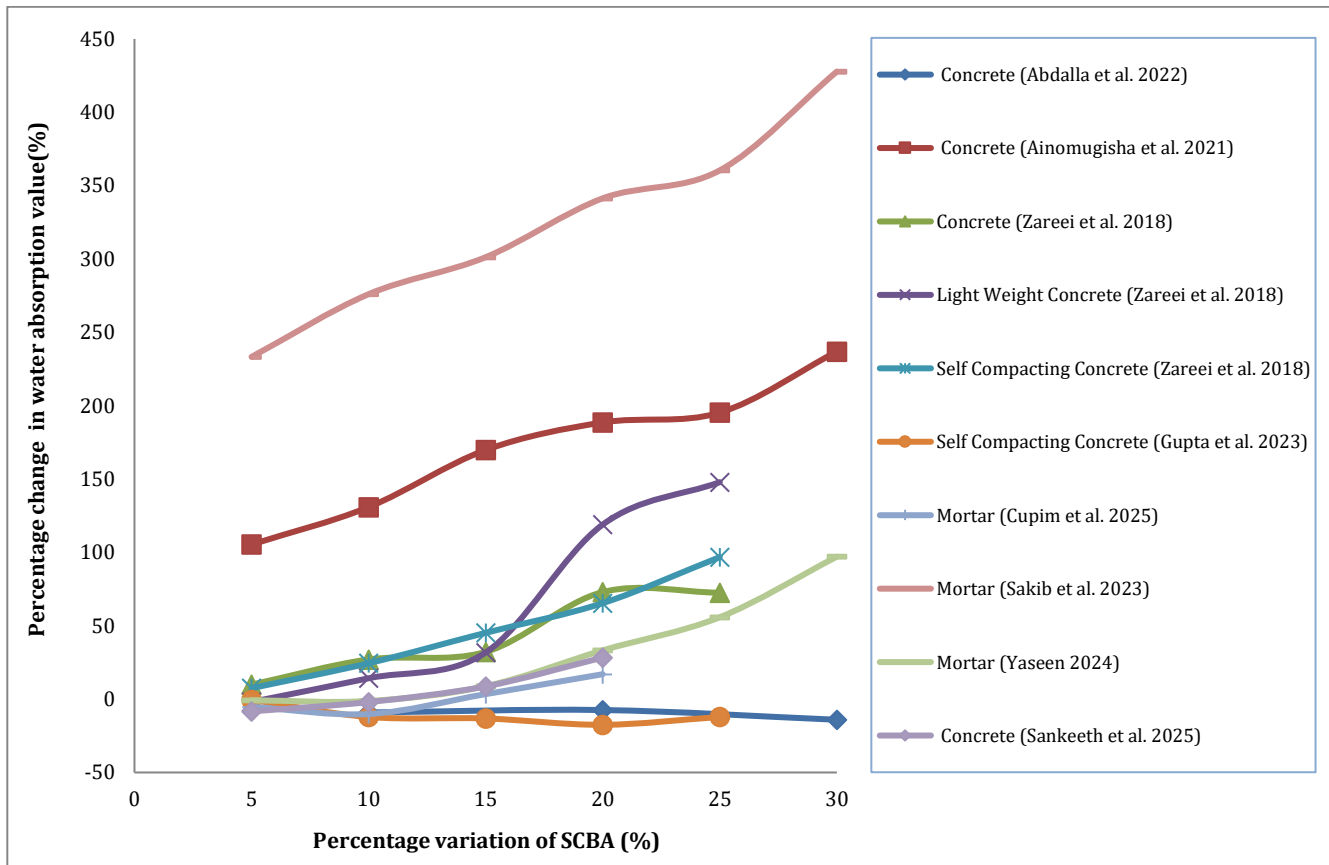


Fig. 9. Effect of SCBA on water absorption of cement-based materials.

7.2. Capillary absorption

Capillary absorption, commonly expressed as sorptivity, is a key transport property used to evaluate the rate at which unsaturated concrete absorbs water through capillary action and, therefore, serves as an important indicator of durability rather than merely a physical descriptor. In SCBA-blended concrete, lower capillary absorption is generally attributed to the filler effect and pozzolanic reaction of fine ash particles, which improve packing density, consume calcium hydroxide, and generate secondary C-S-H, thereby refining the pore structure and reducing transport continuity. This overall mechanism is widely supported in the literature, and several studies have reported improved sorptivity performance at moderate replacement levels when the ash is adequately processed and sufficiently reactive (Bahurudeen and Santhanam 2015; Ganesan et al. 2007; Gupta et al. 2023b).

However, the evidence does not justify a universal conclusion that SCBA always improves capillary performance, because the outcome remains highly dependent on ash quality, fineness, loss on ignition, replacement dosage, curing conditions, and testing protocol. While several studies have observed reduced capillary absorption and improved matrix densification at moderate replacement levels (Bahurudeen and Santhanam 2015; Praveenkumar et al. 2020; Andrade Neto et al. 2021; Memon et al. 2022; Gupta et al. 2023b), others have reported increased sorptivity or noted that improvements in sorptivity may coexist with greater carbonation susceptibility, especially at higher replacement levels or

with insufficiently processed ash (Ainomugisha et al. 2021; Quedou et al. 2021). A critical study of the literature suggests that the central issue is not whether SCBA reduces capillary absorption, but the particular processing and dosage conditions under which such reduction can be achieved consistently.

7.3. Chloride penetration and chloride resistivity

The studies indicate that sugarcane bagasse ash (SCBA) generally enhances resistance to chloride ingress and increases chloride resistivity, although the magnitude of improvement depends on curing age, ash quality, and replacement level. In mortar systems containing untreated or minimally processed SCBA, rapid chloride permeability decreased, with optimum performance commonly observed at about 10–20% replacement (Arenas-Piedrahita et al. 2016; Jiménez-Quero et al. 2019; Cordeiro et al. 2011; Minnu et al. 2021). Similarly, Jha et al. (2021c) reported reduced chloride permeability up to an optimum combination of 10% bagasse ash and 40% stone dust, beyond which performance declined. These findings suggest that chloride durability in SCBA-blended systems is governed by the interplay of filler effect, pozzolanic reactivity, and cement dilution rather than by replacement level alone.

The literature further shows that chloride-related durability becomes more pronounced at later ages and is enhanced in ternary binder systems. Joshaghani and Moeini (2017) observed that SCBA mixtures exhibited lower resistivity than the control at early ages because of slow pozzolanic activity, but showed markedly higher

resistivity and improved chloride resistance at 28 and 90 days; the SCBA–nanosilica system performed best. Comparable trends were reported for SCBA–rice husk ash mixtures, where ternary systems outperformed binary blends because of greater microstructural densification and hydration gel formation (Joshaghani and Moeini 2018; Jittin and Bahurudeen 2022). Kirthiga et al. (2025) likewise found that combining bagasse ash with silica fume significantly reduced charge passed in chloride tests, while also noting that RCPT results reflect not only permeability but also pore-solution chemistry and electrical conductivity. Overall, the evidence from several studies indicates that chloride penetration and chloride resistivity should be interpreted through an integrated microstructural and electrochemical framework, with later-age testing and synergistic SCM combinations providing the most reliable basis for assessing durability.

7.4. Electrical resistivity

Electrical resistivity is a key durability indicator in SCBA-blended mortars and concrete because it reflects resistance to ionic transport and reinforcement corrosion. The literature generally indicates that SCBA increases resistivity when it behaves as a reactive supplementary cementitious material, refining pore structure through filler effects and secondary pozzolanic reactions. However, this improvement is not universal and depends on ash processing, replacement level, and curing age. Early studies established that the hydration and pozzolanic performance of bagasse ash are governed by ash quality and silica reactivity (Singh et al. 2000; Ganesan et al. 2007). Later investigations similarly reported that SCBA can enhance resistivity and durability, particularly at moderate replacement levels. Jiménez-Quero et al. (2019) observed higher resistivity and delayed cracking under accelerated corrosion, while Nassar et al. (2022) found improved later-age resistivity, with 10 wt% replacement giving the most favorable balance of strength and durability. Le and Sheen (2023) further showed that this benefit is highly dosage and processing sensitive, with optimum performance generally occurring at about 5–10% replacement.

The literature also emphasizes that resistivity development in SCBA systems is strongly time-dependent. Joshaghani and Moeini (2017) showed that SCBA mortars may perform below the control at early ages because pozzolanic reactions are slower, yet surpass the control at 28 and especially 90 days as pore connectivity decreases. Samaila et al. (2014) likewise demonstrated that electrical resistivity is sensitive to both hydration progress and porosity evolution, making it useful for monitoring microstructural development as well as durability performance. Nassar et al. (2022) attributed higher later-age resistivity to matrix densification and reduced ionic mobility, whereas recent review evidence attributes variability across studies to differences in ash treatment, particle size, residual carbon, and thermal history (Abdalla et al. 2022). Thus, a critical reading suggests that SCBA should not be treated as uniformly increasing electrical resistivity; rather, its beneficial effect is conditional on processing quality, dosage, and test age.

8. Conclusions

Various studies have been conducted to understand the impact of SCBA in concrete and mortar properties considering various aspects. Considering the prior studies, the key findings of the present study can be summarised as follows:

SCBA shows clear potential to reduce the embodied carbon of cementitious materials through partial cement replacement. However, its environmental benefit is conditional on processing intensity and transport burden. The performance of sugarcane bagasse ash (SCBA) as a supplementary cementitious material in mortar and concrete is not governed solely by its replacement level, but is strongly influenced by its physical and chemical characteristics. The reviewed literature indicates that parameters such as silica content, fineness, particle morphology, burning conditions, and loss on ignition play a crucial role in determining the pozzolanic reactivity and overall engineering suitability of SCBA. In this regard, SCBA should not be regarded as a uniform agricultural by-product; rather, it should be understood as a process-sensitive material whose performance is highly dependent on combustion history and post-treatment quality. Consequently, the wide variation reported in previous studies appears to arise primarily from differences in ash processing and mixture design, rather than from any inconsistency in the intrinsic potential of SCBA itself.

With respect to fresh properties, the reviewed studies generally show that SCBA incorporation reduces slump, workability, and flowability as the replacement level increases. This behaviour is mainly associated with the porous texture, irregular particle shape, high surface area, and residual carbon content of the ash, all of which increase water demand and internal friction. At the same time, the review also indicates that this adverse effect can be moderated through adequate ash processing and the use of suitable admixtures, particularly polycarboxylate-based superplasticizers. Thus, reduced workability should be interpreted as a condition-dependent response rather than an inherent limitation of SCBA use.

For mechanical performance, the reviewed studies show that SCBA can improve both compressive and split tensile strength at low-to-moderate replacement levels, whereas excessive replacement generally leads to strength loss once cement dilution exceeds the benefits of filler action and pozzolanic reactivity. Although the broader beneficial range extends from approximately 5% to 20%, the comparative analysis of the reviewed data indicates that 10% is the most frequently reported global optimum, while 10–15% represents the most consistent practical performance window for strength enhancement. This range appears to provide the best balance between matrix densification, secondary hydration, and clinker dilution. However, the exact optimum remains study-specific and is influenced by ash quality, fineness, curing conditions, and matrix type.

The durability evidence similarly shows that SCBA can improve the long-term performance of cementitious systems when used at appropriate replacement levels. In general, SCBA incorporation reduces water

absorption, capillary absorption, and chloride penetration, while increasing electrical resistivity, thereby enhancing resistance to fluid and ion transport in both mortar and concrete. However, the optimum replacement range for durability does not always coincide with that for strength. The reviewed studies indicate that durability benefits are generally achieved within a wider range of 10–30%, depending on the specific durability indicator, ash characteristics, and binder system considered. This suggests that while lower to moderate SCBA contents are more favourable for mechanical optimisation, somewhat higher replacement levels may be beneficial for transport-related durability performance when a sufficiently reactive and finely processed ash is used.

Notwithstanding the growing number of studies on the utilisation of sugarcane bagasse ash (SCBA) in cementitious materials, the existing literature still reveals substantial gaps. First, the absence of standardized processing and characterization protocols continues to limit meaningful comparison across studies. Second, much of the existing literature remains focused on laboratory-scale and short-term behaviour, while long-term durability under aggressive service conditions is still under-explored. Third, field-scale validation, economic feasibility, and life-cycle assessment require greater attention to support industrial adoption. Future research should therefore prioritise standardized SCBA production criteria, long-term exposure-based durability studies, multi-scale performance evaluation, and hybrid or ternary binder systems involving SCBA with other supplementary cementitious materials. Overall, the evidence suggests that SCBA has strong potential for sustainable cementitious applications, but its successful future industrial adoption will depend on consistent ash quality, performance-based mix optimisation, and clear demonstration of both technical reliability and economic viability.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

REFERENCES

- Abdalla T, Koteng D, Shitote SM, Matallah M (2022). Mechanical and durability properties of concrete incorporating silica fume and a high volume of sugarcane bagasse ash. *Results in Engineering*, 16, 100666.
- Agwa IS, Zeyad AM, Tayeh BA, Adesina A, de Azevedo ARG, Amin M, Hadzima-Nyarko M (2022). A comprehensive review on the use of sugarcane bagasse ash as a supplementary cementitious material to produce eco-friendly concretes. *Materials Today: Proceedings*, 65, 688-696.
- Ainomugisha S, Edwin B, Bazairwe A (2021). Utilization of sugarcane bagasse ash from power co-generation boilers as a supplementary cementitious material. *East African Journal of Science, Technology and Innovation*, 2(2), 1-14.
- Ainomugisha S, Kibwami N, Wesonga R, Adubango EN, Matovu MJ, Manga M (2025). Effect of sugarcane bagasse ash on eco-friendly blended cement production: physicochemical, mechanical, and microstructure properties. *Case Studies in Construction Materials*, 22, e04141.
- Allende S, Tuladhar R, Jacob MV (2024). Sugarcane bagasse-derived carbon for partial replacement of cementitious material in concrete. *Materials Circular Economy*, 6, 3.
- Althaqafi E, Ali T, Qureshi MZ, Islam S, Ahmed H, Ajwad A, Almujiab H, Khan MA (2024). Evaluating the combined effect of sugarcane bagasse ash, metakaolin, and polypropylene fibers in sustainable construction. *Scientific Reports*, 14, 26109.
- Amjad U, Sarir M, Khan D, Haq IU, Khawaja MWA, Mahmood K (2025). Effect of sugar cane bagasse ash incorporated as viscosity modifying agent on fresh, microstructure and mechanical properties of self-compacting concrete. *International Journal of Concrete Structures and Materials*, 19, 2.
- Andrade Neto JdS, de França MJS, Amorim Júnior NSd, Ribeiro DV (2021). Effects of adding sugarcane bagasse ash on the properties and durability of concrete. *Construction and Building Materials*, 266, 120959.
- Andreão PV, Suleiman AR, Cordeiro GC, Nehdi ML (2020). Beneficiation of sugarcane bagasse ash: pozzolanic activity and leaching behavior. *Waste and Biomass Valorization*, 11, 4393-4402.
- Arenas-Piedrahita JC, Montes-García P, Mendoza-Rangel JM, López Calvo HZ, Valdez-Tamez PL, Martínez-Reyes J (2016). Mechanical and durability properties of mortars prepared with untreated sugarcane bagasse ash and untreated fly ash. *Construction and Building Materials*, 105, 69-81.
- Arif E, Clark MW, Lake N (2016). Sugar cane bagasse ash from a high efficiency co-generation boiler: applications in cement and mortar production. *Construction and Building Materials*, 128, 287-297.
- Ashok K, Subhani SM, Sundaram B (2025). Performance characteristics of ternary blended concrete incorporating fine recycled aggregate, sugarcane bagasse ash and ground granulated blast furnace slag. *Journal of Building Pathology and Rehabilitation*, 10(2), 141.
- Bahurudeen A, Santhanam M (2015). Influence of different processing methods on the pozzolanic performance of sugarcane bagasse ash. *Cement and Concrete Composites*, 56, 32-45.
- Bahurudeen A, Wani K, Basit MA, Santhanam M (2016). Assessment of pozzolanic performance of sugarcane bagasse ash. *Journal of Materials in Civil Engineering*, 28(2), 04015095.
- Bayapureddy Y, Muniraj K, Mutukuru MRG (2020). Sugarcane bagasse ash as supplementary cementitious material in cement composites: strength, durability, and microstructural analysis. *Journal of the Korean Ceramic Society*, 57, 513-519.
- Benhelal E, Zahedi G, Shamsaei E, Bahadori A (2013). Global strategies and potentials to curb CO₂ emissions in cement industry. *Journal of Cleaner Production*, 51, 142-161.
- Bheel N, Ali MOA, Tafsirojjaman, Khahro SH, Keerio MA (2022). Experimental study on fresh, mechanical properties and embodied carbon of concrete blended with sugarcane bagasse ash, metakaolin, and millet husk ash as ternary cementitious material. *Environmental Science and Pollution Research*, 29(4), 5224-5239.
- Chen C, Habert G, Bouzidi Y, Jullien A (2010). Environmental impact of cement production: detail of the different processes and cement

- plant variability evaluation. *Journal of Cleaner Production*, 18(5), 478-485.
- Chindaprasirt P, Rukzon S, Sirivivatnanon V (2008). Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash. *Construction and Building Materials*, 22(5), 932-938.
- Chindaprasirt P, Kroehong W, Damrongwiriyanupap N, Suriyo W, Jaturapitakkul C (2020). Mechanical properties, chloride resistance and microstructure of Portland fly ash cement concrete containing high volume bagasse ash. *Journal of Building Engineering*, 31, 101415.
- Chowdhury M, AlHimali A, Ioannou S (2024). Developing greener concretes from spent bleaching earth and sugarcane bagasse ash. *Emirati Journal of Civil Engineering and Applications*, 2(2), 19-30.
- Chusilp N, Jaturapitakkul C, Kiattikomol K (2009). Effects of LOI of ground bagasse ash on the compressive strength and sulfate resistance of mortars. *Construction and Building Materials*, 23(12), 3523-3531.
- Cordeiro GC, Toledo Filho RD, Tavares LM, Fairbairn EMR (2008). Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars. *Cement and Concrete Composites*, 30(5), 410-418.
- Cordeiro GC, Toledo Filho RD, Fairbairn EMR (2009). Effect of calcination temperature on the pozzolanic activity of sugar cane bagasse ash. *Construction and Building Materials*, 23(10), 3301-3303.
- Cordeiro GC, Toledo Filho RD, de Almeida RS (2011). Influence of ultrafine wet grinding on pozzolanic activity of submicrometre sugar cane bagasse ash. *Advances in Applied Ceramics*, 110(8), 453-456.
- Cupim RV, Tostes Linhares Júnior JA, Mesquita LC, Marques MG, Garcez de Azevedo AR, Marvila MT (2025). Rheological and mechanical properties of mortars made with recycled sugarcane bagasse ash. *Journal of Materials Research and Technology*, 36, 3546-3555.
- Dhengare S, Sharma R, Sobti J, Gajbhiye A, Bhagat R (2020). Binary concrete expansion by means of copper slag, fly ash, sugarcane bagasse ash, and rice husk ash as partial replacement of cement. *International Journal of Advanced Science and Technology*, 29(7), 9973-9993.
- Embong R, Shafiq N, Kusbiantoro A, Nuruddin MF (2016). Effectiveness of low-concentration acid and solar drying as pre-treatment features for producing pozzolanic sugarcane bagasse ash. *Journal of Cleaner Production*, 112, 953-962.
- Fairbairn EMR, Americano BB, Cordeiro GC, Paula TP, Toledo Filho RD, Silvoso MM (2010). Cement replacement by sugar cane bagasse ash: CO₂ emissions reduction and potential for carbon credits. *Journal of Environmental Management*, 91(9), 1864-1871.
- Francioso V, Lemos-Micolta ED, Elgaali HH, Moro C, Rojas-Manzano MA, Velay-Lizancos M (2024). Valorization of sugarcane bagasse ash as an alternative SCM: effect of particle size, temperature-crossover effect mitigation and cost analysis. *Sustainability*, 16(21), 9370.
- Frias M, Villar E, Savastano H (2011). Brazilian sugar cane bagasse ashes from the cogeneration industry as active pozzolans for cement manufacture. *Cement and Concrete Composites*, 33, 490-496.
- Ganesan K, Rajagopal K, Thangavel K (2007). Evaluation of bagasse ash as supplementary cementitious material. *Cement and Concrete Composites*, 29(6), 515-524.
- Gupta CK, Sachan AK (2019). A review on properties of self compacting concrete using bagasse ash. *International Journal of Innovative Research in Applied Sciences and Engineering*, 2(11), 352-356.
- Gupta CK, Sachan AK, Kumar R (2021). Examination of microstructure of sugar cane bagasse ash and sugar cane bagasse ash blended cement mortar. *Sugar Tech*, 23, 651-660.
- Gupta CK, Sachan AK, Kumar R (2022). Utilization of sugarcane bagasse ash in mortar and concrete: a review. *Materials Today: Proceedings*, 65, 798-807.
- Gupta CK, Sachan AK, Kumar R (2023a). Experimental study on microstructural and mechanical behaviour of self compacting concrete using agricultural waste. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 47(2), 925-942.
- Gupta CK, Sachan AK, Kumar R (2023b). Durability and microstructural analysis of self-compacting concrete using sugarcane bagasse ash for sustainable development. *Innovative Infrastructure Solutions*, 8(3), 97.
- Hasan NMS, Sobuz MHR, Tamanna N, Talha MS, Islam MS (2014). Properties of concrete by using bagasse ash and recycle aggregate. *Challenge Journal of Concrete Research Letters*, 5(2), 768-785.
- Hasnain M, Javed U, Ali A, Zafar M (2021). Eco-friendly utilization of rice husk ash and bagasse ash blend as partial sand replacement in self-compacting concrete. *Construction and Building Materials*, 273, 121753.
- India Brand Equity Foundation (IBEF) (2025). *Indian Cement Industry Analysis (November 2025)*. <https://www.ibef.org/industry/cement-presentation> [accessed 05-04-2026].
- Jagadesh P, Ramachandra Murthy A, Murugesan R, Sarayu K (2015). Micro-analytical studies on sugar cane bagasse ash. *Sadhana*, 40(5), 1629-1638.
- Jagadesh P, Ramachandra Murthy A, Murugesan R (2020). Effect of processed sugar cane bagasse ash on mechanical and fracture properties of blended mortar. *Construction and Building Materials*, 262, 120846.
- Jha P, Sachan AK, Singh RP (2020). Microstructure analysis of concrete using bagasse ash waste as partial replacement of cement. *Indian Journal of Environmental Protection*, 40(3), 269-275.
- Jha P, Sachan AK, Singh RP (2021a). Agro-waste sugarcane bagasse ash (ScBA) as partial replacement of binder material in concrete. *Materials Today: Proceedings*, 44, 419-427.
- Jha P, Sachan AK, Singh RP (2021b). Bagasse ash (ScBA) and its utilization in concrete as pozzolanic material: a review. In: Kumar Shukla S, Raman SN, Bhattacharjee B, Bhattacharjee J, editors. *Advances in Geotechnics and Structural Engineering*. Springer, Singapore, Singapore, pp. 471-480.
- Jha P, Sachan AK, Singh RP (2021c). Investigation on the durability of concrete with partial replacement of cement by bagasse ash (BAH) and sand by stone dust (SDT). *Materials Today: Proceedings*, 43, 237-243.
- Jha P, Sachan AK, Singh RP (2021d). Properties of concrete with bagasse ash and stone dust exposed to sulphate attack. In: Chandrasekaran S, Kumar S, Madhuri S, editors. *Recent Advances in Structural Engineering*. Springer, Singapore, Singapore, pp. 29-37.
- Jiménez-Quero VG, Ortiz-Guzmán M, Montes-García P (2019). Durability of mortars containing sugarcane bagasse ash. *Journal of Physics: Conference Series*, 1221(1), 012004.
- Jittin V, Bahurudeen A (2022). Evaluation of rheological and durability characteristics of sugarcane bagasse ash and rice husk ash based binary and ternary cementitious system. *Construction and Building Materials*, 317, 125965.
- Joseph A, Murugan SB (2024). Investigating the sustainable application of unprocessed sugarcane bagasse ash and alccofine in cementitious mortar from a physical, mechanical, and microstructural perspective. *Innovative Infrastructure Solutions*, 9(12), 475.
- Joshaghani A, Moeini MA (2017). Evaluating the effects of sugar cane bagasse ash (SCBA) and nanosilica on the mechanical and durability properties of mortar. *Construction and Building Materials*, 152, 818-831.
- Joshaghani A, Moeini MA (2018). Evaluating the effects of sugarcane-bagasse ash and rice-husk ash on the mechanical and durability properties of mortar. *Journal of Materials in Civil Engineering*, 30(7), 04018144.
- Juenger MCG, Snellings R, Bernal SA (2019). Supplementary cementitious materials: new sources, characterization, and performance insights. *Cement and Concrete Research*, 122, 257-273.
- Kajaste R, Hurme M (2016). Cement industry greenhouse gas emissions management options and abatement cost. *Journal of Cleaner Production*, 112, 4041-4052.
- Katare VD, Madurwar MV (2017). Experimental characterization of sugarcane biomass ash: a review. *Construction and Building Materials*, 152, 1-15.
- Kazmi SMS, Munir MJ, Patnaikuni I, Wu YF (2017). Pozzolanic reaction of sugarcane bagasse ash and its role in controlling alkali silica reaction. *Construction and Building Materials*, 148, 231-240.
- Khan MI, Abdy Sayyed MA, Ali MMA (2021). Examination of cement concrete containing micro silica and sugarcane bagasse ash subjected to sulphate and chloride attack. *Materials Today: Proceedings*, 39, 558-562.

- Khan MA, Zhang B, Ahmad M, Niekurzak M, Khan MS, Sabri MMS, Chen W (2025). Optimizing concrete sustainability with bagasse ash and stone dust and its impact on mechanical properties and durability. *Scientific Reports*, 15(1), 1385.
- Kiran K, Kishore IS (2017). An experimental study on partial replacement of cement with bagasse ash in concrete mix. *International Journal of Civil Engineering and Technology*, 8(1), 452-455.
- Kirthiga R, Elavenil S (2023). Potential utilization of sugarcane bagasse ash in cementitious composites for developing inorganic binder. *Ain Shams Engineering Journal*, 14(11), 102560.
- Kirthiga R, Elavenil S, Imjai T (2025). Synergistic effects of bagasse ash and silica fume on strength and durability properties of sustainable cement mortars. *Engineering Research Express*, 7(3), 035109.
- Klathae T, Tanawuttiphong N, Tangchirapat W, Chindaprasit P, Sukontasukkul P, Jaturapitakkul C (2020). Heat evolution, strengths, and drying shrinkage of concrete containing high volume ground bagasse ash with different LOIs. *Construction and Building Materials*, 258, 119443.
- Kolawole JT, Babafemi AJ, Fanijo E, Chandra Paul S, Combrinck R (2021). State-of-the-art review on the use of sugarcane bagasse ash in cementitious materials. *Cement and Concrete Composites*, 118, 103975.
- Krishna YM, Dhevasenaa PR, Srinivasan G, Kumar CNS (2024). Enhancing sustainability in concrete: synergistic effects of sugarcane bagasse ash and iron ore tailings as eco-friendly cement and sand replacements. *Journal of Building Pathology and Rehabilitation*, 9(1), 20.
- Kumar V, Kumar P (2023). Effect of partial cement replacement with sugarcane bagasse ash. *International Journal of Science and Research Archive*, 8, 781-787.
- Kumara GD, Sivapullaiah PV, Sreenivasa Murthy A (2023). Performance evaluation of sugar cane bagasse ash on the strength of concrete: a sustainable approach. *Materials Today: Proceedings*, 75, 106-111.
- Le DH, Sheen YN (2023). Assessment of properties of mortars modified with sugarcane bagasse ash processed by heating at different temperatures as cement replacement. *European Journal of Environmental and Civil Engineering*, 27(1), 393-415.
- Li Y, Chai J, Wang R, Zhang X, Si Z (2022). Utilization of sugarcane bagasse ash (SCBA) in construction technology: a state-of-the-art review. *Journal of Building Engineering*, 56, 104774.
- Lourdu AR, Ali SHM (2023). Study on strength, durable and flexural behaviour of partial replacement of sugarcane bagasse ash over cement. *Materials Research Express*, 10, 095502.
- Lyra GP, Borrachero MV, Soriano L, Payá J, Rossignolo JA (2021). Comparison of original and washed pure sugar cane bagasse ashes as supplementary cementing materials. *Construction and Building Materials*, 272, 122001.
- Maldonado-García MA, Montes-García P, Valdez-Tamez PL (2017). A review of the use of sugarcane bagasse ash with a high LOI content to produce sustainable cement composites. *Academic Journal of Civil Engineering*, 35(2), 597-605.
- Mello L, Anjos M, Sá M, Souza N, Farias E (2020). Effect of high temperatures on self-compacting concrete with high levels of sugarcane bagasse ash and metakaolin. *Construction and Building Materials*, 248, 118715.
- Memon SA, Javed U, Shah MI, Hanif A (2022). Use of processed sugarcane bagasse ash in concrete as partial replacement of cement: mechanical and durability properties. *Buildings*, 12(10), 1769.
- Miller SA, Horvath A, Monteiro PJM (2016). Readily implementable techniques can cut annual CO₂ emissions from the production of concrete by over 20%. *Environmental Research Letters*, 11, 074029.
- Minnu SN, Bahurudeen A, Gopinath A (2021). Comparison of sugarcane bagasse ash with fly ash and slag: an approach towards industrial acceptance of sugar industry waste in cleaner production of cement. *Journal of Cleaner Production*, 285, 124836.
- Mittal DN, Varekar V (2026). Design of sustainable modified concrete mix using industrial waste. *Indian Chemical Engineer*, 68(1), 192-207.
- Mohamad N, Muthusamy K, Embong R, Kusbiantoro A, Hashim MH (2022). Environmental impact of cement production and solutions: a review. *Materials Today: Proceedings*, 48, 741-746.
- Moraes JCB, Cordeiro GC, Akasaki JL, Vieira AP, Payá J (2021). Improving the reactivity of a former ground sugarcane bagasse ash produced by autogenous combustion through employment of two different additional grinding procedures. *Construction and Building Materials*, 270, 121471.
- Morales EV, Villar-Cociña E, Frías M, Santos SF, Savastano H (2009). Effects of calcining conditions on the microstructure of sugar cane waste ashes (SCWA): influence in the pozzolanic activation. *Cement and Concrete Composites*, 31(1), 22-28.
- Nassar RUD, Singh N, Varsha S, Sai AR, Sufyan-Ud-Din M (2022). Strength, electrical resistivity and sulfate attack resistance of blended mortars produced with agriculture waste ashes. *Case Studies in Construction Materials*, 16, e00944.
- Navaneetha E, Rao PN, Bahurudeen A (2025). Development of sustainable and durable ternary blended concrete using sugarcane bagasse ash and glass powder. *Construction and Building Materials*, 466, 140329.
- Ouedraogo M, Sawadogo M, Sanou I, Barro M, Nassio S, Seynou M, Zerbo L (2022). Characterization of sugar cane bagasse ash from Burkina Faso for cleaner cement production: influence of calcination temperature and duration. *Results in Materials*, 14, 100275.
- Özmen HB, Tanrıverdi B (2025). Concrete paradox: economic importance, environmental impacts, and the sustainability of concrete material. *Research and Design*, 2(2), 66-84.
- Patil C, Manjunath M, Hosamane S, Bandekar S, Athani R (2021). Pozzolonic activity and strength activity index of bagasse ash and fly ash blended cement mortar. *Materials Today: Proceedings*, 42, 1456-1461.
- Praveenkumar S, Sankarasubramanian G, Sindhu S (2020). Strength, permeability and microstructure characterization of pulverized bagasse ash in cement mortars. *Construction and Building Materials*, 238, 117691.
- Quedou PG, Wirquin E, Bokhoree C (2021). Sustainable concrete: potency of sugarcane bagasse ash as a cementitious material in the construction industry. *Case Studies in Construction Materials*, 14, e00545.
- Ramesh KV, Goutham R, Siva IS (2017). An experimental study on partial replacement of bagasse ash in basalt concrete mix. *International Journal of Civil Engineering and Technology*, 8(5), 335-341.
- Reddy BLN, Kumar MV (2026). An experimental investigation into the durability properties of sustainable self-curing concrete including copper slag and sugarcane bagasse ash. *Journal of Building Pathology and Rehabilitation*, 11(1), 19.
- Sakib N, Hasan R, Mutalib AA, Jamil M, Raman SN, Kaish ABMA (2023). Utilization of sugar mill waste ash as pozzolanic material in structural mortar. *Minerals*, 13(3), 324.
- Samaila MB, Xiaosheng W, Elkaseem A (2014). Hydration and strength behavior of sugarcane-baggase ash concrete using electrical resistivity measurement. *American Journal of Civil Engineering and Architecture*, 2(5), 174-176.
- Sankeeth S, Prabhath AAN, Damruwan HGH, Herath HMST, Priyadarshana HVV, Kumara SPSNBS, Lewangamage CS, Koswattage KR (2025). Optimizing mechanical properties of concrete using sugarcane bagasse ash. *Results in Engineering*, 27, 105968.
- Shaban WM, Heniegal AM, Amin M, Zeyad AM, Agwa IS, Hassan HH (2024). Effect of agricultural wastes as sugar beet ash, sugarcane leaf ash, and sugarcane bagasse ash on UHPC properties. *Journal of Building Engineering*, 98, 111359.
- Singh NB, Singh VD, Rai S (2000). Hydration of bagasse ash-blended Portland cement. *Cement and Concrete Research*, 30(9), 1485-1488.
- Soares MMN, Poggiali FS, Bezerra ACS, Figueiredo RB, Aguiar MTP, Cetlin PR (2014). The effect of calcination conditions on the physical and chemical characteristics of sugar cane bagasse ash. *Rem: Revista Escola de Minas*, 67(1), 33-39.
- Srinivasan R, Sathiya K (2010). Experimental study on bagasse ash in concrete. *International Journal of Service Learning in Engineering*, 5(2), 60-66.
- Sua-iam G, Makul N (2013). Use of increasing amounts of bagasse ash waste to produce self-compacting concrete by adding limestone powder waste. *Journal of Cleaner Production*, 57, 308-319.
- Subedi S, Hassan MM, Arce GA, Barbato M, Noorvand H, Mohammad L (2023). Properties of engineered cementitious composites using combined systems of fly ash and post-processed bagasse ash as

- supplementary cementitious materials. *Transportation Research Record*, 2677(10), 386-403.
- Tabish M, Zaheer MM, Baqi A (2025). Age dependent properties of concrete incorporating mechanically processed ultra-fine sugarcane bagasse ash. *Construction and Building Materials*, 494, 143509.
- Torres de Sande V, Sadique M, Pineda P (2023). Environmental benefits of using activated sugarcane bagasse ash in cementitious materials. In: *59th Annual Associated Schools of Construction International Conference*, Liverpool, UK, pp. 723-731.
- Ullah MF, Tang H, Ullah A, Toth Z, Ahmad M, Alzlfawi A (2025). Mechanical and environmental performance of sugarcane bagasse ash from Khyber Pakhtunkhwa in sustainable concrete. *Scientific Reports*, 15(1), 24571.
- Wagh M, Waghe U, Bahrami A, Ansari K, Özkılıç YO, Nikhade A (2024). Experimental investigation of mechanical and durability performances of self-compacting concrete blended with bagasse ash, metakaolin, and glass fiber. *Frontiers in Materials*, 11, 1351554.
- Wagh M, Waghe UP (2024). Effect of bagasse ash on performance of self compacting concrete. *AIP Conference Proceedings*, 3188(1), 070015.
- Yaseen N (2024). Exploring the potential of sugarcane bagasse ash as a sustainable supplementary cementitious material: experimental investigation and statistical analysis. *Results in Chemistry*, 10, 101723.
- Zareei SA, Ameri F, Bahrami N (2018). Microstructure, strength, and durability of eco-friendly concretes containing sugarcane bagasse ash. *Construction and Building Materials*, 184, 258-268.
- Zeyad AM, Megat Johari MA, Tayeh BA, Yusuf MO (2016). Efficiency of treated and untreated palm oil fuel ash as a supplementary binder on engineering and fluid transport properties of high-strength concrete. *Construction and Building Materials*, 125, 1066-1079.