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Research Article

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

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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.

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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).

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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.

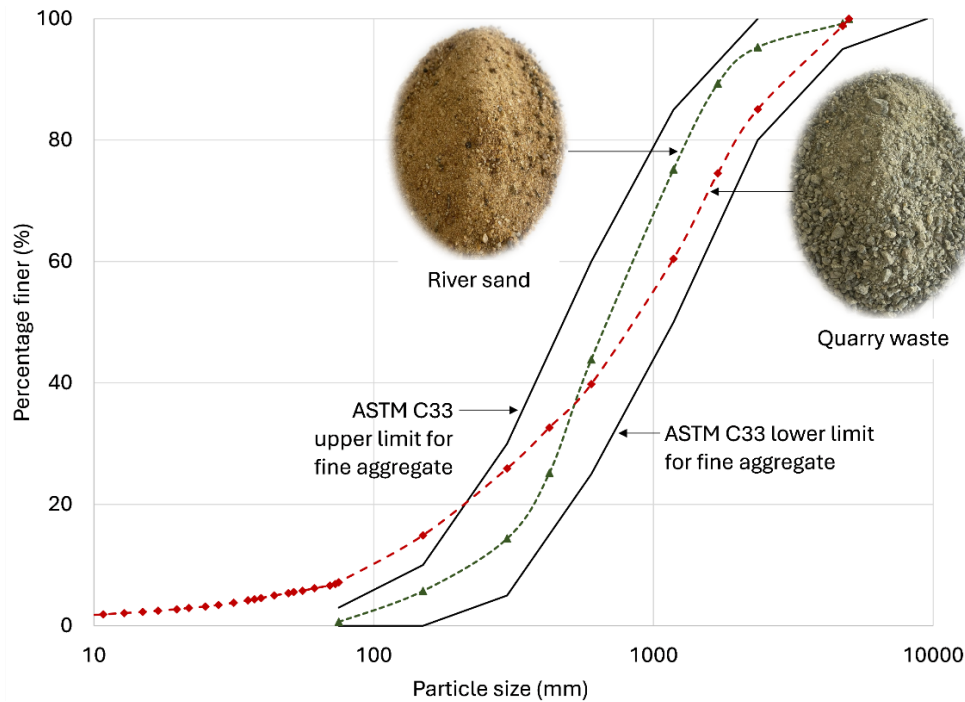


Fig. 1. Particle size distribution of the river sand and quarry waste.

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.

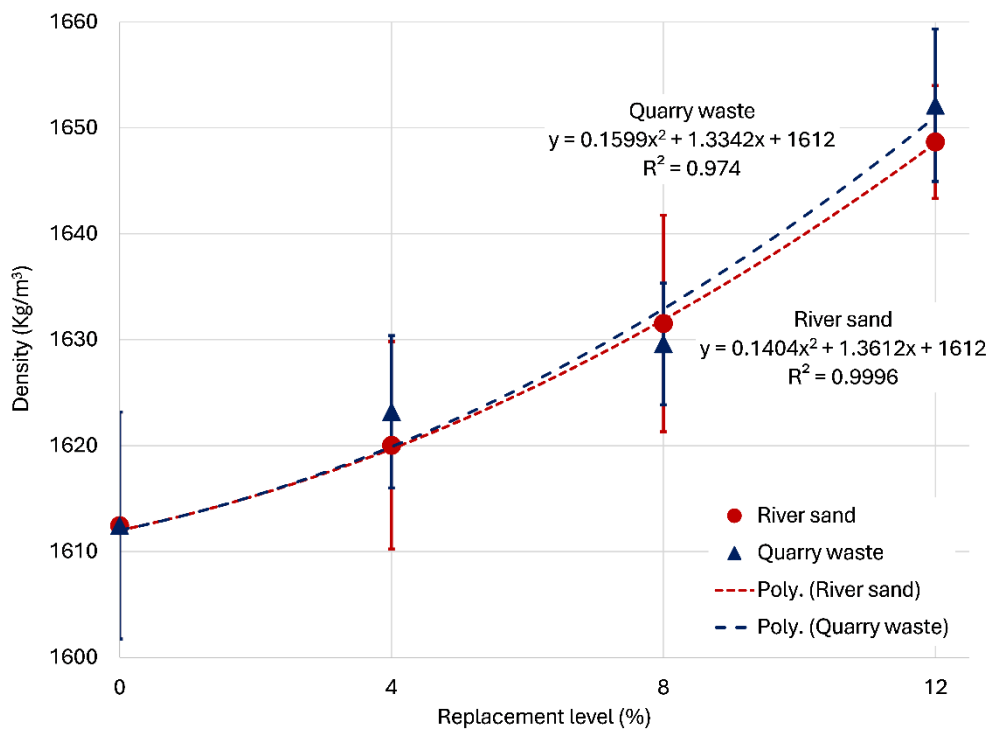


Fig. 4. Density variation for different pervious concrete mixes.

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.

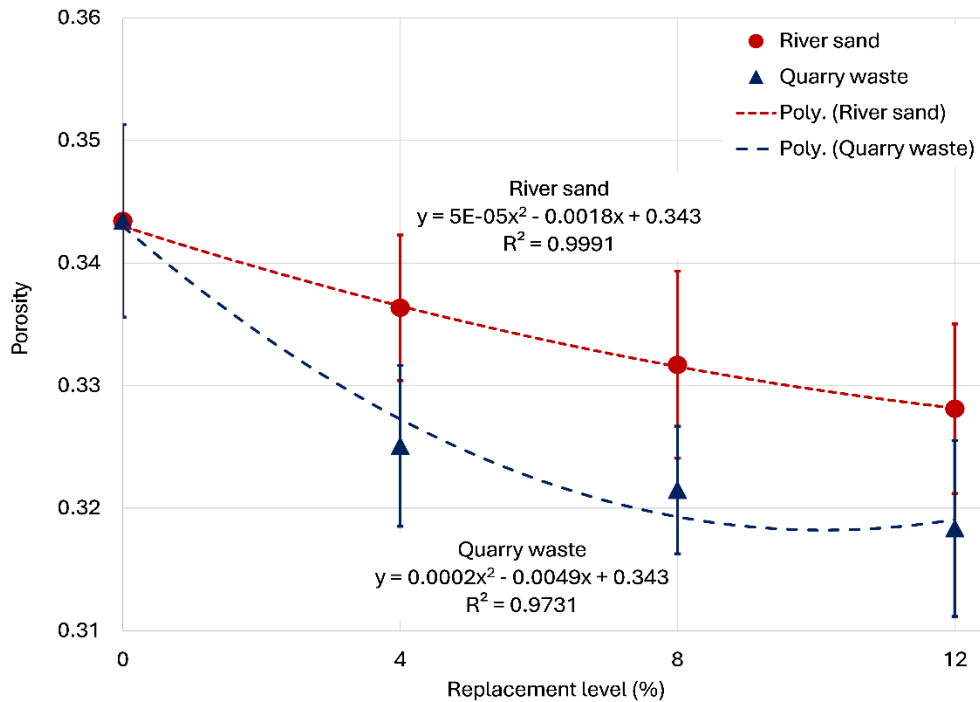


Fig. 5. Porosity variation for different pervious concrete mixes.

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.

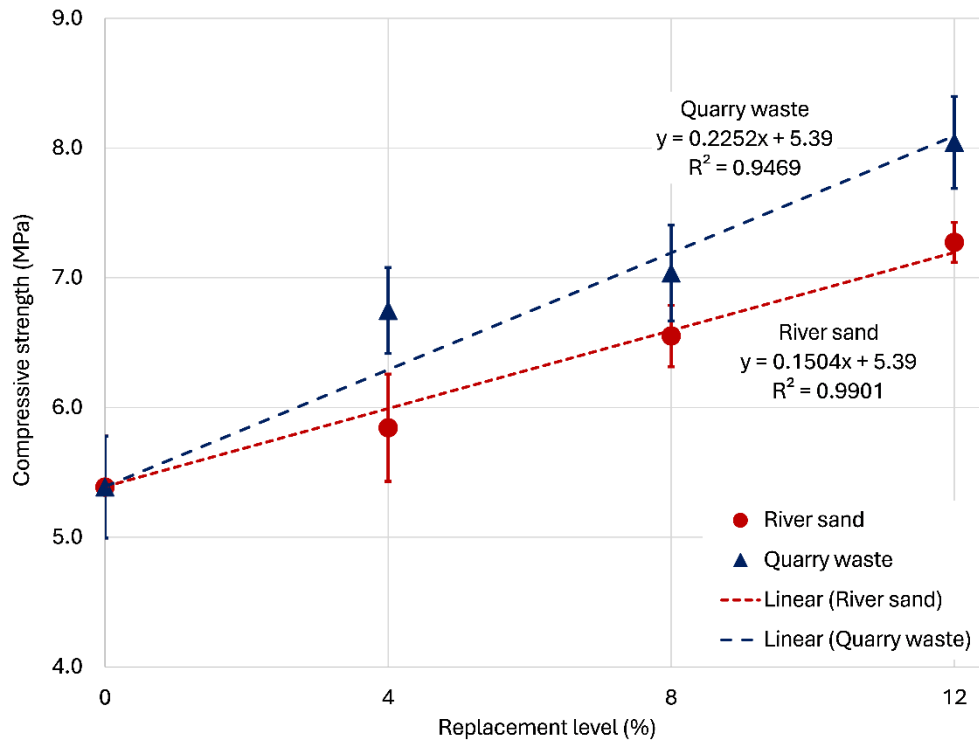


Fig. 6. Compressive strength variation for different pervious concrete mixes.

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).

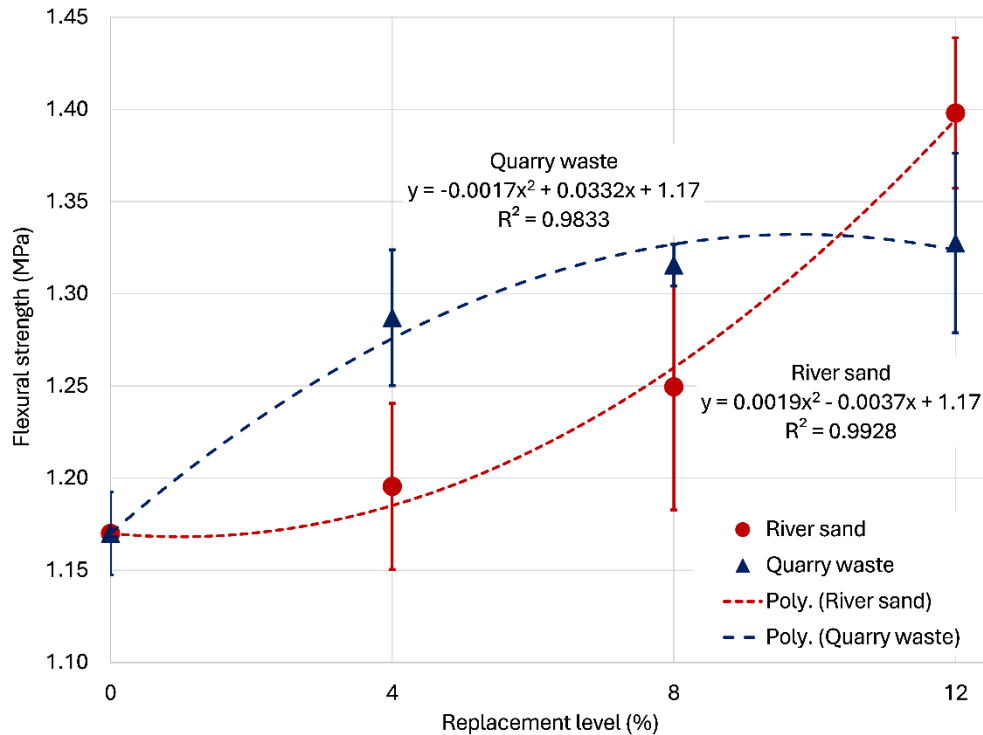


Fig. 7. Flexural strength variation for different pervious concrete mixes.

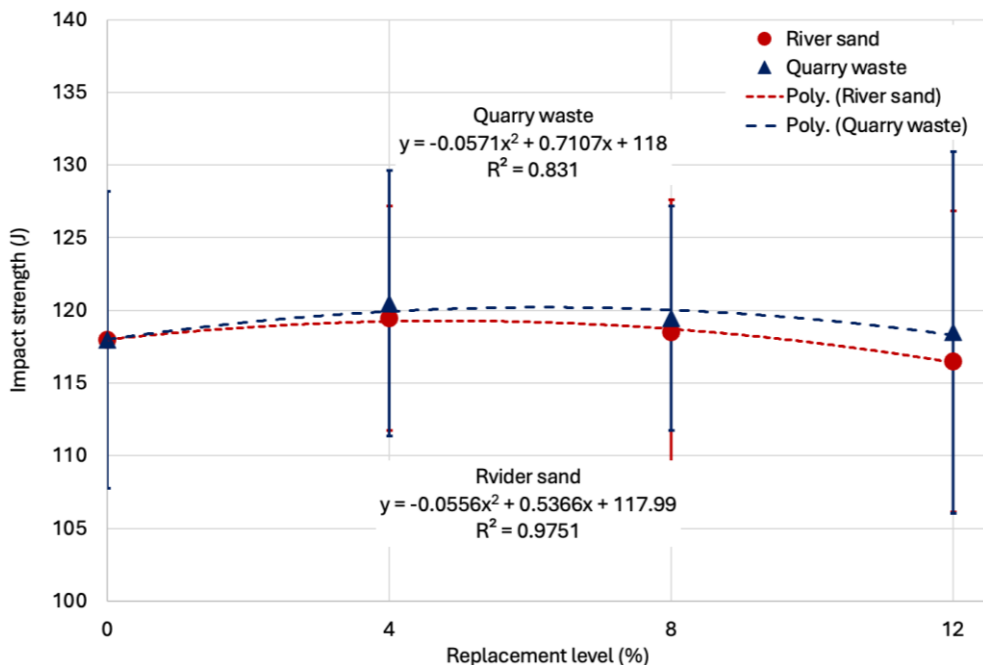


Fig. 8. Impact strength variation for different pervious concrete mixes.

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.

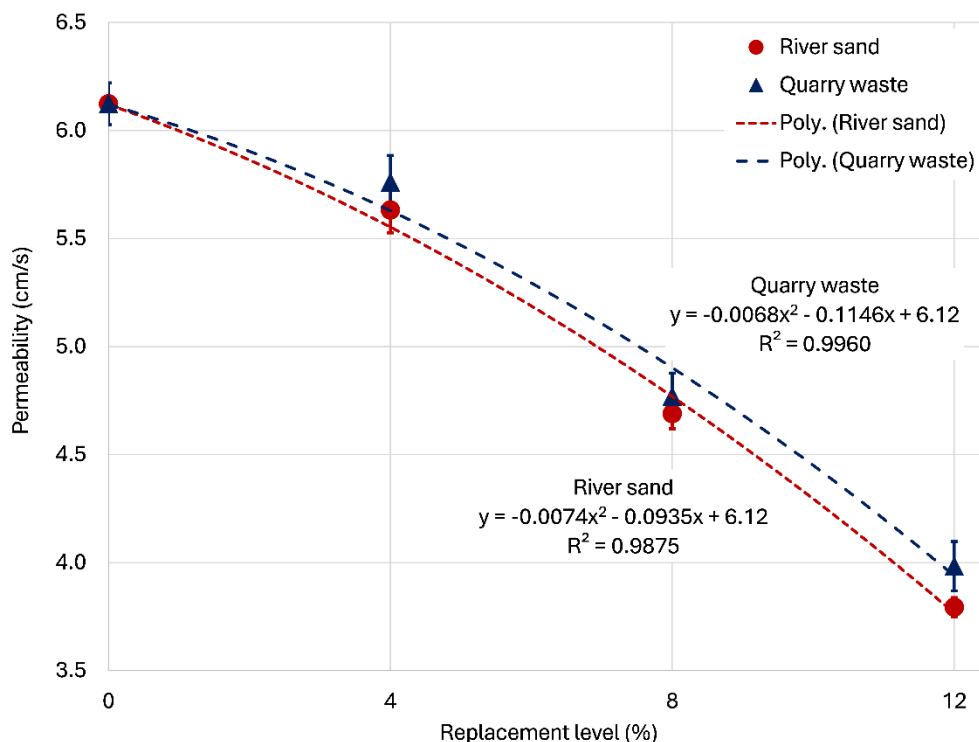


Fig. 9. Permeability variation for different pervious concrete mixes.

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.

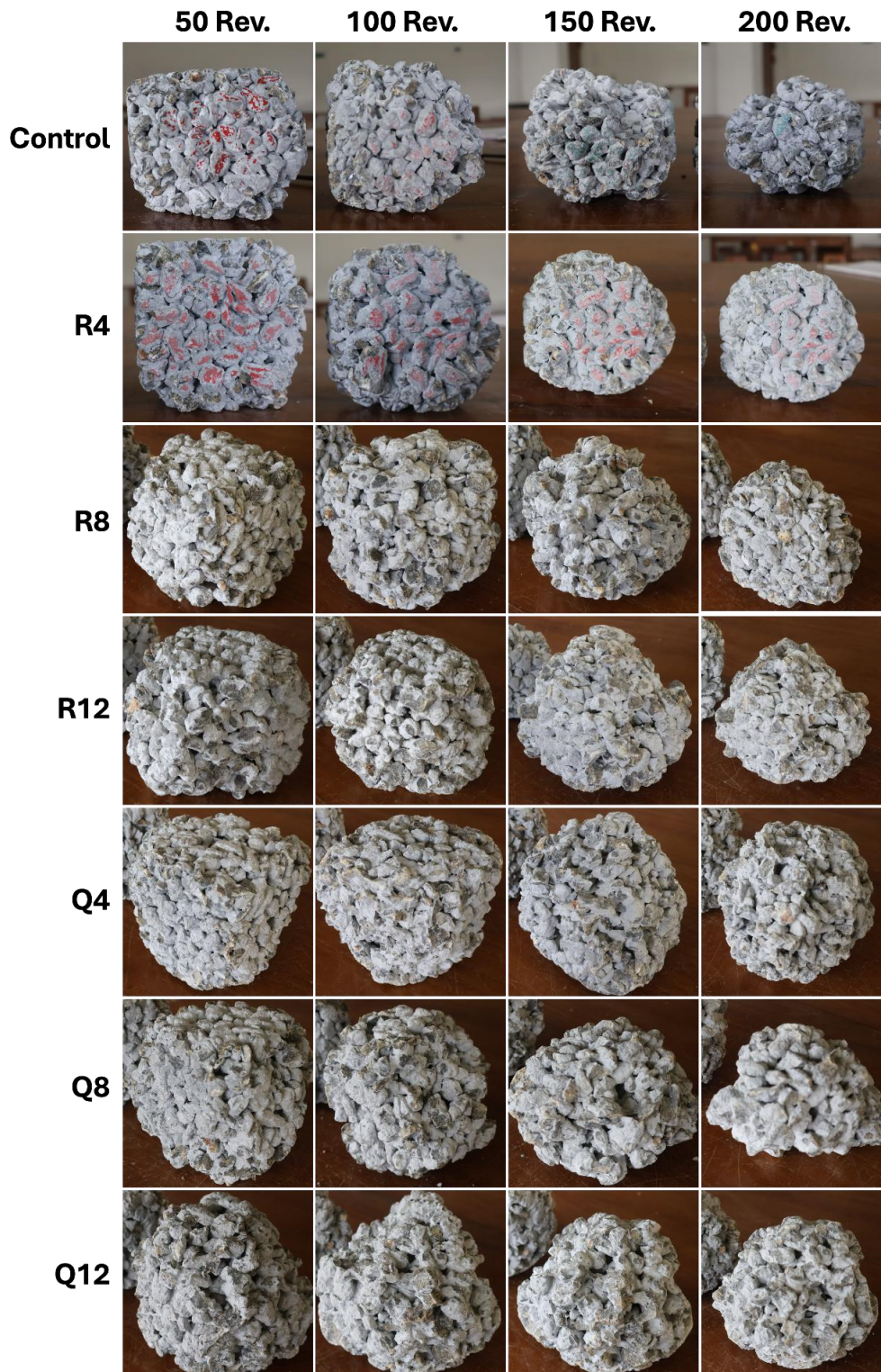


Fig. 10. Pervious concrete specimens after a specific number of revolutions.

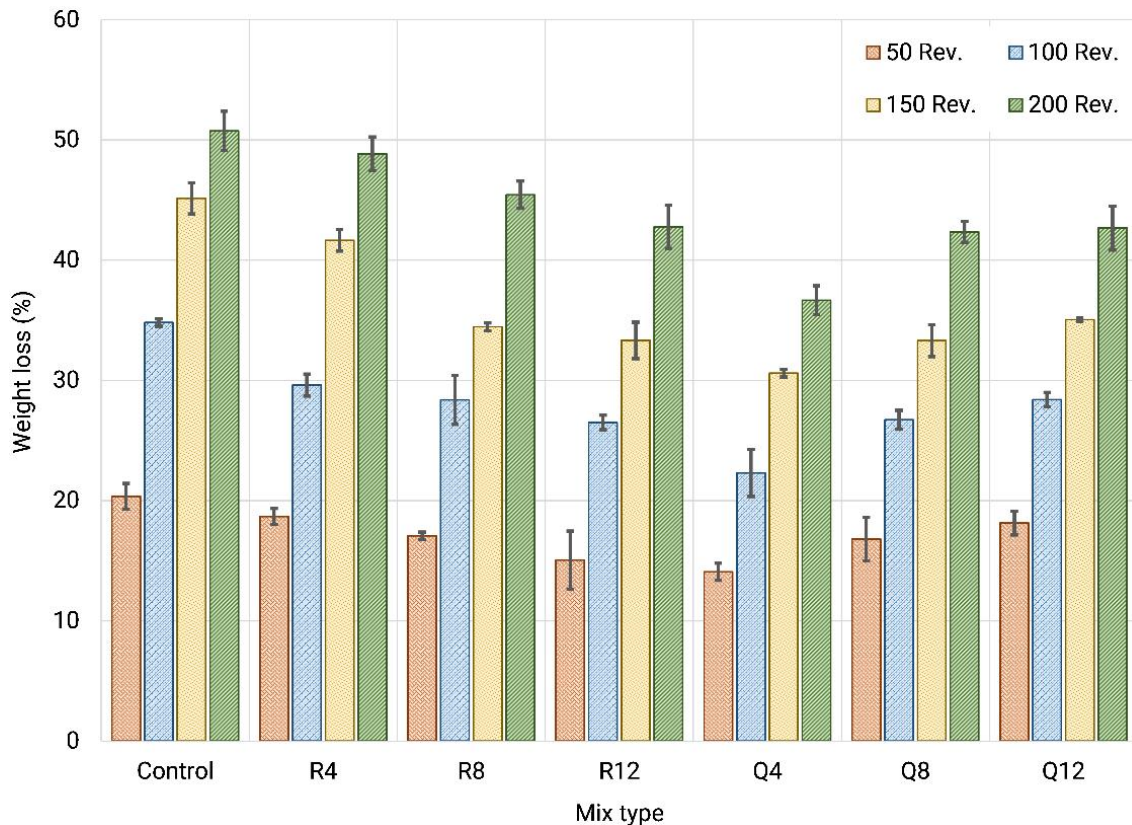


Fig. 11. Weight loss due to abrasion for different pervious concrete mixes.

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.

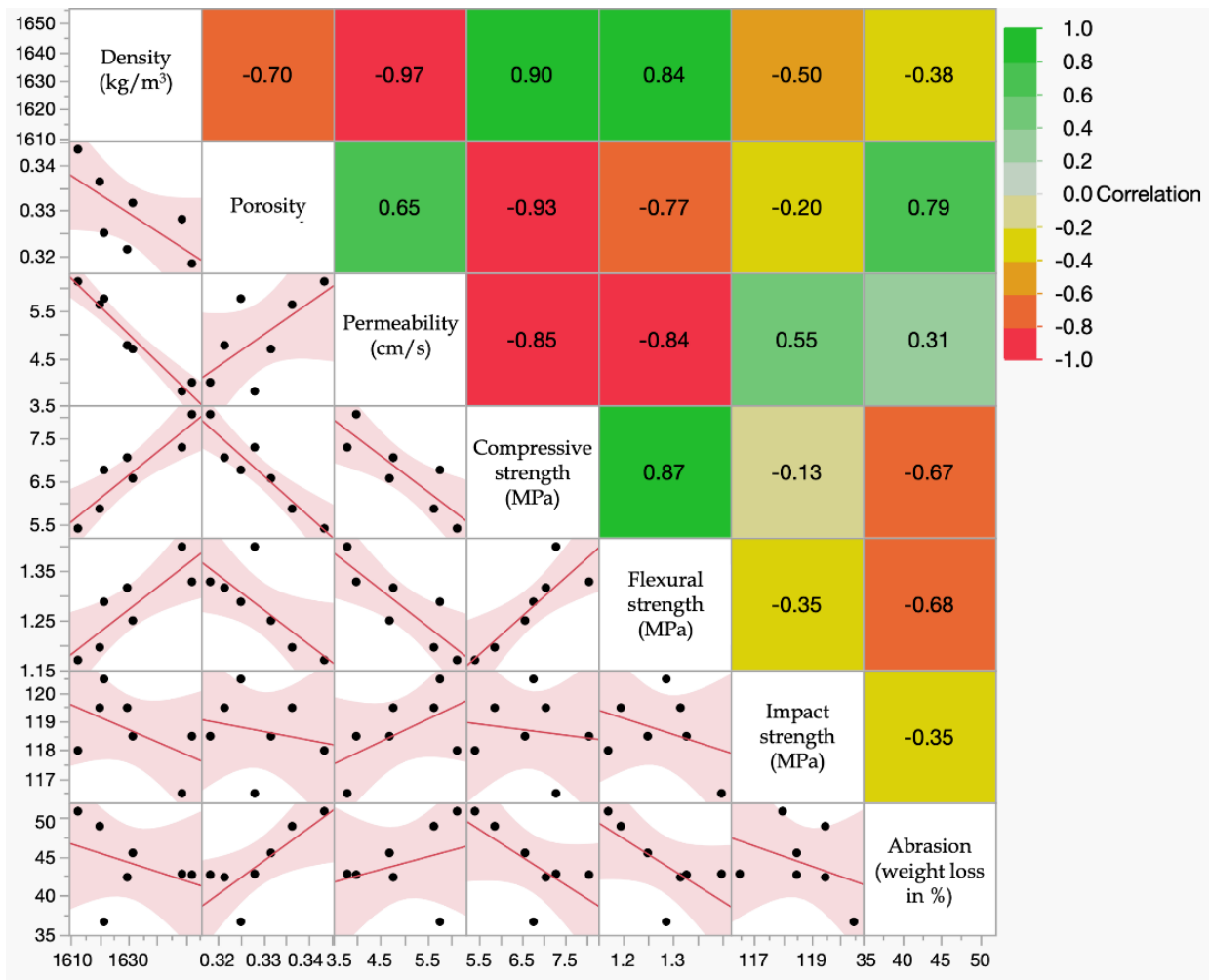


Fig. 12. The correlation analysis of various properties of pervious concrete.

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.

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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.

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