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Research Article

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

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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.

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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

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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.

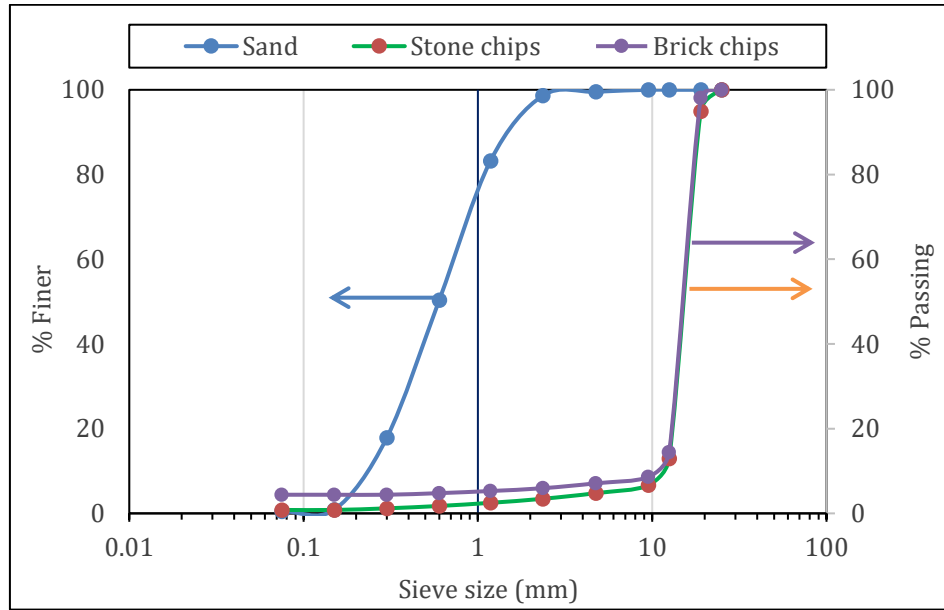


Fig. 2. Gradation curve of sand, stone and brick chips.

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.

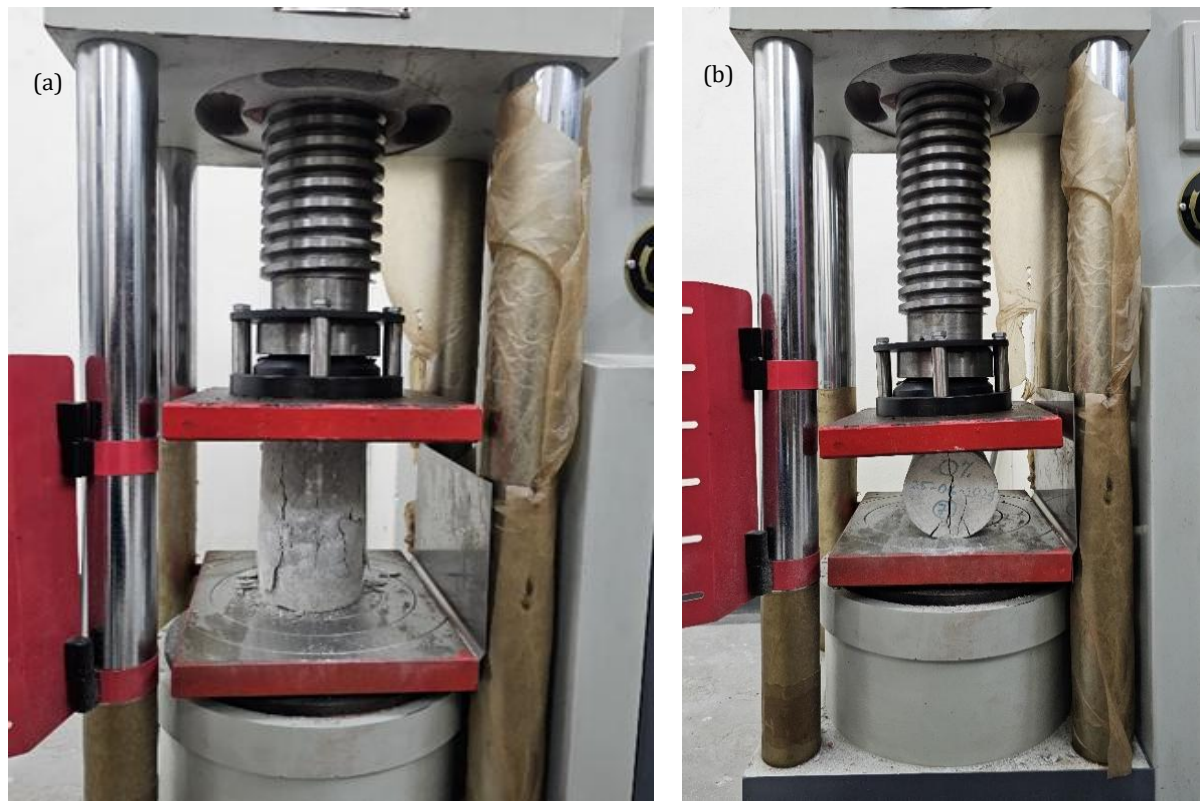


Fig. 3. (a) Compressive and (b) splitting tensile strength test set-up used in this study.

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.

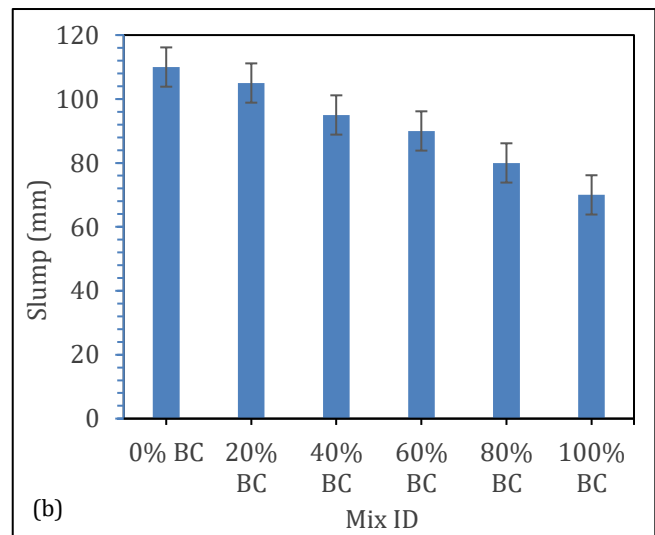


Fig. 5. (a) Workability measurement; (b) Variation of the slump value of the concrete.

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.

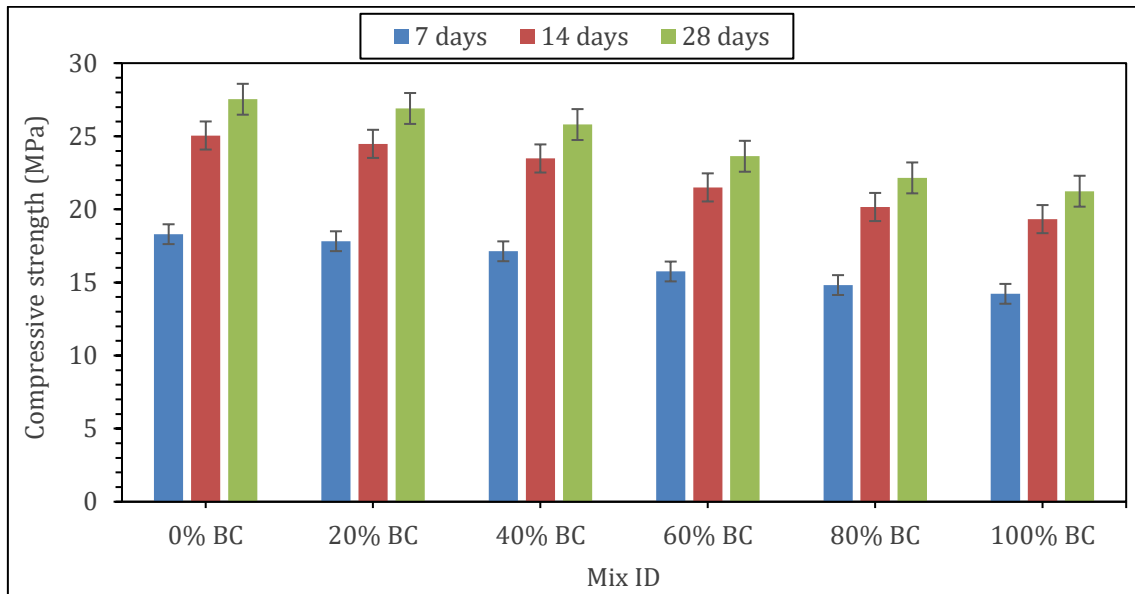


Fig. 6. Compressive strength of concrete at 7, 14, and 28-days.

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.

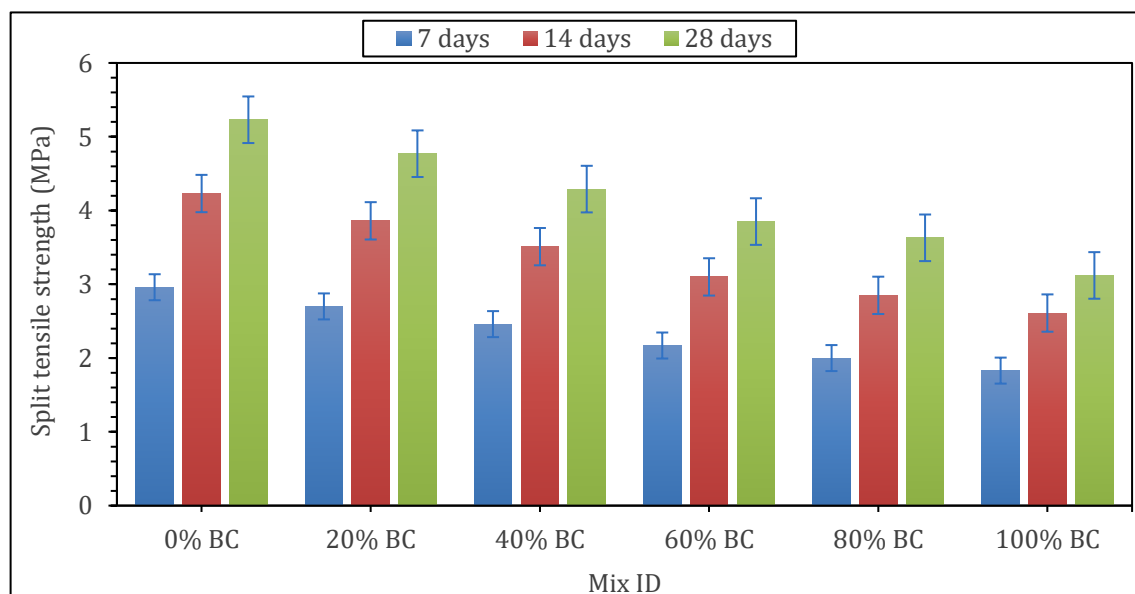


Fig. 7. Splitting tensile strength of concrete at 7, 14, and 28-days.

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.

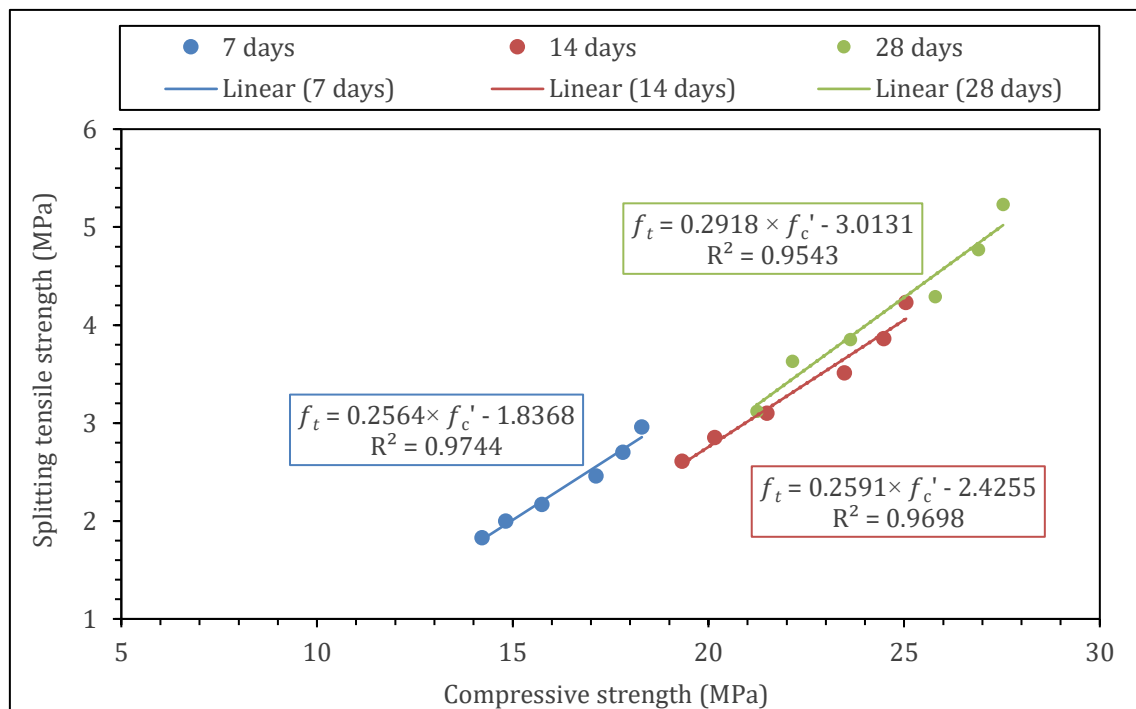


Fig. 8. Correlation between compressive and splitting tensile strength.

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.

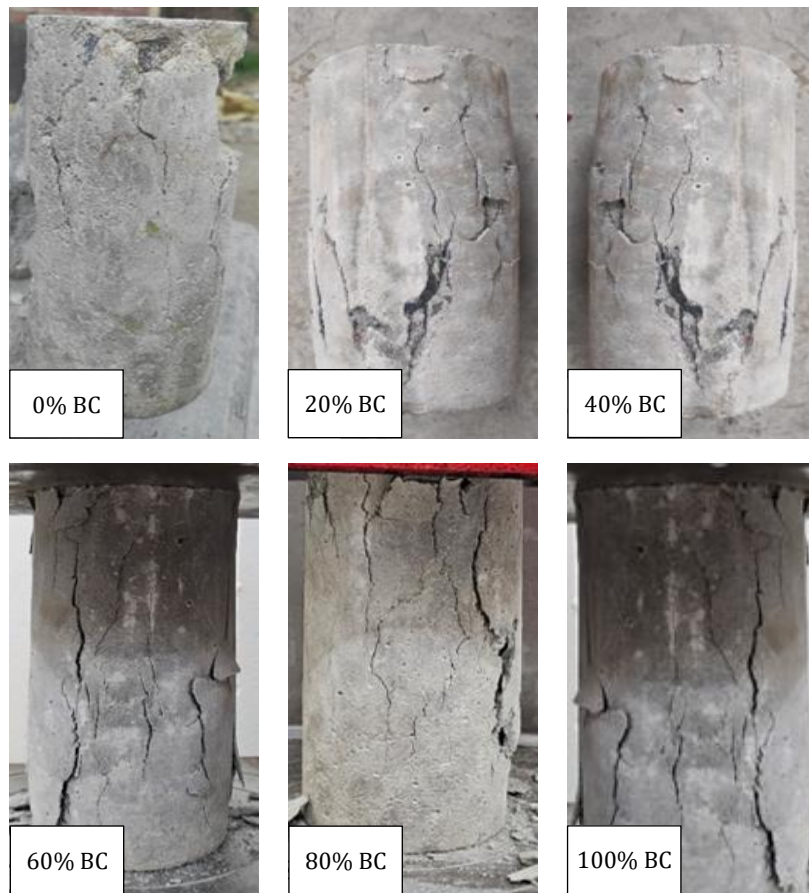


Fig. 9. Failure pattern of concrete specimens at 28 days due to compression load.

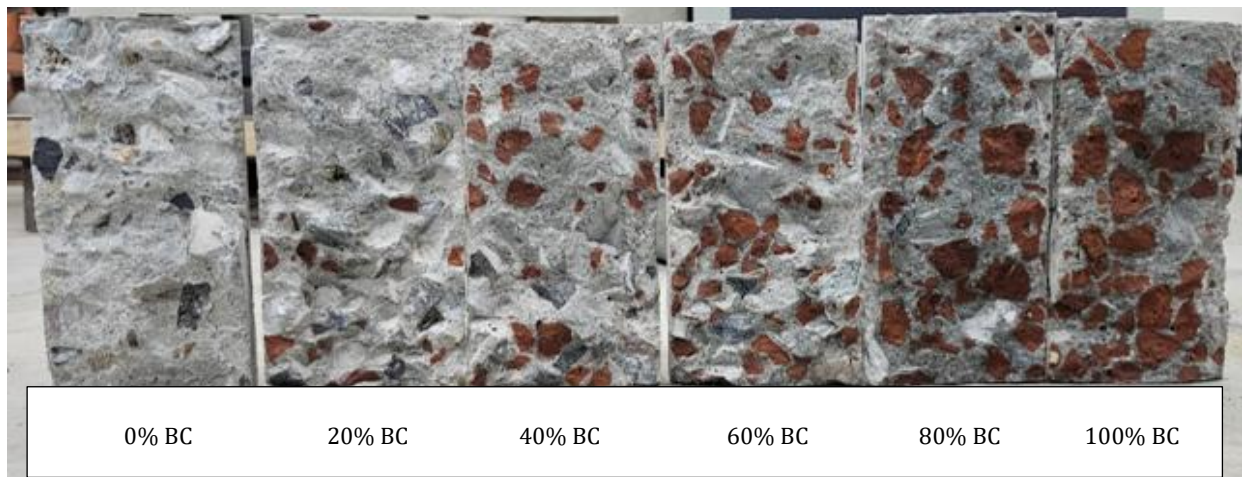


Fig. 10. Failure pattern of concrete specimens at 28 days for splitting tensile load.

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.

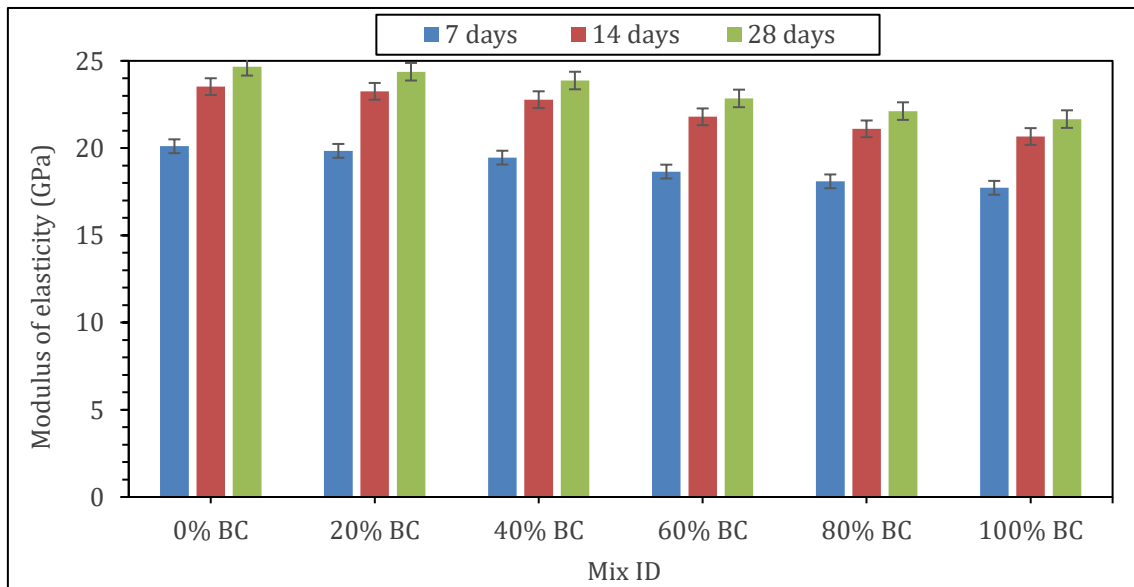


Fig. 11. Modulus of elasticity of concrete at different mix levels.

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.

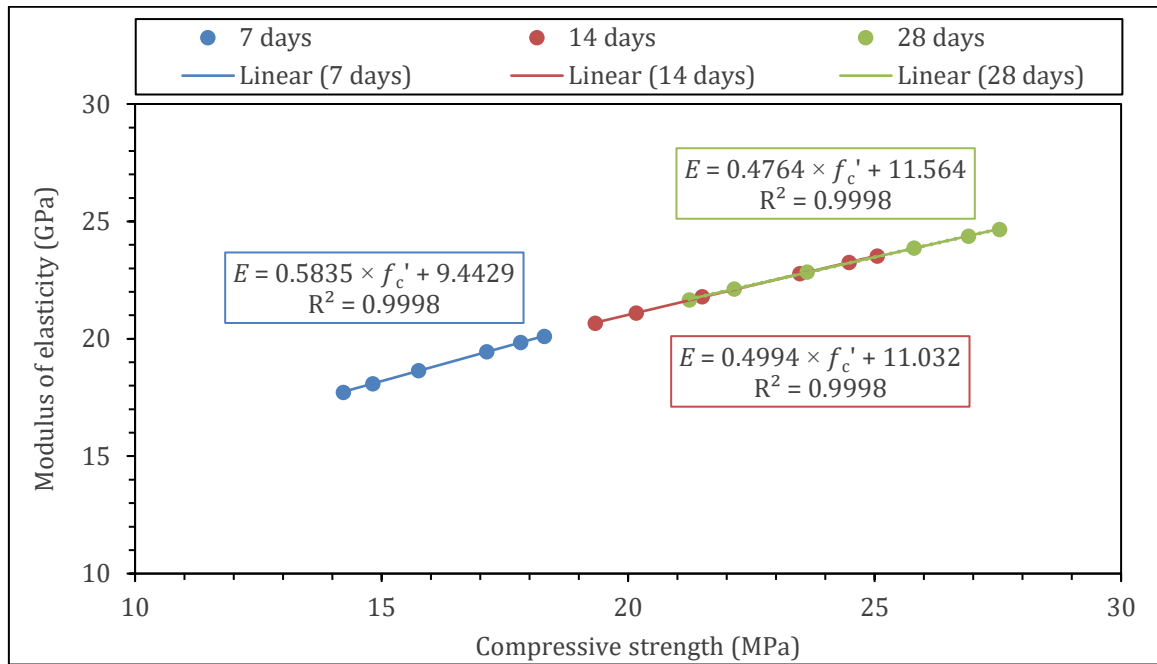


Fig. 12. Correlation between modulus of elasticity and compressive strength.

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.

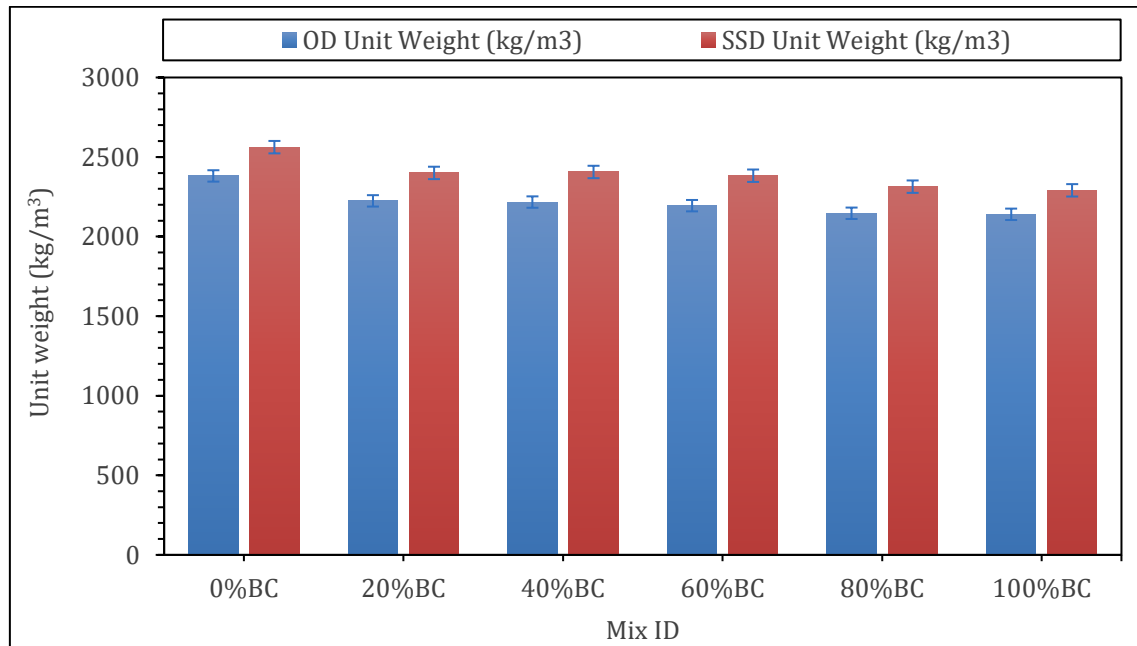


Fig. 13. Comparison between unit weights of various concrete mixes with different percentage replacements.

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.

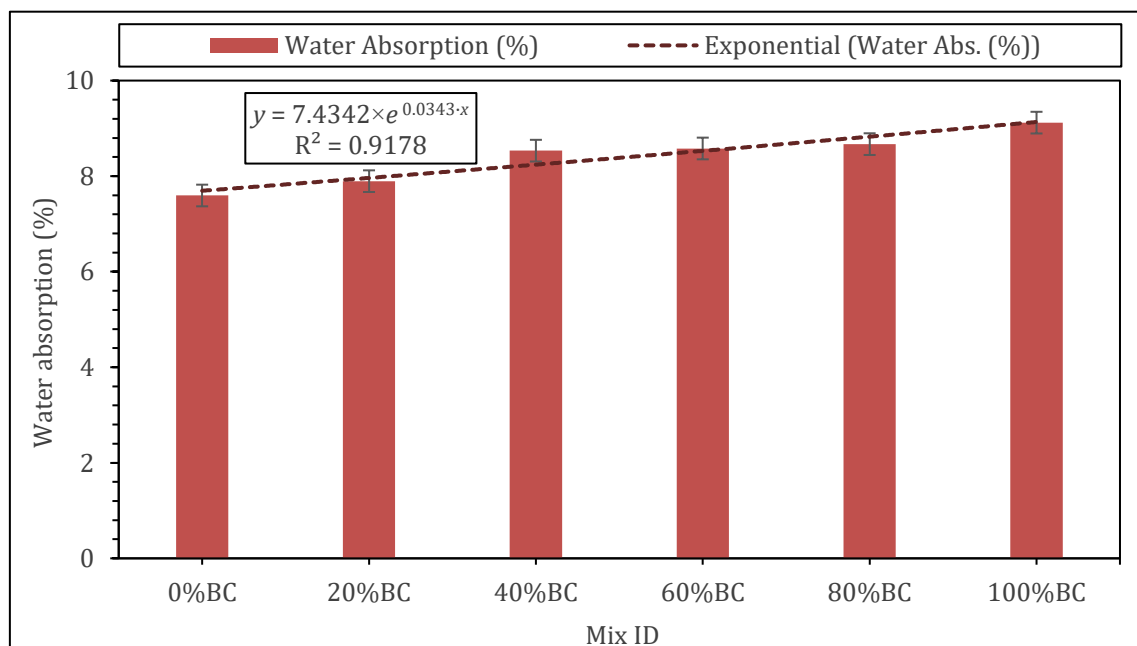


Fig. 14. Water absorption capacity of a concrete specimen with mixed BC proportions.

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.

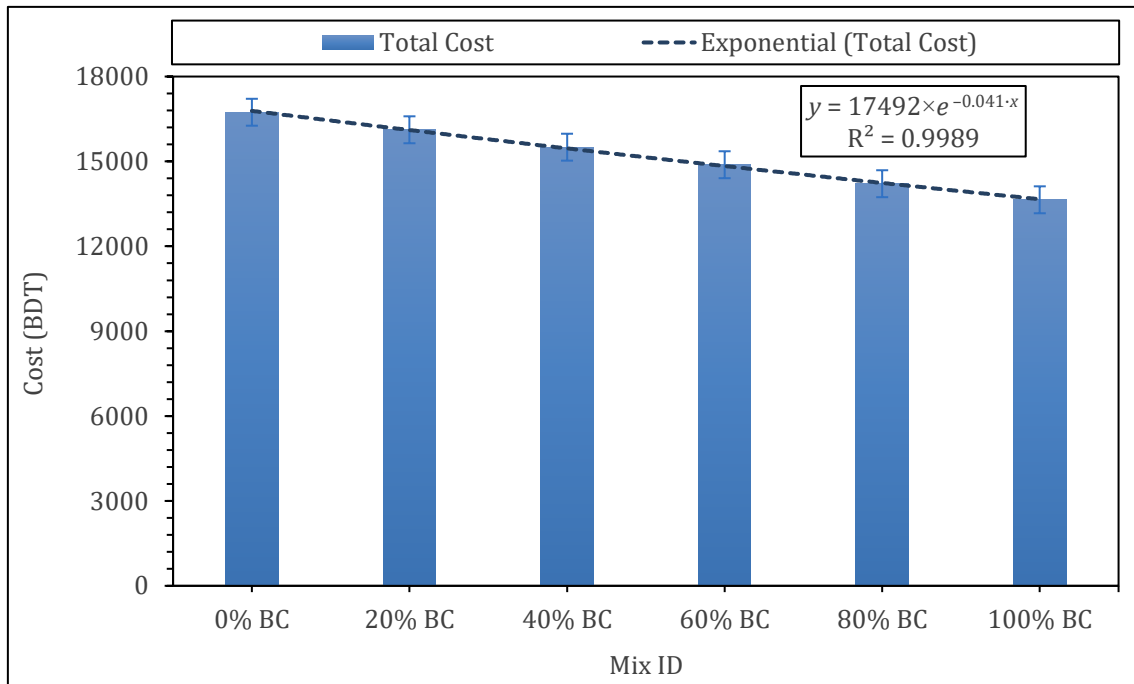


Fig. 15. Comparison between production cost and various BC concrete mixes.

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.

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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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