Challenge Journal of
CONCRETE RESEARCH LETTERS

Research Article

Mechanical properties assessment of recycled brick aggregate concrete using demolition waste from century-old masonry buildings in Nepal

Bipul Niroula [a], Mahesh Raj Bhatt [a,*]

[a] *Department of Civil Engineering, Kathmandu University, 54200 Dhulikhel-Kavre, Nepal*

ABSTRACT

This study explores the potential of recycling bricks from dismantled old buildings into brick aggregates and utilizing them as coarse aggregates in recycled brick aggregate concrete. Nepal, being susceptible to seismic events, generates large amounts of construction debris, with bricks being a major portion of this, which is mainly disposed of through landfilling. Additionally, the increasing use of reinforced cement concrete construction has been significant, which poses a toll on natural aggregate resources, resulting in the depletion of finite resources. To address these issues, this study focuses on recycling bricks as coarse aggregates in concrete. An experimental approach was adopted to determine properties of bricks and concrete ingredients, including cement, sand, brick aggregates, and coarse aggregates. The mechanical and physical properties of concrete, that is, compressive, split-tensile, and flexural strengths were studied by replacing natural coarse aggregates with recycled crushed brick aggregates at different percentages (0%, 10%, 20%, 30%, and 100%), denoted as B0%, B10%, B20%, B30% and B100%, respectively. Meanwhile, ultrasonic pulse velocity was performed to determine the quality of recycled brick aggregate concrete. With respect to the control mix (B0%), percentage decrease in compressive strength, tensile strength, and flexural strength for B10% and B100% are 0.72% and 28.26%, 4.68% and 25.16%, and 2.95% and 7.58%, respectively. From the ultrasonic pulse velocity, all mixes except B100% had excellent quality as per Indian Standards. Results highlight that recycled brick aggregate seems suitable up to 30% replacement, considering the strength decrement in compressive and flexural strengths relative to the control mix.

ARTICLE INFO

Article history:
Received – November 12, 2025
Revision requested – December 9, 2025
Revision received – December 29, 2025
Accepted – January 10, 2026

Keywords:
Recycled brick aggregate concrete
Brick aggregates
Compressive strength
Flexural strength
Ultrasonic pulse velocity
Splitting tensile strength

Citation: Niroula B, Bhatt MR (2026). Mechanical properties assessment of recycled brick aggregate concrete using demolition waste from century-old masonry buildings in Nepal. *Challenge Journal of Concrete Research Letters*, 17(1), 41–56.

1. Introduction

The devastating Gorkha earthquake of 7.6 magnitude occurred on April 25, 2015, followed by a series of aftershocks, including a major 6.8 magnitude aftershock on May 12, 2015 (National Planning Commission 2015). The earthquake resulted in 3.23 million tons of potential debris in the core city area of the Kathmandu Valley, of which 1.07 million tons were cleared, 0.63 mil-lion tons were disposed of on riverbanks and in open spaces, and the remaining 0.44 million tons were salvaged for reuse, recycling, or disposal in isolated areas (Poudel et al. 2019). The debris was further classified, and brick/stone accounted for 74.66% of the total debris (Poudel et al. 2019). Currently, about 82.90% of total houses in Nepal are built with brick/stone bonded in mud or cement mortar for outer walls (Central Bureau of Statistics 2021).

---

* *Corresponding author.* E-mail address: mahesh.bhatt@ku.edu.np (M. R. Bhatt)

ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2026.01.004

Globally, increasing concrete production affects water consumption, natural aggregate use, and cement production. In 2017, the production of natural aggregates was about 45 billion tons, and it was estimated to rise to 65 billion tons by 2025 (De Brito et al. 2019). The construction industry consumes around 40% of global resources, and one third of this is aggregates used in cement-based products (Pacheco-Torgal 2017). In Nepal, based on the number of households, reinforced concrete (RC) buildings have increased tremendously by 63.9% within a span of ten years from 2011 to 2021 (Central Bureau of Statistics 2021). This rapid growth has substantially increased the demand for natural aggregates, resulting in rampant extraction of natural aggregates, degradation of natural landscapes, depletion of finite natural resources, and escalating construction costs. Simultaneously, the disposal of building debris along riverbanks, open spaces, and landfilling has led to land pollution, degradation of the city landscape, a shortage of landfilling areas, and increased landfilling charges (Poudel et al. 2019).

Construction debris, such as concrete, bricks, and stones, is not organic waste and thus cannot decompose naturally (Gyawali 2022). The common practice is disposal by landfilling or dumping it in open spaces, which has a significant impact on the environment and human health. In the United States, recycling one ton of concrete, brick, and block costs approximately $21 per ton, while landfilling costs approximately $136 per ton (Lennon 2005). Recycling such construction debris as aggregates can help preserve finite natural resources, reduce waste, landfill sites, and improve economic efficiency. The first significant use of crushed brick aggregates in new concrete was for reconstruction during the Second World War, while its first documented use dates back to 1860 in Germany, for manufacturing concrete products (Adamson et al. 2015).

Several studies have investigated the mechanical performance of concrete utilizing recycled brick aggregates. De Brito et al. (2005) found a 22% and 45% decrement in compressive strength at 33% and 100% natural aggregate replacement, respectively. Debieb and Kenai (2008) reported a 20% to 35% reduction in strength when both coarse and fine aggregates were replaced with crushed brick aggregates. Cachim (2009) studied the mechanical properties of recycled brick aggregate concrete (RBAC) using bricks from two sources at two water-cement ratios and reported that higher-density brick aggregate yielded better compressive and tensile strengths. Aliabdo et al. (2014) reported increased compressive strength at 25% fine aggregate replacement, while all other mixes resulted in reduced compressive and tensile strength. Bhanbhro et al. (2014) reported a 37% decrease in compressive strength at 100% replacement. Hachemi et al. (2022) found that replacing 20% of both coarse and fine aggregates in concrete improved compressive strength and density. Gyawali (2022) reported an increase in compressive strength when oven-dried brick aggregates at 20% was replaced with natural coarse aggregates. Aboalella and Elmalky (2023) observed increased compressive, tensile, and flexural strength at 50% fine aggregate replacement with crushed brick and 50% coarse aggregate replacement with recycled concrete. Bhatta et al. (2024) found comparable compressive strength to the control mix at 20% replacement, highlighting its potential for construction applications. Basit et al. (2024) studied the structural performance of concrete using recycled concrete aggregates (RCA) and recycled brick aggregates (RBA). Modest decreases in compressive strength were observed when coarse aggregates were replaced, while RCAs showed better bond performance, and 50% natural aggregate replacement showed comparable performance to the control mix in flexure tests. Şamdan et al. (2024) studied the use of crushed brick clay as a replacement for coarse and medium aggregate in concrete at several replacement levels and found that such replacement decreased compressive strength and modulus of elasticity by up to 66%. Poudel et al. (2025) studied on enhancing the mechanical performance of recycled aggregate concrete using glass fibers with fly ash and found that 20% fly ash with 0.5% fibers provided balanced mechanical performance suitable for low-grade structural applications. Bajracharya et al. (2025) explored recycling old concrete as aggregates into concrete. They found that 50% replacement achieved strength comparable to conventional concrete, and also suggested that recycled concrete aggregates are socially, economically, and technically viable based on the sustainability index. Khadka et al. (2025) found a decrease in compressive strength of 34% to 39% when replacing natural coarse aggregates with brick aggregates at 100%, and also developed predictive relationships for concrete compressive strength based on rebound hammer tests.

Although numerous studies have investigated the use of recycled brick aggregates as coarse and fine aggregates in concrete, most have focused on recycled aggregates obtained from relatively recent brick waste. Limited attention has been given to aggregates produced from century-old bricks. Brick aggregates derived from such old bricks may exhibit distinct mechanical and physical characteristics due to prolonged environmental exposure, aging, and material degradation. This study experimentally evaluates the mechanical properties of recycled brick aggregate concrete (RBAC) produced using brick aggregates derived from a dismantled century-old masonry building as a partial to full replacement of natural coarse aggregates. The experimental program was conducted using M20 grade concrete, where M represents the mix and the following number 20 represents the specified compressive strength in MPa measured on a 150 mm cube. The M20 grade concrete was selected because it is widely used in Nepal for low-rise residential and other structures, and represents the minimum standard for reinforced concrete construction under Indian Standards.

The novelty of this research lies in the utilization of brick aggregates derived from century-old bricks exposed to long-term environmental exposure and aging, while comparing the properties of brick, brick aggregates, and recycled concrete with properties of modern and historic bricks from existing literature. Furthermore, the study compares aggregate-level quality indicators in relation to concrete performance and examines the feasibility of partial replacement of natural coarse aggregates under material constraints relevant to developing countries. This research is particularly relevant in the Nepalese context, where bricks have been historically used in structures such as load-bearing masonry buildings, arch bridges, and partition walls. With aging infrastructure, seismic vulnerability, and ongoing expansion projects such as highway widening, large values of historic brick masonry are expected to be dismantled or demolished; however, systematic disposal or recycling practices remain largely absent.

2. Experimental Program

The experimental program comprised testing five concrete mixes with different percentages of recycled crushed brick aggregates, ranging from partial to full replacements of natural coarse aggregates. The replacement levels considered were 0%, 10%, 20%, 30%, and 100%, designated as B0% (control mix), B10%, B20%, B30%, and B100%, respectively. A total of 55 specimens were cast to evaluate compressive strength, splitting tensile strength, and flexural strength tests. Physical and mechanical tests of the constituent materials of concrete were also conducted and subsequently used for the design mix of concrete mixes. All experiments and tests in this study were carried out in accordance with Indian Standards (IS) at the Material Testing Laboratory of Kathmandu University, Dhulikhel, Nepal, and Nepal Engineering Lab Pvt. Ltd., Banepa, Nepal.

2.1. Materials

Ordinary Portland Cement (OPC) of 43 grade, with a specific gravity of 3.06, was used for the preparation of all concrete specimens. Physical tests for hydraulic cement were performed as per IS 4031 (Part 1) (1996), IS 4031 (Part 4) (1988), and IS 4031 (Part 11) (1988). The results from various tests performed on cement are presented in Table 1.

Table 1. Properties of cement.

Properties	Results	IS 4031 limits (parts 1, 4, and 11)
Specific gravity	3.06	–
Consistency	32%	–
Fineness	0.80%	< 10%

A well-graded sand passing a 4.75 mm sieve has been used as fine aggregate for the preparation of concrete. Tests for water absorption and specific gravity were performed as per IS 2386 (Part 3) (1963), while sieve analysis was carried out following IS 2386 (Part 1) (1963). The sand conformed to zone II and satisfied the grade limits conforming to IS 383 (2016). The results of physical tests of natural fine aggregate are tabulated in Table 6, while the particle size distribution and particle size distribution curve are presented in Table 2 and Fig. 1.

Table 2. Particle size distribution of natural fine aggregate (NFA).

Sieve size (mm)	% Passing	IS 383 (2016) limits (% passing)
4.75	100	90–100
2.36	86	75–100
1.18	74	55–90
0.60	54	35–59
0.30	26	8–30
0.15	9	0–10

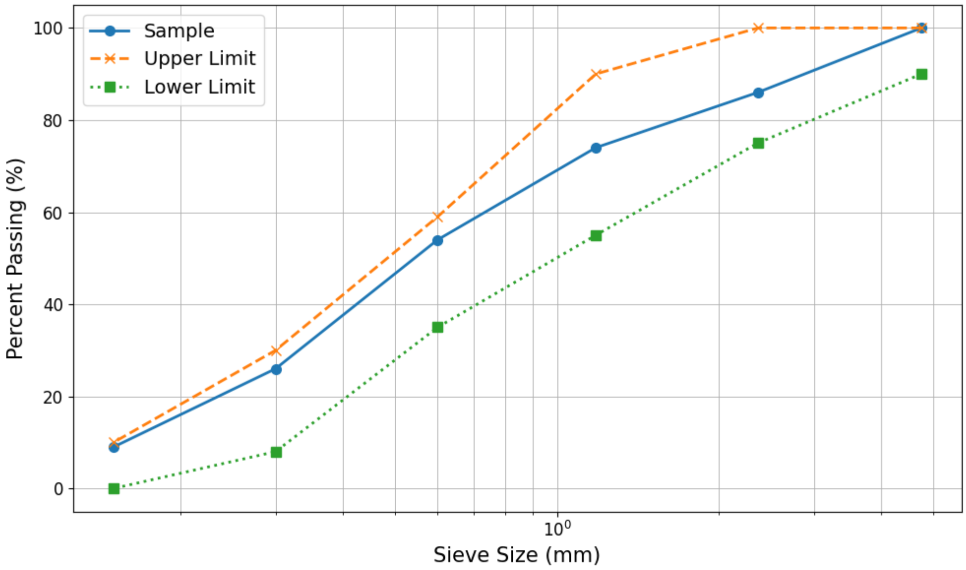

Fig. 1. Particle size distribution curve for natural fine aggregates.

Both natural coarse aggregates (NCA) and recycled crushed brick aggregates (RCBA) were tested for specific gravity, water absorption, Los Angeles abrasion value (LAAV), and aggregate impact value (AIV). Brick aggregates were prepared by manually crushing bricks from a dismantled century-old masonry building located at Sangha, Kabhrepalanchok, Nepal. The preparation process of brick aggregate is illustrated in Fig. 2.

The century-old masonry building from which the bricks were collected and subsequently crushed into brick aggregates is shown in Fig. 3.

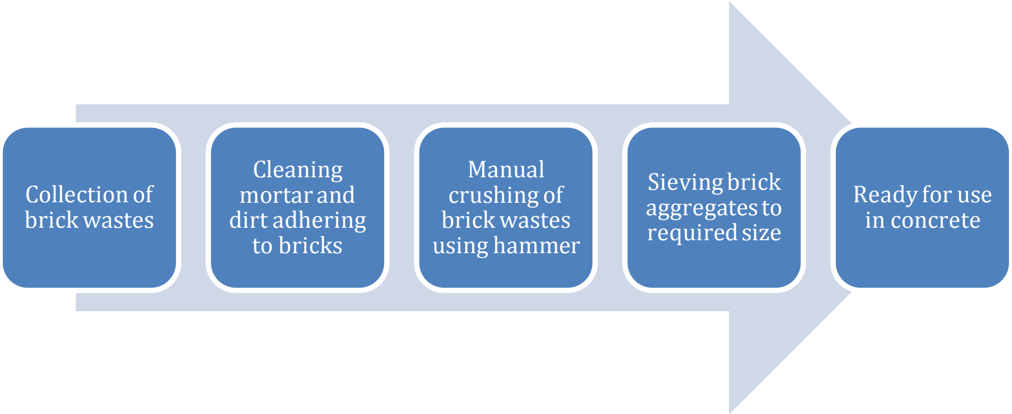

Fig. 2. Preparation process of brick aggregate.

Fig. 3. Collection of bricks and brick aggregates: (a) Century-old brick masonry building located at Sangha, Kabhrepalanchok, Nepal; (b) Dismantled brick from masonry building; (c) Crushed brick aggregates prepared in laboratory.

The specific gravity and water absorption tests were carried out following IS 2386 (Part 3) (1963), while the Los Angeles abrasion test and aggregate impact value test were performed as per IS 2386 (Part 4) (1963). The sieve analysis was conducted following IS 2386 (Part 1) (1963). Both NCA and RCBA were well graded as per IS 383 (2016). The Los Angeles abrasion value (LAAV) and aggregate impact value (AIV) of NCA were within the permissible limits for concrete applications in non-wearing surface (LAAV ≤ 45% and AIV ≤ 50%), whereas RCBA exhibited values exceeding the limits specified in IS 383 (2016). The particle size distributions of NCA and RCBA are presented in Tables 3 and 4. The particle size distribution curve for NCA and RCBA is shown in Fig. 4.

The results from the physical and mechanical tests of the aggregates are compared in Table 5.

The bricks used for the preparation of brick aggregates were approximately a century old, as confirmed by local residents. These bricks were salvaged from a dismantled masonry building constructed using mud mortar. Adhered mud mortar was scraped off and cleaned before crushing the bricks into aggregates. The physical and mechanical properties of the bricks were determined in accordance with IS 1077 (1992), and the test results are summarized in Table 6.

Table 3. Particle size distribution of natural coarse aggregate (NCA).

Sieve size (mm)	% Passing	IS 383 (2016) limits (% passing)
20	100	90–100
10	25	25–55
4.75	1	0–10

Table 4. Particle size distribution of recycled crushed brick aggregate (RCBA).

Sieve size (mm)	% Passing	IS 383 (2016) limits (% passing)
20	100	90–100
10	29	25–55
4.75	1	0–10

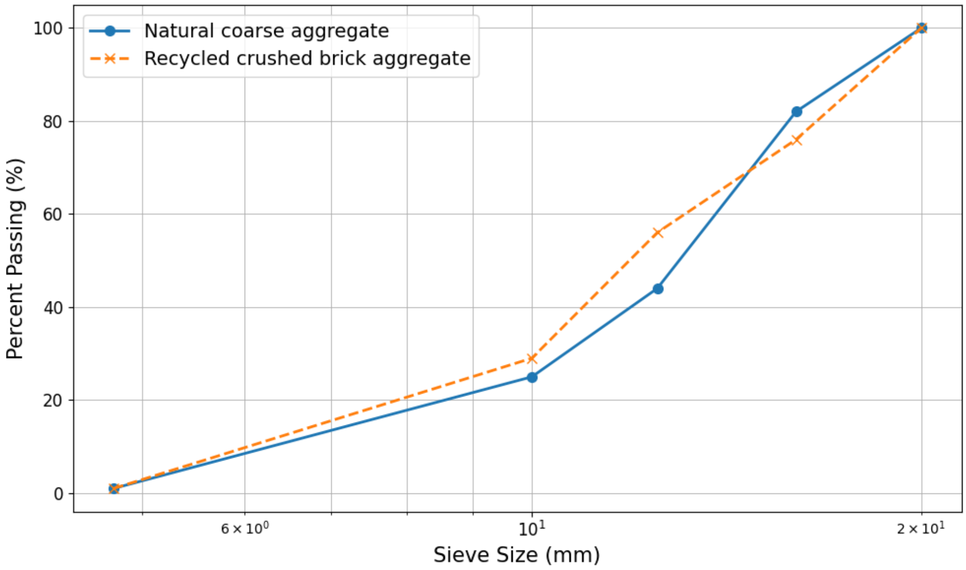

Fig. 4. Particle size distribution curve for natural coarse aggregates and recycled crushed brick aggregate.

Table 5. Test results of aggregates.

Materials	Specific gravity	Water absorption	Open porosity	Apparent density (kg/m³)	Los-Angeles abrasion value	Aggregate impact value
Natural fine aggregate	2.62	1.00%	–	2623.02	–	–
Natural coarse aggregate	2.71	0.60%	1.63%	2702.48	35.60%	15.04%
Recycled crushed brick aggregate	1.61	15.25%	28.94%	2219.46	59.20%	52.94%

Table 6. Experimental results for properties of bricks.

Description	Values
Water absorption (%)	19.51
Apparent porosity (%)	31.12
Bulk dry density (kg/m³)	1597.17
Compressive strength (N/mm²)	4.41
Ultrasonic pulse velocity (UPV) (m/s)	1363.91

2.2. Mix design and preparation

The concrete mix design consisted of five mixes at varying levels of RCBA replacement as coarse aggregate in M20 grade concrete with a water-cement ratio (W/C) of 0.5. The mixes included B0% (control mix), B10%, B20%, B30%, and B100% at 10%, 20%, 30%, and 100% replacement of natural coarse aggregates with recycled crushed brick aggregates by weight, respectively. Mix design calculations were performed following IS 10262 (2019), and the details are presented in Table 7.

Table 7. Proportioning of materials as per the mix design.

Concrete mix	B0%	B10%	B20%	B30%	B100%
Cement (kg/m³)	383	383	383	383	383
Water (kg/m³)	191.58	191.58	191.58	191.58	191.58
Total water-cement ratio	0.535	0.534	0.532	0.53	0.518
Effective water-cement ratio	0.5	0.5	0.5	0.5	0.5
Natural fine aggregate in SSD (kg/m³)	689.58	689.58	689.58	689.58	689.58
Natural coarse aggregate in SSD (kg/m³)	1115.63	1004.07	892.5	780.94	0
Recycled crushed brick aggregate in SSD (kg/m³)	0	66.28	132.56	198.84	662.79

SSD = Saturated Surface Dry

All mixes were prepared with a constant cement content of 383 kg/m³ and designed to achieve a slump of 75 mm, corresponding to medium workability commonly adopted in general construction practice.

To address workability issues, natural fine aggregates (NFA) and natural coarse aggregates (NCA) were washed and oven-dried at 105 ˚C for 24 hours. The additional water required to reach saturated surface dry conditions for NFA and NCA was added during mixing. RCBA was pre-soaked for 2 hours and then dried to saturated surface dry (SSD) condition before mixing. This procedure was adopted to prevent the highly porous RCBA from absorbing water required for the hydration of cement. The pre-wetting duration of 2 hours was selected because RCBA absorbs most of the water during the initial few minutes. The additional water required was calculated based on the water absorption of the coarse and fine aggregates. Consequently, the effective water-cement ratio was maintained at 0.5 while the total water-cement ratio varied from 0.518 to 0.535 depending on the replacement percentage. The total water-cement ratio excludes the water required for pre-saturation of brick aggregates. Preparation of materials, mixing, casting, and curing of concrete for all mixes are illustrated in Fig. 5.

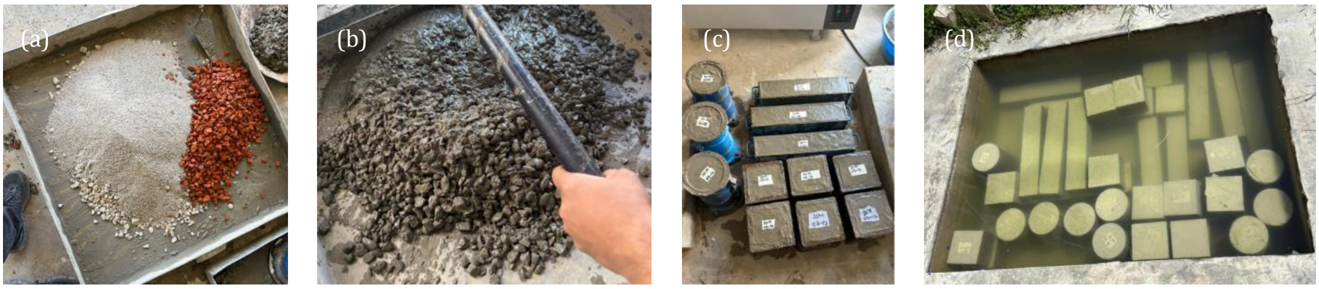

Fig. 5. Preparation process of concrete: (a) Preparation of materials; (b) Mixing of concrete; (c) Casting of concrete specimens; (d) Curing of concrete specimens.

2.3. Test specimens and procedure

Concrete cubes of dimensions 150 mm x 150 mm x 150 mm were cast for compressive strength testing, while cylindrical specimens of 150 mm diameter and 300 mm height were used for splitting tensile strength tests. Similarly, beam specimens measuring 500 mm x 100 mm x 100 mm were cast to evaluate the flexural strength of concrete. Batching, mixing, and casting were done in accordance with relevant Indian Standards. After casting, the concrete specimens were demolded after 24 hours and cured by immersion in a curing pond at a temperature of 23 ± 2 ˚C until the time of testing. All mechanical tests were conducted at 28 days in accordance with IS 516 (Part I/Sec 1) (2021). The tests were performed on calibration-certified testing machines, and the alignment of loading platens was also checked before testing. Error bars were calculated based on the standard deviation obtained from the total number of specimens tested for each mix. Furthermore, the variability of test results was assessed using the coefficient of variation (CoV), calculated as the ratio of standard deviation to mean value. The number of specimens for each mix complied with IS 456 (2000), which specifies a minimum of three specimens per sample, and the number of specimens per mix used in this study is consistent with investigations on recycled brick aggregate concrete (De Brito et al. 2005; Adamson et al. 2015). The number of specimens prepared for each mix and for different testing is shown in Table 8.

2.4. Non-destructive test

Ultrasonic pulse velocity (UPV) test was conducted on concrete cubes before compression strength testing at 28 days. The tests were performed using the direct transmission method on the cubes in SSD conditions, approximately one hour after removal from the curing pond. The time taken by the pulse to travel through the cube was measured. The ultrasonic pulse velocity was calculated by dividing the travel path length by the measured time. The device used for the UPV test was RTUL UX460X, and the calibration of the device was done by observing the time required for the pulse to travel through a standard prism of known time. The UPV was compared against the limits specified by IS 516 (Part 5/Sec 1) (2018) to determine the quality of the concrete. The direct method of the ultrasonic pulse velocity test performed on a concrete cube is shown in Fig. 6.

Table 8. Number of experimental specimens prepared.

	Number of specimens		
	Concrete cubes	Concrete cylinders	Concrete beams
B0% (control mix)	5	3	3
B10%	5	3	3
B20%	6	3	3
B30%	6	3	3
B100%	3	3	3
Total	25	15	15

Fig. 6. Ultrasonic pulse velocity test on a concrete cube using the direct method.

3. Results and Discussion

3.1. Bricks and brick aggregates

The bricks used in this study were collected from a century-old dismantled masonry building and subsequently crushed to produce recycled crushed brick aggregates. The bricks exhibited an average compressive strength of 4.41 MPa and a water absorption of 19.51%. According to IS 1077 (1992), these bricks can be classified as Class 3.5 bricks based on their compressive strength and water absorption. The UPV of the century-old bricks was evaluated against the quality assessment criteria for burnt clay bricks by Azam et al. (2022). The measured pulse velocity was below 2000 m/s, indicating poor brick quality and further corroborating the classification based on mechanical properties.

The physical and mechanical properties of the century-old bricks used in this study are consistent with those reported for historic and ancient bricks in the literature. Studies on historic bricks in Nepal have reported dry density values ranging from 1.2 to 1.8 g/cm^3, water absorption of 10 to 28%, apparent porosity of 17 to 33%, and compressive strength of 3.49 to 26.9 MPa (Parajuli 2012; Parajuli et al. 2020; Bhattarai et al. 2018). Similarly, studies on modern bricks in Nepal have reported dry density values of 1.1 to 2.82 g/cm^3, water absorption of 5 to 30%, apparent porosity of 10 to 53.99%, and compressive strength of 3.35 to 23.49 MPa (Chapagain et al. 2020; Bohara et al. 2020; Subedi 2020; Shrestha, 2019; Khanal and Paudel, 2023; Thapaliya et al. 2024).

A comparative summary of physical and mechanical properties for modern bricks, old bricks, and bricks used in this study is presented in Table 9.

Table 9. Physical and mechanical properties of modern and old bricks of Nepal.

Author	Water absorption (%)	Compressive strength (MPa)	Apparent porosity (%)	Dry density (g/cm^3)	Remarks
Parajuli (2012)	–	11.03	–	1.77	Historical bricks from Patan Durbar Square
Bhattarai et al. (2018)	10 to 28%	5.00 to 23.00	17 to 33%	1.2 to 1.8	Ancient brick of Nepal
Shrestha (2019)	8.8 to 23.93%	7.83 to 22.1	19.28 to 53.99%	1.55 to 2.82	Modern bricks
Bohara et al. (2020)	11 to 23%	15.6 to 17.1	19 to 37%	1.5 to 1.65	Modern bricks
Chapagain et al. (2020)	5 to 30%	3.35 to 10.53	10 to 40%	1.1 to 2.15	Modern bricks
Subedi (2020)	4 to 12%	3.72 to 20.16	-	1.34 to 1.82	Modern bricks
Parajuli et al. (2020)	13 to 18%	3.49 to 26.90	–	–	Historical bricks from Shreemahal and Singhadurbar
Khanal and Paudel (2023)	9.36 to 16.89%	7.02 to 23.49	18.25 to 27.95	1.65 to 1.949	Modern bricks
Thapaliya et al. (2024)	6 to 25%	8.6 to 15		1 to 2	Modern bricks
This study	19.51%	4.41	31.12%	1.6	Century-old brick

The physical and mechanical properties of recycled crushed brick aggregates (RCBA) were further compared with those reported in previous studies (Debieb and Kenai 2008; Aliabdo et al. 2014; Gyawali 2022; Hachemi et al. 2022; Cachim 2009; Adamson et al. 2015). These studies reported water absorption values ranging from 1.79 to 20%, specific gravity from 2.04 to 2.40, porosity from 9.5 to 38.82%, and Los Angeles abrasion values between 30.06 to 31.6%.

In contrast, the RCBA used in this study exhibited a lower specific gravity of 1.61, which can be attributed to the high porosity and lower density of century-old bricks from which the aggregates were derived. Although the water absorption and porosity values of RCBA were within the ranges reported in previous studies, they were relatively higher than those of NCA. The Los Angeles abrasion value of RCBA was higher and exceeded the limits specified by IS 383 (2016), indicating lower abrasion resistance.

Overall, the physico-mechanical behavior of the old bricks used in this study aligns closely with that of historic bricks and also falls within the broad range of properties reported for modern bricks, albeit toward the lower strength and higher porosity. The origin of these properties differs, as the characteristics of century-old bricks are primarily influenced by long-term aging, environmental exposure, and material degradation rather than a controlled manufacturing process for modern bricks. These factors likely contributed to the lower density, higher water absorption, higher porosity, reduced abrasion resistance, and impact resistance observed in the RCBA used in this study as compared to natural coarse aggregates.

3.2. Density of concrete

The density of concrete was determined by measuring the mass of each cube and dividing it by its volume. The density of the recycled brick aggregate concrete (RBAC) decreased with increasing brick aggregate replacement levels. The maximum reduction in density was 13.24% for B100% mix compared to the control mix. This decreasing trend is consistent with the findings reported by De Brito et al. (2005) and Bhanbhro et al. (2014), who observed density reductions of 9.18% and 16%, at 100% replacement, respectively.

The decrement in density is primarily attributed to the lower specific gravity of brick aggregates compared to natural coarse aggregates, resulting in a relatively lighter concrete. The average density values and corresponding coefficient of variation are presented in Table 10. The CoV values ranged from 0.58% to 1.07%, indicating excellent uniformity of the concrete specimens. The density variation across different mixes with error bars is illustrated in Fig. 7.

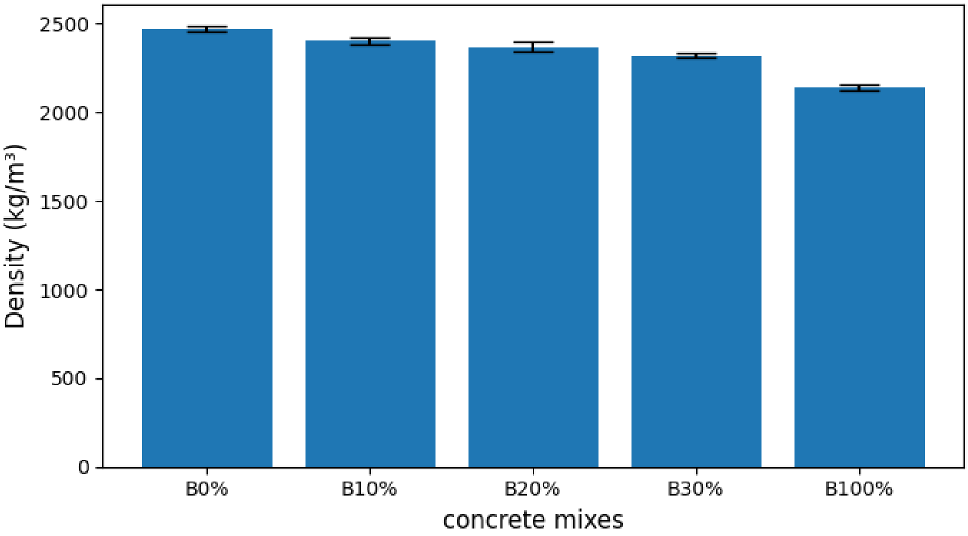

Fig. 7. Density values of various concrete mixes at 28 days.

3.3. Compressive strength

The compressive strength was determined from the peak load at failure, and crack patterns were also observed. The control mix (B0%) exhibited the highest compressive strength, while the strength decreased with increasing RCBA replacement. The reduction in compressive strength relative to the control mix were 0.72%, 3.27%, 5.99%, and 28.26% at 10%, 20%, 30%, and 100% replacement, respectively. The reduction in compressive strength with the increasing replacement percentage is consistent with the findings of previous studies (Debieb and Kenai 2008; Aliabdo et al. 2014; Bhanbhro et al. 2014).

The reduction in compressive strength can be attributed to the replacement of NCA with RCBA, which possesses lower density, higher water absorption, and microcracking induced during crushing. These characteristics lead to a weaker aggregate skeleton and a heterogeneous interfacial transition zone (ITZ) as reported by Silva et al. (2014). Under compressive loading, brick aggregates act as stress concentrators, promoting crack initiation and propagation at the aggregate-paste interface rather than through the cement matrix (Xiao et al. 2012; Silva et al. 2014). At lower replacement levels, brick aggregates are distributed discontinuously within the concrete matrix, which limits the crack connectivity and allows load transfers to be governed predominantly by NCA and hydrated cement paste. This explains the relatively small reduction in compressive strength observed at partial replacement levels, whereas the pronounced loss of strength at 100% replacement is attributed to the formation of a continuous weak aggregate-paste network.

The average compressive strength values and corresponding CoV are presented in Table 10, while Fig. 8 shows the compressive strength results with error bars.

The compressive strength was evaluated as the average of at least three specimens for each concrete mix, or based on the number of specimens indicated in Table 8. In accordance with IS 516 (Part 1/Sec 1) (2021), test results deviating more than ± 15% from the mean compressive strength were treated as outliers and excluded from analysis. One outlier was identified in both B10% and B20% mixes. The standard deviation for mixes B0% to B100% were 1.22, 1.74, 1.54, 2.08, and 0.4, all of which are smaller than the standard deviation value of 4 specified for M20 concrete. The CoV values ranged from 2.22% to 8.86%, indicating low variability and good repeatability of test results after exclusion of outliers.

The failure patterns of the cubes were examined visually, and the Fig. 9 illustrates the observed failure for different concrete mixes. Failure was mostly due to the formation of vertical cracks resulting from laterally induced tensile stress perpendicular to the applied compressive load. Cone-shaped failure was also observed in a limited number of specimens. Overall, the failure behavior was satisfactory as specified in IS 516 (Part 1/Sec 1) (2021).

Table 10. Average values for physical and mechanical properties of concrete with their CoVs.

Concrete mix	Density (kg/m³)	CoV	Compressive strength (MPa)	CoV	Splitting tensile strength (MPa)	CoV	Flexural strength (MPa)	CoV	UPV (m/s)	CoV
B0%	2467.79	0.67	25.05	4.88	2.92	2.14	4.13	6.43	4429.11	1.12
B10%	2404.03	0.80	24.51	7.10	2.79	2.05	3.99	0.68	4152.17	1.30
B20%	2369.58	1.07	24.23	6.37	2.69	1.85	3.95	3.28	4083.14	1.38
B30%	2319.31	0.58	23.55	8.86	2.61	3.17	3.87	1.06	4046.92	0.85
B100%	2141.04	0.65	17.97	2.22	2.19	1.14	3.70	0.88	3655.69	0.28

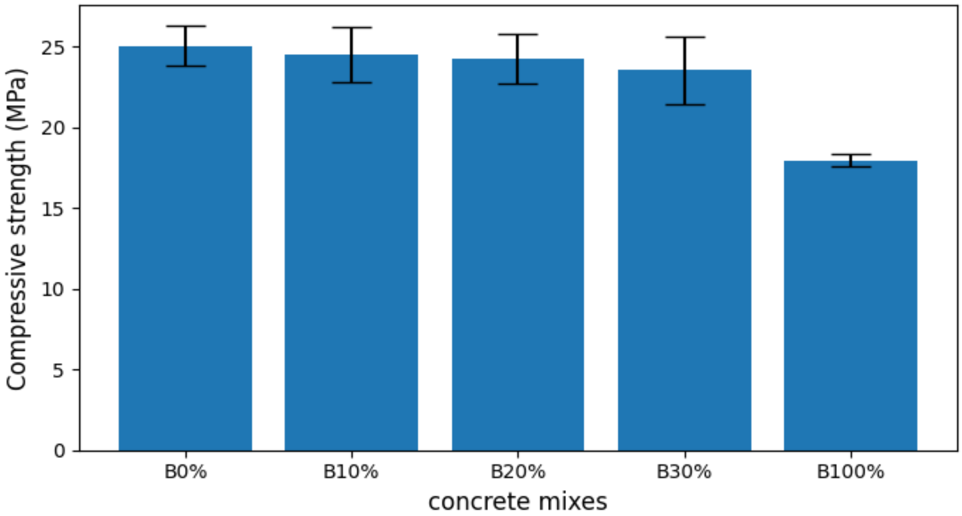

Fig. 8. Compressive strength values of various concrete mixes at 28 days.

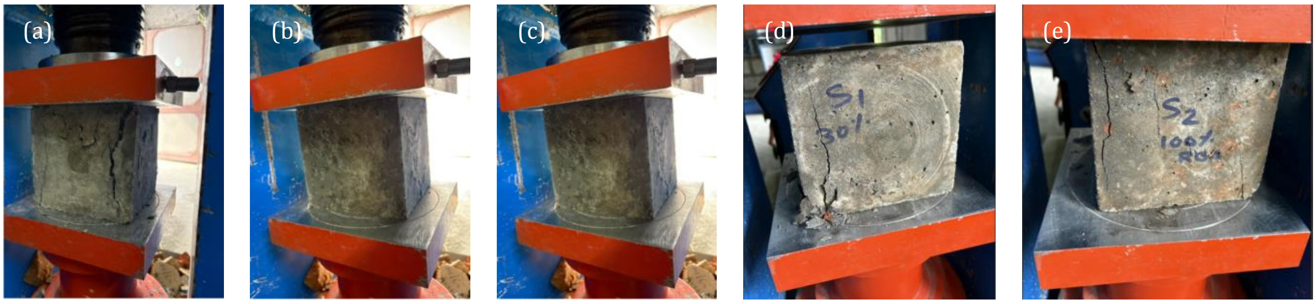

Fig. 9. Typical failure of cubes at different replacement percentages: (a) 0%; (b) 10%; (c) 20%; (d)30%; (e)100%.

3.4. Splitting tensile strength

The splitting tensile strength test of concrete was performed as per IS 516 (Part I/Sec 1) (2021), in which the load was applied to the cylindrical surface radially. The control mix (B0%) exhibited the highest tensile strength, and the tensile strength decreased with an increase in the brick aggregates replacement levels. The decrement in tensile strength relative to the control mix at 10%, 20%, 30%, and 100% replacements were 4.68%, 8.06%, 10.65% and 25.16%, respectively. This decreasing trend of tensile strength is similar to compressive strength and agrees with the findings of Aliabdo et al. (2014), who reported a reduction in tensile strength with increasing RCBA replacement percentage.

The average tensile strength values and their corresponding coefficient of variation are presented in Table 10. Furthermore, the splitting tensile strength results exhibited very low variability, with CoV values ranging from 1.14% to 3.17%, indicating excellent repeatability of experimental results. The tensile strength for various concrete mixes with error bars is presented in Fig. 10.

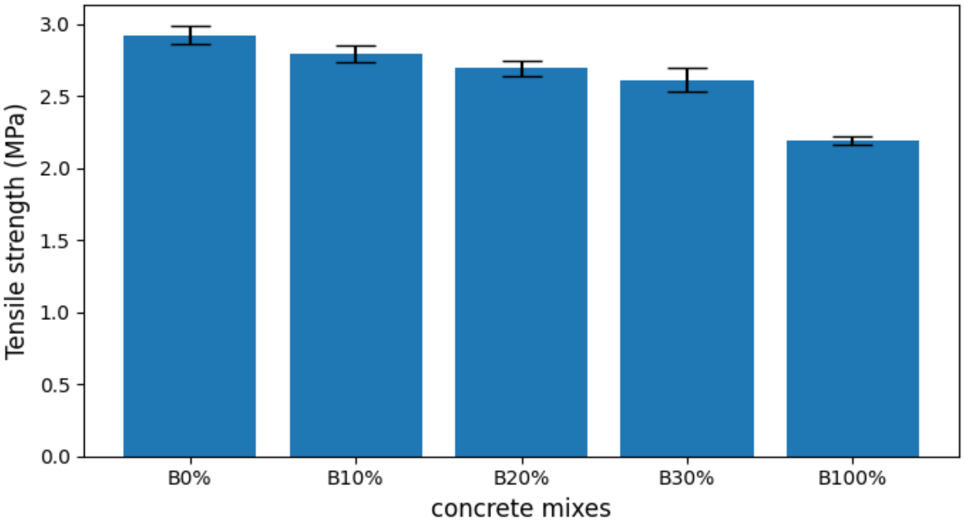

Fig. 10. Splitting tensile strength values of various concrete mixes at 28 days.

The failure was governed by the development of lateral tensile stresses perpendicular to the applied compressive load. This initiated the crack along the loading line, which propagated through the cylinder, resulting in a sudden, brittle failure once the tensile strength of concrete was exceeded. The specimens were split into two halves along the longitudinal axis, as shown in Fig. 11.

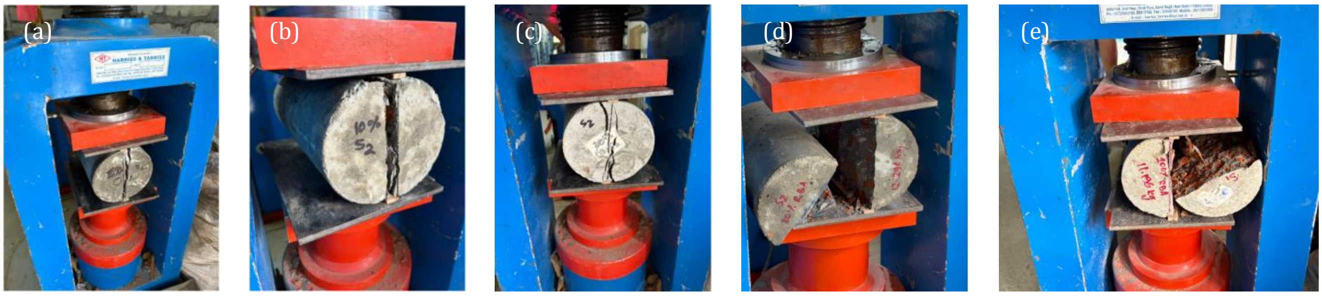

Fig. 11. Typical failure of cylinders at different replacement percentages: (a) 0%; (b) 10%; (c) 20%; (d)30%; (e)100%.

3.5. Flexural strength

Plain cement concrete beams with dimensions 500 x 100 x 100 mm were tested at 28 days to determine the modulus of rupture (MOR) as per IS 516 (Part 1/Sec 1) (2021). A four-point bending test was employed, in which the load was applied through two points at the top, while two supports were provided at the bottom. The B0% mix showed the highest modulus of rupture; however, all concrete mixes exhibited higher experimentally obtained MOR values higher than those calculated using the empirical relationship in IS 456 (2000). The decrease in flexural strength as compared to the control mix at 10%, 20%, 30%, and 100% replacements were 2.95%, 4.42%, 6.32% and 7.58%, respectively. This reduction in flexural strength is similar to the declining trend of compressive strength, where strength decreases with an increase in aggregate replacement percentage and aligns with the findings of De Brito et al. (2005).

The average flexural strength values and the corresponding coefficient of variation are presented in Table 10. The results showed low variability, with CoV values ranging from 0.68% to 6.43%, indicating good to excellent repeatability of experimental data. The flexural strength results with error bars is illustrated in Fig. 12.

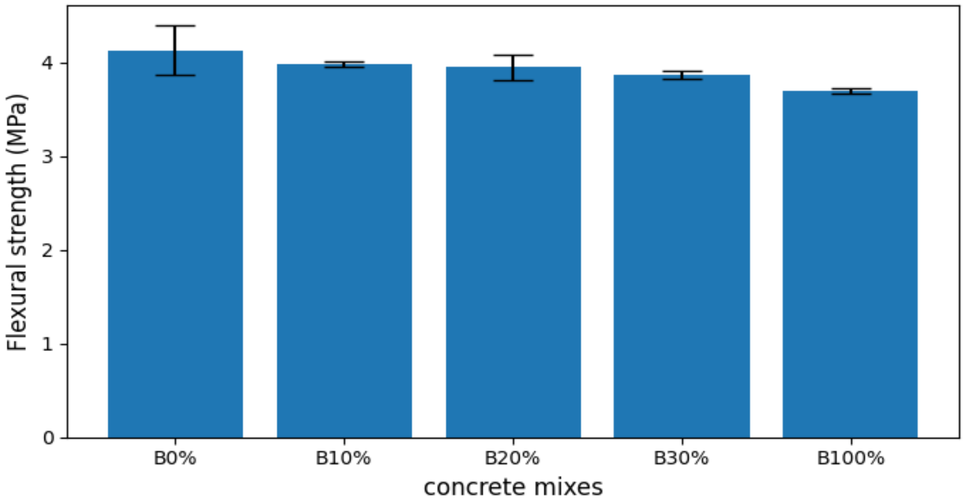

Fig. 12. Flexural tensile strength values of various concrete mixes at 28 days.

Failure of the beams occurred due to the development of flexure cracks parallel to the direction of loading. Cracks initiated from the bottom face and propagated toward the top of the beam. For all concrete mixes, failure was observed in the central region of the beam, and was found to be satisfactory as per IS 516 (Part 1/Sec 1) (2021). The observed failure patterns are presented in Fig. 13.

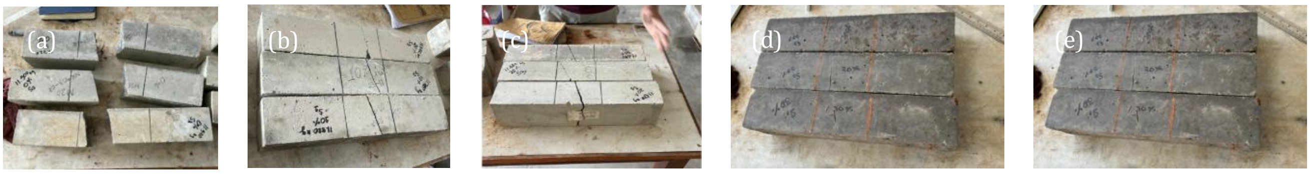

Fig. 13. Typical failure of beams at different replacement percentages: (a) 0%; (b) 10%; (c) 20%; (d)30%; (e)100%.

Fig. 14 illustrates the failure modes of concrete cubes, cylinders, and beams in compression, indirect tension, and flexure, respectively. The post-failure cross-sections of the specimens reveal the distribution of brick aggregates within the concrete matrix.

Fig. 14. Failure of different concrete specimens showing cross-section:
(a) Cubes of B30%; (b) Cylinders of B30%; (c) Cylinders of B100%; (d) Beams of B100%.

3.6. Strength index

Strength index was developed to quantify the contribution of natural coarse aggregates and brick aggregates to the overall strength of concrete, following an approach similar to Cachim (2009). The specific strength ratio, *R*, is given by:

$$R = \frac{f}{q} \tag{1}$$

where *f* is the compressive strength of concrete in MPa, while *q* denotes the quantity of natural coarse aggregate in percentage. The parameter R_n represents the contribution of natural coarse aggregates to overall strength and is the specific strength ratio of concrete with natural coarse aggregates only.

The parameter R_b expresses the contribution of unit natural coarse aggregates to the strength of concrete. $R_n = R_b$ when $q = 100\%$, while R_r is the contribution of brick aggregates to overall strength:

$$R_r = R_b - R_a \tag{2}$$

The specific strength ratio, *K*, is:

$$K = \frac{R_b}{R_n} \tag{3}$$

which is greater than 1 if the reduction in strength is less than the percentage of natural aggregates replaced. Additionally, *P* represents the contribution of brick aggregates to the overall strength of concrete in percentage and is defined as:

$$P = \frac{100R_r}{R_b} \tag{4}$$

The *P* value implies that if it is greater than the amount of aggregate replaced, then it signifies a positive contribution of brick aggregate to overall strength. The strength index developed for concrete cubes tested in compression at 28 days is presented in Table 11. A slight reduction (0.65%) in the contribution of brick aggregate to overall strength at 10% replacement. This contribution of brick aggregates has further decreased with an increase in brick aggregate replacement percentage, as observed for B20% and B30% mixes.

Table 11. Strength Index based on compressive strength.

Concrete mixes	*q*	*f*	R_b	R_r	*K*	*P*
B0%	100	25.05	0.25	0	1	0
B10%	90	24.87	0.28	0.03	1.10	9.35
B20%	80	24.23	0.30	0.05	1.21	17.29
B30%	70	23.55	0.34	0.09	1.34	25.54

3.7. Ultrasonic pulse velocity

The UPV decreased with increasing brick aggregate replacement, while the control mix (B0%) exhibited the highest UPV values. The UPV values were further used to assess the quality of RBAC. According to the limits specified by IS 516 (Part 5/Sec 1) (2018), all concrete mixes except B100% exhibited excellent concrete quality (UPV > 4000 m/s), whereas B100% mix showed doubtful quality (UPV = 3000 m/s to 3750 m/s). As the proportion of brick aggregates increased, the UPV has decreased, which is in agreement with the findings reported by Rao (2018) and Hachemi et al. (2022).

This decrement in UPV is attributed to the higher porosity of RCBA compared to NCA. This increased porosity resulted in greater scattering and attenuation of ultrasonic waves, leading to longer travel times and lower UPV. This trend indicates that increasing brick aggregate content results in reduced concrete density, which is associated with lower compressive strength and degradation in overall concrete quality. Table 10 presents the average UPV values with their coefficient of variation. The CoV for UPV tests ranged from 0.285% to 1.379%, indicating a low variability of results. The UPV for different concrete mixes with error bars are presented in Fig. 15.

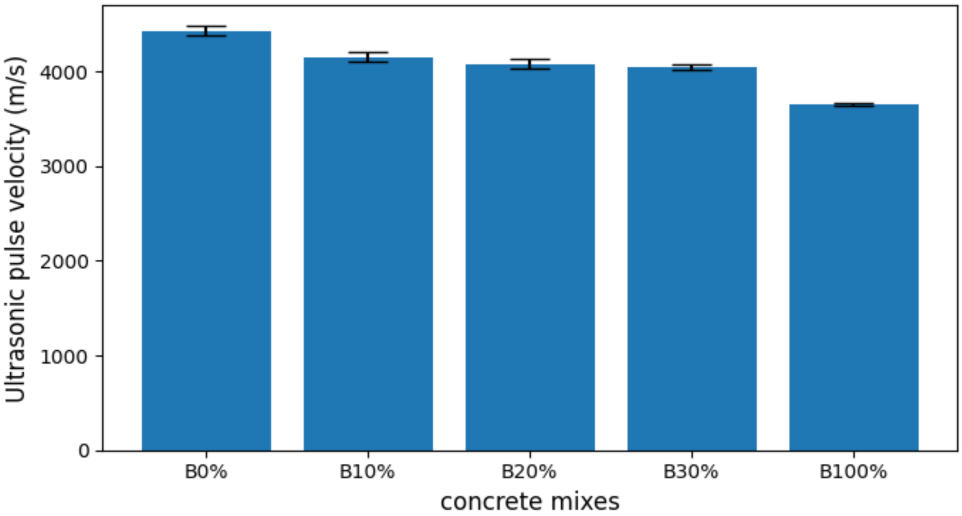

Fig. 15. UPV values of various concrete mixes at 28 days.

3.8. Relationship between physical and mechanical properties of concrete

The results from the experimental test of RBAC were plotted against the density, and linear regression analysis was performed to quantify the influence of density on the mechanical strengths of concrete. Fig. 16 illustrates the relationship between density and strength properties of RBAC. The coefficients of determination (R^2) obtained were 0.93, 0.99, and 0.96 for density versus compressive strength, splitting tensile strength, and flexural strength, respectively. These high R^2 values indicate a strong positive correlation between density and mechanical properties, demonstrating that an increase in density leads to improved mechanical performance of RBAC.

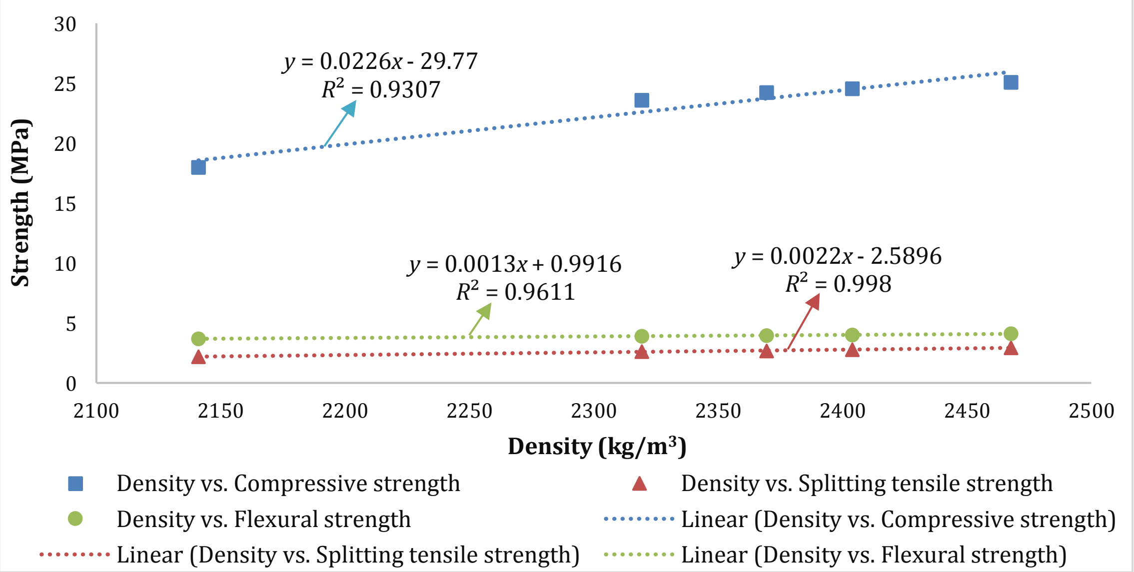

Fig. 16. Relationship between density and strength properties of RBAC.

Similarly, linear regression analysis was conducted to establish relationships among the mechanical properties themselves. Fig. 17 presents the correlation between compressive, splitting and flexural strength of recycled brick aggregate concrete. The coefficients of determination (R^2) were 0.94 for splitting tensile strength versus compressive strength and 0.80 for flexural strength versus compressive strength, respectively. These values indicate a significant correlation between the mechanical properties of recycled concrete, confirming that compressive strength increases with increasing splitting tensile and flexural strengths.

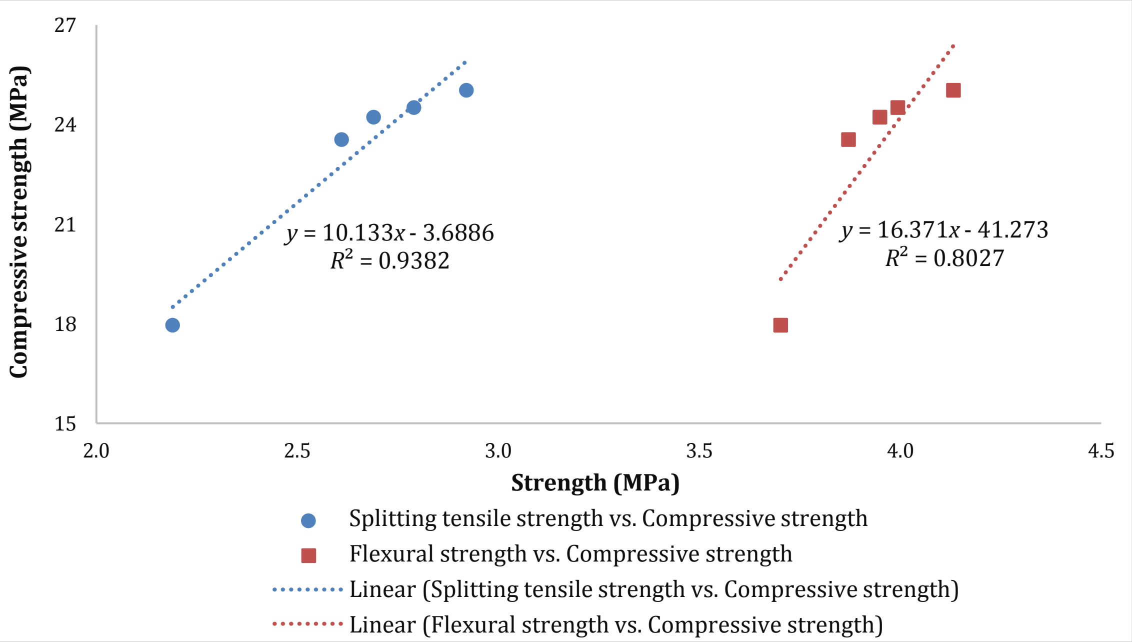

Fig. 17. Relationship between compressive, splitting and flexural strength values of RBAC.

3.9. Comparison of the mechanical performance of recycled brick aggregate concrete

The experimental findings of the present study were compared with findings reported in previous literature. Earlier studies have reported a decrement in the mechanical performance of recycled concrete with increasing brick aggregate replacement percentage, and the results of this study are generally consistent with these findings. Table 12 presents a comparative summary of the mechanical performance of recycled brick aggregate concrete reported in previous studies and the present investigation.

Table 12. Comparison of mechanical properties from various studies.

Authors	Coarse aggregate replacement percentage	W/C ratio	Variation in strength relative to the control mix		
			Compressive strength	Tensile strength	Flexural strength
De Brito et al. (2005)	100%	0.6	−45.00%	–	−25.71%
Debieb and Kenai (2008)	100%	0.57	−35.00%	–	−33.11%
Cachim (2009)	30%	0.45	−10.00% to −24.00%	−10% to −20%	–
		0.5	−10.00% to −20.00%	−12.50% to +4.27%	–
Aliabdo et al. (2014)	100%	0.5	−36.50%	−28.10%	–
		0.7	−30.80%	−60.00%	–
Bhanbhro et al. (2014)	100%	0.5	−37.00%	–	–
Gyawali (2022)	20%	0.5 (oven-dried aggregates)	10.12%	–	–
		0.5 (saturated aggregates)	−14.98%	–	–
This study	10%	0.5	−0.72%	−4.68%	−2.95%
	20%		−3.27%	−8.06%	−4.42%
	30%		−5.99%	−10.65%	−6.32%
	100%		−28.26%	−25.16%	−7.58%

At 100% brick aggregate replacement, the reduction in compressive strength observed in the present study is consistent with findings from previous studies (Debieb and Kenai 2008; Aliabdo et al. 2014; Bhanbhro et al. 2014). Although these studies have reported higher strength reductions, the results are comparable in magnitude. At replacement levels below 100%, most studies have reported a reduction in compressive strength. An exception is reported by Gyawali (2022), who observed a strength gain at 20% replacement when oven-dried brick aggregates were used. In contrast, the present study showed lower strength reductions relative to control mix up to 30% replacement.

Similarly, the percentage reduction in tensile strength at 100% replacement levels is consistent with the results reported by Aliabdo et al. (2014) for a water-cement ratio of 0.5. Although Cachim (2009) reported a tensile strength gain at 30% replacement, the present study showed a gradual reduction in tensile strength with increasing brick aggregate concrete. De Brito et al. (2005) and Debieb and Kenai (2008) reported 25%-34% reductions in flexural strength at 100% replacements. In comparison, the present study recorded a substantially lower reduction of about 8%, despite using brick aggregates sourced from century-old masonry.

Overall, the recycled brick aggregate concrete in this study exhibited smaller percentage reductions in mechanical strength relative to the control mix as compared to previously reported studies, despite the inherently weaker properties of aggregates. This behavior suggests that aggregate-level indicators such as abrasion and impact resistance alone do not fully govern the strength of concrete. One contributing factor may be the higher water absorption capacity of brick aggregates, which can supply additional water for cement hydration, causing an internal curing effect (Cachim 2009; Aliabdo et al 2014; Xiao et al. 2012). Moreover, strict control of the effective water-cement ratio through pre-soaking of brick aggregates to a saturated surface dry condition prevented absorption of mixing water. Even if the absorbed water does not actively participate in cement hydration, it remains within the brick pores, contributing to a denser aggregate structure (Cachim 2009). Collectively, these factors likely contributed to the improved strength retention observed in the present study.

4. Conclusions

This study investigated the effects of replacing natural coarse aggregate with recycled crushed brick aggregates derived from century-old bricks on the mechanical properties of the resulting concrete. The conclusions of the study are drawn as follows:

- The properties of century-old bricks in this study fall within the broader range reported for modern bricks; however, the properties of resulting brick aggregates are comparatively inferior, which may be due to long term environmental exposure and material degradation with aging.
- Brick aggregates exhibited higher porosity and water absorption than natural coarse aggregates. Therefore, the water required for mixing needs to be adjusted to prevent the brick aggregates from absorbing mixing water and to maintain effective cement hydration.
- Brick aggregates presented lower abrasion and impact resistance compared to natural coarse aggregates; however, the mechanical performance of the resulting RBAC was satisfactory based on experimental results of concrete at 28 days.
- Brick aggregates showed lower specific gravity and density as compared to natural coarse aggregates, which resulted in reduced compressive strength with increasing replacement levels of natural coarse aggregates.
- Compressive strength decreased with increasing brick aggregate content; however, all mixes except B100% satisfied the strength requirements for M20 concrete.
- Both splitting tensile strength and flexural strength decreased with increasing brick aggregate replacement. Nevertheless, the experimentally obtained flexural strength values for all mixes exceeded the theoretical values predicted by the empirical relationship specified in IS 456 (2000).
- Ultrasonic pulse velocity decreased with increasing replacement of brick aggregates, supporting the influence of lower density and higher porosity of brick aggregates on reduced compressive strength.
- According to IS 516 (Part 5/Sec 1) (2018), all concrete mixes except B100% exhibited excellent concrete quality based on ultrasonic pulse velocity measurements, while B100% mix demonstrated doubtful concrete quality.
- Strength index analysis indicated that the contribution of brick aggregates to the overall compressive strength of the concrete decreases progressively with increasing brick aggregate replacement levels.

From the results of this study, it can be summarized that natural coarse aggregates can be replaced by recycled coarse brick aggregates up to 30% without significant loss in compressive strength, while achieving adequate flexural strength at all replacement levels. This demonstrates the potential for recycling old masonry bricks as brick aggregates in concrete. The findings suggest that recycled brick aggregates derived from old bricks may be used in non-structural concrete, low-load-bearing concrete structures subjected primarily to gravity loads, and the production of concrete blocks where sustainability is prioritized despite the relatively low abrasion and impact resistance of brick aggregates. However, the long-term durability performance of RBAC was not investigated in this study.

This study was limited to laboratory-scale testing and focused mainly on the mechanical properties of recycled brick aggregate concrete using brick aggregates from a single century-old masonry building. The number of test specimens was limited; therefore, advanced statistical analysis was not considered. Microstructural characterization was beyond the scope of this study, and interpretations related to porosity and interfacial transition zone behavior are based on indirect experimental observations and existing literature.

Future studies should focus on the durability performance and microstructural analysis of recycled brick aggregate concrete. Further investigations are also needed to evaluate the influence of brick age, firing characteristics, source variability, and properties of brick aggregates on the performance of recycled concrete. In addition, design mix optimization of recycled concrete at higher replacement levels using mineral and chemical admixtures could also be a suitable area for further study.

Acknowledgements

The authors would like to thank Mr. Bibek Bhusal, Mr. Aditya Deo, Mr. Anubhav Chaurasiya, Mr. Sanjiv Maharjan, and Mr. Saroj Sapkota from Kathmandu University, Nepal because of their assistance in laboratory works to execute this study and further authors acknowledge Department of Civil Engineering, Kathmandu University, Nepal for the laboratory facility and materials for execution of the research.

Funding

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

Conflict of Interest

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

Data Availability

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

AI Assistance

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

Author Contributions

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

REFERENCES

Aboalella AA, Elmalky A (2023). Use of crushed bricks and recycled concrete as replacement for fine and coarse aggregates for sustainable concrete production. *Challenge Journal of Concrete Research Letters*, 14(2), 39–46.

Adamson M, Razmjoo A, Poursaee A (2015). Durability of concrete incorporating crushed brick as coarse aggregate. *Construction and Building Materials*, 94, 426–432.

Aliabdo AA, Abd-Elmoaty A-E M, Hassan HH (2014). Utilization of crushed clay brick in concrete industry. *Alexandria Engineering Journal*, 53, 151–168.

Azam R, Riaz MR, Haq EU, Shihata A, Zawam M (2022). Development of quality assessment criteria for burnt clay bricks of different ages based on ultrasonic pulse velocity test. *Buildings*, 12, 1069.

Bajracharya S, Phuyal S, Acharya S, Timilsena S, Regmi S, Chaudhary UK, Nepal B, Shrestha AR (2025). Sustainability assessment of recycled concrete aggregate in the Kathmandu Valley: a comparative analysis with natural coarse aggregate. *Discover Civil Engineering*, 2, 78.

Basit A, Hameed R, Abbas S, Karam M, Shahzad S, Kazmi S, Munir M (2024). Impact of recycled concrete and brick aggregates on the flexural and bond performance of reinforced concrete. *Applied Sciences*, 14, 2719.

Bhanbhro R, Memon I, Ansari A, Shah A, Memon BA (2014). Properties evaluation of concrete using local used bricks as coarse aggregate. *Engineering*, 6, 211–216.

Bhatta N, Adhikari A, Ghimire A, Bhandari N, Subedi A, Sahani K (2024). Comparing crushed brick as coarse aggregate substitute in concrete: experimental vs. numerical study. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 48, 4255–4274.

Bhattarai J, Ghale DB, Chapagain YP, Bohara NB, Duwal N (2018). Study on the physical and mechanical properties of ancient clay brick samples of Kathmandu Valley, Nepal. *Tribhuvan University Journal*, 32, 1–18.

Bohara N, Ghale D, Chapagain Y, Duwal N, Bhattarai J (2020). Effect of firing temperature on physico-mechanical properties of contemporary clay brick productions in Lalitpur, Nepal. *Bangladesh Journal of Scientific and Industrial Research*, 55, 43–52.

Cachim PB (2009). Mechanical properties of brick aggregate concrete. *Construction and Building Materials*, 23, 1292–1297.

Central Bureau of Statistics (2021). National Population and Housing Census 2021. National Statistics Office, Office of the Prime Minister and Council of Ministers, Government of Nepal. https://censusnepal.cbs.gov.np/results [accessed 27-10-2025].

Rao MC (2018). Properties of recycled aggregate and recycled aggregate concrete: effect of parent concrete. *Asian Journal of Civil Engineering*, 19, 103–110.

Chapagain YP, Sapkota S, Ghale DB, Bohara NB, Duwal N, Bhattarai J (2020). A case study on mineralogy and physico-mechanical properties of commercial bricks produced in Nepal. *SN Applied Sciences*, 2, 1856.

De Brito J, Agrela F, Silva RV (2019). Construction and demolition waste. In: New Trends in Eco-Efficient and Recycled Concrete. Elsevier, pp. 1–22.

De Brito J, Pereira AS, Correia JR (2005). Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates. *Cement and Concrete Composites*, 27, 429–433.

Debieb F, Kenai S (2008). The use of coarse and fine crushed bricks as aggregate in concrete. *Construction and Building Materials*, 22, 886–893.

Gyawali TR (2022). Re-use of concrete/brick debris emerged from big earthquake in recycled concrete with zero residues. *Cleaner Waste Systems*, 2, 100007.

Hachemi S, Khattab M, Benzetta H (2022). The effects of recycled brick and water/cement ratios on the physical and mechanical performance of recycled aggregates concrete. *Innovative Infrastructure Solutions*, 7, 270.

IS 383 (2016). Coarse and fine aggregate for concrete – Specification. Bureau of Indian Standards, New Delhi, India.

IS 456 (2000). Plain and reinforced concrete – Code of practice. Bureau of Indian Standards, New Delhi, India.

IS 516 (Part I/Sec 1) (2021). Method of tests for strength of concrete – Part I: Determination of strength of hardened concrete. Bureau of Indian Standards, New Delhi, India.

IS 516 (Part 5/Sec 1) (2018). Method of tests for strength of concrete – Part 5: Non-destructive testing of concrete – Section 1: Ultrasonic pulse velocity. Bureau of Indian Standards, New Delhi, India.

IS 1077 (1992). Common burnt clay building bricks – Specification. Bureau of Indian Standards, New Delhi, India.

IS 2386 (Part I) (1963). Methods of test for aggregates for concrete – Part I: Particle size and shape. Bureau of Indian Standards, New Delhi, India.

IS 2386 (Part III) (1963). Methods of test for aggregates for concrete – Part III: Specific gravity, density, voids, absorption and bulking. Bureau of Indian Standards, New Delhi, India.

IS 2386 (Part IV) (1963). Methods of test for aggregates for concrete – Part IV: Mechanical properties. Bureau of Indian Standards, New Delhi, India.

IS 4031 (Part 1) (1996). Methods of physical tests for hydraulic cement – Part 1: Determination of fineness by sieving. Bureau of Indian Standards, New Delhi, India.

IS 4031 (Part 4) (1988). Methods of physical tests for hydraulic cement – Part 4: Determination of consistency of standard cement paste. Bureau of Indian Standards, New Delhi, India

IS 4031 (Part 11) (1988). Methods of physical tests for hydraulic cement – Part 11: Determination of density. Bureau of Indian Standards, New Delhi, India.

IS 10262 (2019). Concrete mix proportioning – Guidelines. Bureau of Indian Standards, New Delhi, India.

Khadka A, Timisina P, Adhikari S (2025). Comparative analysis of compressive strength of natural and brick aggregate concrete. *Journal of UTEC Engineering and Management*, 3, 112–123.

Khanal D, Paudel MR (2023). Quality assessment of bricks produced in Chitwan District, central Nepal. *Journal of Nepal Geological Society*, 65, 141–150.

Lennon M (2005). Recycling construction and demolition wastes: a guide for architects and contractors. *Commonwealth of Massachusetts*, Department of Environmental Protection, Boston, USA.

National Planning Commission (2015). Nepal Earthquake 2015 – Post Disaster Needs Assessment, Vol. B: Sector Reports. National Planning Commission, Government of Nepal. https://nepal.unfpa.org/sites/default/files/pub-pdf/PDNA_volume_BFinalVersion.pdf [accessed 27-10-2025].

Pacheco-Torgal F (2017). High tech startup creation for energy efficient built environment. *Renewable and Sustainable Energy Reviews*, 71, 618–629.

Parajuli HR (2012). Determination of mechanical properties of the Kathmandu World Heritage brick masonry buildings. *Proceedings of the 15th World Conference on Earthquake Engineering.* Lisbon, Portugal.

Parajuli RR, Furukawa A, Gautam D (2020). Experimental characterization of monumental brick masonry in Nepal. *Structures*, 28, 1314–1321.

Poudel R, Hirai Y, Asari M, Sakai S (2019). Field study of disaster waste management and disposal status of debris after Gorkha Earthquake in Kathmandu, Nepal. *Journal of Material Cycles and Waste Management*, 21, 753–765.

Poudel S, Subedi A, Khadka B, Poudel A, Adhikari B, Thapa BB, Gyawali TR (2025). Study on the mechanical properties of concrete with recycled aggregates, glass fibers, and fly ash: exploring environmental waste utilization. *Innovative Infrastructure Solutions*, 10, 377.

Şamdan F, Çelikyürek İ, Canbaz M (2024). Determination of waste crushed baked clay aggregate concrete with granular composite material preparations. *Challenge Journal of Concrete Research Letters*, 15(4), 112–119.

Shrestha S (2019). A case study of brick properties manufacture in Bhaktapur. *Journal of Science and Engineering*, 7, 27–33

Silva RV, de Brito J, Dhir RK (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, 65, 201–217.

Subedi SK (2020). Study of characteristics of bricks produced in Kathmandu, Nepal. *American Journal of Civil Engineering*, 8, 64.

Thapaliya N, Karki N, Badu L, Karki R, Bagale U, Timalsina I, Ali Y, Thapa S, Bhatt MR (2024). Study on properties and uses of clay burnt bricks as a popular construction material: A case study of Bhaktapur, Nepal. *Proceedings of the 11th International Conference on Challenges in Earth-Based Interior Architecture; Current Issue in Earth-Based Materials, Construction Techniques and Approaches*, Kayseri, Turkey.

Xiao J, Li W, Fan Y, Huang X (2012). An overview of study on recycled aggregate concrete in China (1996–2011). *Construction and Building Materials*, 31, 364–383.