ELECTRONIC JOURNAL OF STRUCTURAL ENGINEERING

eJSE INTERNATIONAL

Original Article

Cite this:
DOI:10.56748/ejse.261060

Received Date: 7 July 2024
Accepted Date: 16 October 2025

1443-9255
https://ejsei.com/ejse
Copyright: © The Author(s). Published by Electronic Journals for Science and Engineering International (EJSEI). This is an open access article under the CC BY license. https://creativecommons.org/licenses/by/4.0/

Mechanical Performance and Durability of Concrete Incorporating Crushed Clay Brick Aggregate as a Partial Replacement for Natural Coarse Aggregate

Mohammed Khaleel Ibrahim[a], Mohammed Mustafa Qasim[a], Diyar N. Qader[b]*, Ghassan Hussein Humur[b], Mohammed Kamal Ali[b]

[a] Civil Engineering Department, College of Engineering, Tikrit University, Saladin, Iraq
[b] Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq
*Corresponding author: diyar.nasih@uokirkuk.edu.iq

Abstract

Construction and demolition waste (CDW) is a major and increasing environmental problem that is little used in concrete manufacturing, especially crushed clay brick. In this study, the mechanical and durability performance of concrete made of crushed clay brick aggregate (CBA) as a partial volumetric replacement of natural coarse aggregate (NCA) at the replacement level of 0%, 25%, 50%, 75% and 100% has been evaluated. The proportioning of all the mixtures was designed for a nominal 28-day cube strength of 30MPa, the brick aggregate was soaked for 24 hours and dried to a saturated surface-dry (SSD) condition before mixing to account for the effect of water absorption by the aggregate. The fresh and hardened properties were evaluated by slump test, 7 days and 28 days compressive strength, splitting tensile strength at 7 days and at 28 days, ultrasonic pulse velocity (UPV) at 28 days and water absorption at 28 days. As the amount of CBA increased, the workability, strength, and UPV decreased consistently while the water absorption increased. In addition, slump dropped from 78 mm at 0% replacement to 26 mm at 100%, and 28-day compressive strength decreased from 35.6 MPa to 17.7 MPa (a 50.3% reduction), while splitting tensile strength dropped from 2.85 MPa to 1.96 MPa (a 31.2% reduction), suggesting that tensile capacity was relatively less affected by the incorporation of CBA. The UPV decreased from 4.87 km/s to 3.21 km/s and water absorption increased from 4.19% to 7.44% with the same range, and the inverse relationship between compressive strength and water absorption has been identified. Better balances between mechanical adequacy and sustainability gains were obtained for 25% CBA replacement while 50% and higher replacement levels showed significant loss of performance, limiting their use to non-structural applications.

Keywords

Crushed clay brick aggregate, Compressive strength, Ultrasonic pulse velocity, Water absorption, Sustainable concrete response

1. Introduction

The growth of cities and the construction industry have created a new demand for infrastructure materials, especially concrete, which is the most widely used construction material in the world, in an unprecedented manner (Tam et al., 2007, Poon et al., 2002, Qahtan et al., 2022, Qader et al., 2025, Fediuk et al., 2023, Dai et al., 2022). This has contributed to the increasing pressure on natural aggregate resources and raised environmental concerns over the quarrying, transportation and carbon emissions from concrete manufacturing (Meyer, 2009, Vijerathne et al., 2024, Ali et al., 2026). At the same time, Construction and Demolition Waste (CDW) is a major environmental problem rapidly increasing in size. CDW accounts for a significant amount of waste is produced every year due to the demolition and urban renovation, and it is estimated that more than 10 billion tons per year of CDW are produced globally (Wu et al., 2019). Crushed clay brick is one of the major components of CDW and is typically disposed of in landfills (Pereira-de-Oliveira et al., 2012).

Within this context the circular economy's principles have been growing in the construction industry. The use of Crushed Clay Brick Aggregate (CBA) as a partial replacement of Natural Coarse Aggregate (NCA) in concrete production has come out as one of the most promising ways towards material recycling and waste valorization (Pacheco-Torgal and Jalali, 2010, Wong et al., 2018, Humur et al., 2026). The results showed in several studies at low-to-moderate replacement levels were encouraging as the acceptable mechanical properties can be achieved in concrete using brick aggregate (Noaman et al., 2021, Khatab et al., 2021). The use of crushed Clay Brick does present some technical difficulties, however, due to its physical properties which have higher porosity and water absorption than natural aggregate (Silva et al., 2014, Bektas et al., 2009). The properties can have a detrimental effect on the workability, compression strength and durability of the resulting concrete, and can also change the qualities of the Interfacial Transition Zone (ITZ) between aggregate and cement paste (Aliabdo et al., 2014).

There are many basic properties that are different between CBA and natural aggregate. Its specific gravity is about 1.46 to 1.68 (Khalaf, 2006) which is lower than that of natural aggregate (2.64-2.65), so it could be used as a candidate material for lightweight concrete production. The water absorption property of masonry units can be as high as 17.7% compared with the commonly used natural gravel, which has 1.1-3.84% water absorption (Khatab et al., 2021) due to the porous structure developed during the firing of the brick. The study of brick fragments by scanning electron microscopy (SEM) has confirmed the particle angularity and the visible pore structure directly relates to the behavior of the fresh and hardened concrete (Roy and Islam, 2024).

One common conclusion from the literature is that the higher the percentage of CBA, the lower the workability of the concrete. This behavior is attributed to the high absorption capacity of the brick particles, which reduces the effective water available for lubrication, and to the angular particle shape, which increases internal friction within the fresh mix (Noaman et al., 2021, Khatab et al., 2021). Khatab et al. (2021) reported a slump reduction from 43 mm at 0% replacement to 12 mm at 60% replacement of natural aggregate by crushed concrete masonry unit (CMU) aggregate, despite increasing the water-to-cement ratio from 0.45 to 0.55. Pre-soaking of the brick aggregate to saturated surface-dry (SSD) condition is widely recommended as a mitigation measure (Aliabdo et al., 2014, Lafhaj and Goueygou, 2009).

Studies consistently demonstrate a reduction in compressive strength with increasing brick replacement ratios. Noaman et al. (2021) reported compressive strength reductions of 12.2% and 22.3% at 100% coarse yellow and red brick replacement, respectively, relative to a reference mix with a 28-day strength of 34.9 MPa. Khatab et al. (2021) recorded reductions of 1%, 12%, and 20% at 20%, 40%, and 60% CMU replacement. These reductions are achieved through the inherent crushing strength of brick particles being lower than natural stone, an increase in internal porosity and ITZ deterioration at higher replacement level (Aliabdo et al., 2014, Lafhaj and Goueygou, 2009). However, several studies have demonstrated that concrete with good structural properties is still possible at moderate replacement ratios (Noaman et al., 2021, Hussein et al., 2021).

In the research work which uses recycled aggregate, water absorption and Ultrasonic Pulse Velocity (UPV) are commonly used as indicators of porosity and internal quality of the concrete. For instance, Noaman et al. (2021) reported 28-day water absorption values of 5.1% to 7.1% for brick

aggregate mixes, higher than the 4.5% of the reference concrete, owing to the porous nature of the brick particles. Roy and Islam (2024) reported that the absorption of geopolymer concrete containing recycled brick aggregate ranged from 7% to 20%. With the increase in brick content, the absorption of the bricks also increases due to the cumulative effect of the porous brick particles in the concrete. This is supported by UPV measurements, which show that as the internal void content increases, the UPV decreases and the homogeneity decreases (Lafhaj and Goueygou, 2009, Hussein et al., 2021).

Although the amount of data is increasing on the brick aggregate concrete, the optimal ratio from the replacement of bricks within this mix has not been determined, and various levels of replacement are recommended for different kinds of brick, mix design, and intended use (from 10% to 30% of brick replacement) (Noaman et al., 2021, Khatab et al., 2021, Hussein et al., 2021). Moreover, the available studies generally address the mechanical or the durability-related properties separately, and they differ in the type of brick, the mix proportioning, the conditioning of the aggregate, and the range of replacement, so their results cannot be compared directly or used to relate the loss of strength to the porosity and transport properties of the concrete. A consistent experimental program that covers the full range of replacement and links these properties is therefore still needed.

The novelty of the present study, beyond the existing literature, is therefore as follows. First, one mix-design framework (a nominal 28-day strength of 30 MPa, with constant cement content, sand content and water-cement ratio, and brick aggregate pre-saturated to the SSD condition) is applied over the full range of volumetric replacement of NCA by CBA (0, 25, 50, 75, and 100%), so that the effect of the CBA content is isolated from differences in proportioning and aggregate conditioning. Second, the mechanical properties (compressive and splitting tensile strength), the non-destructive quality (UPV) and the transport-related durability indicators (water absorption and sorptivity) are measured on the same mixes at the same ages and are interpreted together, which makes it possible to link the loss of strength directly to the density, internal quality and pore-related behavior of CBA concrete. Third, the relationship between compressive strength, water absorption and UPV is examined across the whole replacement range and is used to identify the replacement level at which the performance remains close to that of the control concrete (25%) and the levels (50% and above) that are limited to non-structural use, which gives practical guidance on where CBA can be used.

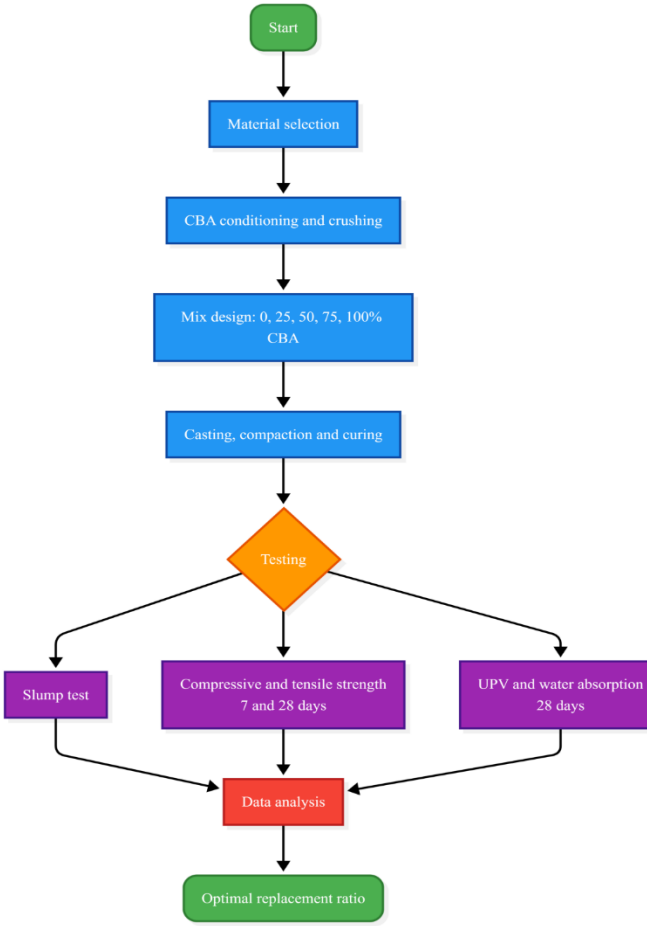


Fig. 1 Flowchart of the methodology utilized in this experimental study.

Hence, the aim of the present study is to assess the mechanical performance and durability characteristics of concrete such as compressive strength, splitting tensile strength, UPV, sorptivity and water absorption for concrete made by replacing 0%, 25%, 50%, 75%, and 100% of the NCA with CBA. The specific objectives are: (i) to design and manufacture concrete mixes with the desired target strength of 30 MPa; (ii) to evaluate the effect of increasing brick percentage on the workability, strength attainability, internal quality, and water absorption of the concrete; and (iii) to determine the optimum replacement ratio which would meet the performance requirement while adhering to the sustainability goals. Fig. 1 shows the methodology flowchart of the present study.

2. Experimental program

2.1 Materials

All mixtures were made with ordinary Portland cement (OPC) as the only binder to assure uniformity of the cementitious properties. The fine aggregate used is the natural sand in SSD condition. The reference coarse aggregate used was natural gravel of particle size range 10-20mm. Crushed clay brick, obtained from local demolition waste and prepared to the same 10-20 mm size range, was used as the replacement aggregate. Potable water was used for both mixing and curing.

Cement

An OPC conforming to ASTM C150 Type I (ASTM-C150, 2024) was used and it was stored in sealed containers in a dry environment. Setting time was determined according to ASTM C191 (ASTM-C191, 2021) and compressive strength of mortar according to ASTM C109 (ASTM-C109, 2021). The measured properties are listed in Table 1 and satisfy the limits of the standard.

Table 1. Physical and mechanical properties of the cement.

Property	Measured value	ASTM C150 limit (ASTM-C150, 2024)
Initial setting time (min)	105	≥ 45
Final setting time (min)	285	≤ 375
Compressive strength, 3 days (MPa)	18.9	≥ 12.0
Compressive strength, 7 days (MPa)	26.3	≥ 19.0
Fineness (residue on No. 170 sieve) (%)	4.8	≤ 10
Specific gravity	3.15	—

Fine aggregate

Natural river sand was used as fine aggregate and was batched in saturated surface-dry (SSD) condition. Sieve analysis was carried out according to ASTM C136 (ASTM-C136, 2006) and the grading was checked against the limits of ASTM C33 (ASTM-C33, 2018). Specific gravity and water absorption were determined according to ASTM C128 (ASTM-C128, 2022). The fineness modulus of the sand was 2.63 and its grading complied with ASTM C33 (ASTM-C33, 2018). The other properties of the sand are given in Table 2.

Coarse aggregates (NCA and CBA)

NCA with a particle size range of 10-20 mm was used as the reference coarse aggregate, and CBA of the same size range, obtained from local demolition waste, was used as the replacement aggregate. Specific gravity, water absorption, and bulk density of both aggregates were measured according to ASTM C127 (ASTM-C127, 2024) and ASTM C29 (ASTM-C29, 2023). The results are summarized in Table 2, and the particle size distributions are given in Table 3. The preparation of the CBA is described below.

The waste clay bricks were initially crushed and sieved to obtain aggregate particles within the required size range (see Fig. 2). Subsequently, the crushed brick aggregates were immersed in water for 24 hours and surface-dried to achieve saturated surface-dry (SSD) conditions before concrete mixing. This pre-treatment is essential to prevent the highly porous brick particles from absorbing mixing water and inducing uncontrolled variation in the effective water-to-cement ratio (Aliabdo et al., 2014, Lafhaj and Goueygou, 2009).

As shown in Table 2, the CBA is lighter and more porous than the natural gravel: its oven-dry specific gravity is 1.85 compared with 2.65 for the gravel, and its 24 h water absorption is 12.5% compared with 0.8%. The crushing value and abrasion loss of the CBA (30% and 38%) are also higher than those of the gravel (18% and 22%), which shows that the brick particles are weaker. These properties explain the lower density, workability, and strength and the higher water absorption of the CBA mixes discussed in Section 3. Because the aggregates were replaced by volume, the lower density of the CBA is reflected in the aggregate masses given in Table 4.



Fig. 2 Broken brick units for use as coarse aggregate.

Table 2. Physical and mechanical properties of the fine and coarse aggregates.

Property	Sand	Natural gravel (NCA)	Crushed brick (CBA)
Particle size range (mm)	0-4.75	10-20	10-20
Specific gravity (oven-dry)	2.6	2.65	1.85
Specific gravity (SSD)	2.63	2.67	2.08
Water absorption, 24 h (%)	1.2	0.8	12.5
Dry-rodded bulk density (kg/m^3)	1650	1550	1050
Fineness modulus	2.63	—	—
Aggregate crushing value (%)	—	18	30
Los Angeles abrasion loss (%)	—	22	38

Table 3. Sieve analysis of the aggregates (cumulative passing, %)

Sieve size (mm)	Sand	NCA	CBA	Standard limits (ASTM-C33, 2018)
25	100	100	100	100 (coarse)
19	100	96	95	90-100 (coarse)
12.5	100	52	50	20-55 (coarse)
9.5	100	6	8	0-15 (coarse)
4.75	98	2	3	95-100 (sand)/0-5 (coarse)
2.36	91	—	—	80-100 (sand)
1.18	73	—	—	50-85 (sand)
0.600	46	—	—	25-60 (sand)
0.300	22	—	—	5-30 (sand)
0.150	7	—	—	0-10 (sand)

2.2 Mix design and proportions

Five concrete mixtures were proportioned using a volumetric replacement method, in which the NCA was substituted by CBA at ratios of 0%, 25%, 50%, 75%, and 100% by volume. The use of volumetric replacement over mass replacement was used to retain the volume of aggregate in the concrete and to consider the bulk density of crushed brick is less than that of natural gravel (Aliabdo et al., 2014). The reference concrete was proportioned for a nominal 28-day compressive strength of 30 MPa. The same cement content, water-to-cement ratio, and fine aggregate content were maintained in all mixtures to isolate the influence of CBA replacement. The aggregate masses in Table 4 were calculated from the SSD specific gravities of the natural gravel and the crushed brick given in Table 2.

Table 4. Concrete mix proportions.

Mix ID	CBA (vol%)	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	CBA (kg/m^3)
B0	0	415	187	775	1051	0
B25	25	415	187	775	788.3	204.7
B50	50	415	187	775	525.5	409.3
B75	75	415	187	775	262.8	614
B100	100	415	187	775	0	818.6

The replacement ratios were selected for the following reasons. First, previous studies indicate that satisfactory performance is generally obtained at low-to-moderate replacement levels of about 10-30% (Noaman et al., 2021, Khatab et al., 2021, Hussein et al., 2021); the 25% level was therefore chosen to represent this range, with 0% as the control. Second, the higher levels of 50% and 75% were included because the replacement level recommended in the literature varies with the type of brick, the mix design, and the intended use, and intermediate levels are needed to determine at which point the performance begins to deteriorate and whether the trend is linear. Third, 100% replacement was included as the upper limit, which represents the maximum utilization of the waste brick and bounds the full range of behavior. The uniform step of 25% gives equally spaced levels that make the trends easy to compare, while keeping the program to five mixes and 40 specimens.

2.3 Specimen preparation and curing

The mass-batching was carried out with the aid of an electronic balance using constituent materials. The coarse aggregates were placed in the mixer first, then sand and cement and finally the mixing water was added gradually, to achieve uniform dispersion of the water in the paste and to coat the particles of porous brick. The fresh concrete was placed in three layers in cube molds and each layer consolidated by 25 blows of the rod to remove the entrapped air. Specimens were demolded after 24 hours and transferred to a water-curing tank maintained at 20 ± 2°C until the respective testing ages. For each mix, four cube specimens (150 mm) and four cylindrical specimens were produced for compressive strength, splitting tensile strength, UPV, water absorption, and sorptivity tests and the complete specimen matrix totaled 40 specimens across five mixes (see Fig. 3).



Fig. 3 Concrete cube and cylindrical specimens after casting and compaction.

2.4 Test methods

Slump test

Workability was assessed by the slump test conducted on fresh concrete immediately after mixing. The test was performed in accordance with standard procedure (ASTM-C143, 2020).

Compressive strength

Compressive strength was determined on 150 mm cube specimens at curing ages of 7 and 28 days. Two specimens per mix per age were tested, and the average value was reported. The testing machine and failure mode of a cube specimen tested at 28 days is shown on Fig. 4.





Fig. 4 Compressive strength testing and representative failure of a concrete cube specimen.

Splitting tensile strength

Spitting tensile strength was determined on 150 x 300 mm cylindrical specimens at curing ages of 7 and 28 days. Two specimens per mix per age were tested, and the average value was reported.

UPV

UPV measurements were conducted at 28 days on intact specimens prior to compression testing, using a direct transmission arrangement (ASTM-C597, 2022). UPV serves as a non-destructive indicator of internal homogeneity and void content; pulse velocity decreases with increasing porosity and internal discontinuities (Lafhaj and Goueygou, 2009, Hussein et al., 2021). Fig. 5 shows the instruments used for testing the UPV of concrete specimens.



Fig. 5 UPV test and measurement procedure.

Water absorption

Water absorption was measured at 28 days on fragments obtained from specimens after compression testing. Fragments were oven-dried to constant mass, after which they were fully immersed in water and the mass gain was expressed in percentage as the ratio of the mass gain to the mass of the oven-dry fragment (ASTM-C642, 2021). The immersed specimens and surface weighing procedure are depicted in Fig. 6, respectively.



Fig. 6 Immersion and surface weighing of concrete specimens for the water absorption test.

Sorptivity

Sorptivity was determined at 28 days in accordance with ASTM C1585 (ASTM-C1585, 2020), using specimens that were extracted from those used for the compressive strength tests. A 50 ± 3 mm thick slice was sawn from the middle of a 150 mm cube of each mix, discarding the outer layers, and the slices were conditioned at 50 °C and 80% relative humidity for three days and then stored in sealed containers for at least 15 days. The lateral and top surfaces were sealed so that water entered only through the bottom face. The bottom face was placed 1 to 3 mm below the water level, and the mass gain was recorded at 1, 5, 10, 20, 30, and 60 min, then hourly up to 6 h, after blotting the surface water.

3. Results and discussion

3.1 Workability

The slump value of mixes reduced monotonically with increasing CBA content, from 78 mm for B0 up to 26 mm for B100, which is a drop of 67% (Table 5). There was a reduction which was about linear with replacement range, which corresponds to the cumulative requirement for mixing water and the increase in inter-particle friction, as a result of the porous and angular brick particles. Although pre-treatment with SSD was used to control water demand, the rough surface texture and inherent porosity of brick aggregate caused a reduction in the fresh concrete fluidity, which is in line with the findings of Noaman et al. (2021) and Khatab et al. (2021).

Table 5. Slump test results.

Mix ID	CBA replacement (%)	Slump (mm)	Reduction (%)
B0	0	78	—
B25	25	66	15
B50	50	52	33
B75	75	37	53
B100	100	26	67

3.2 Density and UPV

The measured UPV values for all concrete mixtures are presented in Table 6. As shown in Table 6, the SSD densities of concrete decreased gradually as the percentage of CBA increased from 0% (B0) to 100% (B100) with a total reduction of 9.1%. This phenomenon is mainly due to the intrinsic characteristics of crushed brick compared with natural gravel. The specific gravity of CBA is much lower than that of natural gravel, and its internal structure is extremely porous and vesicular, which is formed during the firing process (Debieb and Kenai, 2008, Khalaf and DeVenny, 2004).

The bulk unit weight of the composite, naturally, decreases with the increased percentage of the lighter and more porous gravel replacement material. In practical terms, the density range obtained (2200-2420 kg/m^3) is within the normal weight concrete range (2000-2600 kg/m^3) (EN-206:2013+A2:2021, 2021) although the lower limit has approached the boundary of lightweight/semi-lightweight concrete classifications. This implies that CBA concretes, especially at higher percentages, might also potentially provide a secondary benefit of lower self-weight which may be beneficial for non-structural or moderately loaded structural components where the reduction of dead loads is an important factor.

UPV values decreased from 4.87 km/s (B0) to 3.21 km/s (B100), corresponding to a reduction of approximately 34%. According to (IS-13311, 1992), the UPV quality classification changed from “Excellent” for B0 (>4.5 km/s) to “Good” for B25–B75 (3.5-4.5 km/s) and “Medium” for B100 (3.0-3.5 km/s). This progressive reduction in UPV indicates a decrease in the internal homogeneity and integrity of the concrete with increasing CBA content. The lower pulse velocity can be attributed to the higher porosity and internal discontinuities associated with the porous brick aggregate and the aggregate–paste interface (Lafhaj and Goueygou, 2009, Hussein et al., 2021, IS-13311, 1992). The classifications confirm the compressive strength data and show that the internal quality of the concrete decreases as the brick content increases.

3.3 Compressive strength

The compressive strength results of the tested concrete mixtures are summarized in Table 7 and Fig. 7. As shown in Table 7 and Fig. 7, the compressive strength decreased progressively and steeply with increasing CBA replacement at both curing ages, falling from 24.92 MPa to 12.39 MPa at 7 days and from 35.6 MPa to 17.7 MPa at 28 days between B0 and B100 a reduction of 50.3% at 28 days relative to the control mix. This decrease was not linear, but rather minor (5.1%) for B0 to B25, and most significant (26.6%) for B25 to B50, implying that the aggregate is relatively impervious to low replacement of CBA, while the aggregate's porosity and inferior particle strength at high replacement levels (B50 to B75) significantly affected the matrix. This progressive loss is consistent with the well-established mechanical limitations of weak, porous aggregates such as fired-clay brick used as coarse replacement: such particles are inherently weaker and more porous than natural aggregate, and the ITZ between cement paste and the replacement particles tends to be more heterogeneous due to higher water absorption during mixing, which can locally alter the effective water-cement ratio around each particle. As replacement content increases, the load path through the concrete matrix increasingly passes through this weaker, more porous phase, so the composite's compressive capacity becomes increasingly governed by the aggregate's own strength rather than the cement paste strength — the classic transition from "paste-controlled" to "aggregate-controlled" failure behavior reported for weak recycled aggregates in the literature. This strength reduction can be attributed to three concurrent mechanisms: (i) the inherently lower crushing value of the replacement particles compared to natural aggregate; (ii) the increase in total matrix porosity resulting from the pore structure contributed by the replacement material; and (iii) the potential weakening of the ITZ due to the rough, absorptive surface of the replacement particles, which may alter the local water-to-cement ratio in the transition zone (Aliabdo et al., 2014, Lafhaj and Goueygou, 2009).

3.4 Splitting tensile strength

The splitting tensile strength results of the tested concrete mixtures are summarized in Table 7 and Fig. 8. As shown in Table 7 and Fig. 8, the splitting tensile strength showed the same progressive decrease with the increase of CBA content from B0 to B100, from 2.41 MPa to 1.65 MPa at 7 days and 2.85 MPa to 1.96 MPa at 28 days as the compressive strength did, a decrease of 31.2% at 28 days compared to the control mix. Although this decrease was in the same direction, the loss in compressive strength (50.3%) was much greater than the loss in tensile strength, indicating that tensile strength is less sensitive to the addition of CBA. The incremental pattern was similar but again not linear, as for compression, with B0 to B25 having little effect on tensile capacity (1.8%) and B25 to B50 having the largest single step decrease (15.0%) which falls at the same critical replacement level indicated in the compressive strength results, B50 to B75 experiencing a reduction (10.9%) but not as acute, and B75 to B100 a reduction (7.5%).

The behavior can be rationalized in terms of the very different failure mechanisms that occur under tensile vs compressive loading. Compressive strength is determined more by the overall strength of the aggregate-paste system and splitting tensile strength is more determined by the bond strength between the cement matrix and the surface of the aggregate and the crack initiation and propagation resistance of the composite along the failure plane. Even though CBA particles create a highly porous structure with a lower density, the rough, angular and porous nature of the particles can also provide partial mechanical interlocks and bonding at the aggregate-paste interface, which may result in a relatively high proportion of the crack-resisting capacity of the composite remaining even when the bulk load-bearing capacity of the cement matrix decreases in compression (Guinea et al., 2002).

Table 6. Density, UPV results at 28 days.

Mix ID	Replacement level of CBA (%)	Density (kg/m^3)	Reduction in density (%)	UPV (km/s)	UPV Quality (IS-13311, 1992)
B0	0	2420	-	4.87	Excellent
B25	25	2350	-2.9	4.27	Good
B50	50	2300	-5.0	3.91	Good
B75	75	2280	-5.8	3.79	Good
B100	100	2200	-9.1	3.21	Medium

Table 7. Compressive strength and splitting tensile strength at 7 and 28 days.

Mix ID	CBA (%)	Compressive strength at 7 days (MPa)	Compressive strength at 28 days (MPa)	Splitting Tensile Strength (MPa) for 7 days	Splitting Tensile Strength (MPa) at 28 days
B0	0	24.92	35.6	2.41	2.85
B25	25	23.66	33.8	2.36	2.80
B50	50	17.36	24.8	1.92	2.38
B75	75	13.58	19.4	1.71	2.12
B100	100	12.39	17.7	1.65	1.96

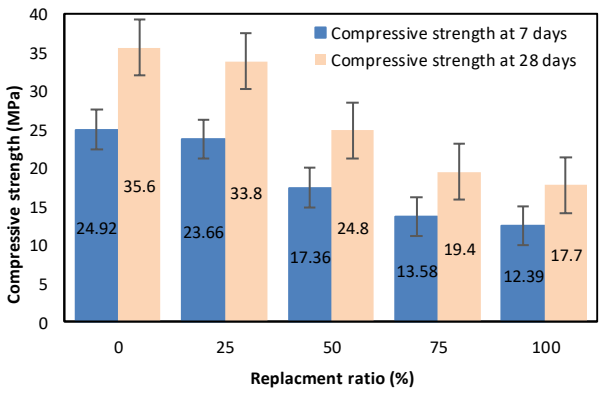


Fig. 7 Compressive strength of concrete at 7 and 28 days for different replacement ratios.

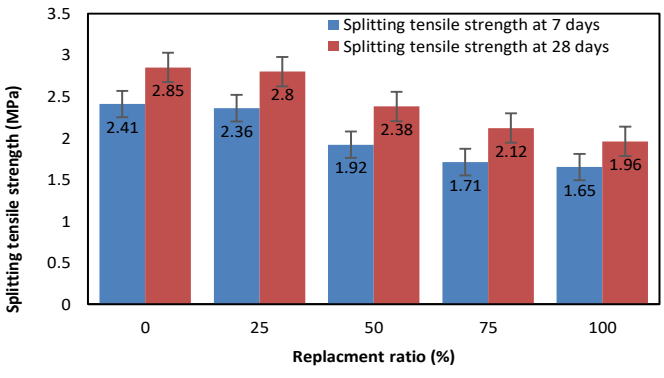


Fig. 8 Splitting tensile strength of concrete at 7 and 28 days for different replacement ratios.

3.5 Water absorption

The water absorption results are summarized in Table 8 and illustrated in Fig. 9. As shown in Table 8 and Fig. 9, an increase in thwaterbsorption was observed with the increase in CBA replacement, which increased from 4.19% of the water at B0 to 7.44% of water at B100, representing an overall increase of 77.6% compared to the control mix. The incremental trend is moderate between B0 and B25 (12.4%), and it is quite high between B25 and B50 (40.3%) with a slower rate of change after that: between B50 and B75, it is 9.5%, and between B75 and B100, it is 2.8%. For the pattern, it shows that after CBA content is greater than 25%, the water absorption capacity will increase the most, and then the matrix will exhibit a saturation-like behavior, making the value of additional CBA content a decreasing marginal impact. This is a trend consistent with the inherent nature of CBA's porosity and vesicular structure which contains more open and interconnected pores than NCA. The pore volume and water connectivity of the composite matrix also increase with CBA content, which results in more water entering and staying within the material (Khatab et al., 2021, Bektas et al., 2009). The significant differences in CBA's porosity between B25 and B50 further indicate the presence of an optimum replacement level where the matrix's transport properties are dominated by the CBA, as was found in the compressive and tensile strength results.

3.6 Sorptivity

The sorptivity results are summarized in Table 8 and illustrated in Fig. 9. As shown in Table 8 and Fig. 9, the sorptivity was also found to increase with increasing CBA replacement with the increase ranging from B0 to B100, from 0.092 mm/min$^{0.5}$ to 0.123 mm/min$^{0.5}$, respectively, which is an overall increase of 33.7%. The pattern of incremental increases in sorptivity is slightly different from the water absorption results, with a modest increase of 6.5% from B0 to B25, followed by the largest single step increase of 18.4% from B25 to B50, the smallest single step increase of 1.7% from B75 to B100, and the remaining sorptivity increases as indicated. The improvement is most marked between B25 and B50, as in the water absorption case, indicating that this replacement range is the most critical in the pore structure development of CBA modified mixes. The increased sorptivity is attributed to the increased capillary pore connectivity and the increased pore size within the cementitious matrix, which are both very much influenced by the porous nature of the CBA particles, and the possibility of a weaker and more permeable ITZ around the CBA particles. The small increases in incremental increases beyond B75 (to B100) indicate the capillary transport network may be near saturation as the pore structure is heavily altered and any additional CBA added results in relatively small additional capillary pathway.

Table 8. Water absorption and sorptivity results at 28 days.

Mix ID	Replacement level of CBA (%)	Water absorption (%)	Sorptivity (mm/min$^{0.5}$)	Increase in sorptivity (%)
B0	0	4.19	0.092	-
B25	25	4.71	0.098	+6.5%
B50	50	6.61	0.116	+26.1%
B75	75	7.24	0.121	+31.5%
B100	100	7.44	0.123	+33.7%

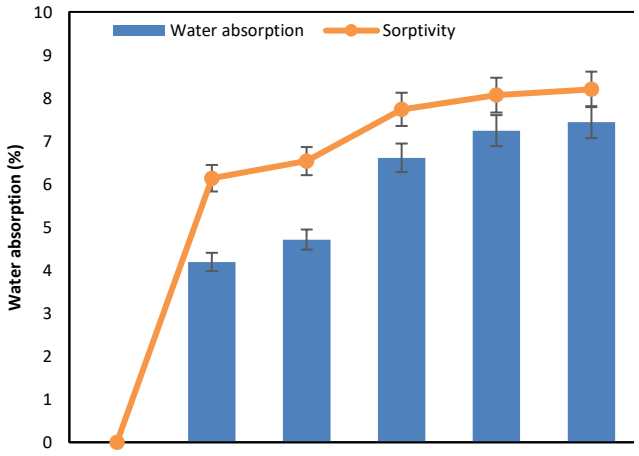


Fig. 9 Water absorption and sorptivity for different replacement ratios.

3.7 Interrelationships among test results

The compressive strength and water absorption had an inverse relationship in all five mixes with a clear trend. The 28-day compressive strength progressively decreased as water absorption increased from 4.19% to 7.44%, indicating that the mixes with higher water absorption generally exhibited lower compressive strength. It is physically meaningful since both the variables are controlled by same variable i.e. total porosity of the concrete that increases with brick content. The rise in porosity lowers the load bearing area available for stress transfer, and also increases the number of pores that are available for water to enter (higher absorption) (Poon et al., 2002, Aliabdo et al., 2014). This is confirmed by UPV data: the decrease in pulse velocity corresponds to decrease in compressive strength and increase in absorption, which shows the absorption content as key factor in determining all three responses. Having three independent test methods generate the same mechanistic interpretation increases confidence in the experimental results.

3.8 Practical engineering implications of the optimum replacement level

The 25% replacement (B25) gives the best balance between performance and sustainability in this study. It retained almost the strength of the control, with a 28-day compressive strength of 33.8 MPa (5.1% lower than B0) and a splitting tensile strength of 2.80 MPa (1.8% lower), so it met the 30 MPa design target, while the slump (66 mm), the density (2350 kg/m^3) and the UPV (4.27 km/s, "Good" according to IS 13311) remained acceptable. The water absorption (4.71%) and the sorptivity (0.098 mm/min$^{0.5}$) increased by only 12.4% and 6.6%, respectively. In practice, B25 concrete can therefore be considered for ordinary reinforced concrete elements of normal strength, such as slabs, beams, columns, and footings of buildings under mild, non-aggressive exposure, subject to the limits of the applicable design code for recycled aggregate. At the same time, it reduces the self-weight by about 70 kg/m^3 and the consumption of natural gravel by about 257 kg per cubic meter of concrete, using 200 kg/m^3 of brick waste that would otherwise be landfilled.

Because the water absorption and sorptivity of B25 are higher than those of the control, severe exposure conditions (such as freeze–thaw, chlorides, or sulfates) require additional durability testing before use. The mixes with 50% CBA and above had a 28-day strength of 24.8 MPa or less and a water absorption of 6.61% or more, so they are suitable only for non-structural or low-demand applications, such as blinding and leveling layers, pavement sub-bases, footpaths, kerbs, non-load-bearing precast units, and fill. These applications are suggested from the laboratory results of this study and should be confirmed by further tests (long-term durability, shrinkage, and creep) before field use.

4. Conclusions

Based on the experimental results, the following conclusions are drawn:

1. The workability was found to decrease regularly with the increase in CBA content, from 78 mm for 0% to 26 mm for 100% CBA replacement. Partially water demand reduction is achieved by pre-soaking brick aggregate to SSD condition but the reduction in workability is not removed.
2. Compressive strength at 28 days declined from 35.6 MPa (B0) to 17.7 MPa (B100). The replacement levels above 25% were found not suitable for structural applications as only the B0 and B25 mixes achieved the 30 MPa targets.
3. The UPV values dropped from 4.87 km/s to 3.21 km/s, which showed the progressive degradation of the internal quality of concrete. According to IS 13311, the UPV quality was 'Excellent' for B0, 'Good' for B25–B75, and 'Medium' for B100.
4. The water absorption and sorptivity also increased regularly with increase in the content of CBA, which indicates the increase in overall porosity and permeability of the CBA composite. The overall increase in water absorption is proportionately greater (77.6%) than the increase in sorptivity (33.7%), however.
5. An inverse relationship was observed between the compressive strength and water absorption property, and this applies uniformly to all levels of replacement based on the significance of total porosity to both characteristics.
6. The level of replacement of 25% has been found to be optimum since it gives performance that is almost the same as the control concrete. The 50% and higher replacement is suitable only for secondary use.

The results of this investigation should be interpreted within its limitations. Only one type of clay brick from a single source of demolition waste was used, the brick aggregate was pre-saturated to the SSD condition without any other treatment, and the mixes were designed for one target strength (30 MPa) at a constant water-cement ratio, with only the coarse aggregate replaced. Testing was limited to ages of 7 and 28 days, on a small number of specimens per mix, and the relationship between strength, absorption, and UPV was evaluated qualitatively, without a regression model. Long-term durability, shrinkage, creep, the modulus of elasticity, flexural behavior, and the microstructure of the

interfacial transition zone were not investigated. Future research should therefore consider other brick types, water-cement ratios, strength grades, and admixtures or supplementary cementitious materials to offset the strength loss. It should also examine surface treatment of the brick aggregate, long-term durability, shrinkage, creep, elastic modulus, SEM of the interfacial transition zone, predictive modelling, combination with other recycled aggregates, structural-scale tests, and life cycle and cost assessments.

Competing interests

The authors declare no conflict of interest.

Funding

This research received no external funding.

Data availability

All data generated or analyzed during this study are included in this published article.

References

ALI, M. K., QADER, D. N., ALI, O. A. A., RAHEEM, A. M., NASER, I. J. & AL-LUHYBI, A. S. 2026. Mechanical and durability performance of sustainable cement mortars: Experimental optimization and multi-regression modelling. Next Materials, 12, 102418. https://doi.org/10.1016/j.nxmate.2026.102418

ALIABDO, A. A., ABD-ELMOATY, A.-E. M. & HASSAN, H. H. 2014. Utilization of crushed clay brick in concrete industry. Alexandria Engineering Journal, 53, 151-168. https://doi.org/10.1016/j.aej.2013.12.003

ASTM-C29 2023. Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate.

ASTM-C33 2018. Standard Specification for Concrete Aggregates.

ASTM-C109 2021. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens).

ASTM-C127 2024. Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate.

ASTM-C128 2022. Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate.

ASTM-C136 2006. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.

ASTM-C143 2020. Standard Test Method for Slump of Hydraulic-Cement Concrete.

ASTM-C150 2024. Standard Specification for Portland Cement.

ASTM-C191 2021. Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle.

ASTM-C597 2022. Standard Test Method for Ultrasonic Pulse Velocity Through Concrete.

ASTM-C642 2021. Standard Test Method for Density, Absorption, and Voids in Hardened Concrete.

ASTM-C1585 2020. Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes.

BEKTAS, F., WANG, K. & CEYLAN, H. 2009. Effects of crushed clay brick aggregate on mortar durability. Construction and Building materials, 23, 1909-1914. https://doi.org/10.1016/j.conbuildmat.2008.09.006

DAI, L., WU, X., ZHOU, M., AHMAD, W., ALI, M., SABRI, M. M. S., SALMI, A. & EWAIS, D. Y. Z. 2022. Using machine learning algorithms to estimate the compressive property of high strength fiber reinforced concrete. Materials, 15, 4450. https://doi.org/10.3390/ma15134450

DEBIEB, F. & KENAI, S. 2008. The use of coarse and fine crushed bricks as aggregate in concrete. Construction and building materials, 22, 886-893. https://doi.org/10.1016/j.conbuildmat.2006.12.013

EN-206:2013+A2:2021 2021. Concrete-Specification, Performance, Production and Conformity. Brussels, Belgium: European Committee for Standardization (CEN).

FEDIUK, R., MAKAROVA, N., QADER, D. N., KOZIN, A., AMRAN, M., PETROPAVLOVSKAYA, V., NOVICHENKOVA, T., SULMAN, M. & PETROPAVLOVSKII, K. 2023. Combined effect on properties and durability performance of nanomodified basalt fiber blended with bottom ash-based cement concrete: ANOVA evaluation. Journal of Materials Research and Technology, 23, 2642-2657. https://doi.org/10.1016/j.jmrt.2023.01.179

GUINEA, G., EL-SAYED, K., ROCCO, C., ELICES, M. & PLANAS, J. 2002. The effect of the bond between the matrix and the aggregates on the cracking mechanism and fracture parameters of concrete. Cement and concrete research, 32, 1961-1970. https://doi.org/10.1016/S0008-8846(02)00902-X

HUMUR, G. H., ABED, H. T., HAMADA, H. M., ABDULHALEEM, K. N. & QADER, D. N. 2026. Impact of Recycled Fine Aggregate Replacement on the Properties of Self-Compacting Concrete Exposed to Sulfuric Acid. JES. Journal of Engineering Sciences. https://doi.org/10.21608/jesaun.2026.449188.1991

HUSSEIN, Z. M., KHALIL, W. I. & AHMED, K. 2021. Impact strength and shrinkage of sustainable fiber reinforced crushed brick aggregate concrete. Materials Today: Proceedings, 42, 3022-3027. https://doi.org/10.1016/j.matpr.2020.12.818

IS-13311 1992. Non-Destructive Testing of Concrete-Methods of Test-Part 1: Ultrasonic Pulse Velocity. New Delhi, India: Bureau of Indian Standards (BIS).

KHALAF, F. M. 2006. Using crushed clay brick as coarse aggregate in concrete. Journal of Materials in Civil Engineering, 18, 518-526. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:4(518)

KHALAF, F. M. & DEVENNY, A. S. 2004. Recycling of demolished masonry rubble as coarse aggregate in concrete. Journal of materials in civil engineering, 16, 331-340. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:4(331)

KHATAB, H. R., AL-SAMARAIE, M. I., MOHAMMED, Z. Q. & AL-SAMARAIE, A. A. 2021. The influence of waste of concrete masonry units as coarse aggregate on concrete properties. Materials Today: Proceedings, 42, 1810-1815. https://doi.org/10.1016/j.matpr.2020.12.186

LAFHAJ, Z. & GOUEYGOU, M. 2009. Experimental study on sound and damaged mortar: Variation of ultrasonic parameters with porosity. Construction and building materials, 23, 953-958. https://doi.org/10.1016/j.conbuildmat.2008.05.012

MEYER, C. 2009. The greening of the concrete industry. Cement and concrete composites, 31, 601-605. https://doi.org/10.1016/j.cemconcomp.2008.12.010

NOAMAN, A. T., JAMEEL, G. S. & AHMED, S. K. 2021. Producing of workable structural lightweight concrete by partial replacement of aggregate with yellow and/or red crushed clay brick (CCB) aggregate. Journal of King Saud University-Engineering Sciences, 33, 240-247. https://doi.org/10.1016/j.jksues.2020.04.013

PACHECO-TORGAL, F. & JALALI, S. 2010. Reusing ceramic wastes in concrete. Construction and building materials, 24, 832-838. https://doi.org/10.1016/j.conbuildmat.2009.10.023

PEREIRA-DE-OLIVEIRA, L. A., CASTRO-GOMES, J. P. & SANTOS, P. M. 2012. The potential pozzolanic activity of glass and red-clay ceramic waste as cement mortars components. Construction and Building Materials, 31, 197-203. https://doi.org/10.1016/j.conbuildmat.2011.12.110

POON, C. S., KOU, S. & LAM, L. 2002. Use of recycled aggregates in molded concrete bricks and blocks. Construction and building materials, 16, 281-289. https://doi.org/10.1016/S0950-0618(02)00019-3

QADER, D. N., JAMIL, A. S., BAHRAMI, A., ALI, M. & ARUNACHALAM, K. P. 2025. A systematic review of metakaolin-based alkali-activated and geopolymer concrete: A step toward green concrete. Reviews on Advanced Materials Science, 64, 20240076. https://doi.org/10.1515/rams-2024-0076

QAHTAN, A.-S., HUANG, J., AMRAN, M., QADER, D. N., FEDIUK, R. & WAEL, A.-D. 2022. Seismic composite metamaterial: a review. Journal of Composites Science, 6, 348. https://doi.org/10.3390/jcs6110348

ROY, A. & ISLAM, G. S. 2024. Geopolymer using different size fractions of recycled brick-based mixed demolition waste. Cleaner Materials, 11, 100224. https://doi.org/10.1016/j.clema.2024.100224

SILVA, R., DE BRITO, J. & DHIR, R. 2014. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Construction and Building Materials, 65, 201-217. https://doi.org/10.1016/j.conbuildmat.2014.04.117

TAM, V. W., TAM, C. M. & LE, K. N. 2007. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resources, Conservation and Recycling, 50, 82-101. https://doi.org/10.1016/j.resconrec.2006.05.012

VIJERATHNE, D., WAHALA, S. & ILLANKOON, C. 2024. Impact of crushed natural aggregate on environmental footprint of the construction industry: enhancing sustainability in aggregate production. Buildings, 14, 2770. https://doi.org/10.3390/buildings14092770

WONG, C. L., MO, K. H., YAP, S. P., ALENGARAM, U. J. & LING, T.-C. 2018. Potential use of brick waste as alternate concrete-making materials: A review. Journal of cleaner production, 195, 226-239. https://doi.org/10.1016/j.jclepro.2018.05.193

WU, H., ZUO, J., ZILLANTE, G., WANG, J. & YUAN, H. 2019. Construction and demolition waste research: a bibliometric analysis. Architectural Science Review, 62, 354-365. https://doi.org/10.1080/00038628.2018.1564646

Disclaimer

The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of EJSEI and/or the editor(s). EJSEI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.