Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Mechanical, microstructural, and load–displacement performance of sustainable concrete incorporating recycled brick waste coarse aggregate

Rehab H. Obead [1,a], Sheelan M. Hama [*,1,b], Firas Al-Mahmoud [2,c]

[1]*Department of Civil Engineering, University of Anbar, Ramadi 31001, Iraq*
[2]*Université de Lorraine, CNRS, IJL, Nancy, F-54000, France*

Article Info

Article History:

Received 21 July 2026
Accepted 11 Aug 2026

Keywords:

Crushed brick waste; Sustainable concrete; Load–deflection behavior; Mechanical properties; Ultrasonic pulse velocity

Abstract

The increasing generation of construction and demolition waste has created significant environmental challenges for the construction industry. Among these wastes, brick debris produced from demolished masonry structures represents a considerable portion that is often disposed of in landfills. Recycling such materials in concrete production can contribute to sustainable construction and reduce the consumption of natural aggregates. This study experimentally investigates the mechanical performance and load–deflection behavior of concrete incorporating crushed brick waste as a partial replacement for natural coarse aggregate. Five concrete mixtures were prepared with brick waste coarse aggregate (BWCA) replacement ratios of 0%, 10%, 15%, 20%, and 25% by volume of natural gravel. The fresh and hardened properties of concrete were evaluated through slump, compressive strength, splitting tensile strength, flexural strength, ultrasonic pulse velocity (UPV), and load–deflection response obtained from flexural tests. The experimental results showed that workability decreased with increasing BWCA content due to the high-water absorption and porous nature of brick aggregates. Moderate replacement levels improved certain mechanical properties. The mixture containing 10% BWCA exhibited the highest compressive strength, with an increase of approximately 15% compared with the control mixture. Splitting tensile strength also showed slight improvement at lower replacement ratios, while flexural strength gradually decreased as BWCA content increased. UPV measurements indicated acceptable internal quality for all mixtures. SEM observations confirmed that moderate BWCA incorporation enhanced matrix densification and aggregate–paste bonding, whereas higher replacement ratios increased porosity and weakened microstructures. The results suggest that a moderate replacement level of approximately 10% BWCA provides a favorable balance between mechanical performance and sustainability, making it a viable alternative for partially replacing natural coarse aggregates in concrete production.

1. Introduction

Concrete is the most widely used construction material due to its structural versatility, availability of raw materials, and relatively low production cost. It is extensively employed in a wide range of engineering applications, including residential buildings, bridges, pavements, and other infrastructure projects. The production of conventional concrete requires a large number of natural resources, particularly aggregates, which constitute the largest volume fraction of the mixture. Continuous extraction of natural aggregates has raised serious environmental concerns related to resource depletion, land degradation, and energy consumption during quarrying and

*Corresponding author: drsheelan@uoanbar.edu.iq
[a]orcid.org/0009-0001-3627-7533; [b]orcid.org/0000-0001-7265-583X; [c]orcid.org/0000-0003-3104-9352
DOI: http://dx.doi.org/10.17515/resm2026-1997ic0721rs

transportation processes [1,2]. In parallel with the rapid growth of the construction sector, the generation of construction and demolition waste has significantly increased worldwide. A considerable portion of this waste originates from clay bricks used in masonry structures. Clay bricks have been widely utilized in building construction for centuries due to their durability, availability, and favorable thermal properties [3]. Nevertheless, the demolition of old structures produces large quantities of brick debris, which are often disposed of in landfills, creating environmental and logistical challenges. Therefore, recycling such waste materials in new construction applications has become an important strategy for promoting sustainable construction practices. In recent years, researchers have increasingly focused on incorporating waste materials into cement-based composites in order to improve sustainability and reduce the environmental impact of construction activities. Various types of industrial and agricultural wastes have been investigated as alternative to aggregate in mortar and concrete, including eggshell, brick, and recycled plastic aggregates etc. [3-5]. These approaches not only reduce the consumption of natural resources but also contribute to waste management and circular economy strategies in the construction industry. Among the different recycling approaches, the use of crushed brick waste as aggregate in concrete has attracted considerable attention. Recycled brick aggregates obtained from demolished masonry structures can potentially replace natural aggregates in concrete production. This practice offers several environmental benefits, including the reduction of landfill waste and the conservation of natural aggregate resources. Due to the relatively porous structure and higher water absorption of brick particles compared with conventional aggregates, the incorporation of crushed brick aggregates may influence the mechanical and physical properties of concrete [6]. Several studies have examined the feasibility of using brick waste as aggregate in concrete. Bheel et al. [7] investigated the performance of concrete containing brick waste as a replacement for natural coarse aggregates and reported that increasing the replacement ratio generally led to reductions in compressive and flexural strengths. Similarly, Ji et al. [8] conducted experimental and numerical studies on recycled brick aggregate concrete and found that higher brick aggregate contents may reduce workability and density while altering the internal cracking patterns of the concrete matrix. Liu et al. [9] also observed that moderate replacement levels of brick waste could still produce concrete with acceptable mechanical performance for certain structural applications. Other researchers have explored the recycling of brick materials in different forms within cementitious systems. For example, brick waste has been successfully used as a supplementary powder material to partially replace cement in mortar mixtures, demonstrating its potential to improve sustainability while maintaining acceptable mechanical performance [5]. Previous investigations have shown that recycled aggregates derived from construction waste may affect key properties of concrete such as density, durability, and water absorption due to their higher porosity compared with natural aggregates [10].

The potential of recycled brick aggregates as sustainable substitutes for natural aggregates in structural concrete has been further shown by recent research. A comprehensive review [11] highlighted the growing research interest in recycled brick aggregate concrete while emphasizing the need for integrated investigations combining mechanical performance, durability, and sustainability assessment. Additionally, recent studies have looked at the combined mechanical and transport characteristics of concrete that contains recycled crushed clay bricks [12]. Also, a comprehensive linkage between aggregate dispersion, non-destructive evaluation, and structural behavior; these recent discoveries suggest that more research is still needed in this regard [13]. The structural performance of reinforced concrete with recycled brick coarse aggregates has been the subject of more recent experimental research, which has confirmed that moderate replacement levels can produce acceptable mechanical behavior while encouraging the reuse of waste from construction and demolition [14]. According to Joyklad et al. [15], the stress-strain response structural performance of brick-waste aggregate concrete were significantly enhanced by externally bonded, inexpensive Fiberglass Chopped Strand Mat (FCSM) sheet composites. This suggests that the drawbacks of recycled brick aggregates can be successfully reduced with the right strengthening methods. Additionally, Islam et al. [16] investigated the behavior of FRP-confined concrete columns using brick aggregates and demonstrated that external confinement significantly increased the ductility and load-bearing capability of recycled aggregate concrete. According to Mansur et al. [17], utilizing crushed brick as aggregate is feasible and can produce acceptable mechanical characteristics at moderate replacement amounts. Yang et al. [18] examined concrete that contained crushed clay bricks and recycled concrete aggregate, emphasizing the impact of aggregate quality on durability and mechanical performance. Similarly, Poon et al. [19] showed that recycled aggregates, such as brick aggregates, may be successfully used in concrete masonry products, encouraging the recycling of waste from building and demolition. Both coarse and fine crushed brick aggregates can be successfully added to concrete, according to Debieb and Kenai [20]. However, because brick aggregates are porous, high replacement ratios negatively impacted strength. Hasan and Hama [21] investigated the use of waste brick fine aggregate as a partial replacement for natural sand and reported that moderate replacement levels maintained satisfactory fresh, mechanical, and durability performance.

Many research studies have been done on the use of recycled brick aggregates in concrete, but most of them have mainly focused on the typical mechanical properties such as compressive strength, tensile strength, or durability. Only a few studies have attempted to establish correlations between non-destructive testing, microstructural characteristics and structural behavior. Moreover, the quantitative evaluation of internal distribution of recycled brick aggregates by digital image analysis has been very limitedly addressed. Therefore, the combined influence of BWCA on the mechanical performance, ultrasonic pulse velocity, flexural load–displacement response, microstructural characteristics, and aggregate distribution within concrete remains insufficiently understood. In an integrated experimental program, the present study integrates destructive testing, non-destructive evaluation, scanning electron microscopy (SEM) and ImageJ-based image analysis to address these research gaps. The comprehensive strategy leads to a systematic investigation of the relationship between the internal distribution of BWCA particles, microstructural development and structural properties, thus providing a better understanding of sustainable concrete containing BWCA than has been reported so far.

2. Experimental Works

2.1 Material and Mix Proportion

Ordinary Portland cement (CEM I) was used as the main binder in this study. The cement had a specific gravity of 3.15 and complied with the requirements of the Iraqi Standard Specification I.S. No. 5/2019 [22]. Natural river sand was used as fine aggregate with a maximum particle size of 4.25 mm and a specific gravity of 2.62. The gradation of the sand satisfied the limits specified by the Iraqi Standard Specification I.S. No. 45/1984 for aggregates used in concrete [23]. Crushed gravel was employed as the natural coarse aggregate. The aggregate had a maximum particle size of 10 mm and a specific gravity of 2.67, and its particle size distribution conformed to the requirements of I.S. No. 45/1984 [23]. Recycled brick waste was obtained from demolition sites of municipal buildings located in Ramadi city. After collection, the brick debris was processed using a mechanical crusher to produce brick aggregates.

Table 1. Sieve analysis results (% passing) of natural coarse aggregate and BWCA with Iraqi Specification No. 45/1984 upper and lower limits

Sieve size (mm)	Natural coarse aggregate	BWCA (% passing)	Lower limit (I.S. No.45/1984)	Upper limit (I.S. No.45/1984)
2.36	0	0	0	4
4.75	2	5	0	10
6.3	10	15	0	35
9.5	40	47	12	60
12.5	85	92	40	100

The crushed brick particles were then sieved to obtain the required size suitable for use as coarse aggregate with a maximum particle size of 12 mm, water absorption of 15.85% and a specific gravity of 1.64, as illustrated in Figure 1. Before mixing, BWCA was preconditioned to Saturated Surface Dry (SSD) condition as per the standard concrete mixing practice. This pre-conditioning reduced water absorption during batching and guaranteed a constant effective water/cement ratio for all concrete mixes. A Constant 1% quantity of High-range water-reducing admixture (superplasticizer) of Type F has been utilized in accordance with ASTM C494 [24]. The experimental program consisted of several concrete mixtures, including a control mix without BWCA and other mixes the BWCA were used as partial replacements for natural gravel. The replacement ratios of BWCA were 0%, 10%, 15%, 20%, and 25% of the gravel volume. The detailed mix proportions of all concrete mixtures are summarized in Table 2.

Table 2. Mix proportions in (kg/ m^3)

Mix ID	BWCA%	Cement	Fine Aggregate	Coarse Aggregate	BWCA	Water	Superplasticizer
BWCA 0	0%	422	821	1100	0.0	148	4.22
BWCA 10	10%	422	821	990	67.5	148	4.22
BWCA 15	15%	422	821	935	101.3	148	4.22
BWCA 20	20%	422	821	880	135.1	148	4.22
BWCA 25	25%	422	821	825	168.8	148	4.22

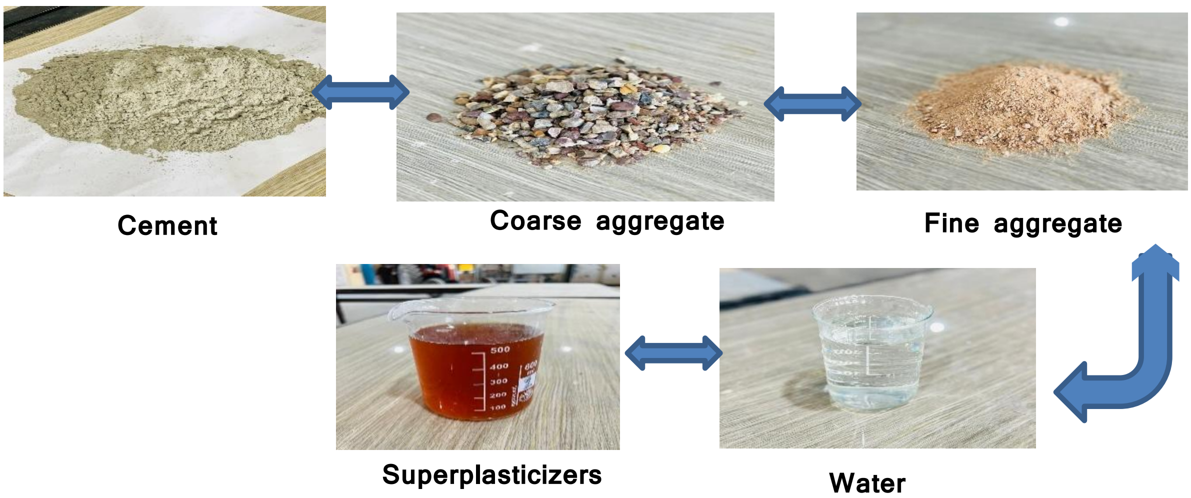


Fig. 1. The materials used in this work

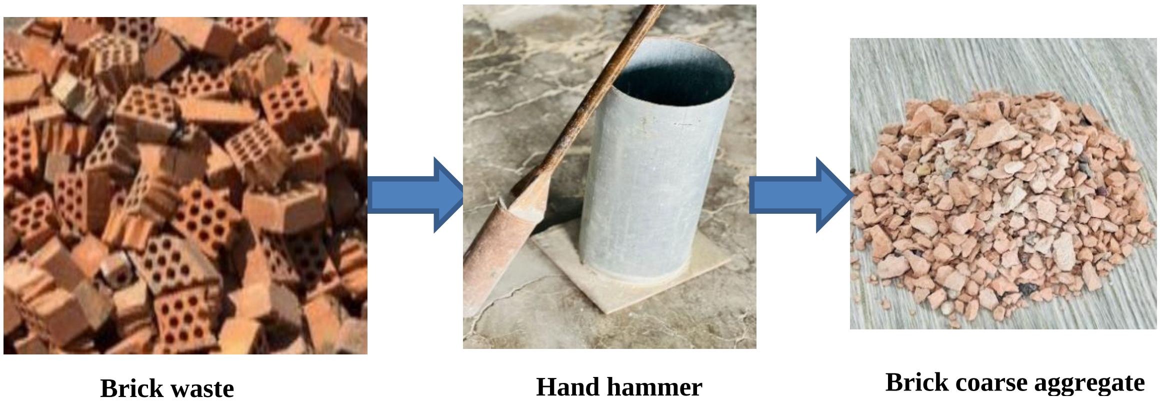


Fig. 2. Preparation of coarse waste brick aggregate procedure

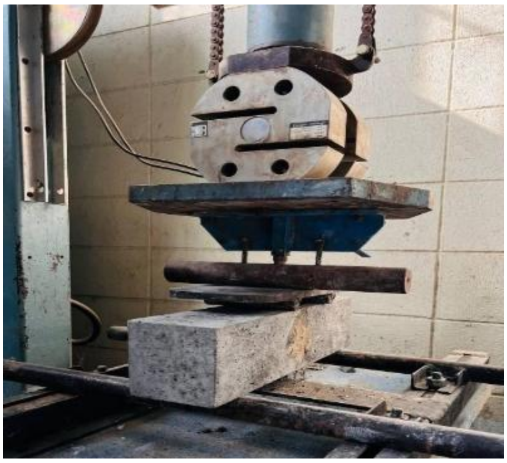
2.2 Tests

The workability of the fresh concrete mixtures was evaluated using the slump test in accordance with ASTM C143 [25]. The compressive strength of the hardened concrete was determined at the age of 28 days. For each mixture, three cube specimens with dimensions of 100 × 100 × 100 mm were prepared and tested according to the procedures specified in BS EN 12390-3 [26]. The compression tests were performed using a hydraulic testing machine with a maximum capacity of 5000 kN. During the test, the load was applied at a constant loading rate of approximately 1800 N/s until failure occurred. The splitting tensile strength of concrete was measured using cylindrical specimens with dimensions of 100 mm in diameter and 200 mm in height. After curing for 28 days, the specimens were tested following the requirements of ASTM C496/C496M [27]. Flexural strength was determined using three prismatic specimens for each concrete mixture, following the procedure specified in ASTM C78/C78M [28]. The flexural toughness of the specimens was determined as the area under the load–deflection curve obtained during the flexural test. The ultrasonic pulse velocity of hardened concrete was measured in accordance with ASTM C597/C597M [29]. UPV readings were obtained at the age of 28 days to assess the concrete quality and internal integrity.

Compressive strength

Slump test

Splitting tensile strength tests



Flexural test

Fig. 3. Laboratory testing conducted in this work

3. Results and Discussion

This section analyzes and discusses the experimental results of concrete mixtures incorporating waste brick aggregate as a partial replacement for natural coarse aggregate. The influence of BWCA content on the performance of concrete was evaluated through several parameters, including workability, compressive strength, splitting tensile strength, flexural strength, flexural toughness, and UPV. These properties were selected to provide a comprehensive understanding of both the mechanical performance and internal quality of the produced concrete. The experimental results for all mixtures are summarized in Table 3. In addition, the percentage variations of the measured properties relative to the control mixture were calculated and are presented in Table 4 in order to facilitate comparison between the different replacement levels. Particular attention was also given to the load–deflection response obtained from the flexural tests, as it provides valuable information about the post-cracking behavior and energy absorption capacity of the concrete. This analysis allows a deeper evaluation of the structural performance of concrete incorporating recycled brick aggregates. The results provide insight into how the incorporation of RBA influences the fresh and hardened properties of concrete, as well as the internal integrity of the material as indicated by UPV measurements.

Table 3. Summary of results of tests that have been conducted in this work

BWCA%	Slump (mm)	Compressive strength (f c) (MPa)	Flexural strength (fr) (MPa)	Splitting tensile strength (MPa)	UPV (km/sec.)
0.0%	90	35	3.68	3.5	4.6
10%	89.25	40.25	3.90	3.75	4.4
15%	86.6	40.0	3.75	3.68	4.25
20%	84.6	38.5	3.50	3.48	4.06
25%	80.8	35.8	3.42	3.36	3.86

Table 4. Summary of Percentage change in properties relative to the control mix

BWCA %	Slump Change	Compressive Strength Change	Flexural Strength Change	Splitting Tensile Change	UPV Change
0%	—	—	—	—	—
10%	−0.83%	+15.00%	+5.98%	+7.14%	−4.35%
15%	−3.78%	+14.29%	+1.90%	+5.14%	−7.61%
20%	−6.00%	+10.00%	−4.89%	−0.57%	−11.74%
25%	−10.22%	+2.29%	−7.07%	−4.00%	−16.09%

3.1 Workability

The workability of the concrete mixtures decreased gradually with increasing BWCA content, as shown in Figure 4. The control mixture exhibited a slump value of 90 mm, which slightly decreased to 89.25 mm, 86.6 mm, 84.6 mm, and 80.8 mm for mixtures containing 10%, 15%, 20%, and 25% BWCA, respectively. These values correspond to reductions of 0.83%, 3.78%, 6.00%, and 10.22% relative to the control mixture.

The reduction in workability is primarily attributed to the rough surface texture, angular shape, and irregular shape of the BWCA, which increase inter-particle friction and reduce the fluidity of the fresh concrete mixture. Since the BWCA was used in an SSD condition, water absorption during mixing was minimized, and the effective water/cement ratio remained essentially constant. Therefore, the observed reduction in slump is mainly associated with the physical characteristics of the recycled brick aggregates rather than a loss of mixing water. Similar observations have been reported in previous studies on recycled aggregate concrete [30–33].

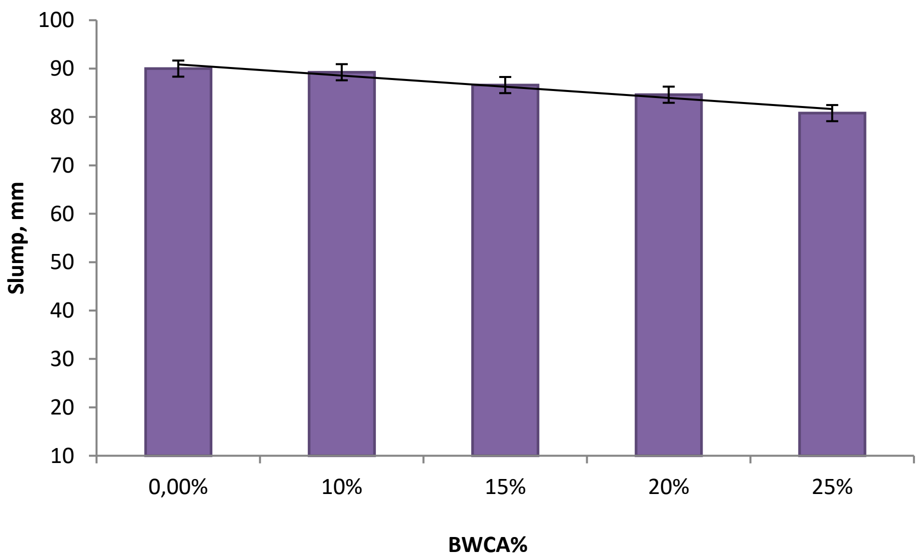


Fig. 4. Slump vs. BWCA%

3.2 Compressive Strength

The compressive strength results at 28 days for the different RBA replacement ratios are summarized in Table 3 and Figure 5. The compressive strength results demonstrate that the incorporation of BWCA significantly influences the mechanical performance of concrete. The control mixture achieved a compressive strength of 35 MPa, while the mixtures containing 10%, 15%, and 20% BWCA showed improved strengths of 40.25 MPa, 40.00 MPa, and 38.5 MPa, respectively. A further increasing the BWCA content to 25% resulted in a reduction to 35.8 MPa but still close to the control mix.

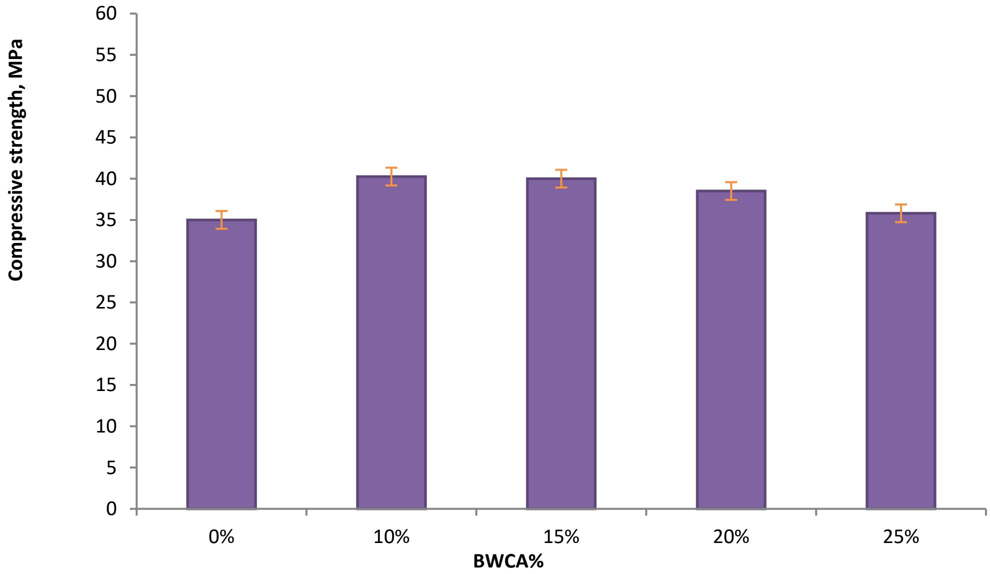


Fig. 5. Compressive strength vs. BWCA%

The rough surface texture of the recycled brick aggregates, which improves mechanical interlocking and fortifies the aggregate–paste contact, is primarily responsible for the improvement in compressive strength at low BWCA replacement levels (especially 10–15%). Additionally, the presence of fine particles produced during the crushing process and the irregular particle shape may enhance particle packing and aid in matrix densification. Previous investigations have demonstrated similar improvements in bonding behavior for concrete with recycled brick aggregate [7, 8]. The fundamental constraints of brick aggregates start to control the concrete's mechanical reaction when the BWCA replacement level rises above 15%. Compared to natural aggregates, brick particles usually have higher porosity and lower mechanical strength, which may result in weak spots in the concrete and raise the possibility of microcrack formation under load. As a result, even with the benefits shown at modest replacement levels, the overall compressive strength starts to decline. Similar patterns have been documented in previous research on recycled aggregate concrete, which found that modest replacement ratios were best for preserving mechanical properties [8,9,34].

3.3 Splitting Tensile and Flexural Strength

The splitting and flexural tensile strength results are listed in Table 3 and Figure 6. The flexural and splitting strengths showed a non-monotonic behavior as the BWCA content increased. For the low replacement levels, the initial improvement in flexural strength was observed from 3.68 MPa of the control mixture to 3.90 MPa (+5.98%), and 3.75 MPa (+1.90%) for 10% and 15% BWCA, respectively. The flexural strength decreased to 3.50 MPa and 3.42 MPa for the 20% and 25% mixes, respectively, when the BWCA replacement level was over 15%. The same trend was observed for splitting strength. The decrease at higher replacement levels is mainly attributed to the higher porosity, lower stiffness and lower intrinsic strength of the BWCA, which facilitates crack initiation and propagation under bending loads. Such trends have also been reported in previous studies on recycled brick aggregate concrete, where low replacement levels enhanced the flexural performance, while excessive replacement led to reductions [8,9,32].

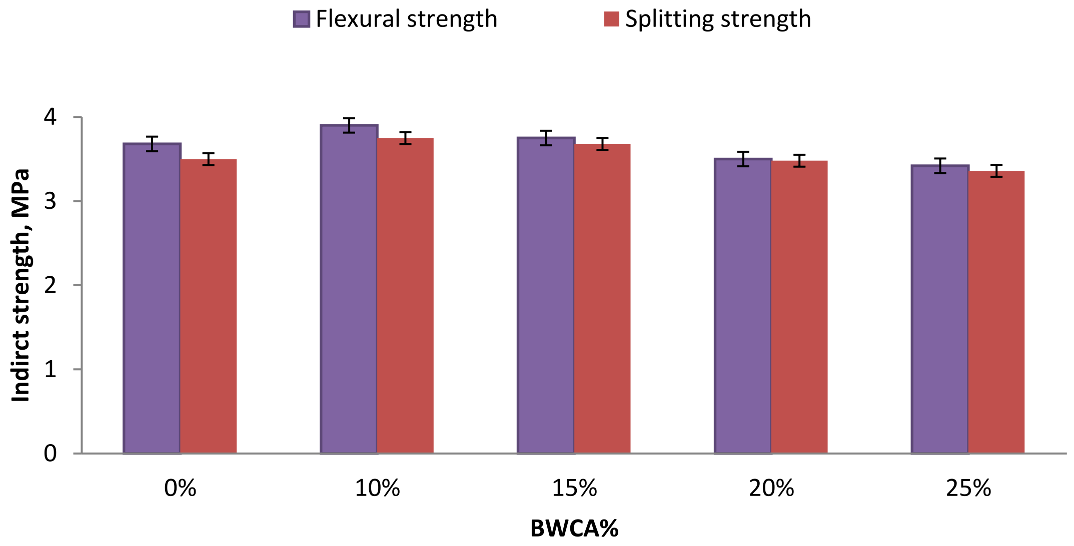


Fig. 6. Indirect tensile strengths vs. BWCA%

Figure 7 illustrates the relationship between compressive strength (f_c) and both flexural strength (f_r) and splitting tensile strength (f_{sp}) for the concrete mixtures containing different BWCA replacement ratios. The results demonstrate a strong correlation between compressive strength and the tensile-related properties of concrete. This relationship is expected since both flexural and splitting tensile strengths are governed by the quality of the cementitious matrix, the aggregate paste bond, and the development of microcracks within the concrete structure. To quantify this relationship, polynomial regression equations were established based on the experimental results. The flexural strength can be estimated as a function of compressive strength according to the following equation:

$$f_r = 0.0559\, f_c^2 - 4.1594\, f_c + 80.78\ (R^2 = 0.9365) \quad 35 \le f_c \le 40.25\, MPa. \tag{1}$$

Similarly, the splitting tensile strength can be predicted from the compressive strength using the following relationship:

$$f_{sp} = 0.033\, f_c^2 - 2.433\, f_c + 48.189\ (R^2 = 0.9703) \quad 35 \le f_c \le 40.25\, MPa. \tag{2}$$

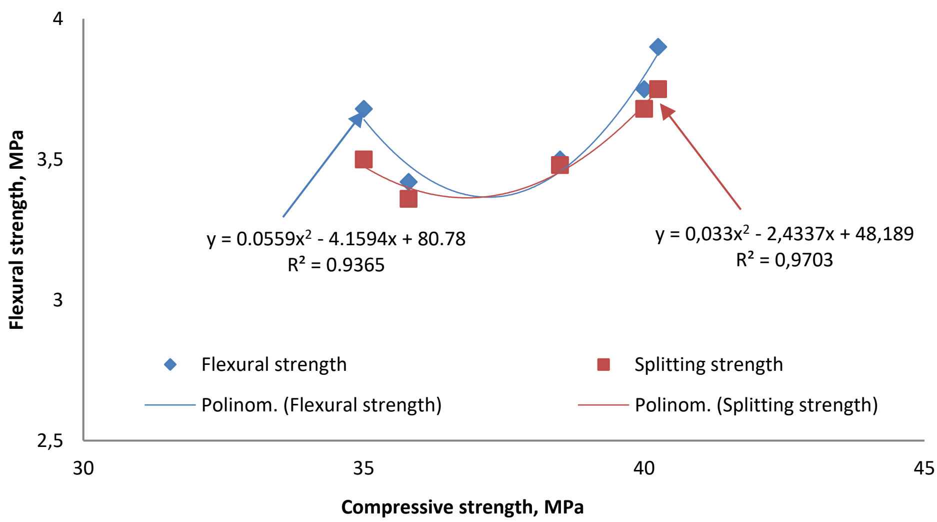


Fig. 7. Relation between flexural and compressive strengths for mixes with various BWCA%

The relatively high coefficients of determination suggest that the compressive strength can be utilized as a reliable parameter to estimate the tensile properties of concrete with crushed brick waste coarse aggregate in the strength range investigated. Equations (1) and (2) are empirical regression models based on the current experimental data and are valid only for concrete with compressive strength ranging from 35 to 40.25 MPa, corresponding to the BWCA replacement levels studied in this work. Therefore, these equations should not be extrapolated beyond this range as polynomial regression models may give unrealistic predictions beyond their calibration domain. As a result, even if the resulting coefficients of determination show a strong correlation within the dataset under investigation, an independent experimental database has not been used to confirm the equations. As a result, their applicability should be restricted to combinations with traits comparable to those investigated in this investigation, and before to widespread use, additional validation using bigger datasets is advised.

3.4 Load–Displacement Behavior and Flexural Toughness

The load–deflection curves obtained from the flexural tests provide important information regarding the deformation characteristics, stiffness, and energy absorption capacity of the concrete mixtures incorporating BWCA. As shown in Figure 8, all mixtures showed a typical flexural response consisting of an initial linear elastic stage followed by a nonlinear stage until the peak load was reached. In the initial stage, the load increased proportionally with deflection, indicating elastic behavior of the concrete before crack initiation. After the formation of microcracks within the cement matrix and along the aggregate–paste interface, the curves gradually deviated from linearity, reflecting a reduction in stiffness and the onset of crack propagation.

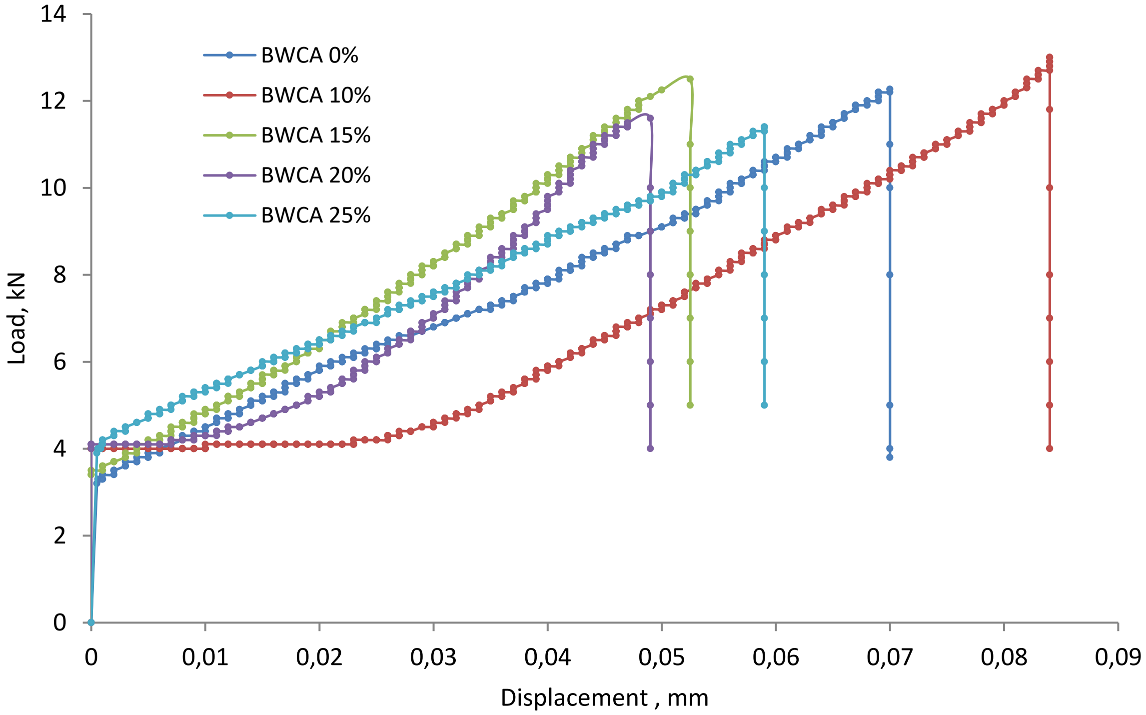


Fig. 8. Load-displacement relation for various BWCA%

To provide a quantitative interpretation of the flexural response, several structural parameters were extracted from the load–displacement curves, including the peak load, peak displacement, and energy absorbed up to the peak load. The calculated values are summarized in Table 5. The addition of 10% BWCA resulted in the best structural behavior, as shown in Table 5, with the largest peak displacement of 0.084 mm and the maximum peak load of 13.00 kN. When compared to the control mix this behavior shows an improvement in both load-carrying capacity and deformation capacity. In addition, the absorbed energy increased by almost 10.1%, from 0.524 kN·mm for the control specimen to 0.577 kN·mm, showing improved resistance to crack initiation and propagation. Structural efficiency gradually declined as the BWCA replacement level was raised over 10%. For the 15%, 20%, and 25% combinations, the peak load dropped to 12.50, 11.60, and 11.40 kN, respectively. Similarly, for the 15% and 20% BWCA, the absorbed energy dropped to 0.406 and 0.330 kN·mm, respectively, indicating the concrete's diminished capacity to support load following crack start. Despite having the lowest peak load, the 25% BWCA mixture's absorbed energy (0.446 kN·mm) was higher than that of the 15% and 20% mixtures due to its comparatively larger displacement prior to failure. However, as is common with plain concrete without fiber reinforcing, all combinations showed a brittle post-peak response marked by a rapid loss of load-carrying capability.

Table 5. Structural parameters obtained from the load–displacement curves

BWCA%	Peak Load (kN)	Peak Displacement (mm)	Energy to Peak (kN·mm)*
0.0%	12.27	0.070	0.524
10%	13.00	0.084	0.577
15%	12.50	0.0525	0.406
20%	11.60	0.049	0.330
25%	11.40	0.059	0.446

** The energy calculated here is the area under the load-displacement curve up to the maximum load using numerical integration.*

3.5 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity test was performed to assess the internal quality and integrity of the hardened concrete mixtures. UPV measurements were obtained at 28 days, and the results are presented in Table 3 and Figure 9.

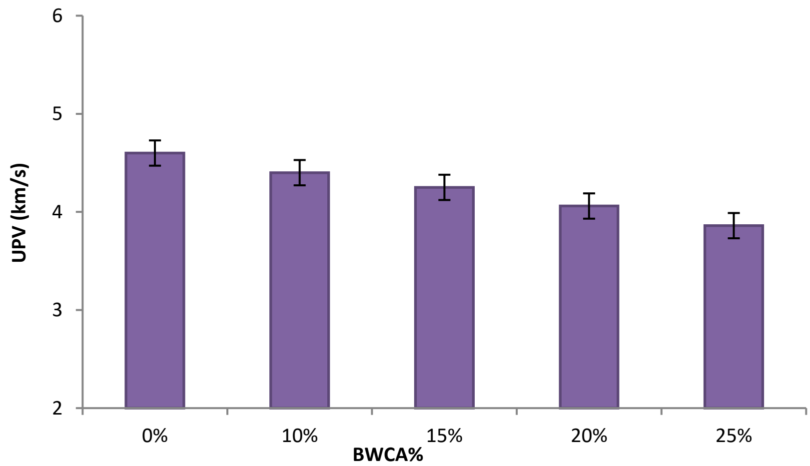


Fig. 9. UPV vs. BWCA%

The quality of concrete based on ultrasonic pulse velocity can be classified according to commonly accepted criteria. Concrete with UPV values greater than approximately 4.5 km/s is generally considered to possess excellent quality, values between 3.5 and 4.5 km/s indicate good quality concrete, while values between 3.0 and 3.5 km/s are typically classified as medium or doubtful quality. Based on these criteria, the results obtained in the present study indicate that all tested mixtures fall within the range of good to excellent quality concrete. The control mixture recorded the highest UPV value of approximately 4.6 km/s, corresponding to excellent concrete quality, while mixtures containing BWCA exhibited values between approximately 4.4 and 3.86 km/s, which still fall within the range of good quality concrete. The relationship between ultrasonic pulse velocity and compressive strength is presented in Figure 10. A strong correlation between these two parameters was observed, indicating that higher compressive strength values are generally associated with higher pulse velocity values. This relationship can be attributed to the fact that both properties are influenced by the internal density and integrity of the concrete matrix. As the microstructure becomes denser and the internal void content decreases, the propagation of ultrasonic waves becomes more efficient, resulting in higher UPV values. Regression analysis of the experimental results produced the following relationship between compressive strength and UPV:

$$f_c = -35.171\,(UPV)^2 + 297.54\,(UPV) - 589.02\ (R^2 = 0.9157) \tag{3}$$

where UPV is the ultrasonic pulse velocity expressed in km/s. In the same way, an empirical polynomial relationship between UPV and compressive strength was established. The suggested equation should only be regarded as appropriate to the materials and testing conditions used in this investigation due to the small number of experimental data points.

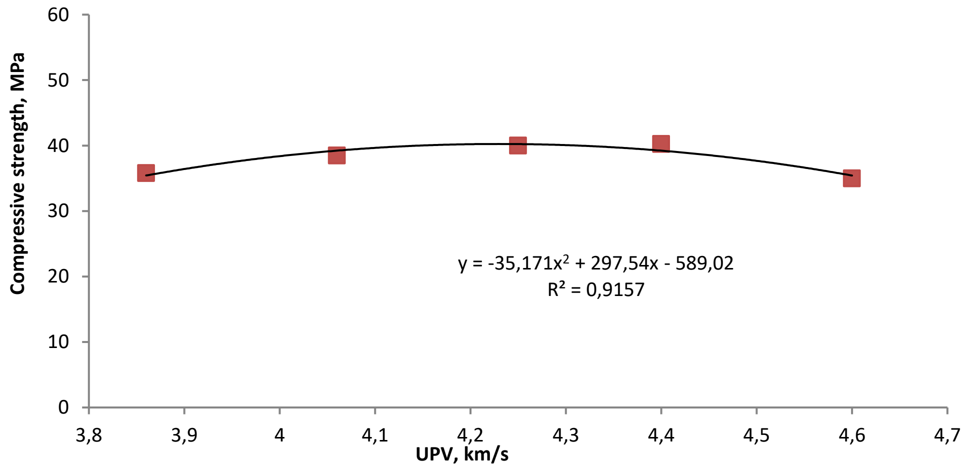
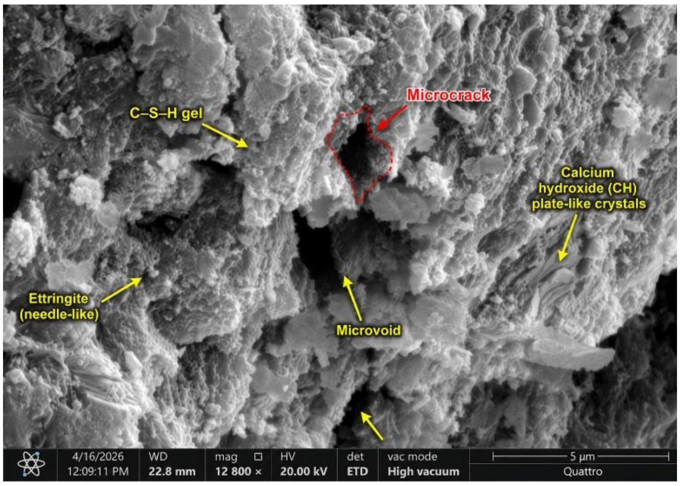


Fig. 10. Compressive strength vs. UPV for various BWCA %

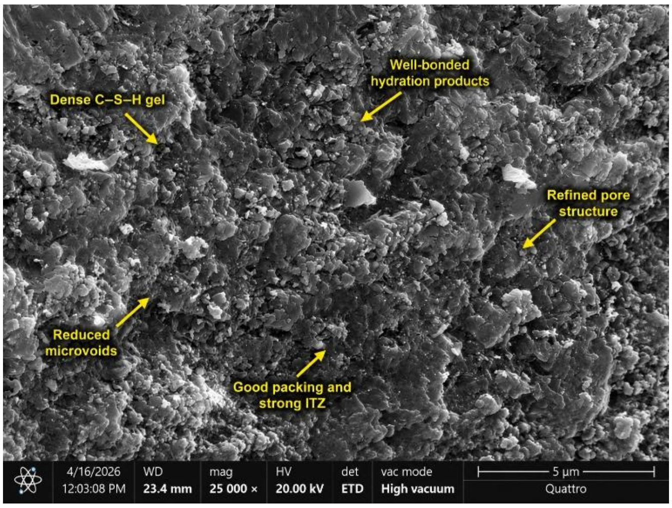
3.6 Microstructure Assessment by SEM

Scanning electron microscopy (SEM) was conducted to investigate the internal morphology, hydration products, pore structure, and interfacial transition zone (ITZ) characteristics of selected concrete mixtures incorporating BWCA. Representative micrographs of the control mixture, 10% BWCA, and 25% BWCA are shown in Figure 11. The control mixture (0% BWCA) exhibited a relatively dense and homogeneous microstructure characterized by a compact cementitious matrix with well-distributed hydration products and limited internal voids. The aggregate–paste interface appeared continuous and well bonded, indicating efficient stress transfer between constituents. Such dense morphology is consistent with the relatively high ultrasonic pulse velocity (4.6 km/s) and stable mechanical performance obtained experimentally. For the mixture containing 10% BWCA, the SEM image revealed a denser internal structure with increased formation of secondary hydration products partially filling micro voids. The rough and irregular surface texture of recycled brick particles promoted stronger mechanical interlocking with the surrounding cement paste. In addition, due to the porous nature of brick aggregates, absorbed water may have been gradually released during curing, enhancing cement hydration through an internal curing mechanism. This densification effect likely contributed to the improved compressive strength, splitting tensile strength, and acceptable flexural behavior observed for this mixture. At higher replacement content (25% BWCA), the microstructure became visibly more porous and discontinuous. Numerous capillary voids, microcracks, and loosely packed regions were detected.

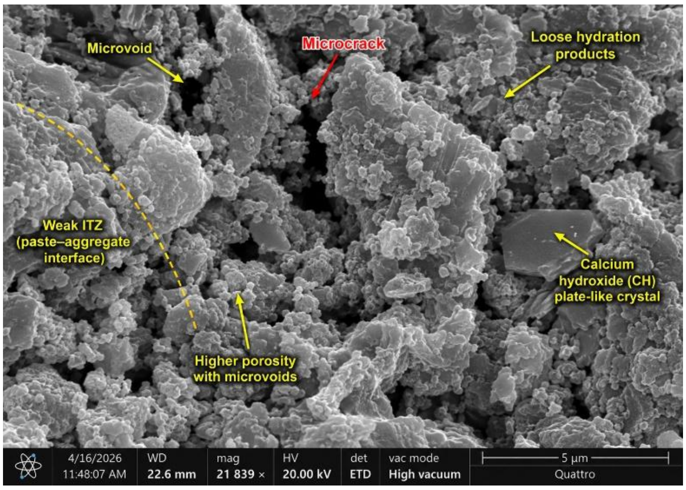
The progressive reduction in UPV values with increasing BWCA content can therefore be directly attributed to the increase in internal porosity and reduced continuity of the cementitious matrix, which hinder ultrasonic wave transmission. Similarly, the decrease in flexural strength at higher replacement levels is strongly associated with crack-sensitive weak ITZ regions observed in the SEM images. Overall, SEM observations confirm that moderate incorporation of BWCA (around 10–15%) can beneficially modify the concrete microstructure through internal curing, improved particle interlocking, and void refinement, whereas excessive replacement levels adversely affect matrix integrity due to increased porosity and weaker interfaces. SEM analysis validated that moderate BWCA incorporation improved matrix densification and bonding, while excessive replacement generated porous weak zones that reduced structural performance.



(a) Control specimens



(b) 10% BWCA



(c) 25% BWCA

Fig. 11. Scanning electron microscopy images of (a) 0% (b) 10% BWCA(c) 25% BWCA

3.7 Distribution of BWCA in Concrete by Image Analysis

The distribution of BWCA within the concrete matrix was evaluated using digital image analysis in order to investigate the homogeneity of the mixtures and the spatial dispersion of recycled brick particles throughout the concrete cross-sections. Hardened concrete specimens with dimensions of 10×10×10cm were cut into seven consecutive slices along the specimen depth. A very fine white powder was then carefully applied to the surface of each slice to enhance the visibility of the BWCA particles and improve the accuracy of the image analysis process. The images of the prepared slices were captured under constant lighting conditions and analyzed using the ImageJ software. Initially, the original RGB images were imported into ImageJ and converted into 8-bit grayscale images to facilitate particle detection. Since the recycled brick aggregates appeared in reddish while the natural aggregates appeared in white tones, thresholding analysis was applied to isolate the BWCA particles from the surrounding mortar matrix and natural aggregates. After applying the threshold function, the detected BWCA particles were highlighted and converted into binary images suitable for quantitative measurements. Representative images of the concrete sections before and during the image-processing procedure are shown in Figure 12.

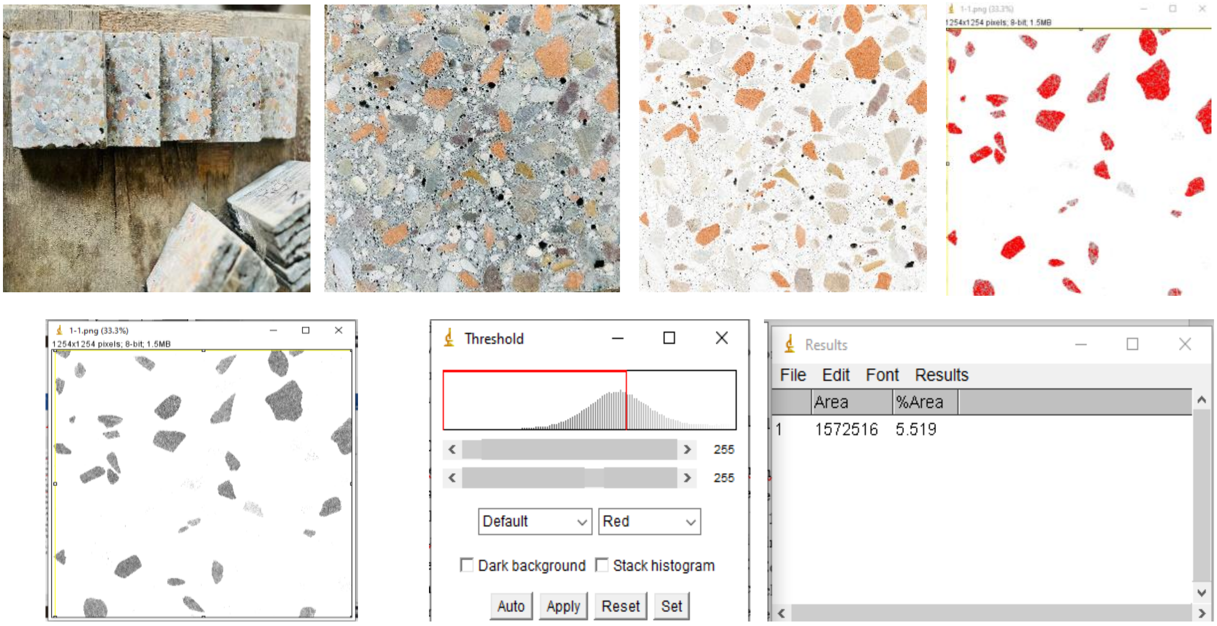


Fig. 12. Sequential image-analysis steps for BWCA detection and area calculation using ImageJ

The same digital camera was used to take all of the images under the same lighting circumstances and at a constant distance perpendicular to the sample surface in order to guarantee accurate quantitative readings. With a resolution of 1280 × 960 pixels, each image was captured with enough precision to differentiate BWCA particles from the surrounding mortar matrix.

Each image's spatial scale was adjusted in ImageJ before image processing using a reference dimension that was taken straight from the concrete slice. In order to guarantee consistency across all specimens, all measured areas were automatically transformed from pixels to actual geometric dimensions. ImageJ's Threshold function was used to identify BWCA particles. The threshold limits were manually chosen for the first image in order to precisely isolate the BWCA particles because the recycled brick aggregates had a distinctive reddish color while the natural aggregates appeared light gray to white after the application of fine white powder. To ensure uniformity and get rid of operator bias, the same threshold values were then applied to every slice made from the same concrete mixture. The Analyze Particles tool was used to generate and analyze binary images following thresholding. Before determining the predicted BWCA region, a minimum particle size filter was applied to eliminate small, isolated pixels and image noise. Every image was analyzed three times under the same processing parameters in order to assess repeatability. The adopted image-processing method was found to have high repeatability, as evidenced by the variance between repeated measurements being less than 2%. For quantitative image analysis of concrete cross-sections, the estimated overall measurement uncertainty was within ±2%.

Subsequently, the "Analyze Particles" function available in ImageJ was used to determine the projected area of BWCA particles within each slice. The percentage area occupied by BWCA was calculated according to the following equation:

$$Area\ of\ BWCA(\%)\ =(\frac{Area\ of\ BWCA\ particles}{Total\ slice\ area})\times 100 \tag{4}$$

The image-analysis results demonstrated that the BWCA particles were uniformly distributed throughout the concrete sections with no obvious signs of segregation or particle accumulation in specific regions. As illustrated in Figure 13, the percentage area of BWCA within the seven slices showed only slight variations for all replacement levels, indicating that the recycled brick aggregates were adequately dispersed during the mixing and casting processes. This behavior reflects the good cohesiveness and internal stability of the concrete mixtures despite the incorporation of recycled brick aggregates.

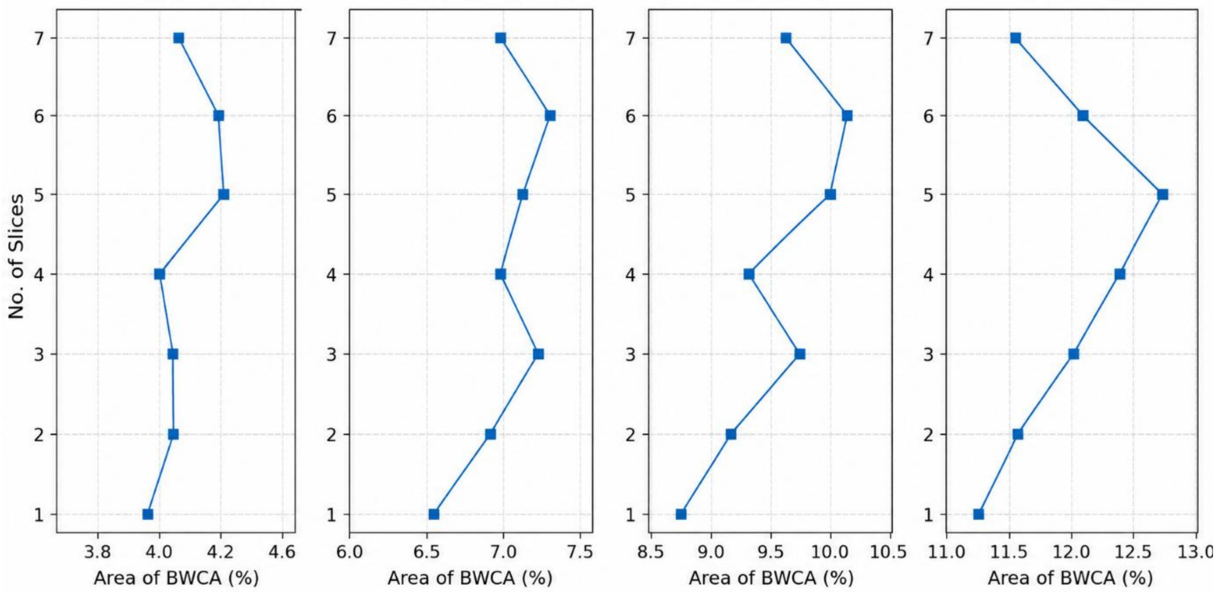


Fig. 13. Sequential image-analysis steps for BWCA detection and area calculation using ImageJ

For the 10% and 15% BWCA mixtures, the obtained values were highly consistent among the slices, which indicates excellent homogeneity and stable particle distribution within the concrete matrix. Such uniformity suggests that the amount of BWCA at these replacement levels did not adversely affect the workability or lead to segregation during casting. Moreover, the relatively smooth variation between adjacent slices confirms that the BWCA particles were randomly distributed within the specimen cross-sections. At higher replacement levels (20% and 25%), slightly greater fluctuations in the BWCA area percentages were observed between the slices.

Table 6. Mix proportions in (kg/ m^3)

BWCA Replacement of Coarse Aggregate (%)	Expected BWCA Area in Concrete Section (%)	ImageJ Measured Area (%)
10	4.0	4.1
15	6.0	7.0
20	8.0	9.7
25	10.0	12.0

Table 6 presents a comparison between the area fractions derived from ImageJ analysis and the theoretical projected BWCA area, which is computed from the volumetric replacement of coarse material. Despite the inherent uncertainty associated with two-dimensional sectioning, the actual values nearly match predicted trend, indicating the uniform distribution of BWCA throughout the concrete matrix. The measured area fractions agree reasonably well with the theoretical projected area expected from the replacement of coarse aggregate. The slight increase observed at higher replacement levels is attributed to local aggregate distribution, particle orientation, and the inherent variability associated with two-dimensional stereological measurements.

5. Conclusion

The following conclusions can be made with consideration of the experimental results:

- All mixes remained workable without changing the water/cement ratio or superplasticizer dose, indicating the practical validity of utilizing BWCA in conventional concrete production. However, the addition of BWCA somewhat decreased the workability of fresh concrete.
- The best overall performance was obtained by substituting 10–15% BWCA for natural coarse aggregate. Improved compressive, splitting tensile, and flexural behavior was demonstrated by these mixes, and their structural response under flexural loading was acceptable. Splitting tensile strength exhibited a slight increase at lower replacement levels, reaching its highest value at approximately 15% BWCA. The improvement can be attributed to enhanced mechanical interlocking and stronger interfacial bonding between the brick aggregates and the cement matrix.
- Increasing the replacement ratio of ordinary coarse aggregate with BWCA to over 20% resulted in a gradual decrease in mechanical and structural performance. However, even a concrete mix containing 25% BWCA exhibited mechanical properties not significantly inferior to those of the reference concrete, indicating that relatively high replacement ratios are still feasible for applications with moderate strength requirements.
- The enhanced behavior of the 10–15% BWCA combinations was linked to a denser internal matrix and a more uniform distribution of recycled brick aggregates throughout the concrete, according to SEM observations and ImageJ-based image analysis.
- Ultrasonic pulse velocity values ranged between 4.6 and 3.86 km/s, indicating that all tested mixtures fall within the range of good to excellent quality concrete. A strong correlation was also observed between UPV and compressive strength, confirming that UPV can be used as a reliable non-destructive indicator for assessing the quality of BWCA concrete.
- From an engineering perspective, the findings show that substituting 10–15% of the natural coarse aggregate with BWCA effectively achieves the right balance between sustainable material use and structural behavior. Therefore, this replacement level can be regarded as a reasonable choice for making structural concrete while lowering the usage of virgin natural aggregates and encouraging the advantageous reuse of waste from building and demolition.
- For the concrete mixes under investigation, the suggested regression equations offer empirical correlations. However, additional experimental data covering wider mixture proportions and independent validation datasets are required before these relationships can be generalized for practical prediction purposes.
- The present investigation was limited to short-term fresh, mechanical, microstructural, and structural characterization. Long-term durability aspects, including water absorption, sorptivity, chloride penetration, sulfate resistance, drying shrinkage, carbonation, freeze–thaw resistance, and comprehensive life-cycle assessment, were beyond the scope of this study and should be addressed in future research to further evaluate the long-term performance and environmental benefits of BWCA concrete.

References

[1] Hasan MJ, Al-Shamaa MF. Effect bubbles on the behavior of reinforced reactive powder concrete deep beams. Int J Civ Eng Technol. 2018;9(12):592-602.

[2] Hama SM, Abdulghafor AM. Load deflection behaviour and properties of sustainable lightweight aggregate concrete slabs. Int J Comput Aided Eng Technol. 2022;17(1):45-56. https://doi.org/10.1504/IJCAET.2022.124529

[3] Dalkılıç N, Nabikoğlu A. Traditional manufacturing of clay brick used in the historical buildings of Diyarbakir (Turkey). Front Archit Res. 2017;6(3):346-359. https://doi.org/10.1016/j.foar.2017.06.003

[4] Rajab O, Ali ZM, Hama SM. Influence of crushed eggshell content as fine aggregate replacement on cement mortars properties. AIP Conf Proc. 2023;2787(1):080018. https://doi.org/10.1063/5.0148183

[5] Mohammed TK, Hama SM. Studying the concrete characteristics using waste plastic as a partial replacement for fine aggregate. AIP Conf Proc. 2024;3009(1):030046. https://doi.org/10.1063/5.0190538

[6] Théréné F, Keita E, Naël-Redolfi J, Boustingorry P, Bonafous L, Roussel N. Water absorption of recycled aggregates: Measurements, influence of temperature and practical consequences. Cem Concr Res. 2020;137:106196. https://doi.org/10.1016/j.cemconres.2020.106196

[7] Bheel N, Kumar KR, Kumar A, Bhagam R, Adesina A, Meghwar S, et al. Innovative use of brick wastes as coarse aggregate in concrete. IOP Conf Ser Mater Sci Eng. 2020;981(1):012023. https://doi.org/10.1088/1757-899X/981/1/012023

[8] Yongcheng J, Wang D, Wang L. Numerical and experimental investigation of recycled brick coarse aggregate concrete. Appl Sci. 2022;12(18):9035. https://doi.org/10.3390/app12189035

[9] Liu X, Wu J, Zhao X, Yan P, Ji W. Effect of brick waste content on mechanical properties of mixed recycled concrete. Constr Build Mater. 2021;292:123320. https://doi.org/10.1016/j.conbuildmat.2021.123320

[10] Mohammed VB, Hama SM, Aziz KI. Assessment strength properties of modified reactive powder concrete by adding waste bricks. In: Proceedings of the 12th International Conference on Developments in eSystems Engineering (DeSE). IEEE; 2019. p. 83-87. https://doi.org/10.1109/DeSE.2019.00025

[11] Abbas SN, Qureshi MI. Variation in mechanical properties of concrete having recycled brick aggregates, recycled concrete aggregates and recycled plastic aggregates: A review. Next Res. 2025;2(2):100324. https://doi.org/10.1016/j.nexres.2025.100324

[12] AbdElMoaty AMN, Ibrahim HHA, Ismail MK. Mechanical and transport properties of concrete incorporating recycled crushed clay bricks as coarse and fine aggregates. Sci Rep. 2025;15(1):31782. https://doi.org/10.1038/s41598-025-16833-5

[13] Joyklad P. Evaluating research on the utilization of recycled brick aggregates in concrete. Discov Appl Sci. 2024;6(4):167. https://doi.org/10.1007/s42452-024-05840-2

[14] Hama SM, Hama SM, Abdulghafor AM, Alfahdawi IH, Jahami A. Performance of structural concrete incorporating waste brick as coarse aggregate. Adv Civ Eng. 2025;2025:6676240. https://doi.org/10.1155/adce/6676240

[15] Joyklad P, Ali N, Chaiyasarn K, Poovarodom N, Yooprasertchai E, Maqbool HM, et al. Improvement of stress–strain behavior of brick-waste aggregate concrete using low-cost FCSM composites. Constr Build Mater. 2022;351:128946. https://doi.org/10.1016/j.conbuildmat.2022.128946

[16] Islam MN, Choudhury MSI, Amin AFMS. Dilation effects in FRP-confined square concrete columns using stone, brick, and recycled coarse aggregates. J Compos Constr. 2016;20(1):04015017. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000574

[17] Mansur MA, Wee TH, Cheran LS. Crushed bricks as coarse aggregate for concrete. ACI Mater J. 1999;96(4):478-484. https://doi.org/10.14359/649

[18] Yang J, Du Q, Bao Y. Concrete with recycled concrete aggregate and crushed clay bricks. Constr Build Mater. 2011;25(4):1935-1945. https://doi.org/10.1016/j.conbuildmat.2010.11.063

[19] Poon CS, Kou SC, Lam L. Use of recycled aggregates in molded concrete bricks and blocks. Constr Build Mater. 2002;16(5):281-289. https://doi.org/10.1016/S0950-0618(02)00019-3

[20] Debieb F, Kenai S. The use of coarse and fine crushed bricks as aggregate in concrete. Constr Build Mater. 2008;22(5):886-893. https://doi.org/10.1016/j.conbuildmat.2006.12.013

[21] Hasan AN, Hama SM. The efficiency of partially substituting waste brick fine aggregate for sand on concrete fresh state, strength, and durability. AIP Conf Proc. 2026;3248(1):020011. https://doi.org/10.1063/5.0330458

[22] Central Organization for Standardization and Quality Control. Iraqi Standard Specification No. 5: Portland cement. Baghdad: COSQC; 2019.

[23] Central Organization for Standardization and Quality Control. Iraqi Standard Specification No. 45: Aggregate from natural sources for concrete and building construction. Baghdad: COSQC; 1984.

[24] ASTM International. ASTM C494/C494M: Standard specification for chemical admixtures for concrete. West Conshohocken, PA: ASTM International; 2005. https://doi.org/10.1520/C0494_C0494M-05

[25] ASTM International. ASTM C143/C143M-03: Standard test method for slump of hydraulic-cement concrete. West Conshohocken, PA: ASTM International; 2003. https://doi.org/10.1520/C0143_C0143M-03

[26] British Standards Institution. BS EN 12390-3: Testing hardened concrete. Compressive strength of test specimens. London: BSI; 2009. https://doi.org/10.3403/30163363

[27] ASTM International. ASTM C496/C496M-17: Standard test method for splitting tensile strength of cylindrical concrete specimens. West Conshohocken, PA: ASTM International; 2017. https://doi.org/10.1520/C0496_C0496M-17

[28] ASTM International. ASTM C78/C78M-15: Standard test method for flexural strength of concrete (using simple beam with third-point loading). West Conshohocken, PA: ASTM International; 2015. https://doi.org/10.1520/C0078_C0078M-15
[29] ASTM International. ASTM C597/C597M-16: Standard test method for pulse velocity through concrete. West Conshohocken, PA: ASTM International; 2016. https://doi.org/10.1520/C0597_C0597M-16
[30] Hama SM, Ali ZM, Zayan HS, Mahmoud AS. Structural behavior of reinforced concrete incorporating glass waste as coarse aggregate. J Struct Integr Maint. 2023;8(1):59-66. https://doi.org/10.1080/24705314.2023.2165470
[31] Al-Kerttani OMG, Hilal N, Hama SM, Banyhussan QS, Tawfik TA. Durability and hardened characteristics of cement mortar incorporating waste plastic and polypropylene exposed to $MgSO_4$ attack. Results Eng. 2024;24:103310. https://doi.org/10.1016/j.rineng.2024.103310
[32] Guo H, Shi C, Guan X, Zhu J, Ding Y, Ling TC, et al. Durability of recycled aggregate concrete – A review. Cem Concr Compos. 2018;89:251-259. https://doi.org/10.1016/j.cemconcomp.2018.03.013
[33] Thomas C, Setién J, Polanco JA, Alaejos P, Sánchez de Juan M. Durability of recycled aggregate concrete. Constr Build Mater. 2013;40:1054-1065. https://doi.org/10.1016/j.conbuildmat.2012.11.106
[34] Farhan OS, Hama SM, Fayadh OK. Flexural and shear behavior of reinforced sustainable concrete beams incorporating waste walnut shells as lightweight aggregate. Int J Adv Sci Eng Inf Technol. 2025;15(3):952-959. https://doi.org/10.18517/ijaseit.15.3.13144