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Comparative mechanical performance evaluation of recycled brick aggregate concrete and natural aggregate concrete

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ABSTRACT

The global increase in construction and demolition (C&D) waste due to natural disasters and urban redevelopment presents a significant environmental challenge. This study evaluates the mechanical performance of reinforced concrete (RC) beams incorporating recycled brick aggregates (RBA) as a sustainable alternative to natural aggregates (NA). Four concrete mixes were tested: 100 % NA, 100 % RBA, and two hybrid combinations of fine and coarse aggregates. RC beams were subjected to four-point bending tests, and companion cylindrical and prismatic specimens were tested for compressive strength and modulus of rupture (MOR). Results indicate that RC beams made with RBA can achieve shear capacities comparable to those made with NA. While beams incorporating coarse brick aggregates showed a more pronounced reduction in shear strength, with values dropping to 53.0 kN, the highest shear strength (71 kN) was observed in mixes using brick fine aggregates and natural coarse aggregates, nearly matching the 70.8 kN of the 100 % NA mix. However, 100 % RBA mixes exhibited a 24 % reduction in compressive strength and a 16 % reduction in MOR compared to NA mixes. Despite these reductions, the structural behavior and failure modes remained consistent across all compositions. From a sustainability perspective, the use of RBA offers a dual benefit: reducing the demand for virgin aggregates and diverting substantial volumes of brick waste from landfills. In regions where C&D waste constitutes a significant portion of total solid waste, adopting RBA concrete could conserve millions of tons of natural resources annually. This study demonstrates the feasibility of using 100 % recycled brick aggregates in structural concrete, supporting a circular economy approach in the construction sector.

1. Introduction

The construction industry has long been a cornerstone of human development, evolving from ancient techniques to modern engineering marvels such as bridges, skyscrapers, and transportation infrastructure [1]. Today, concrete remains the most widely used construction material globally – second only to water in terms of consumption [2] – with an estimated three tons used per person

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annually [3]. Its widespread use is attributed to its strength, versatility, and cost-effectiveness. However, the built environment is increasingly recognized as one of the major contributors to climate change, both in terms of energy consumption and environmental impact [4,5]. As urbanization accelerates globally, the need to optimize the use of resources – particularly materials and energy – has become a central concern for sustainable development [6,7].

This is especially relevant in the construction sector, which relies heavily on concrete, a material whose production is energy-intensive and environmentally taxing. Indeed, the environmental footprint of concrete production, particularly that of cement, has become a growing concern. Although comprising only 10–15 % of the concrete mix by volume, cement is responsible for approximately 8 % of global CO_2 emissions due to its energy-intensive manufacturing process [8,9]. Each ton of Portland cement produced releases nearly one ton of CO_2 into the atmosphere [9]. With global cement production exceeding 4,100 megatons annually, the environmental implications are substantial [10]. The increasing demand for cement also accelerates the depletion of non-renewable resources such as limestone and clay, raising concerns about long-term sustainability [11].

In parallel, modern industrial, agricultural, and urban activities contribute to widespread environmental degradation through the release of pollutants and improper waste management [12,13]. In response to growing environmental concerns, numerous physico-chemical and biological methods have been developed to remediate contaminated water sources [14,15] and polluted soils [16–18]. These challenges have prompted a global shift toward green technologies and sustainable development practices [19–21]. In the construction sector, this has led to growing interest in alternative materials and methods that reduce environmental impact without compromising structural integrity and energy performance [22–27]. At the same time, it is becoming increasingly important to maximize the durability and structural soundness of existing concrete buildings [28–30].

One promising approach is the partial or complete substitution of conventional concrete components with recycled or locally sourced materials [31–34]. This not only conserves natural resources but also supports circular economy principles by repurposing construction and demolition (C&D) waste [35,36]. As industry seeks to balance performance with sustainability, innovative solutions such as recycled aggregate concrete are gaining traction as viable options for future infrastructure development [37].

In regions frequently affected by climate-related disasters, such as floods and earthquakes, the destruction of infrastructure generates vast quantities of C&D waste [38]. This waste, if not properly managed, contributes to pollution and environmental degradation [39,40]. For example, in recent years, severe flooding events have led to the destruction of hundreds of thousands of homes, resulting in large volumes of concrete and clay brick debris. These materials, traditionally destined for landfills, can instead be recycled and reused in new construction projects [41,42].

Historically, recycled concrete aggregates (RCA) were used primarily as landfill material due to limited recycling facilities. However, advancements in concrete technology have enabled their use in non-structural applications such as partition wall blocks, flooring, foundation mats, road base layers, and paving blocks [23,43]. Despite this progress, the use of recycled brick aggregates (RBA) in structural concrete remains underexplored. Recycled brick was first used with Portland cement concrete in the 19th century, and its broader application emerged after World War II during reconstruction efforts [44].

Recent studies have investigated the mechanical performance of concrete incorporating recycled brick aggregates. Tek Raj Gyawali [45] demonstrated that using 100 % recycled coarse aggregate can increase 28-day compressive strength by 4.5 %. Conversely, using 20 % brick aggregates in saturated surface dry (SSD) condition decreased compressive strength by 15 %, while oven-dry conditions improved it by 10.1 %. Dey and Pal [46] found that flexural strength of concrete with crushed brick aggregates exceeded the Indian code recommendation of $0.7\sqrt{fck}$. Bogdan Rosca [47] showed that replacing sand with brick fine aggregates reduced structural strength by 17 %.

The shear capacity of reinforced concrete (RC) beams made with recycled aggregates has also been widely studied. Muhammad et al. [48] identified key variables affecting shear capacity: shear span-to-depth ratio, compressive strength, and longitudinal tensile steel ratio. Their findings indicated that increasing steel ratio and compressive strength enhances shear capacity, while increasing span-to-depth ratio reduces it. Liu et al. [49] reported that increasing recycled brick coarse aggregate (RBCA) content decreases compressive strength and elastic modulus but has minimal effect on splitting tension and flexural strength when total recycled content is below 30 %.

Sharba et al. [50] explored the use of treated waste brick and steel slag in RC beams, noting a slight reduction in shear strength at low replacement levels and negative effects beyond 22 % substitution. Mohammed and Hasnat [51] found no significant difference in modulus of rupture between recycled brick aggregates and conventional aggregates at water-cement ratios of 0.45 and 0.55. Rahman et al. [52] studied the influence of brick strength on concrete properties, showing that modulus of rupture varied significantly depending on brick class and mix ratio.

Further research by Muhammad et al. [53] involved testing 32 RC beams made with brick and recycled brick aggregates without shear reinforcement. Their results confirmed that shear capacity decreases with increasing span-to-depth ratio and increases with higher steel ratio and compressive strength. Aly et al. [54] and Ignjatović et al. [55] also found that RC beams made with recycled aggregates exhibit shear behavior comparable to those made with natural aggregates.

In many countries, the depletion of natural resources used for concrete production is becoming a pressing issue. The construction industry consumes vast quantities of coarse aggregates to meet growing demand, contributing to environmental degradation. Globally, C&D waste accounts for a significant portion of total solid waste – up to 30 % in some [56]. Recycling this waste into useable construction materials offers a sustainable solution that aligns with international goals for climate resilience and resource conservation [57,58].

This study investigates the structural performance of RC beams made with recycled brick aggregates under shear loading, without shear reinforcement. Beams with cross-sectional dimensions of 100 × 200 mm and a length of 1200 mm were cast and tested using four-point bending. Cylindrical and prismatic specimens were also prepared to evaluate compressive strength and modulus of rupture.

Unlike previous studies, this research focuses on using 100 % recycled brick aggregates – both fine and coarse – as a complete replacement for natural aggregates. The findings contribute to the growing body of knowledge on sustainable construction practices and demonstrate the potential of RBA concrete as a viable alternative in structural applications.

2. Materials and methods

2.1. Materials

In this study, ordinary Portland cement conforming to the requirements of ASTM C150 [59] was used as a binding material to prepare all concrete mixes. Recycled brick aggregates (RBA) were produced by crushing commercially tested burnt clay bricks. The following step-by-step procedure was adopted to produce RBA:

- Damaged bricks were broken into small pieces with a hammer.
- The broken pieces sized 60–75 mm were passed through a roller crusher to achieve a maximum particle size of 19 mm.
- Recycled brick aggregates obtained after roller crushing were separated into coarse and fine aggregates using ASTM Sieve 4.

The production process of RBA is shown in Fig. 1. The properties of fine and coarse RBA along with fine and coarse natural aggregates are presented in Table 1. For concrete preparation, normal tap water was used. Sargodha crush, with a maximum size of 19 mm, was used for natural coarse aggregates, and Lawrencepur sand, with a maximum size of 4.76 mm, was used for natural fine aggregates.

2.2. Concrete mixes

A total of eight RC beams were cast using four concrete mixes. For all concrete mixes in this study, a fixed mix ratio of 1:2:4 (cement: fine aggregates: coarse aggregates) by weight was adopted. Details of all four mixes with respect to the type of fine and coarse aggregates used are provided in Table 2. It is important to note that coarse recycled brick aggregates were used in SSD condition, and that extra water, equivalent to the water absorption of fine recycled brick aggregates, was added to each mix containing these fine aggregates. More specifically, brick coarse aggregates were used in SSD condition to support proper cement hydration according to the designed water-to-cement (w/c) ratio. This practice contributes to the formation of a denser ITZ, which in turn enhances the overall strength of the concrete.

2.3. Details of tests specimens

A total of eight RC beams with a cross-sectional size of 100 × 200 mm and a length of 1200 mm were cast for testing under four-point loading. The size and reinforcement details of the RC beams are provided in Fig. 2, where it can be observed that two #4 bars of Grade 60 were provided as flexure reinforcement. No shear reinforcement was provided. Only two #2 stirrups (one on both sides) were provided at the support location to support the top bars. To determine the compressive strength and modulus of rupture of the

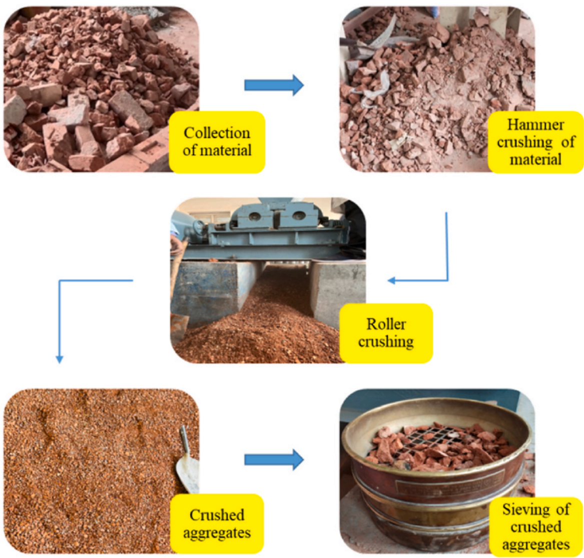

Fig. 1. Production process of RBA

Table 1
Properties of fine and coarse aggregates.

Property	Testing Standard	Recycled Brick Aggregates		Natural Aggregates	
		Coarse	Fine	Coarse	Fine
Water Absorption (%)	ASTM C128 [60]	14.24	13.68	1	0.75
Moisture Content (%)	ASTM C566 [61]	0.20	0.63	–	–
Compacted Bulk Density (kg/m^3)	ASTM C29 [62]	1030	1310	1530	1600
Fineness Modulus	ASTM C117 [63]	–	2.85	–	2.75
Aggregates Impact Value, AIV (%)	BS 812-112 [64]	30	–	11.6	–
10 % Fine Value, TFV (kN)	BS 812-111 [65]	60	–	240	–

Table 2
Concrete mixes with reference to aggregates type and related label.

Mix No.	Types of Aggregates		Label
	Fine	Coarse	
1	Recycled Brick	Recycled Brick	FA-R, CA-R
2	Natural	Natural	FA-N, CA-N
3	Recycled Brick	Natural	FA-R, CA-N
4	Natural	Recycled Brick	FA-N, CA-R

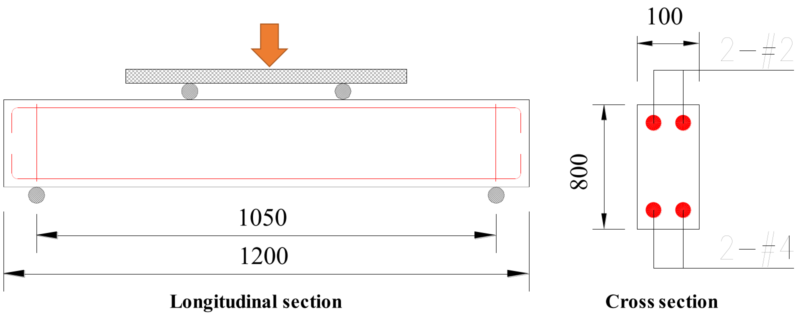

Fig. 2. Reinforcement detail of RC beam.

concrete, cylinders of 100 mm diameter and 200 mm height and prismatic specimens with a cross-section of 75 × 75 mm and a length of 300 mm were cast in the laboratory.

2.4. Sample testing

Shear, compressive strength, and modulus of rupture tests were performed on the concrete samples to investigate their behavior. Fig. 3 shows the process flow of the study under consideration.

2.4.1. Compressive strength test

The compressive strength test was performed on the cylinders 28 days after casting using a 100-ton Shimadzu Universal Testing Machine (UTM). The cylinders were tested in accordance with ASTM C39/C39M [66].

The cylinders were placed in the testing machine with their flat surfaces aligned with the loading platen. A compressive load was applied at a constant rate of 1 mm/min until failure occurred, at which point the failure load was recorded. The compressive strength of the cylinders was calculated as the maximum load applied to the cylinders divided by their cross-sectional area. A minimum of three cylinders were tested from each composition.

2.4.2. Modulus of rupture test

The modulus of rupture test was performed on prisms 28 days after casting using a 100-ton Shimadzu Universal Testing Machine (UTM). The prisms were 300 mm long with a clear span of 225 mm. The test on the prisms was performed using the four-point loading method in accordance with ASTM C78/C78M [67] and ASTM C67 [68].

As shown in Fig. 4, the prisms were placed in the machine with the supports positioned at a distance of 1/3 of the clear span from each end of the prism. The load was applied at two points, 75 mm from each end of the shear span. The loading rate for the test was set at 0.5 mm/min, and the test continued until failure occurred. The modulus of rupture was calculated for the maximum load.

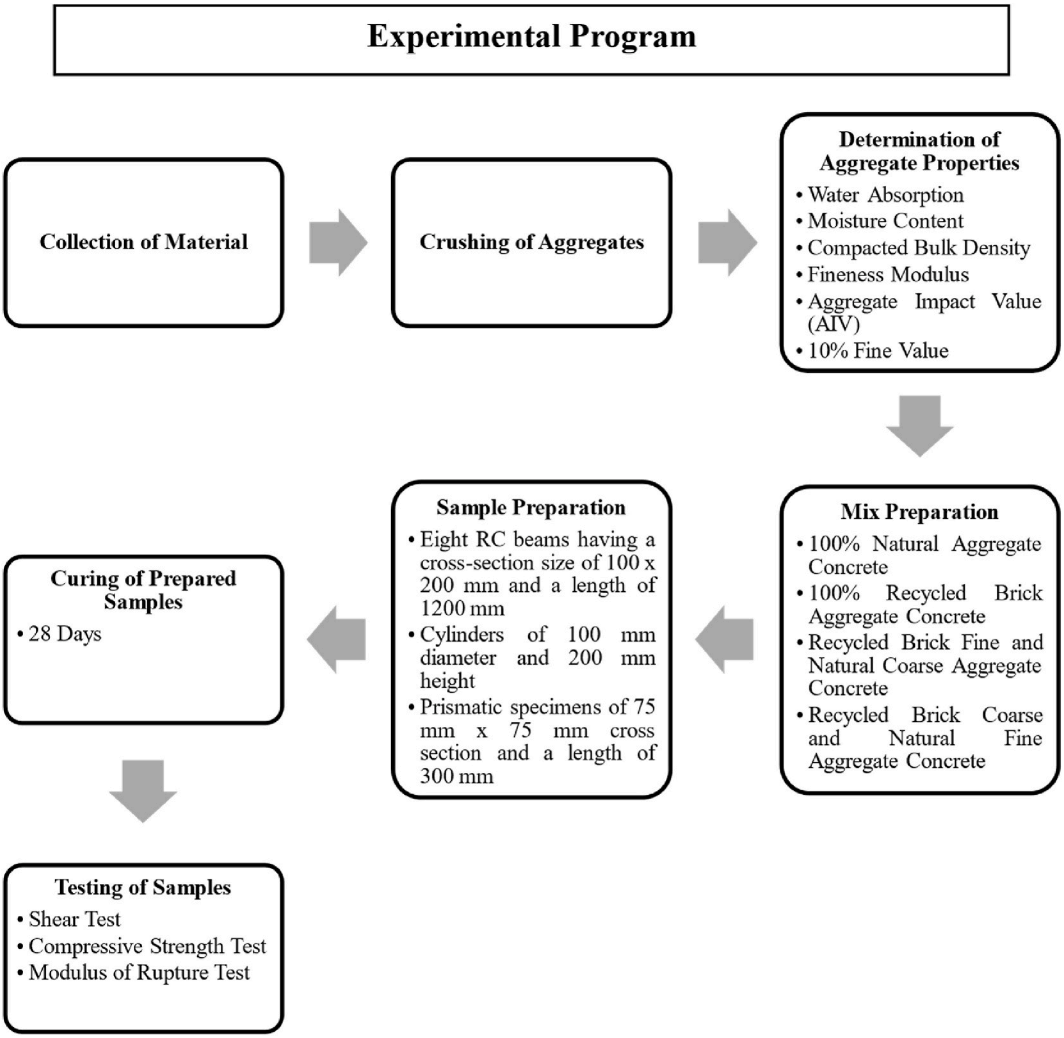

Fig. 3. Experimental procedure of the study under consideration.

2.4.3. *Shear test*

Shear tests were performed on the beams 28 days after casting. The tests were performed using a 100-ton Shimadzu Universal Testing Machine (UTM) connected to a data acquisition system. The beams were 1200 mm long, with a clear span of 1050 mm and a shear span of 350 mm. The shear span-to-depth ratio was 1.75. The four-point loading method was adopted for this test. The UTM was calibrated prior to testing to ensure accurate and consistent results.

The beams were placed with the supports positioned at a distance of 1/3 of the clear span from each end of the beam, as shown in Fig. 5. The loading setup was such that the load was applied at two points, 75 mm from each end of the shear span. The loading rate for the test was set at 1 mm/min, and the test continued until shear failure occurred. During the test, a data acquisition system was used to obtain load and deformation data. Additionally, the load at which the first visible crack appeared was recorded as the shear capacity of the beam.

2.4.4. *Prediction of shear capacity*

Researchers have proposed a variety of codes and equations to calculate the shear capacity of RC beams. Among the various approaches available, the shear capacity of RC beams with minimal shear reinforcement was evaluated in accordance with ACI Code 318-M [69] using the following empirical equation:

$$V_c = 0.17\sqrt{f_c'}b_w d \tag{1}$$

where:

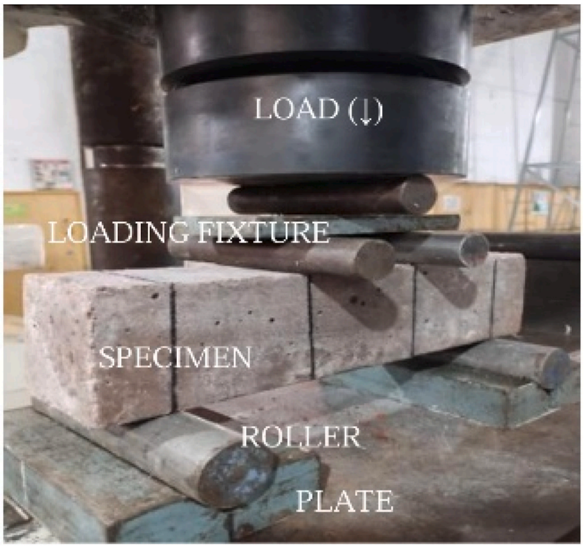

Fig. 4. Modulus of rupture test.

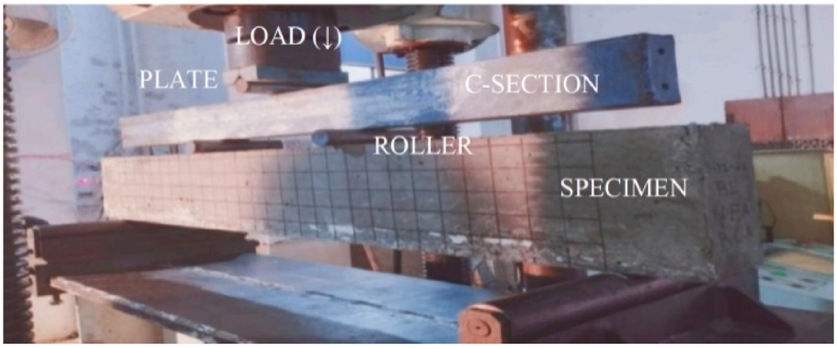

Fig. 5. Test setup for shear test on RC beam.

$f_c{}'$ = compressive strength of concrete in MPa
b_w = width of the beam in mm
d = effective depth of the beam in mm
V_c = shear capacity of concrete in kN

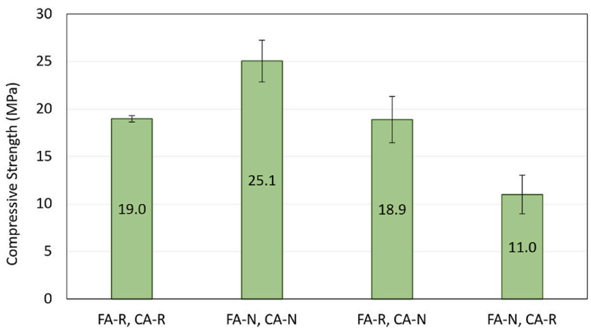

Fig. 6. 28-day compressive strength of cylinders. Data are reported as mean and standard deviation.

3. Results and discussion

The main results obtained are discussed below. Although the number of beams tested for each mix was limited in relation to structural assessment criteria, care was taken to maintain consistency throughout the experimental cycle and minimize variability. As a result, the findings provide a reliable representation of the structural response of the different concrete mixes.

3.1. Compressive strength

As mentioned above, the test for compressive strength was performed on 100 × 200 mm cylinders 28 days after casting. A minimum of three cylinders were tested from each composition, and the results are reported as mean and standard deviation in Fig. 6. As Fig. 6 shows, 100 % NAC showed the highest compressive strength, with a water-to-cement ratio of 0.55. Conversely, 100 % RBAC cylinders exhibited 24 % lower strength than those of NAC. The water-to-cement ratio was kept at 0.4 for this composition. FA-R + CA-N cylinders exhibited an average compressive strength of 18.9 MPa, which is close to that of the 100 % RBAC cylinders. The water-cement ratio for this mix was also kept close to that of 100 % NAC, which was 0.53. FA-N + CA-R composition showed the lowest strength of the four compositions, with an average compressive strength value of 11 MPa due to the weak bond between the brick coarse aggregates and the matrix.

3.1.1. Failure modes in compressive strength test

When the cylinders were subjected to an axial compressive load, cracks began to propagate along their length. As the load increased, crushing of concrete occurred. The maximum compressive load at which considerable cracking occurred and no further increase in the load was noted was considered the compressive strength of that type of concrete. Fig. 7 shows the typical failure mode in compression of each type of cylinder tested in this study.

3.2. Flexural strength

As shown in Fig. 8, all the tested prisms passed the standard MOR value of 1.96 MPa. Prisms with 100 % natural aggregates showed the highest value of MOR, about 4.25 MPa. Prisms with natural fine aggregates and brick coarse aggregates exhibited the lowest value of MOR, 3.52 MPa. Concrete with 100 % Recycled Brick aggregate showed an MOR value of about 3.56 MPa, while the prism cast with natural brick aggregates and brick fine aggregates exhibited an MOR value close to that of the 100 % NAC prism. This is because the matrix formed with brick fine aggregates developed more strength than the matrix in natural concrete.

3.2.1. Failure modes in flexural strength test

The failure mode of concrete prisms in flexure was characterized by brittle failure, occurring without any prior warning signs. Cracks originated in the tensile zone and propagated through the entire depth of the prism up to the compression zone. In prisms made with brick coarse aggregates, the failure plane passed directly through the aggregates, whereas in those made with natural coarse aggregates, the failure plane passed around the aggregates through the Interfacial Transition Zone (ITZ). Fig. 9 illustrates the typical failure mode in flexure exhibited by each type of prism tested in this study.

The passing of the failure plane through the brick aggregates indicates that the recycled brick coarse aggregates (RBCA) are weaker than the ITZ. Although using aggregates in Saturated Surface Dry (SSD) conditions improved ITZ formation, the inherent weakness of brick aggregates contributed to a reduction in overall concrete strength. It is worth noting that the irregular surface texture and high porosity of brick aggregates can enhance interfacial bonding [70]. A nested zone forms as hydration products precipitate within the pores, improving the integrity between the aggregate and the calcium silicate hydrate (C-S-H) matrix; this process strengthens the interfacial bond between the aggregate and the surrounding cementitious material [71].

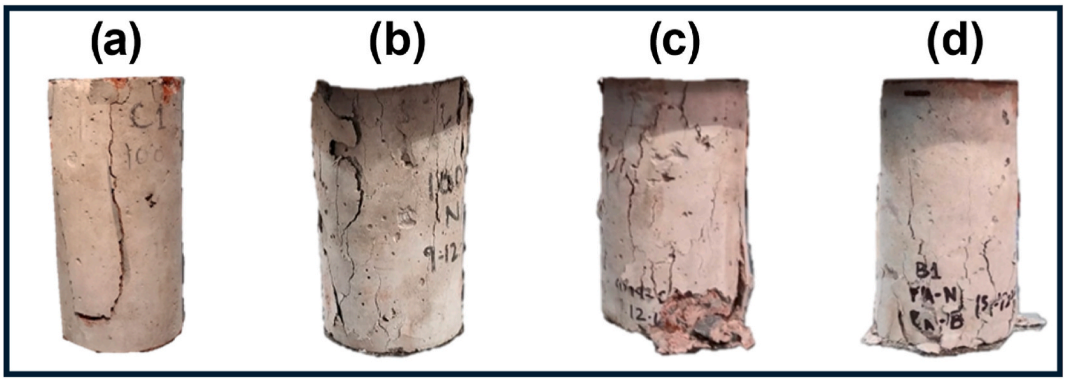

Fig. 7. Failure modes in compression: (a) FA-R, CA-R; (b) FA-N, CA-N; (c) FA-R, CA-N; (d) FA-N, CA-R.

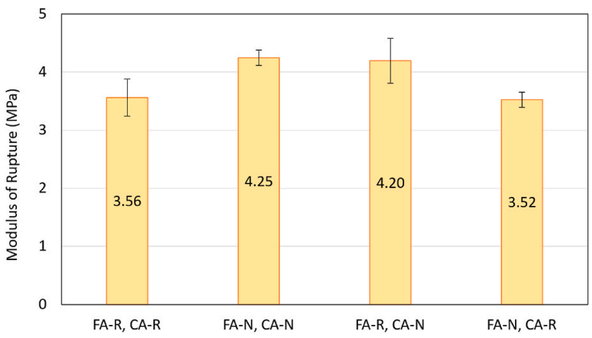

Fig. 8. Modulus of Rupture. Data are reported as mean and standard deviation.

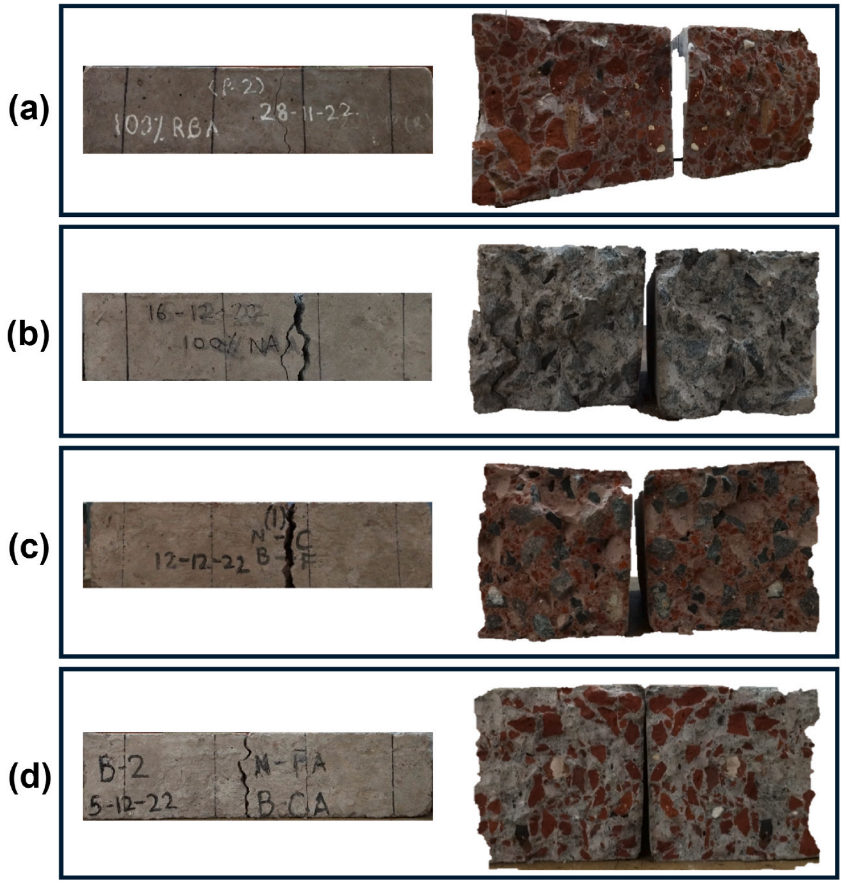

Fig. 9. Failure modes in flexure: (a) FA-R, CA-R; (b) FA-N, CA-N; (c) FA-R, CA-N; (d) FA-N, CA-R.

3.3. Shear capacity of RC beams

Eight beams, two from each composition, were tested for shear under four-point loading conditions in a UTM connected to a data acquisition system. Fig. 10 shows the load and deflection response of the beams from each composition. As shown in this figure, reinforced RBAC with brick fine aggregates and natural coarse aggregates, as well as reinforced NAC, exhibited the highest shear strengths, at 71 kN and 70.8 kN, respectively. Reinforced RBAC with brick coarse aggregates and natural fine aggregates showed nearly 19 % less shear strength as compared to reinforced RBAC with brick fine aggregates and natural coarse aggregates. 100 % reinforced RBAC exhibited around 25 % less strength as compared to reinforced RBAC with brick fine aggregates and natural coarse aggregates.

3.3.1. Failure modes of RC beams in shear

All of the tested reinforced beams failed in shear, exhibiting the same cracking pattern. The cracks developed near the support at a

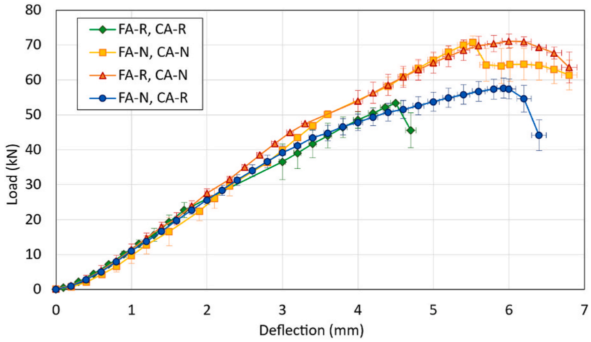

Fig. 10. Load vs deflection curve.

45 ° angle and propagated upwards. Fig. 11 shows the typical failure mode in shear exhibited by each type of beam tested in this study.

3.3.2. *Comparison of experimental observation and analytical prediction*

Comparison of shear capacity for various mix compositions obtained from the shear test as well as predicted through the above-mentioned codes is summarized in Table 3.

The experimental shear capacity surpassed all the values predicted by the ACI code. This could be because the equation in the code is designed to analyze the behavior of conventional concrete beams. Therefore, the non-conventional concrete beams investigated did not demonstrate the same shear capacity. In this study, shear capacity is defined as the load at which the first diagonal crack large enough to be visible to the naked eye forms. The true shear capacity is essentially the load at which the first hairline crack forms in concrete. However, due to a lack of the latest technology and devices, the exact load value at which the first micro-crack develops in concrete cannot be determined. This factor also contributes to the significant difference between the observed experimental shear capacity and the predicted shear capacities. As in previous studies, both the shear capacity and the compressive strength of the RBA concrete decreased compared to the NA concrete. Additionally, the modulus of rupture also decreased due to the replacement of natural aggregates with recycled brick aggregates in the concrete mix. Although the shear capacity of the RBA concrete beam approached that of the NA concrete beam, it was still lower; therefore, no positive influence with respect to NA concrete was observed for the RBA concrete. The analytical shear strength of the FA-R, CA-N concrete beam was closer to that of the FA-R, CA-R concrete beam.

4. Conclusions

The study was conducted to maximize the use of construction and demolition (C&D) waste produced by natural disasters, which causes significant environmental problems. Moreover, the study aimed to promote sustainable development by preserving natural resources and minimizing the high cost of conventional concrete aggregates. Recycled brick aggregates were produced from the tested bricks and used in four different compositions: 100 % RBFA and 100 % RBCA, 100 % NFA and 100 % NCA, 100 % RBFA and 100 % NCA, 100 % NFA and 100 % RBCA. Beams were tested using a four-point bending test in shear; prisms were tested using a four-point bending test in flexure; and cylinders were tested using a compressive load test. Casting and testing were carried out under ordinary laboratory conditions, where recycled brick coarse aggregates were utilized in Saturated Surface Dry (SSD) conditions. Based on the experiment, the following conclusions were drawn:

1 28-day compressive strength of recycled brick-aggregate concrete was approximately 24 % lower than that of natural aggregate concrete, and the modulus of rupture (MOR) was 16 % lower.
2 Among the four types of RC beams tested in shear, beam FA-R, CA-R attained the minimum load of 53 kN, while beams FA-R, CA-N and FA-N, CA-N exhibited the maximum load of 71 kN.
3 The mode of failure of the RC beams containing recycled brick aggregates was observed to be similar to that of the RC beams made using natural aggregate concrete.
4 Among the four compositions, the concrete mix made of 100 % natural aggregates exhibited the highest compressive strength and modulus of rupture.
5 The shear capacity of the beam made entirely of natural aggregates was the highest, as predicted by ACI 318M-14; however, a considerable difference was observed between the predicted and experimental values.
6 After failure, it was observed that the recycled brick coarse aggregates in the concrete mix were crushed, while the natural coarse aggregates did not exhibit such behavior.

5. Recommendations for future perspective

Before considering the use of 100 % recycled brick aggregates as a viable option, the following recommendations should be taken

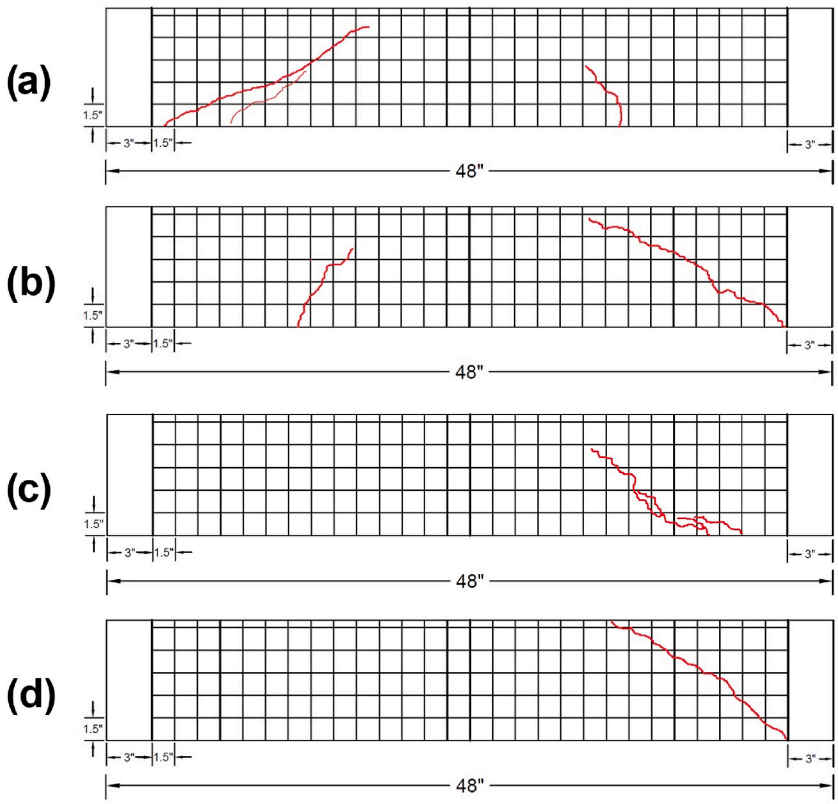

Fig. 11. Failure modes in shear: (a) FA-R, CA-R; (b) FA-N, CA-N; (c) FA-R, CA-N; (d) FA-N, CA-R.

Table 3
Experimental and Analytical Shear Capacities. Data are reported as mean and standard deviation.

	V_c for different compositions (kN)			
	FA-R, CA-R	FA-N, CA-N	FA-R, CA-N	FA-N, CA-R
Experimental value	23.53 ± 2.86	28.90 ± 2.74	22.44 ± 1.75	22.25 ± 2.37
ACI 318 [69]	13.82 ± 0.12	15.85 ± 0.71	13.74 ± 0.88	10.43 ± 0.98

into consideration:

- Studies should be conducted by varying the span-to-depth ratio and mix compositions to gain thorough, in-depth knowledge of RBA concrete.
- Further investigations with larger sample sizes should be carried out to improve structural evaluation and to identify any potential variability in the observed behavior of RBAC.
- Study regarding the flexural behavior of RBA concrete should also be conducted.
- Future researchers should perform different mechanical tests at longer intervals to ensure consistent behavior of RBA concrete.
- Studies should conduct LCA (Life Cycle Assessment) and cost-benefit analysis on the use of concrete RBAs in real-world scenarios.
- Additional investigations should be performed on the thermophysical properties of the new material to assess its behavior in terms of energy performance and ability to maintain indoor thermal comfort conditions.
- Further research should be conducted with pilot projects or field trials to validate lab findings.

CRediT authorship contribution statement

Muhammad Yousaf: Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Conceptualization. **Muhammad Shajih Zafar:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis. **Muhammad Rizwan Nazir:** Writing – original draft, Visualization, Investigation. **Laura Cirrincione:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Marco Vocciante:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] M. Yousaf, M. Usama, M.U. Yousaf, M.U. Ali, M.S. Zafar, M. Vocciante, Performance of molasses waste as a cement replacement to study concrete compressive strength, Appl. Sci. 14 (2024) 10102, https://doi.org/10.3390/app142210102.

[2] A. Ferrucci, M. Vocciante, Improved management of water resources in process industry by accounting for fluctuations of water content in feed streams and products, J. Water Process Eng. 39 (2021) 101870.

[3] F. Farooq, M.N. Amin, K. Khan, M.R. Sadiq, M.F. Javed, F. Aslam, R. Alyousef, A comparative study of random forest and genetic engineering programming for the prediction of compressive strength of high strength concrete (HSC), Appl. Sci. 10 (2020) 7330, https://doi.org/10.3390/app10207330.

[4] International Energy Agency, Global Status Report for Buildings and Construction – towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector, UN Environment Programme, International Energy Agency (IEA), 2019. ISBN: 978-92-807-3768-4.

[5] JRC Science for Policy Report, Energy Consumption and Energy Efficiency Trends in the EU-28 for the Period 2000–2018, 2020.

[6] L. Cirrincione, M.L. Gennusa, G. Peri, G. Scaccianoce, M.C. Camarda, Towards the energy optimization and decarbonization of urban settings: proposal of a strategy at neighbourhood level to foster nearly zero and positive energy districts, in: Proc. 2023 IEEE Int. Conf. Environ. Electr. Eng., 2023.

[7] L. Cirrincione, V. Geropanta, G. Peri, G. Scaccianoce, Enhance urban energy management and decarbonization through an EC-based approach, in: Proc. 2023 IEEE Int. Conf. Environ. Electr. Eng., 2023.

[8] R.M. Andrew, Global CO_2 emissions from cement production, 1928–2018, Earth Syst. Sci. Data 11 (2019) 1675–1710, https://doi.org/10.5194/essd-11-1675-2019.

[9] N. Mohamad, K. Muthusamy, R. Embong, A. Kusbiantoro, M.H. Hashim, Environmental impact of cement production and solutions: a review, Mater. Today Proc. 48 (2022) 741–746, https://doi.org/10.1016/j.matpr.2021.02.212.

[10] M. Soomro, V.W.Y. Tam, A.C. Jorge Evangelista, Production of cement and its environmental impact, in: V.W.Y. Tam, M. Soomro, A.C. Jorge Evangelista (Eds.), Recycled Concrete, Woodhead, Sawston, UK, 2023, pp. 11–46. ISBN 978-0-323-85210-4.

[11] A. Hatami Shirkouh, F. Meftahi, A. Soliman, S. Godbout, J. Palacios, Performance of eco-friendly zero-cement particle board under harsh environment, Appl. Sci. 14 (2024) 3118, https://doi.org/10.3390/app14073118.

[12] M. Triassi, R. Alfano, M. Illario, A. Nardone, O. Caporale, P. Montuori, Environmental pollution from illegal waste disposal and health effects: a review on the "Triangle of Death", Int. J. Environ. Res. Publ. Health 12 (2015) 1216–1236, https://doi.org/10.3390/ijerph120201216.

[13] M. Vocciante, V. Meshalkin, An accurate inverse model for the detection of leaks in sealed landfills, Sustainability 12 (2020) 5598, https://doi.org/10.3390/su12145598.

[14] A. de Folly d'Auris, F. Rubertelli, A. Taini, M. Vocciante, A novel polyurethane-based sorbent material for oil spills management, J. Environ. Chem. Eng. 11 (2023) 111386, https://doi.org/10.1016/j.jece.2023.111386.

[15] Y. Liu, Y. Fei, Y. Li, X. Bao, P. Zhang, A review of the pollution source identification methods and remediation technologies of groundwater, China Geol (2022), https://doi.org/10.31035/cg2022080. **0**, 0.

[16] F. Pedron, M. Grifoni, M. Barbafieri, G. Petruzzelli, I. Rosellini, E. Franchi, R. Bagatin, M. Vocciante, Applicability of a Freundlich-like model for plant uptake at an industrial contaminated site with a high variable arsenic concentration, Environments 4 (2017) 67, https://doi.org/10.3390/environments4040067.

[17] P. Song, D. Xu, J. Yue, Y. Ma, S. Dong, J. Feng, Recent advances in soil remediation technology for heavy metal contaminated sites: a critical review, Sci. Total Environ. 838 (2022) 156417, https://doi.org/10.1016/j.scitotenv.2022.156417.

[18] K.A. Skjennum, T. Hartnik, G. Breedveld, E. Sørmo, J. Mulder, Advances and potential for the use of waste materials as sorbents in remediation of PFAS contaminated soil – a review, J. Hazard. Mater. Adv. 100752 (2025), https://doi.org/10.1016/j.hazadv.2025.100752.

[19] K. Voit, O. Zeman, I. Janotka, R. Adamcova, K. Bergmeister, High-durability concrete using eco-friendly slag-pozzolanic cements and recycled aggregate, Appl. Sci. 10 (2020) 8307, https://doi.org/10.3390/app10228307.

[20] S. Yagüe, V. Rosales-Prieto, A. Sánchez-Lite, C. González-Gaya, Properties of green mortar containing granite sawmill, Appl. Sci. 11 (2021) 2136, https://doi.org/10.3390/app11052136.

[21] F. Pedron, M. Grifoni, M. Barbafieri, G. Petruzzelli, E. Franchi, C. Samà, L. Gila, S. Zanardi, S. Palmery, A. Proto, M. Vocciante, New light on phytoremediation: the use of luminescent solar concentrators, Appl. Sci. 11 (2021) 1923, https://doi.org/10.3390/app11041923.

[22] L. Cirrincione, LCA of wall infill made with agriculture waste, in: Advances in Bio-based Materials for Construction and Energy Efficiency, 2025, pp. 337–364.

[23] C. Capitano, L. Cirrincione, G. Peri, G. Rizzo, G. Scaccianoce, A simplified method for the indirect evaluation of the "embodied pollution" of natural stones (marble) working chain to be applied for achieving the ecolabel brand of the product, J. Clean. Prod. 362 (2022) 132576, https://doi.org/10.1016/j.jclepro.2022.132576.

[24] Y. Yang, H. Chen, J. Peng, Y. Dong, Machine learning-based probabilistic prediction model for chloride concentration in the interfacial zone of precast and cast-in-place concrete structures, Structures 72 (2025) 108224, https://doi.org/10.1016/j.istruc.2025.108224.

[25] A.H. Shirkouh, F. Meftahi, A. Soliman, S. Godbout, J. Palacios, Performance of eco-friendly zero-cement particle board under harsh environment, Appl. Sci. 14 (2024) 3118, https://doi.org/10.3390/app14073118.

[26] D.P. Acharya, T.R. Gyawali, Investigation of the performance of natural molasses on physical and mechanical properties of cement mortar, Ain Shams Eng. J. 15 (2023) 102355, https://doi.org/10.1016/j.asej.2023.102355.

[27] L. Cirrincione, M.L. la Gennusa, G. Peri, G. Scaccianoce, A. Alfano, Energy Performance and Indoor Comfort of a 1930s Italian School Building: a Case Study, 21st IEEE Int. Conf. on Environment and Electrical Engineering and 5th IEEE Industrial and Commercial Power System Europe, EEEIC/I and CPS Europe 2021 – Proc., 2021, https://doi.org/10.1109/EEEIC/ICPSEurope51590.2021.9584678.

[28] E.O. Fanijo, J.T. Kolawole, A. Almakrab, Alkali-silica reaction (ASR) in concrete structures: mechanisms, effects and evaluation test methods adopted in the United States, Case Stud. Constr. Mater. 15 (2021) 563, https://doi.org/10.1016/j.cscm.2021.e00563.

[29] K.H. Mo, T.-C. Ling, T.H. Tan, G.W. Leong, C.W. Yuen, S.N. Shah, Alkali-silica reactivity of lightweight aggregate: a brief overview, Constr. Build. Mater. 270 (2021) 121444, https://doi.org/10.1016/j.conbuildmat.2020.121444.

[30] M. Yousaf, M.S. Zafar, M. Usman, M. Usama, M.U. Yousaf, G. Scaccianoce, L. Cirrincione, M. Vocciante, Alkali–silica reactivity potential of aggregates from different sources in Pakistan, Sustainability 17 (2025) 3203, https://doi.org/10.3390/su17073203.

[31] J. Pizoń, K. Matýsková, M. Horňáková, M. Gołaszewska, G. Kratošová, Recycled concrete paving block waste as a selected sustainable substitute for natural aggregate in cement composites, Constr. Build. Mater. 478 (2025) 141356, https://doi.org/10.1016/j.conbuildmat.2025.141356.

[32] W. Ye, M. Dai, S. Li, J. Hu, S. Li, Y. Tan, Artificial aggregate as a sustainable substitute for natural aggregate in structure concrete applications, J. Build. Eng. 112761 (2025), https://doi.org/10.1016/j.jobe.2025.112761.

[33] H. Xu, Y. Huang, S. Feng, H. Jin, L. Chen, X. Chen, L. Li, Utilization of limestone powder and silica fume as sustainable cement replacements in shotcrete: experimental, molecular dynamics simulations, and microstructural analysis, Powder Technol. 121493 (2025), https://doi.org/10.1016/j.powtec.2025.121493.
[34] S. Zaland, J. Wang, K. Li, S.I. Sadat, K. Akhunzada, Geopolymers as a sustainable alternative to Portland cement: synthesis, durability, applications, environmental impacts, and cost analysis, Renew. Sustain. Energy Rev. 225 (2026) 116157, https://doi.org/10.1016/j.rser.2025.116157.
[35] H. Martin, D. Chebrolu, A. Chadee, T. Brooks, Too good to waste: examining circular economy opportunities, barriers, and indicators for sustainable construction and demolition waste management, Sustain. Prod. Consum. 48 (2024) 460–480, https://doi.org/10.1016/j.spc.2024.05.026.
[36] Y. Gao, T.W. Yiu, X. Shen, V.W. Tam, Life cycle insights into construction and demolition waste management: past, present and emerging futures, J. Build. Eng. 113441 (2025), https://doi.org/10.1016/j.jobe.2025.113441.
[37] J. Soto-Paz, O. Arroyo, L.E. Torres-Guevara, B.A. Parra-Orobio, M. Casallas-Ojeda, The circular economy in the construction and demolition waste management: a comparative analysis in emerging and developed countries, J. Build. Eng. 78 (2023) 107724, https://doi.org/10.1016/j.jobe.2023.107724.
[38] U.E. Temelli, N. Sezgin, B.O. Cumali, S. Nemlioglu, Analysis of construction and demolition waste prediction post-earthquake disasters, Eng. Sci. Technol. Int. J. 67 (2025) 102078, https://doi.org/10.1016/j.jestch.2025.102078.
[39] A. Balali, S. Gholami, M. Javanmardi, A. Valipour, A. Yunusa-Kaltungo, Assessment of heavy metal pollution in the soil of a construction and demolition waste landfill, Environ. Nanotechnol. Monit. Manag. 20 (2023) 100856, https://doi.org/10.1016/j.enmm.2023.100856.
[40] Y. Chen, Y. Ou, M.S. Mohamed, Z. Bao, Life cycle assessment of construction and demolition waste upcycling: a critical review of studies from 2010 to 2025, Dev. Built Environ. 22 (2025), https://doi.org/10.1016/j.dibe.2025.100685.
[41] G. Bonifazi, C. Grosso, R. Palmieri, S. Serranti, Current trends and challenges in construction and demolition waste recycling, Curr. Opin. Green Sustain. Chem. 53 (2025) 101032, https://doi.org/10.1016/j.cogsc.2025.101032.
[42] R.K. Sakthibala, P. Vasanthi, C. Hariharasudhan, P. Partheeban, A critical review on recycling and reuse of construction and demolition waste materials, Cleaner Waste Syst. 100375 (2025), https://doi.org/10.1016/j.clwas.2025.100375.
[43] K. Rekha, P. Malasani, Response of recycled brick aggregate concrete to high temperatures, Int. J. Innov. Technol. Explor. Eng. 8 (10) (2019) 224–227, https://doi.org/10.35940/ijitee.i7889.0881019.
[44] T.C. Hansen, Recycling of Demolished Concrete and Masonry, CRC Press, 1992.
[45] T.R. Gyawali, Re-use of concrete/brick debris emerged from big earthquake in recycled concrete with zero residues, Cleaner Waste Syst. 2 (2022) 100007, https://doi.org/10.1016/j.clwas.2022.100007.
[46] G. Dey, J. Pal, Use of brick aggregate in standard concrete and its performance in elevated temperature, Int. J. Eng. Technol. (2013), https://doi.org/10.5176/2301-394X_ACE13.110.
[47] B. Rosca, Comparative aspects regarding concrete of structural grade made with recycled brick aggregate with/without fine particles from crushing, Mater. Today Proc. 60 (2022) 982–987.
[48] T.U. Muhammad, K.H. Shikdar, J.A. Joy, Shear strength of RC beams made with brick aggregate without shear reinforcement, J. Civil Eng. (IEB) 47 (1) (2019) 31–45.
[49] X. Liu, J. Wu, X. Zhao, P. Yen, Effect of brick waste content on mechanical properties of mixed recycled concrete, Constr. Build. Mater. 292 (2021) 123320, https://doi.org/10.1016/j.conbuildmat.2021.123320.
[50] A.A.K. Sharba, A.A.G.A. Altemen, M.M. Hason, Shear behaviour of exploiting recycled brick waste and steel slag as an alternative aggregate for concrete production, Mater. Today Proc. 42 (2021) 2621–2628, https://doi.org/10.1016/j.matpr.2020.12.591.
[51] T.U. Mohammed, A. Hasnat, Modulus of rupture of concrete made with recycled brick aggregate. https://doi.org/10.13140/2.1.4672.8000, 2014.
[52] Md M. Rahman, Md S.H. Pavel, Md R. Islam, Y. Ali, Md S. Islam, Md S. Islam, Md A. Gone, S. Rahman, Properties of brick aggregate concrete as influenced by the strength of brick, Int. J. Trend Sci. Res. Dev. 4 (2020) 1735–1740.
[53] T.U. Muhammad, K.H. Shikdar, M.A. Awal, Shear strength of RC beam made with recycled brick aggregate, Eng. Struct. 189 (2019) 497–508.
[54] S.A. Aly, M.A. Ibrahim, M.M. Khttab, Shear behavior of reinforced concrete beams casted with recycled coarse aggregate, Eur. J. Adv. Eng. Technol. 2 (9) (2015) 59–71.
[55] I.S. Ignjatović, S.B. Marinković, N. Tošić, Shear behaviour of recycled aggregate concrete beams with and without shear reinforcement, Eng. Struct. 141 (2017) 386–401.
[56] K. Iqbal, M.A. Baig, Quantitative and qualitative estimation of construction waste material in Punjab Province of Pakistan, Am.-Eurasian J. Agric. Environ. Sci. 16 (4) (2016) 770–779.
[57] G. Peri, L. Cirrincione, D. Mazzeo, N. Matera, G. Scaccianoce, Building resilience to a warming world: a contribution toward a definition of "Integrated Climate Resilience" specific for buildings – literature review and proposals, Energy Build. 315 (2024) 114319.
[58] United Nations, Sustainable Development Goals. https://www.un.org/sustainabledevelopment/sustainable-development-goals/(accessed 19 August 2025).
[59] ASTM C150/C150M-16, Standard Specification for Portland Cement, ASTM International, West Conshohocken, PA, 2016, https://doi.org/10.1520/C0150_C0150M-16.
[60] ASTM C128, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate, ASTM International, West Conshohocken, PA, USA, 2015.
[61] ASTM C566, Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying, ASTM International, West Conshohocken, PA, USA, 2019.
[62] ASTM C29/C29M-97, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate, ASTM, West Conshohocken, PA, USA, 2023.
[63] ASTM C117, Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing, ASTM International, West Conshohocken, PA, USA, 2023.
[64] BS 812-112, Testing Aggregates - Method for Determination of Aggregate Impact Value (AIV), BSI Group, London, UK, 1990.
[65] BS 812-111, Testing Aggregates - Method for Determination of Ten per Cent Fines Value (TFV), BSI Group, London, UK, 1990.
[66] ASTM C39/C39M, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, USA, 2023.
[67] ASTM C78/C78M, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-point Loading), ASTM International, West Conshohocken, PA, USA, 2021.
[68] ASTM C67, Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile, ASTM International, West Conshohocken, PA, USA, 2018.
[69] ACI 318M-14, Building Code Requirements for Structural Concrete, American Concrete Institute, Farmington Hills, MI, USA, 2015.
[70] Z. Wang, Y. Yang, Y. Su, J. Wang, Z. Wei, Y. Li, J. Li, C. Zhu, Damage mechanism of concrete with recycled brick aggregate, Therm. Sci. 27 (2023) 2145–2153, https://doi.org/10.2298/TSCI2303145W.
[71] L. Huang, L. Yu, H. Zhang, Z. Yang, Composition and microstructure of 50-year lightweight aggregate concrete (LWAC) from Nanjing Yangtze River Bridge (NYRB), Constr. Build. Mater. 216 (2019) 390–404, https://doi.org/10.1016/j.conbuildmat.2019.05.015.