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Influence of Recycled Fine Aggregates on the Structural Behavior of Reinforced Concrete Beams

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Abstract

The research specifically focuses on the effects of recycled fine aggregates as partial replacements for natural aggregates, contributing to the growing body of knowledge on sustainable construction materials. This study contributes to the understanding of how recycled materials can be effectively utilized in concrete construction, promoting sustainability while maintaining structural integrity. The testing program includes 13 beams, all designed with a target compressive strength of 15 MPa, using seven different types of fine aggregates. All tested beams experienced mixed shear failure, starting with flexural cracks beneath the loading point and progressing to flexural-shear and diagonal shear cracks as the load increased. Failure was marked by significant diagonal cracks leading to brittle collapse and reduced beam capacity. Recycled aggregate beams exhibited a slight increase in flexural cracks, with critical shear cracks widening significantly when loads exceeded 50% of ultimate strength. The use of recycled brick aggregates, recycled concrete aggregates, fly ash, and sugarcane bagasse ash led to reduced shear strength and deflection capacity. Notably, recycled fine aggregate concrete beams with 10% cement clay interlocking bricks performed better than the control beam. The load-deflection response was similar across beams, indicating no impact on elastic stiffness.

Keywords: Recycled fine aggregates; Sustainable materials; Concrete; Beams; Shear failure.

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1. Introduction

As urbanization continues to advance, the generation of construction waste is steadily increasing each year.[1,2] Concrete, a crucial building material, is widely employed in various engineering endeavors.[3,4] In 2021, China consumed approximately 3.06 billion cubic meters of commercial concrete, reflecting a growth of around 5.53% compared to the previous year.[5] Typically, construction waste is managed through disposal methods such as dumping and landfilling, which pose significant environmental challenges.[6,7] Alexandridou *et al*., 2018 used recycled aggregates to produce sustainable concrete. The authors reported that the strength of concrete made with recycled aggregates were slightly lower than the concrete made with natural aggregates.[8] Yooprasertchai *et al*. 2024 investigated the use of plastic waste to produce concrete. The authors reported that the use of plastic waste into concrete is a promising for reducing environmental impact while providing viable construction materials [9]. With rapid urbanization, the demand for natural sand and gravel is rising rapidly and is expected to exceed their natural replenishment.[10–12] However, construction waste production and consumption can be repurposed as secondary resources for other industries.[13] Kabirifar *et al*.[14] estimate that roughly 35% of global construction and demolition waste (CDW) is sent to landfills. To tackle the increasing construction waste and dwindling supply of sand and gravel, old concrete blocks and broken bricks can be reused. By crushing these materials, recycled aggregates can be generated and utilized to partially or entirely replace natural aggregates (NA) in the production of recycled brick aggregate concrete (ReBAC).[15] This method aids in conserving natural resources,

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reducing the demand for landfill space, and promoting the sustainable development of building materials.[16] Moreover, it can significantly contribute to achieving carbon peak and carbon neutrality objectives.[17]

The use of recycled aggregates in concrete production has been extensively studied.[18–21] Previous research has shown that incorporating recycled aggregates may negatively affect the properties of concrete.[22,23] The performance of recycled concrete aggregates (RCA) in structural elements such as beams and columns has also been extensively investigated by researchers.[24,25] While research on ReBAC is limited, it is evident that the strength and properties of ReBAC are significantly affected by the quality of the original brick aggregate,[26, 27] as well as the quality of the cement and the mixing proportions. Factors such as gradation, shape, and texture of recycled brick aggregates (RBA) notably influence the strength parameters of ReBAC.[28,29] Additionally, ReBAC can be improved over successive generations to reach desirable strength levels.[30,31] Basit *et al*.[32] examined the impact of using RCA and RBA in concrete. They found that replacing fine natural aggregates with RCAs or RBAs had little effect on density, while partial replacement of coarse aggregates with RAs reduced compressive strength slightly.

RCAs offered better bond strength with steel rebar than RBAs. Flexural tests showed that beams with up to 50% NA replacement performed similarly to controls, but those with 100% RA replacement had reduced stiffness and different cracking patterns. Tusher *et al*.[33] conducted pull-out tests on 80 specimens to evaluate the bond performance of deformed rebars in rubberized recycled brick aggregate concrete (RRBAC). They investigated various factors including percentage, rebar diameter, embedment length, and concrete cover-to-rebar diameter ratio. Their tests revealed that bond strength decreased with the inclusion of RBAs and CRs, although higher RBA percentages showed some improvement. Concrete split failure occurred in 79% of specimens, with no rebar fractures. Jia *et al*.[34] simulated reinforced concrete beams and columns using NA, RCA, and RBA. They found that columns showed better energy dissipation under horizontal loading compared to vertical, and beams had lower energy dissipation. Seismic performance was lower for RBA compared to NA and RCA, indicating RBA is more suitable for beams. Zhang *et al*.[35] investigated the bond-slip behavior between ReBAC and reinforcement bars through 45 pull-out tests. Results showed that ReBAC with higher RBA replacement ratios generally had increased bond strength compared to natural aggregate concrete (NAC), with the highest increase at 50% RBA. Higher compressive strength in ReBAC improved ultimate bond strength and reduced slip.

A bond stress-slip model for BCRC was developed, showing high accuracy and offering useful insights for structural design. Mansour *et al*.[36] tested twelve RC beams to analyze the shear behavior of RCA beams strengthened with carbon fiber reinforced polymer (CFRP) sheets. Their findings revealed that higher RA ratios decreased compressive strength, but the beam with 20% RA and four CFRP layers had the highest ultimate load, 22.9% greater than the control beam. They also compared continuous and intermittent CFRP sheets using a 3D finite element model. The use of CFRP was also found useful to alter the behavior of non-prismatic beams.[37] Some other low-cost materials were used in past to alter the behavior of concrete members. [38,39] Recently, the use of CFRP ropes and strips was also found useful to alter the behavior of reinforced concrete beams.[40,41] Few studies have also reported the temperature and shrinkage effects for lightweight and self-consolidating reinforced concrete beams.[42,43]

As highlighted, there is a notable gap in research regarding the structural performance, particularly the shear behavior, of ReBAC. This study addresses this gap by investigating how replacing natural fine aggregates with recycled brick aggregates affects shear performance. To provide a thorough understanding, the study examines different types of recycled bricks, considering variations in brick origin and earth strata, to determine their impact on concrete properties. Additionally, the study includes a comparative analysis with beams where natural fine aggregates are substituted with alternative materials such as fly ash and sugarcane bagasse ash. By exploring these different materials and conditions, the research aims to provide a comprehensive evaluation of ReBAC's structural behavior, contributing valuable insights into the optimization and application of recycled materials in concrete. The significance of this research lies in its focus on addressing a critical gap in the understanding of the structural performance of ReBAC, particularly in terms of its shear behavior. Despite extensive studies on recycled aggregates, there has been limited exploration of how substituting natural fine aggregates with recycled brick aggregates influences shear performance. This study seeks to fill this gap by investigating the effects of different types of recycled bricks, considering variations in their origin and earth strata, on concrete properties. Furthermore, the research includes a comparative analysis with beams where natural fine aggregates are replaced by alternative materials such as fly ash and sugarcane bagasse ash. Through this comprehensive examination of different materials and conditions, the study aims to provide a deeper understanding of ReBAC's structural behavior, offering valuable insights that could enhance the optimization and practical application of recycled materials in concrete construction.

2. Experimental program

2.1 Test plan

The testing program includes 13 beams, all designed with a target compressive strength of 15 MPa, using seven different types of fine aggregates. For each type of fine aggregate, two beams were constructed with recycled fine aggregate replacements at 10% and 20% ratios, while the remaining beam was made with natural aggregate. A key parameter in the shear behavior of reinforced concrete beams is the shear span-to-depth ratio (a/d). In this experimental program, the load was applied at a location that resulted in an a/d ratio of 3.6. Table 1 provides a summary of the experimental test program and the labeling of the 13 test beams. Recycled aggregates used were obtained from three different brick types (with details in following sections), RCA, fly ash, and sugarcane bagasse ash. Beams were recognized with the type of RA, and their replacement levels. For example, the name B-SCBA10 referred to the beam made by replacing 10% of natural fine aggregates with sugarcane bagasse ash.

2.2 Material properties

The test matrix utilized recycled concrete from demolished buildings and three different types of building bricks. The first two types of bricks were composed of clay (solid and hollow), while the third type was a hydraulically compressed cement clay interlocking brick, as illustrated in Fig. S1. Terms RBA, RBB, and RBC referred to RBAs obtained from fired clay solid, fired clay hollow, and cement-clay interlocking bricks. Each type of brick and concrete was locally acquired, and a brick crusher machine was used for crushing them. The bricks were crushed and screened to standard fine aggregate sizes. The grading stayed same to find the grading of fine aggregates. Sieves with sizes ranging from 0.15 mm to 5 mm were used. The mechanical characteristics of the bricks were determined by compressive testing and water absorption percentages, as shown in Table 2. Table 3 presents the physical and mechanical characteristics of the recycled fine aggregates, which were determined in accordance with ASTM C-0128-22.[44] The replacement ratios of brick aggregate with recycled brick and concrete fine aggregates were 10% and 20%, respectively, to assess the impact on mechanical properties.

2.3 Details of Specimens

The aim of this work was to explore the impact of recycled fine aggregates on the shear strength of RC beams. The RC beams in this work were intentionally devised to exhibit shear

Table 1: Details of beams tested.

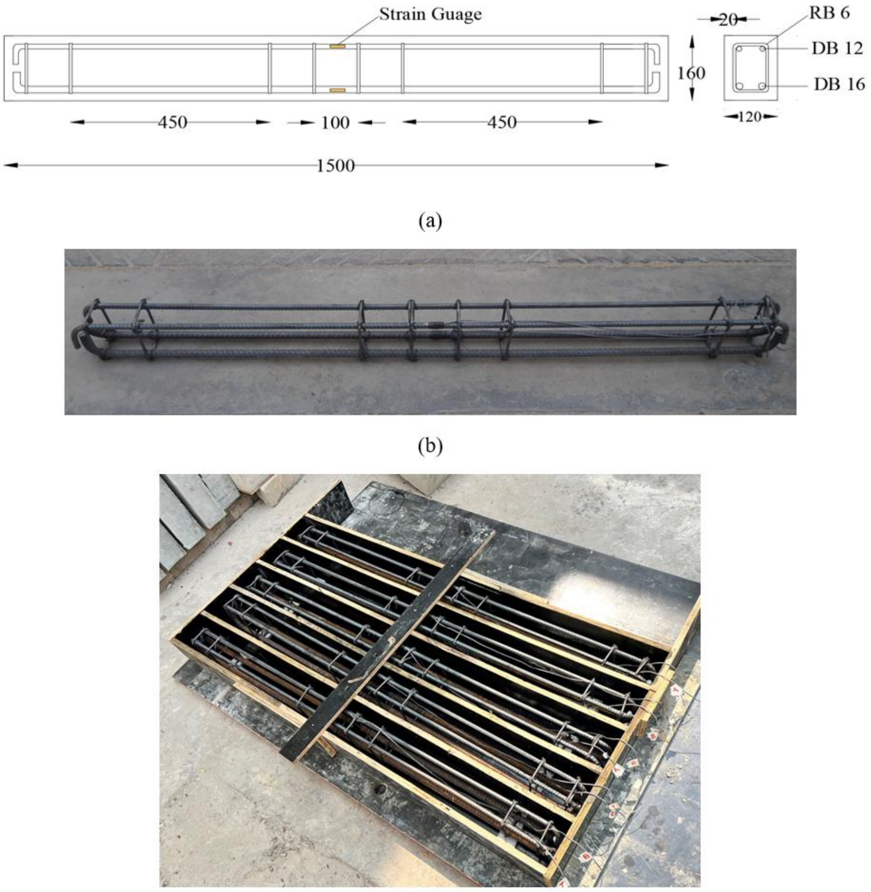
ID	Recycle aggregate origin	Replacement (%)
B-Con	Natural	0
B-RBA10	Fired clay solid brick	10
B-RBA20	Fired clay solid brick	20
B-RBB10	Fired clay hollow brick	10
B-RBB20	Fired clay hollow brick	20
B-RBC10	Cement clay interlocking brick	10
B-RBC20	Cement clay interlocking brick	20
B-DRC10	Demolished recycled concrete	10
B-DRC20	Demolished recycled concrete	20
B-FA10	Fly ash	10
B-FA20	Fly ash	20
B-SCBA10	Sugarcane bagasse ash	10
B-SCBA20	Sugarcane bagasse ash	20

Table 2: Mechanical properties of bricks.

Types	Density (kg/m3)	Compressive strength (MPa)	Water absorption (%)
RBA	1200	3.14	22
RBB	1400	8.10	13.10
RBC	1450	6.26	12.30

Table 3: Properties of fine aggregates.

Property	NA	RBA	RBB	RBC	DRC	FA	SCBA
Bulk specific gravity (kg/m3)	2.27	2.40	2.44	2.30	2.28	1.99	1.59
Water absorption (%)	0.44	1.47	0.6	0.94	2.44	0.51	0.65



(a)

(b)

(c)

Fig. 1: (a) Structural details of RC beams, (b) steel bars, (c) typical formwork (*Note: All units are in mm*).

dominated behavior by excluding internal stirrups, as shown in Fig. 1. But, to avoid concrete crushing under the loads, stirrups were added within the central section of the beam, spaced 100 mm apart, and at the ends of the beam. The experimental section of this work involved testing thirteen half-scale beams with a total length of 1500 mm, a width of 120 mm, and a depth of 150 mm. For longitudinal steel bars, deformed bars with 16 mm diameter and 12 mm diameter were used for tension and compression steel, respectively. Vertical stirrups were made from 6 mm diameter round steel bars. To prevent pull-out collapse, appropriate anchorage for steel bars was ensured. The concrete cover was maintained at 20 mm.

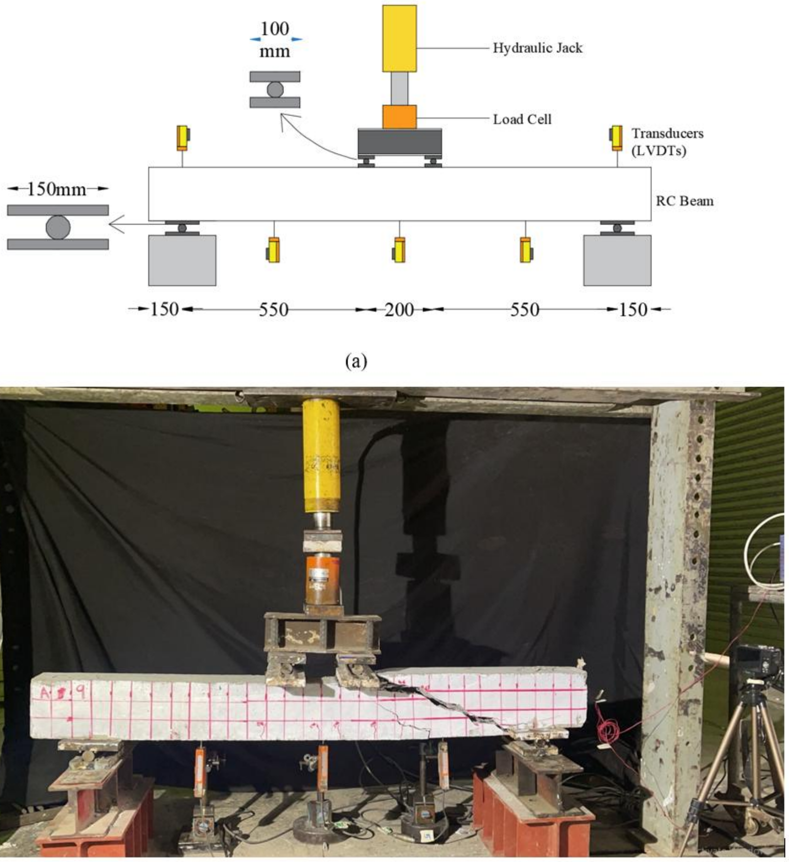
2.4 Test setup

In the beam test setup, the high-shear region was devoid of stirrups, while the rest of the beam featured No. 6 stirrups spaced 100 mm apart to prevent premature failure. Specimens were simply supported over a 1.3-meter span and loaded with a single concentrated force in a manually controlled displacement environment. A strain gauge model was affixed to the midpoint of the steel bar, designed to measure strains up to approximately 0.050 mm/mm. Strain gauges were placed on the longitudinal tensile reinforcement and the top bar of beams. Linear variable differential transducers (LVDTs) were utilized to monitor beam deflections, with three LVDTs positioned at the bottom under the load and two LVDTs installed on the top surface at both ends of the beams. The testing apparatus included a reaction frame, hydraulic jack, and load cell with capacities of 1000 kN, 500 kN, and 500 kN, respectively. The test setup and instrumentation for the two-point loading test of the RC beam are illustrated in Fig. 2.

3. Experimental results

3.1 Failure modes of beams

All specimens exhibited mixed shear failure. As the load progressed, initial flexural cracks began to occur beneath the loading region, where the bending moment was maximum. These cracks steadily multiplied in that region, maintaining a vertical orientation. Following the formation of these flexural cracks, flexural-shear cracks emerged near the bottom support. Subsequently, diagonal shear cracks formed, initiating at regions close to the support and extending towards the loading region within the instrumented part. As the load continued to rise, these diagonal cracks propagated further till diagonal tension failure occurred. In nearly all beams, failure was triggered by the development of a major diagonal crack, leading to a sudden and brittle failure, characterized by a significant reduction in beam capacity, as depicted in Figs. 3 and S2. Notably, the utilization of recycled aggregates resulted in a slight increase in the number of flexural cracks. Following



(a)

(b)

Fig. 2: Test setup adopted (a) schematic, (b) lab view (*Note: All units are in mm*).

ultimate loading, the primary shear crack widened significantly until the load dropped to 50% of its ultimate strength. For beams B-RBA10 and B-RBA20, the first shear crack emerged on the web of the shear span. As the load increased, additional shear cracks appeared on the web and both sides of the beam in B-RBA20. These parallel shear cracks developed with smaller widths, reaching up to 23 mm in B-RBA20. Ultimately, the concrete compression strut in the shear spans crushed, and the critical diagonal crack expanded to over 42 mm. In contrast, for beams B-RBB10 and B-RBB20, the first crack originated on the bottom surface and then angled towards the loading point. Critical shear cracks developed quickly, nearly along the interface within the support and the loading point, as the load reached 60% of the ultimate capacity. As the load increased further, parallel shear cracks developed with smaller widths in B-RBB10.

For beams B-RBC10 and B-RBC20, the initial shear crack occurred within the shear span near the load. As the load increased, a second shear crack formed near support and tilted toward the load. In B-RBC10, two critical shear cracks developed and gradually widened with increasing load. Both beams ultimately failed when the critical diagonal crack expanded to 42 mm on one side. In beams B-DRC10 and B-DRC20, the first shear crack emerged on within the shear span web. With further loading, additional shear cracks formed on the web, and parallel shear cracks developed with a smaller width, reaching up to 13 mm. For beams B-FA10 and B-FA20, the cracking pattern resembled that of B-RBB10 and B-RBB20, with a greater diagonal angle in the shear span due to bending-shear response near the load. As the load increased, second and third diagonal cracks appeared, leading to failure as the critical cracks rapidly widened beyond 43 mm. In beams B-SCBA10 and B-SCBA20, additional shear cracks also formed within the shear span web in B-SCBA20, with parallel shear cracks in B-SCBA10 developing with a smaller width, up to 7 mm. Ultimately, the critical diagonal cracks widened up to 42 mm, leading to failure.

3.2 Shear strength of beams

The test findings of all beams are given in Table 4. The data indicate that the impact of RAs to the shear strength of RC beams was not significantly improved. Both the solid clay brick and hollow clay brick aggregates showed only slight increases in the ultimate capacity of the beams when the replacement level was increased from 10% to 20%. However, the recycled fine aggregate concrete beams incorporating cement clay interlocking bricks outperformed the other beams. Apart from Beam B-RBC10, all types of brick aggregates resulted in reduced shear capacity compared to the natural aggregate beam. The results in Table IV also reveal that brick fine aggregate beams had significantly lower deflection capacity than the control beam. The most notable decrease in

Table 4: Summary of beam test results.

No	Name	Ultimate Load (kN)	Deflection (mm)
B-1	B-Con	47.87	6.64
B-2	B-RBA10	42.19	5.64
B-3	B-RBA20	42.35	3.50
B-4	B-RBB10	33.42	5.80
B-5	B-RBB20	40.73	5.52
B-6	B-RBC10	48.84	6.41
B-7	B-RBC20	33.59	3.28
B-8	B-DRC10	42.35	6.70
B-9	B-DRC20	43.77	2.95
B-10	B-FA10	38.55	6.25
B-11	B-FA20	38.22	4.34
B-12	B-SCBA10	42.14	3.22
B-13	B-SCBA20	43.45	3.1

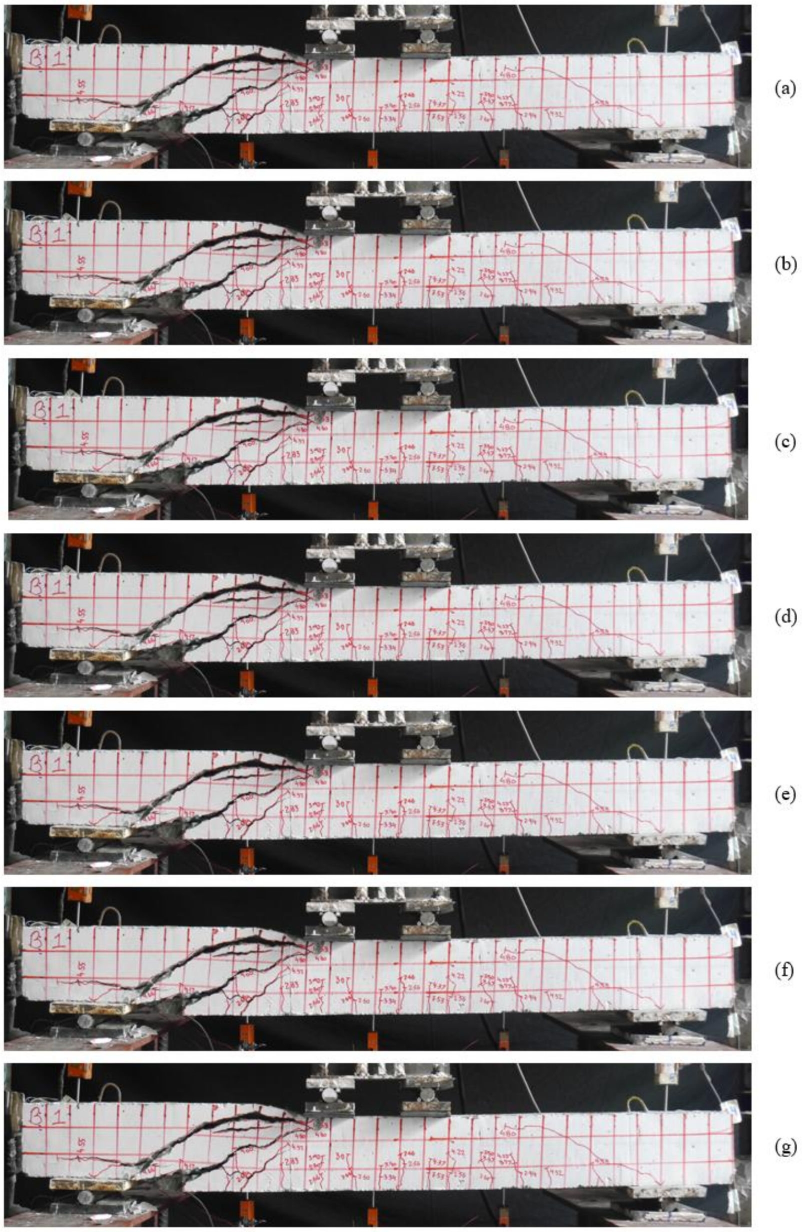


Fig. 3: Failure modes of beams: (a) B-Con, (b) B-RBA10, (c) B-RBA20, (d) B-RBB10, (e) B-RBB20, (f) B-RBC10, and (g) B-RBC20.

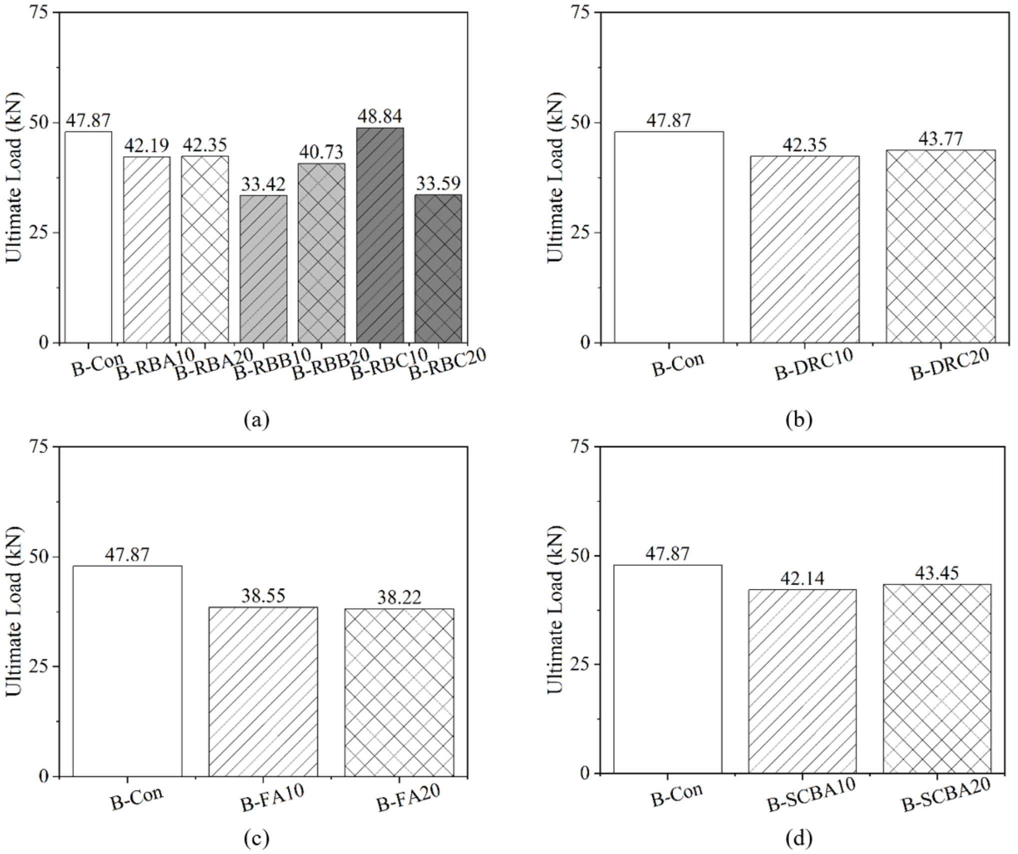


Fig. 4: Comparison of load capacities of beams with control beam: (a) recycled brick aggregates, (b) demolished recycled concrete, (c) fly ash, and (d) sugarcane bagasse ash.

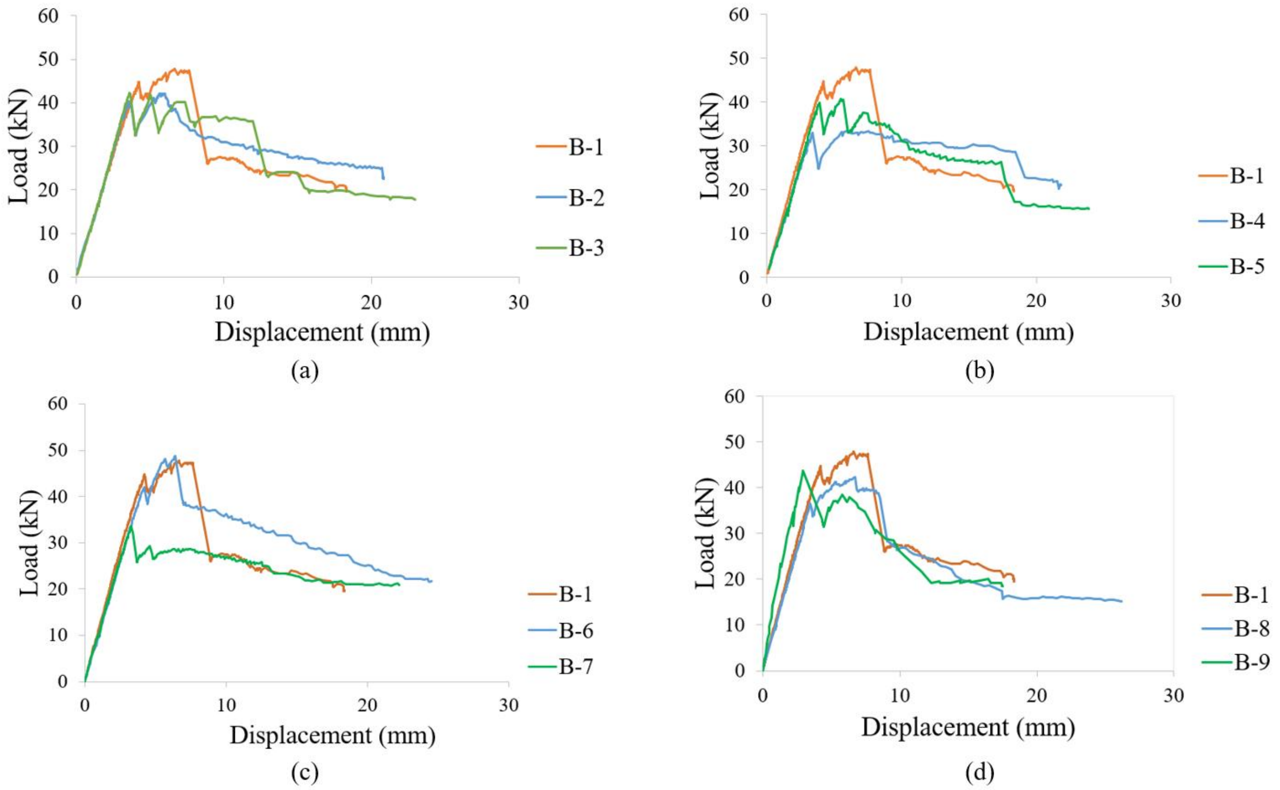


Fig. 5: Load-deflection (a) control and RBA-based beams, (b) control and RBB-based beams, (c) control and RBC-based beams and (d) control and RCA-based beams.

deflection at ultimate load was observed in the beam with 20% CCI brick, showing a 51% reduction. Beams with solid clay brick and hollow clay brick aggregates also demonstrated decreased deflection at ultimate load as the replacement level increased. For the remaining beams, the least reduction in capacity was observed for Beam B-DRC20, followed by B-SCBA20 and B-DRC20, respectively. Beams with 10% and 20% RCA showed strength reduction of 11.53% and 8.56%, respectively. Beams with 10% and 20% FA showed strength reduction of 19.47% and 20.16%, respectively. Beams with 10% and 20% SCBA showed strength reduction of 11.97% and 9.23%, respectively. Fig. 4 shows the comparison of load capacities of beams with control beam.

3.3 Load vs. deflection curves

The load vs. deflection relationships for all beams specimens are illustrated in Figs. 5 and S3. As anticipated, most load-deflection curves show a reduction in beam stiffness immediately after cracking. The behavior remained linear up until the first flexural crack, with RAC beams exhibiting a smaller slope compared to NAC beams. After the initial cracking, recycled aggregate beams displayed flatter slopes than natural aggregate beam, indicating a reduction in stiffness. This difference is often attributed to the lower flexural stiffness of RAC, which stems from a reduced elastic modulus and tensile strength. Importantly, the post-peak response of the control beam accompanied a sudden drop. However, the rate of strength degradation of RAC beams was slightly lower than the control beam. Moreover, no significant reduction in elastic modulus was observed between control and RAC beams.

3.4 Strain measurements

The strain measurements of all beams demonstrated a linear response. All beams showed linear strain readings, demonstrating that the behavior was dominated by shear. In most of the cases, the maximum strain attained by longitudinal bars remained below that of the control beam. Beam B-RBC10 showed slightly greater strain than the control beam, as shown in Fig. 6. This was expected as the same beam also demonstrated a greater capacity than the control beam.

4. Conclusion

This study presents the impact of recycled fine aggregates as partial substitute of natural aggregates on shear capacity of reinforced concrete beams. The main conclusions are as follows.

1. All tested beams experienced mixed shear failure with initial flexural cracks developing beneath the loading point, progressing to flexural-shear and diagonal shear cracks as the load increased. The failure was characterized by significant diagonal cracks, leading to a sudden and brittle collapse with notable reductions in beam capacity. Recycled aggregate beams showed a slight increase in flexural cracks, and the critical shear cracks widened significantly as loads approached and exceeded 50% of ultimate strength. Various beam types displayed different cracking patterns, but all ultimately failed due to the expansion of diagonal cracks, with widths reaching up to 43 mm.
2. Recycled aggregates had a detrimental impact on shear strength. Recycled fine aggregate concrete beams with cement clay interlocking bricks (10%) outperformed others, but still, all brick aggregate beams had reduced shear capacity compared to natural aggregate beam. Notably, the deflection capacity decreased significantly, with a 51% reduction observed in the beam with 20% CCI brick. Strength reductions were 11.53% and 8.56% for RCA, 19.47% and 20.16% for FA, and 11.97% and 9.23% for SCBA at 10% and 20% replacement levels, respectively.

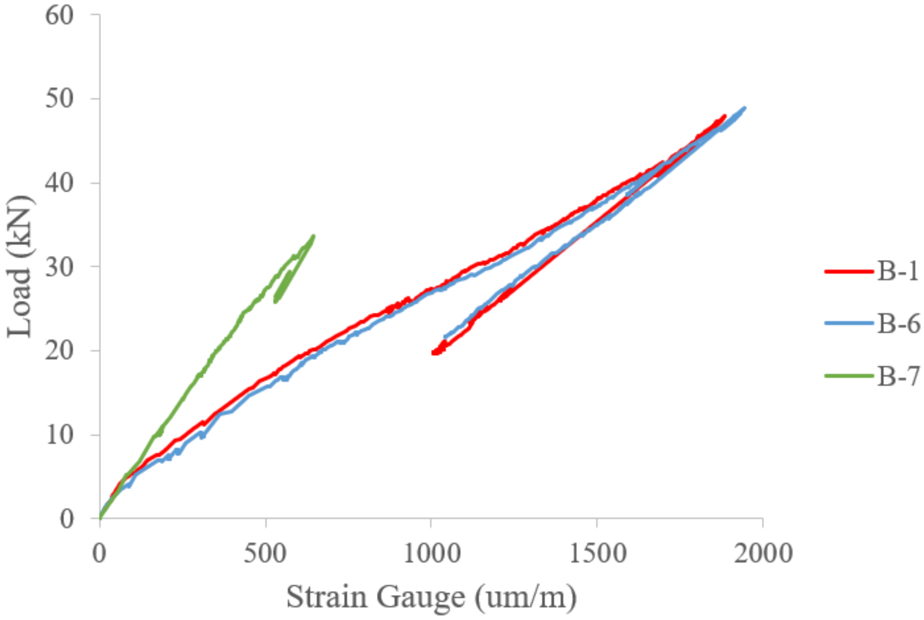


Fig. 6: Comparison of strain of longitudinal bars in control and RBC-based beams.

3. The load vs. deflection response of all beams showed similar elastic stiffness, signifying that the inclusion of RA of various studied types up to 20% had no impact on the elastic stiffness of reinforced concrete.
4. The strain readings of longitudinal bars showed that the bars remained linear. The inclusion of 10% of RBC aggregates enhanced the capacity beyond the control beam. As a result, the maximum strain in Beam B-RBC10 was also greater than the control beam.
5. This is one of the preliminary studies on studying the shear behavior of RC beams with different recycled aggregate types. This work utilized 10% and 20% replacement ratios. Future studies should explore other replacement percentages of recycled aggregates. Additional supplementary cementitious materials should be explored in future studies. The shear behavior under cycled loading needs to be investigated. In addition, future studies should be assess the performance of existing analytical models for predicting the shear strength of RC beams in predicting the shear capacity of beams fabricated with different recycled aggregates used in this work.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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