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SHEAR STRESSES OF HOLLOW CYLINDRICAL CONCRETE BEAMS MADE WITH RECYCLED CERAMICS AGGREGATES

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The main focus of the study presented in the work is an experimental investigation into the effects related to recycled ceramic coarse aggregates from the industrial brick waste on reinforced concrete beams (RCBs) shear behavior. For such an aim, a total of twelve concrete beams with 250mm height, 1200mm length, and 140mm width have been employed. A total of six Normal Concrete Beams (NCB) models made up of three Solid Normal Concrete Beams (SNCB) and Hollow Normal Concrete Beams (HNCB). Of the six models of Recycled Ceramic Concrete Beams (RCCB), there are also three Solid Recycled Ceramic Concrete Beams (SRCCB) and three Hollow Recycled Ceramic Concrete Beams (HRCCB). At such percentages of 0% and 30%, the weight related to coarse aggregate in concrete mixes is replaced with crushed ceramic that is acquired from building demolition wastes. A total of four points on the samples were examined for bending. The mid-span of the beam had the most deflection. The test evaluated the behavior related to beam concrete with the waste material by measuring the ultimate shear strength and diagonal cracking load. The experiment was designed to determine the impact of crushed ceramic on mechanical characteristics of RCBs. Additionally, the results show that, when compared to control samples, adding crushed ceramic improved the properties of the samples in shear behavior with reference to crushed ceramic concrete beams. Results have shown that the use of recycled ceramic aggregates caused a reduction in ultimate shear capacity of approximately 10–15% compared with conventional beams, while reducing stirrup spacing significantly enhanced shear resistance and crack control. Results have confirmed that recycled ceramic aggregates can be effectively used in reinforced concrete beams without significantly compromising structural performance. This study is limited to a 30% replacement ratio and monotonic static loading conditions. To the best of the authors' knowledge, limited studies investigated combined effect of recycled ceramic aggregates and longitudinal hollow sections on shear behavior of reinforced concrete beams. This study provides additional information about the feasibility of utilizing ceramic waste in structural applications, thereby supporting sustainable construction practices and reducing environmental impacts associated with construction waste.

Keywords: shear behavior, recycled ceramic aggregates, hollow concrete beams, reinforced concrete beams, sustainable concrete, crack patterns, load–deflection behavior

HIGHLIGHTS

- This study systematically evaluates the shear and flexural performance of hollow and solid reinforced recycled ceramic aggregates incorporating recycled ceramics as a partial aggregate replacement.
- An experimental program was conducted using 4-point bending tests on twelve RC beams, comprising three solid and three hollow specimens, which have been tested under 4-point bending loading to characterize their flexural response.
- Results indicate that beams containing a 30% replacement ratio of conventional aggregate with recycled ceramics aggregate exhibit load–deflection behavior comparable to that of conventional reinforced concrete beams.
- The results indicate that recycled ceramic aggregates can be used for structural purposes and their use can promote sustainability in the construction sector.

1 Introduction

The utilization of natural resources, like cement and natural aggregates, is presently posing problems for the building sector [1, 2]. Using different waste ratio materials as aggregate substitutes in production of new concrete has gained popularity lately [3–9]. Several of CDW's components are highly valuable resources that could be utilized again in a variety of construction-related applications [10]. Ceramic waste is one type of waste from demolition and construction that has a lot of potential for use in mortar and concrete. For the past few years, there has been a lot of research on using ceramic wastes in concrete [10–34]. Bricks from demolished construction [12, 18, 29] as well as recovered floor and wall tiles [14, 40] are the sources associated with ceramic waste. Most of such wastes are being evaluated as coarse aggregates [10, 11, 13, 16, 18, 21–23, 25, 26, 28, 29, 34] to partially substitute natural aggregates in the concrete production. Tensile splitting strength, compressive strength, elasticity modulus, flexural tensile strength, shrinkage, density, abrasion resistance, creep, water permeability, water absorption, freeze-thaw resistance, pore size distribution, carbonation, and chloride penetration are the properties regarding concrete that have been hardened and are being assessed in the published studies using ceramic wastes [15–40]. The slump test, as well as the bulk density test, has been used in such investigations to consistently assess the fresh characteristics of concrete. Using recycled concrete aggregate (RCA), which includes crushed ceramic, in the making of concrete has been shown in numerous studies for the enhancement of durability of concrete blocks. Lotfi et al. (2015) concluded that adding ceramic waste to concrete increased the material's resistance to chloride penetration, improving its durability against corrosion [41]. Pešta et al. (2020) proved that a sustainable construction requires reusable constructions using recycled aggregate. They compared different forms of concrete building using the life cycle assessment (LCA) method. According to their findings, conventional concrete walls had a greater influence on the majority of impact categories. The primary variables that influence environmental impact are the reuse and recycling of aggregate and blocks [42].

In spite of the growing body of research about the recycled ceramic aggregates in concrete, most previous investigations have focused primarily on basic material characteristics like compressive strength, tensile strength, and durability characteristics. Comparatively limited research has examined structural performance of reinforced concrete members produced with recycled ceramic aggregates, particularly with respect to their shear behavior. In addition, there is limited research on hollow RCBs made with recycled ceramic aggregates.

Hollow concrete beams have been under the attention of people in the field of structural engineering due to the advantages of decreasing its self-weight and ensuring its structural capacity. But the presence of such voids can affect the stress distribution and crack behavior as well as failure modes of RC beams, particularly subjected to shear loading. Thus, it is important to know the structural properties of hollow beams fabricated with recycled aggregates to ensure safe and efficient structural applications.

The literature survey reveals that, the substitution of construction aggregates by crushed ceramic in the concrete blocks significantly enhances the characteristics of the concrete blocks. This investigation was planned based upon the background. A well-planned experimental investigation of the shear behavior of hollow as well as solid concrete beams that are composed of recycled ceramic aggregates is presented in the manuscript. This aligns with the current sustainability activities being implemented in the construction sector. Twelve RC beams have been made with different steel ratio and aggregate (recycled ceramic aggregates, virgin aggregates etc.). The beams have been tested under 4-point bending loading that was applied to the beams during testing. The ultimate moment, failure pattern and cracking moment are noted for comparison with virgin ceramic aggregates.

The novelty of the present study is based on an experimental investigation of the combined effect of recycled ceramic coarse aggregates and hollow beam configuration on the shear behavior of RC beams. This study aims to assess the structural performance, crack propagation, ultimate shear capacity and load–deflection response of solid and hollow reinforced concrete beams with various stirrup spacing under four point bending loading unlike previous studies which mainly focused on material properties or solid reinforced concrete elements. The research also offers deeper insights into the viability of recycled ceramic aggregates to be used in structural concrete elements, helping to construct in a more sustainable way and decreasing the environmental impact that is caused by construction waste.

2 Materials and methods

In the present research, recycled concrete beams (RCBs) have been manufactured with the use of ceramic waste and granular waste as coarse aggregates, in combination with box plastic, Portland cement, and steel reinforcing bars as primary constituent materials.

2.1 Materials properties

Natural coarse aggregates (NCA), Portland cement, ceramic RCA, and natural sand (NFA) are the raw materials that have been utilized in the study, as shown in Figure 1. Table 1 and Table 2 list the mechanical and physical characteristics of ceramic RCAs. Reinforcing Bars:

Fig. 1. Ceramic recycled coarse aggregates (RCA)

Table 1. Physical characteristics of ceramic recycled coarse aggregates

Physical characteristics	Values obtained
Specific gravity	2.40
Water absorption (%)	2.50

Table 2. Mechanical characteristics of ceramic recycled coarse aggregates

Chemical properties	Values obtained
CaO (%)	22.03
SiO_2 (%)	27.52
Al_2O_3 (%)	22.21
Fe_2O_3 (%)	5.71
MgO (%)	2.93
K_2O (%)	1.58
Loss on ignition (LOI) (%)	0.51

2.2 Steel reinforcement

This research uses longitudinal steel bars that are ribbed and have nominal diameters of 12, 16, and 6mm. Steel bars' mechanical properties, including their average yield tensile strength, maximum elongation, and ultimate tensile strength, have been listed in Table 3, and each one of the inspections of steel bars' compliance with ASTM standards.

Table 3. Steel bars' mechanical characteristics

Steel bar diameter	Bar type	Yield strength (fy)	Ultimate strength (fu)	Max. elongation (%)
6mm	Round	463MPa	492MPa	31
12mm	Ribbed	651MPa	756MPa	22
16mm	Ribbed	542MPa	647MPa	20

2.3 Box plastic

Plastic pipe: pipes were made of plastic. The diameter of hollow concrete beams is 6.5 cm across the entire beam, as depicted in (Fig. 2). Mixing Water: tap water is utilized for casting and curing all beam specimens.

Fig. 2. Reinforcing bars and plastic pipe

2.4 Mix design

Table 4 indicates the concrete mix by weight.

Table 4. Mixture proportions by weight

Mix No.	Portland cement (C), (kg/m³)	Natural fine aggregates (NFA) (kg/m³)	Natural coarse aggregates (NCA) (kg/m³)	Ceramic recycled coarse aggregates (RCA)		Water (w) (kg/m³)
				Coarse aggregates replacement of recycled ceramic (%) by weight	Recycled ceramic (kg/m³)	
Group 1	425	635	1090	0%	0	200
Group 2	425	635	763	30%	315	200

2.5 Descriptions of molds and specimens

Twelve concrete beams with a 140 mm width, 250 mm height, and 1200 mm length have been used as cement, and transverse reinforcement spaces have always been the same. Models that have been utilized in the presented work included specifications that complied with ACI-318 guidelines, which are crucial as a foundation for further research. Both the computation for the reinforcing steel ratio as well as the ratio of width, length, and height fell within specification parameters, six models of NCB in all, including three SNCB without hollow and three HNCB with poured Hollow Low Diameter of 6.5cm over all of the 120cm beams, were created. Three HRCCBs and three SRCCBs without hollows were among the six additional RCCB variants that were prepared. Cross-sectional characteristics of those specimens have been depicted in Fig3, and all of the measurements are in millimeters. The mean cube compressive strength (fcu) related to recycled ceramic concrete was 38 MPa, compared to 42 MPa for regular concrete. For deforming to steel reinforcing bars with 12mm and 16mm diameters, all the beams have undergone longitudinal reinforcement from top to bottom. Furthermore, reinforcing bars with vertical stirrups with a 6mm diameter have been positioned at intervals of 50, 14, and 7 cm, as shown in Figures 4 and 5. Every measurement is expressed in millimeters.

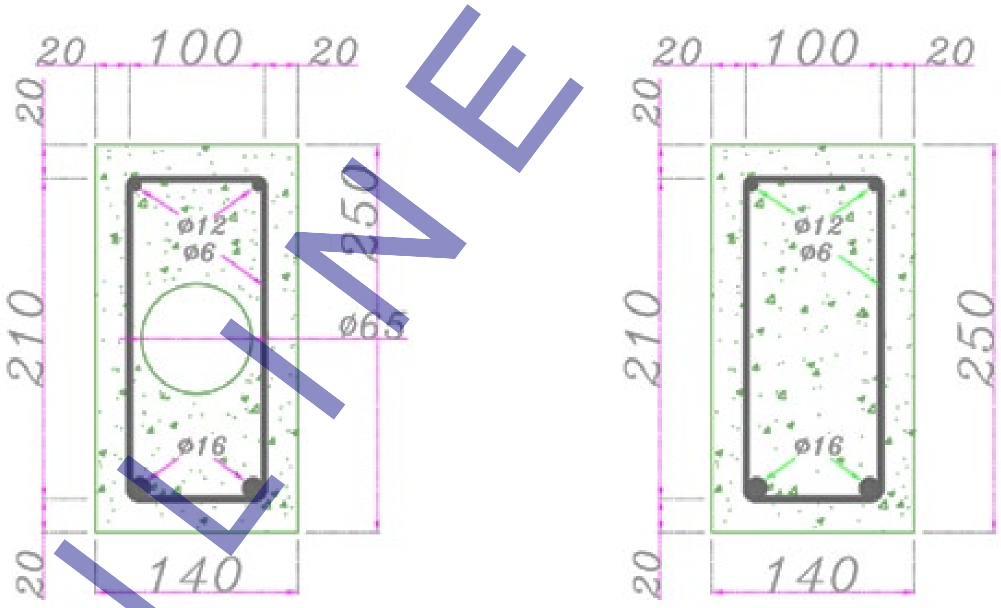
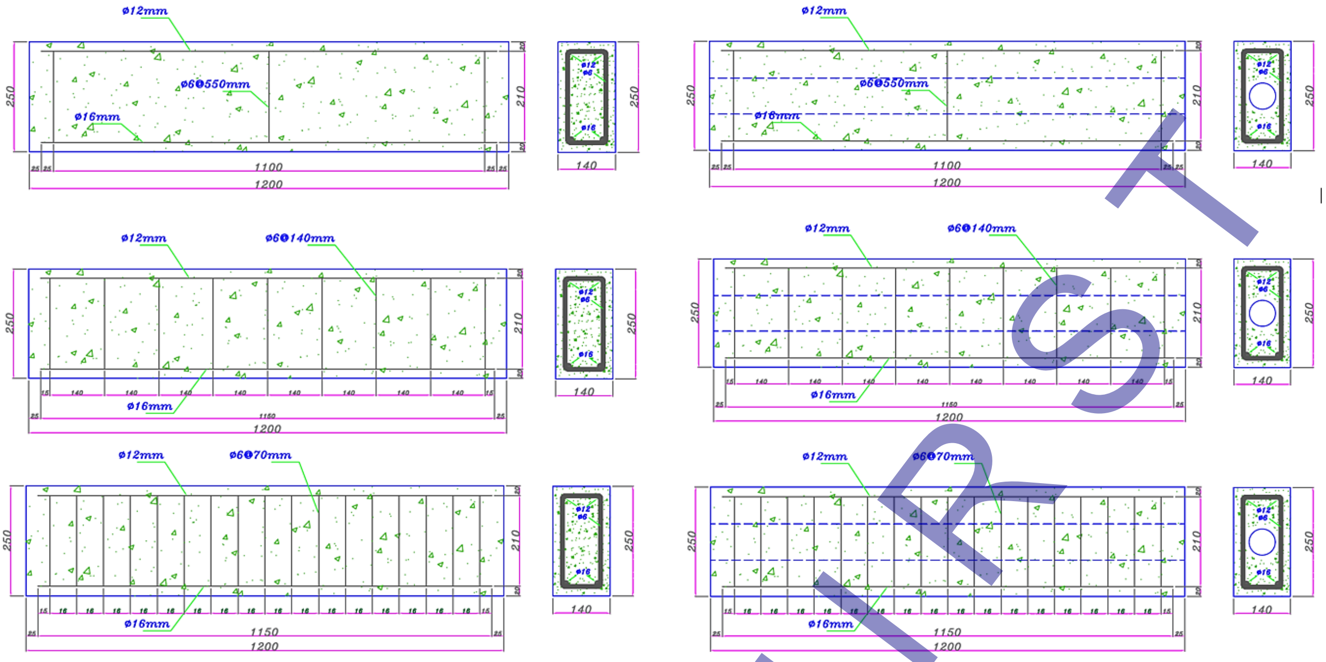
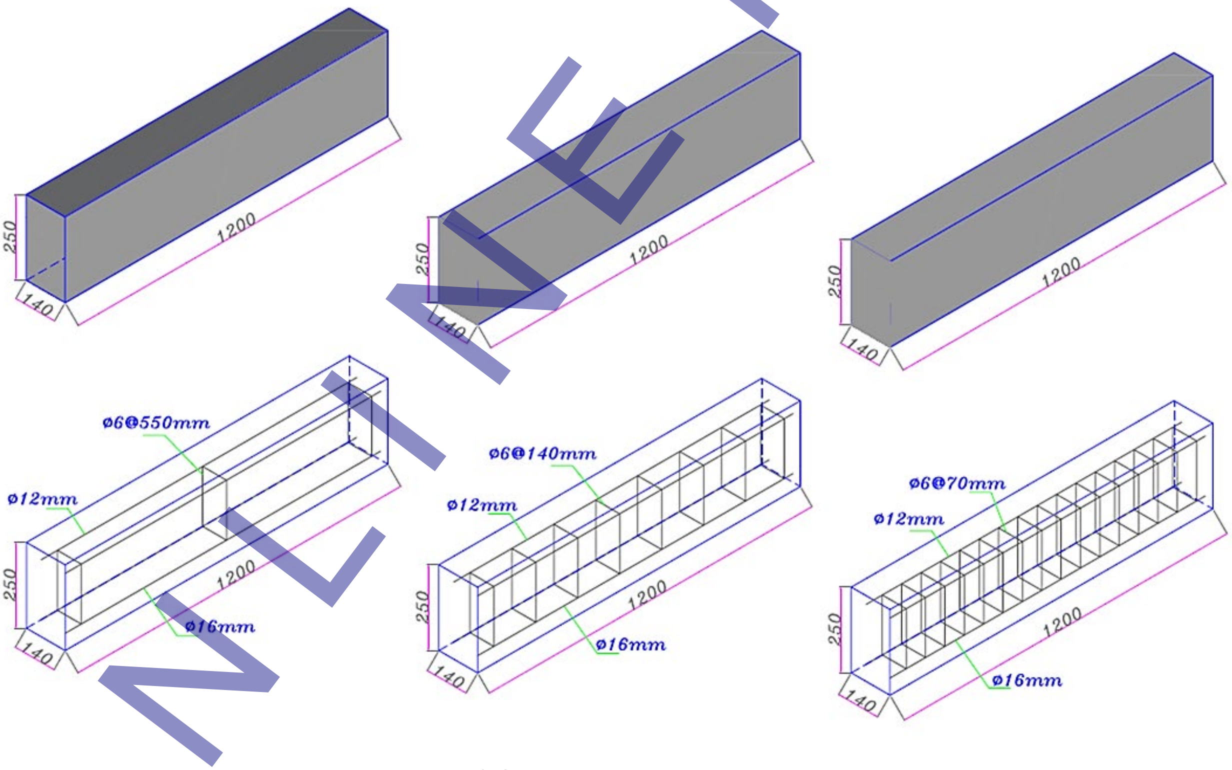


Fig. 3. Cross-sectional details of the hollow and solid concrete beams

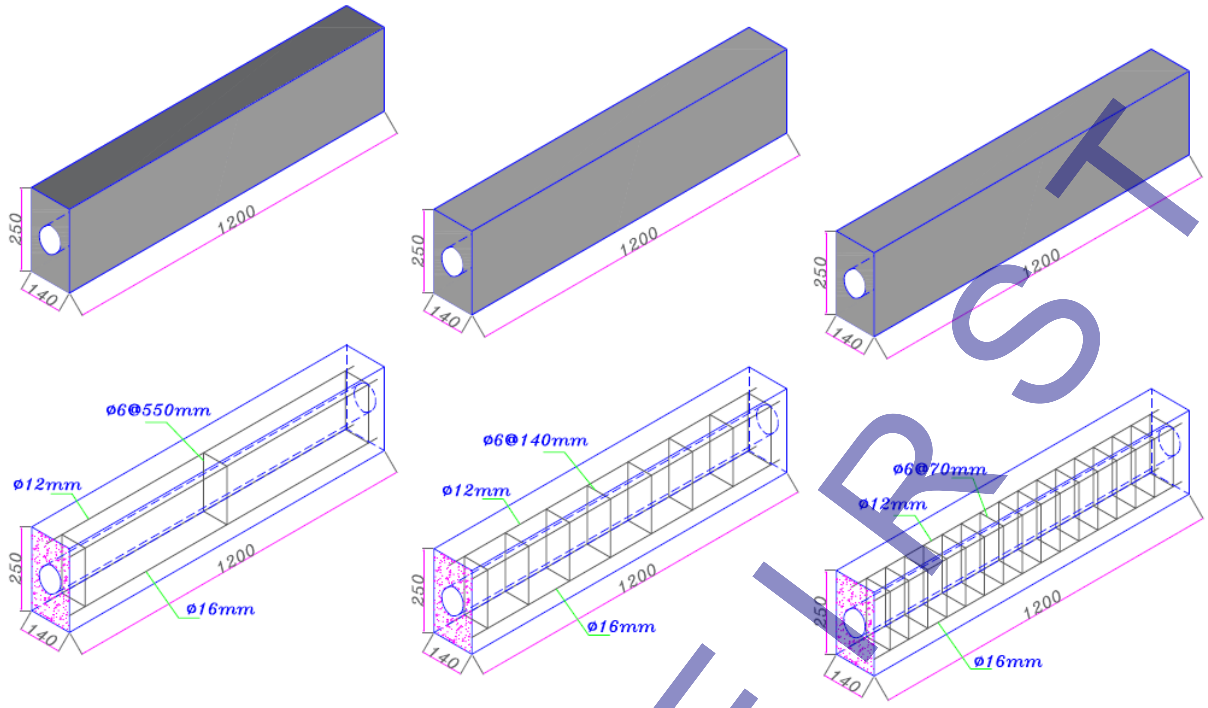


a) Solid concrete beam b) Hollow concrete beam

Fig. 4. Elevation details of beam [cross section] (2-D)



a) Solid concrete beam



b) Hollow concrete beam

Fig. 5. Elevation details of beam [cross section] (3-D)

2.6 Specimen preparation

In the lab, each specimen has been prepped. All SNCB, HNCB, SRCCB, and HRCCB were cast using mixed concrete. One day later, exactly twenty-eight days later, the beams have been removed from the curing water tank. As seen in (Fig. 6).

2.7 Test setup and instrumentation details

The structural responses of SNCB, HNCB, SRCCB, and HRCCB are represented by a single dial gauge (ELE type). For verifying the downward deflection, it was placed halfway beneath the beams, as seen in Fig. 7.

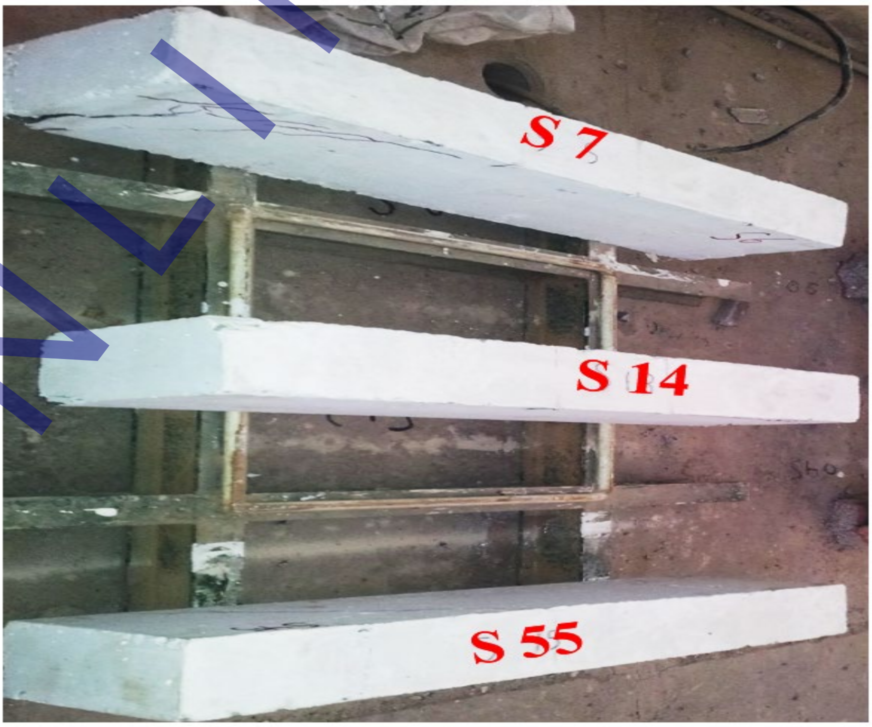
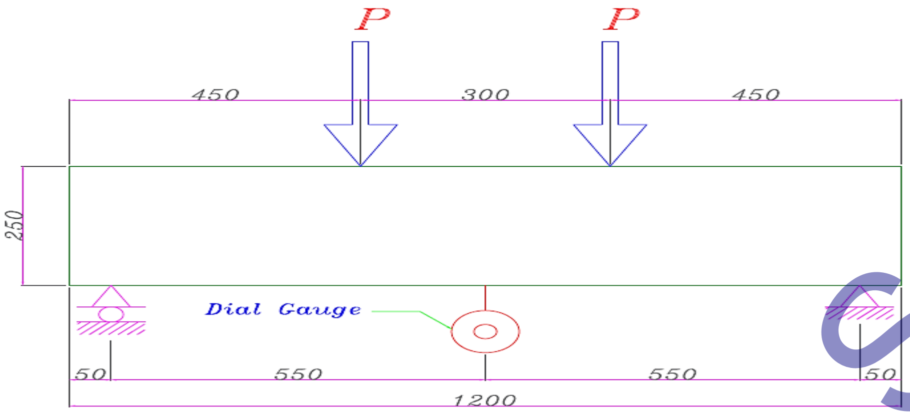


Fig. 6. SNCB, HNCB, HRCCB, and SRCCB out of water



a) Side view of the beam

b) Universal Testing Machine (MFL System)

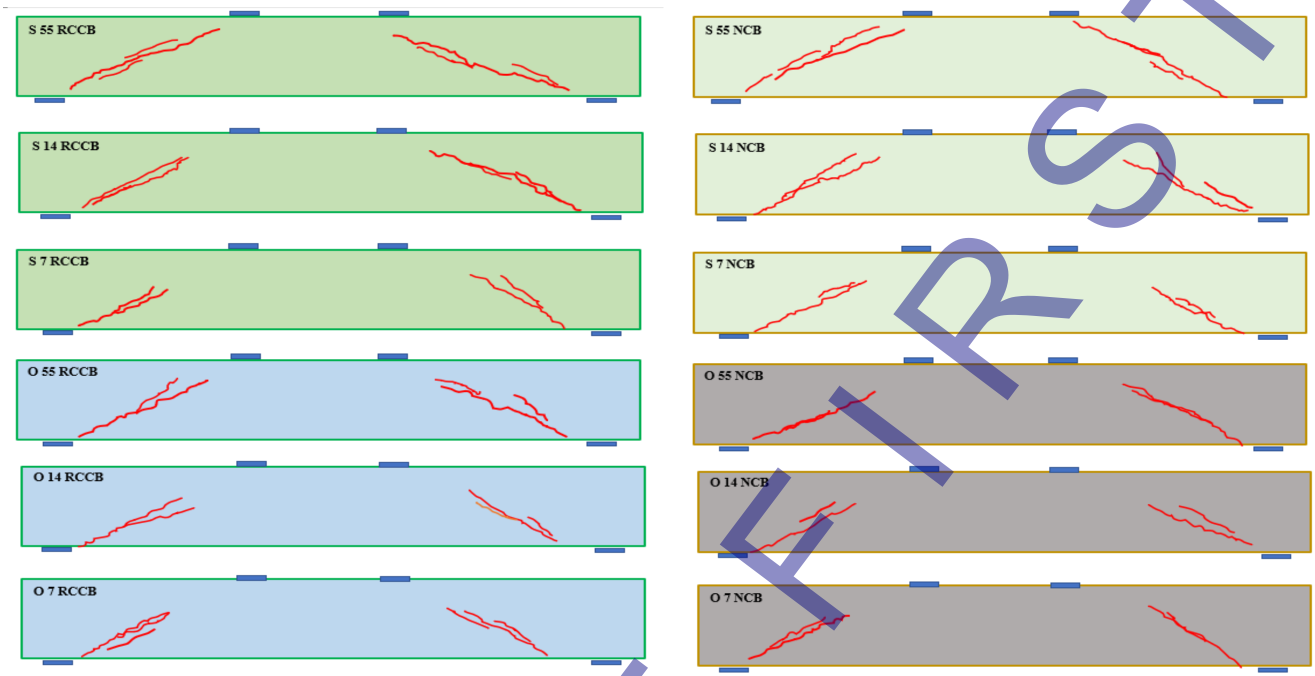
Fig. 7. Instrumentation of Testing

3 Results and discussion

The presented work examines twelve instances of RCBs. The thickness, width, and length of RCB are all the same. A number of 6 mm-diameter steel stirrup bars spaced 550 mm, 140 mm, and 70 mm apart were manufactured as web reinforcement. Six RCB models (S 55 RCCB, S 14 RCCB, and S 7 RCCB) have three SRCCBs without a hollow. The three extra HRCCBs (O 55 RCCB, O 14 RCCB, and O 7 RCCB) poured 65mm diameter cavities along a 1200mm al beam. Six RCB models have three hollow-free SNCB (S55 NCB, S14 NCB, and S7 NCB). Along the 1000mm al beam, the 3 additional HNCB (O55 NCB, O14 NCB, and O7 NCB) poured cavities that measured 65mm in diameter. Results have been analyzed in terms of first cracking load, ultimate load capacity, crack patterns, and load–deflection response.

3.1 Mechanical properties (first crack loads, ultimate loads, and crack patterns)

Initial cracks were observed in the constant moment region near mid-span and were predominantly flexural in nature. As the applied load increased, inclined cracks developed within shear spans, indicating the onset of shear-related stresses. The results of the load-carrying level capability and cracking tests are shown in Table 5. SRCCB and HRCCB specimens were subjected to Load Level (kN) (Experimental) carry capacity; the first cracks had formed at around 17.0–29.0% of RCB's Load Level (kN) (Experimental) carry capacity. Also, SNCB and HNCB have a carry capacity of approximately 17.4–28.1% regarding experimental load level (kN) for RCB. RCB models include three SRCCB models with no hollow (S 55 RCCB, S 14 RCCB, and S 7 RCCB). The initial values of crack load (Pcr) are 14.50, 15.50, and 16.50kN. The kN values of the three additional HRCCBs are 15, 17.5, and 19.5 for O 55 RCCB, O 14 RCCB, and O 7 RCCB. In RCB models, the first crack load (Pcr) for three SNCB models (S55NCB, S14NCB, and S7 NCB) with no hollow is 17.50, 18.50, and 19.50kN. The three additional HNCB (O 55 RCCB, O 14 RCCB, and O 7 RCCB) have respective values of 18, 20, and 22 kN. Three SRCCB (S 55 RCCB, S 14 RCCB, and S 7 RCCB) had Ultimate Load Level (Pu) values of 66, 82, and 97kN, but three HRCCB (O55 RCCB, O14 RCCB, and O7 RCCB) had values of 49, 58, and 69 kN. The Ultimate Load Level (Pu) values of 3 SNCB (S55 NCB, S14 NCB, and S7 NCB) were 78, 97, and 112 kN, whereas the Ultimate Load Level (Pu) values of three HNCB (O55 NCB, O14 NCB, and O7 NCB) were 64, 78, and 93 kN. Three HRCCB (O 55 RCCB, O 14 RCCB, and O 7 RCCB) and three SRCCB (S 55 RCCB, S 14 RCCB, and S 7 RCCB) RCB models demonstrate shear cracks that follow yielding related to steel reinforcement as well as the eventual crushing of the RC Beam in the compression zone (Fig. 8). The difference between all of these RCCB test results, as well as 6 NCBs of normal weight, has been < 15%. Because the hollow cylindrical diameter extends along the concrete beam, hollow beam models are less tolerant or weaker of forces than solid beams, which improves the accuracy. For both conventional concrete beams (NCB) and recycled ceramic concrete beams (RCCB), the crack propagation followed a similar pattern. However, RCCB specimens exhibited slightly wider and more distributed cracking. This behavior can be a result of higher porosity and weaker ITZ (i.e., interfacial transition zone) that is related to recycled ceramic aggregates, which reduces crack resistance and stiffness. The final failure mode for most specimens was characterized by diagonal shear cracking followed by concrete crushing in the zone of compression. This behavior confirms that the beams were predominantly governed by shear-related failure mechanisms. Reducing stirrup spacing improved crack distribution and delayed shear failure by enhancing confinement and shear transfer mechanisms.



a) HRCCB and SRCCB

b) HNCB and SNCB

Fig. 8. Patterns of cracks

Table 5. First crack and ultimate loads (SNCB, HNCB, HRCCB, & SRCCB)

Group name	Beam designation	f_{cu} (MPa)	First crack load level (P_{cr}) (kN)	Ultimate load (P_u)(kN)	$\frac{P_{cr}}{P_u}$ (%)
Solid normal concrete beams (SNCB)	S 55 NCB	42.0	17.5	78	22.4
	S 14 NCB	41.5	18.5	97	19.07
	S 7 NCB	43.5	19.5	112	17.4
HNCB	O 55 NCB	43.0	18	64	28.1
	O 14 NCB	42.5	20	78	25.6
	O 7 NCB	41.0	22	93	23.7
SRCCB	S 55 RCCB	38.5	14.5	66	22.0
	S 14 RCCB	37.0	15.5	82	18.9
	S 7 RCCB	37.5	16.5	97	17.0
Hollow recycled ceramics concrete beams (HRCCB)	O 55 RCCB	39.0	15.0	60	25.0
	O 14 RCCB	37.5	17.5	74	23.6
	O 7 RCCB	38.0	19.5	88	22.2

3.2 Ultimate loads values

According to test results in Figure 9 and Table 5, Ultimate Load Levels for SRCCB (S 55 RCCB, S 14 RCCB, and S 7 RCCB) were stronger compared to HRCCB Load Levels (O 55 RCCB, O 14 RCCB, and O 7 RCCB). RCCB and NCB comparison is shown in Figures 10–11. The load-carry level capacity with regard to all beams (SRCCB and HRCCB) increases with distance related to vertical stirrup bar reinforcement (6.0mm diameter), as shown in Figures 12–13. Figures (14–15) show the comparison between RCCB and NCB. The average load level capacity decline of solid beams (S 55 RCCB, S 14 RCCB, and S 7 RCCB) is approximately 10% lower than that of hollow beams (O55 RCCB, O14 RCCB, and O7 RCCB). Despite this reduction, the overall structural behavior remained comparable, suggesting that recycled ceramic aggregates can be successfully utilized in reinforced concrete beams with acceptable performance. The reduction in ultimate load observed in recycled ceramic concrete beams is mainly related to the porous nature of ceramic aggregates and the weaker interfacial transition zone (ITZ), which reduces stiffness and accelerates diagonal crack propagation under shear loading.

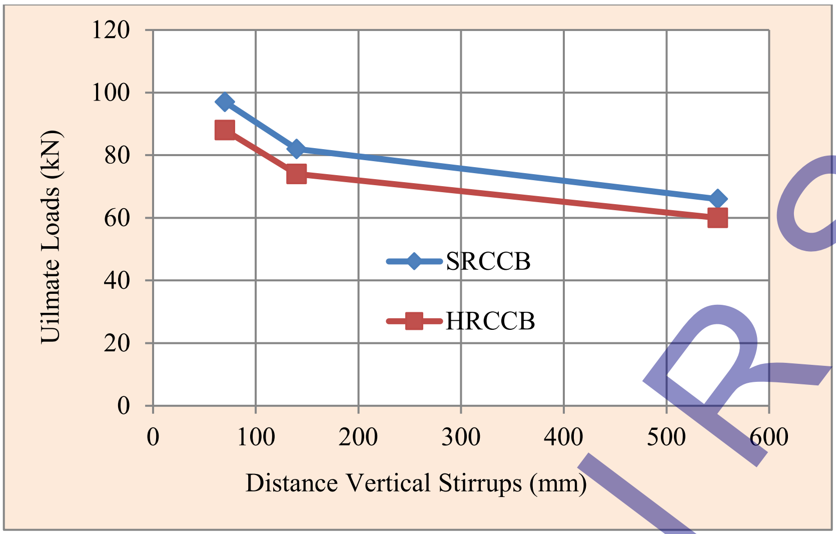


Fig. 9. Ultimate load-distance vertical stirrups bar reinforcement (7cm, 14cm, 55cm) relationships for SRCCB & HRCCB

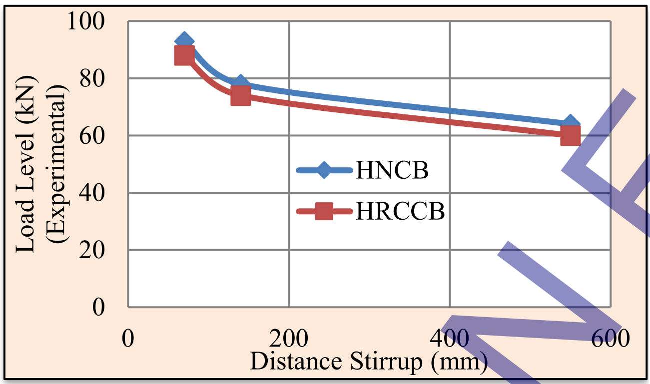


Fig. 10. Ultimate load-distance vertical stirrups bar correlations for HNCB and HRCCB

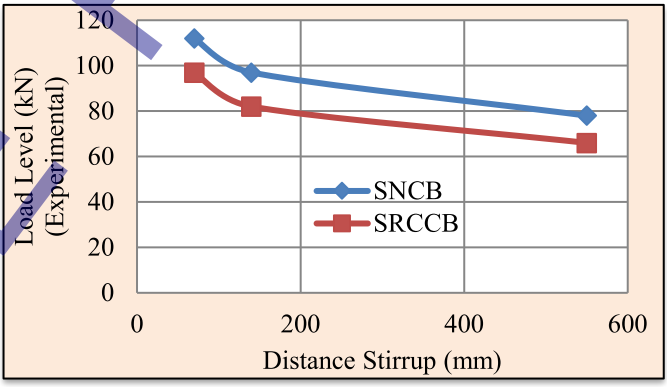


Fig. 11. Ultimate load-distance vertical stirrups bar correlations for SNCB and SRCCB

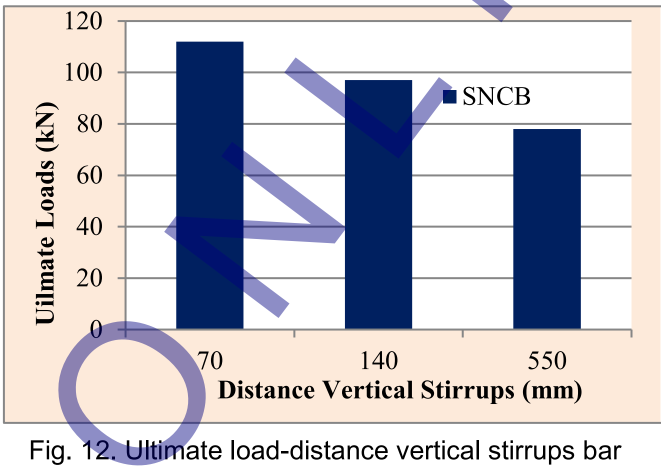


Fig. 12. Ultimate load-distance vertical stirrups bar reinforcement correlations with SNCB

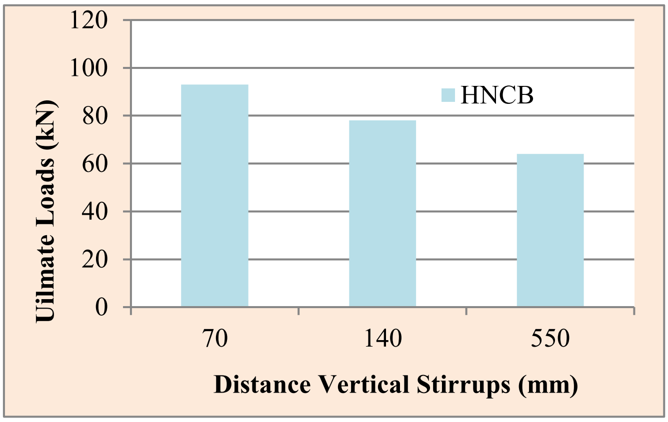


Fig. 13. Ultimate load-distance vertical stirrups bar reinforcement correlations with HNCB

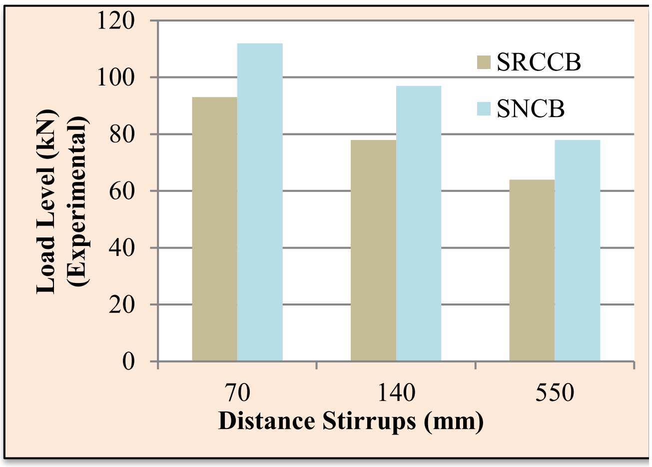


Fig. 14. Ultimate load-distance vertical stirrups bar reinforcement correlations with SNCB and SRCCB

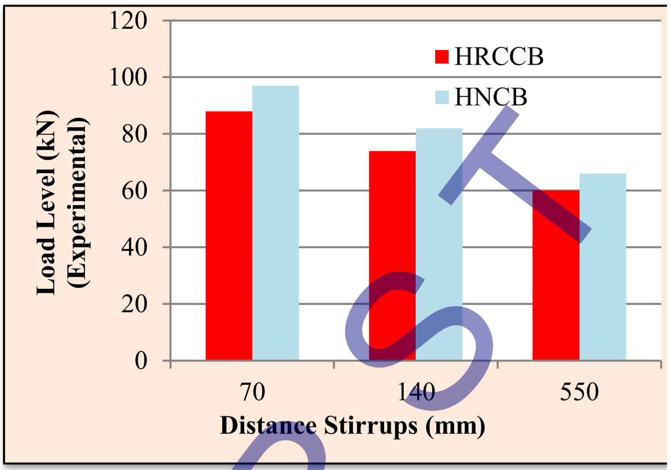


Fig. 15. Ultimate load-distance vertical stirrups bar reinforcement correlations with HRCCB & HNCB

3.3 Load - deflection correlations

The deflection experimental results for SNCB, HNCB, SRCCB, and HRCCB beams have been shown in Table5. Results that are associated with experimental testing show that, similar to HNCB and HRCCB beams, SRCCB and SNCB beams show max deflection at ultimate load of 7cm in a case where distance between vertical stirrup bar reinforcement (6 mm diameter) is 6 cm. Fig16 and Fig17 show the load-deflection relation for beams (SNCB and HNCB beams). Beams with smaller results showed that the stiffness and deflection of the stirrup spacing under the progressive loading improved. The results of this observation indicate the importance of shear reinforcement in the control of crack propagation and load carrying capacity of RCBs. Figures 18 to 23 show a comparison related to recycled ceramic concrete as well as normal-weight beams.

Table 6. Mid span deflection at first crack and load level carry capacity

Group name	Beam designation	Mid-span deflection at first crack	Mid-span deflection at ultimate load level
SRCCB	S 55 RCCB	0.09mm	2.15mm
	S 14 RCCB	0.10mm	2.40mm
	S 7 RCCB	0.14mm	2.73mm
HRCCB	O 55 RCCB	0.20mm	1.93mm
	O 14 RCCB	0.26mm	2.10mm
	O 7 RCCB	0.31mm	3.41mm

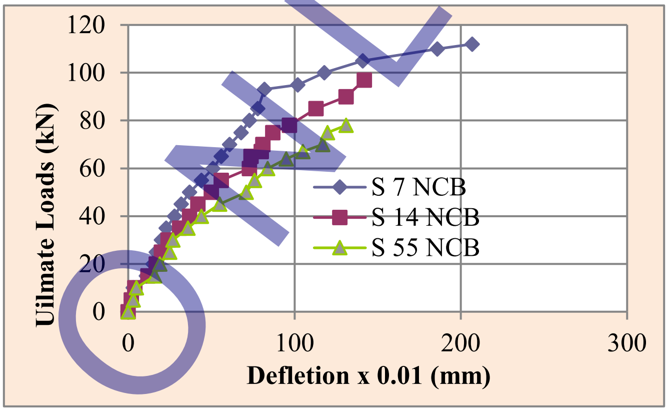


Fig. 16. Load-deflection relations for SRCCB (S7, S14, S55)

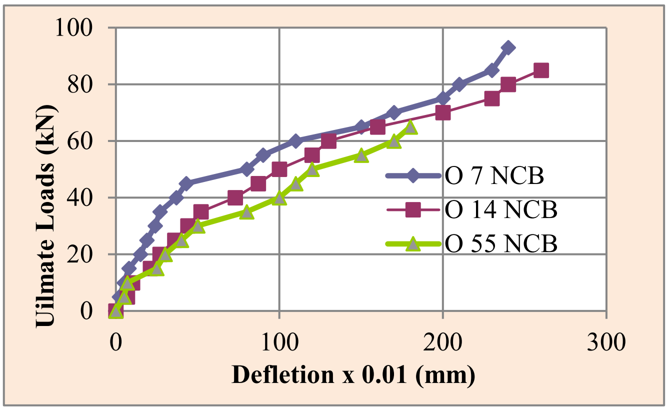


Fig. 17. Load-deflection relations for HRCCB (O7, O14, O55)

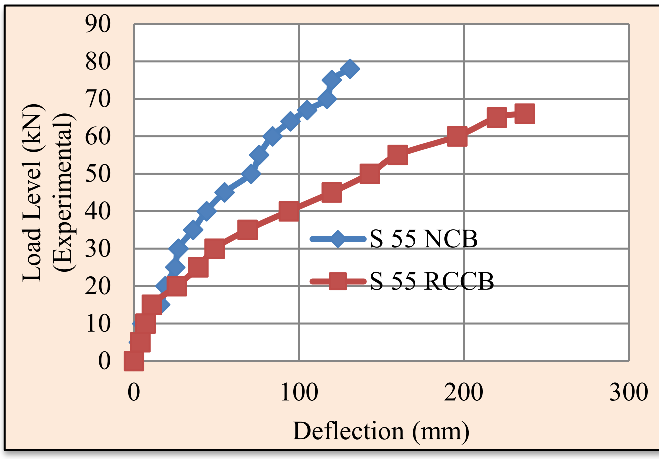


Fig. 18. Load-deflection correlations for SNCB and SRCCB (S 55)

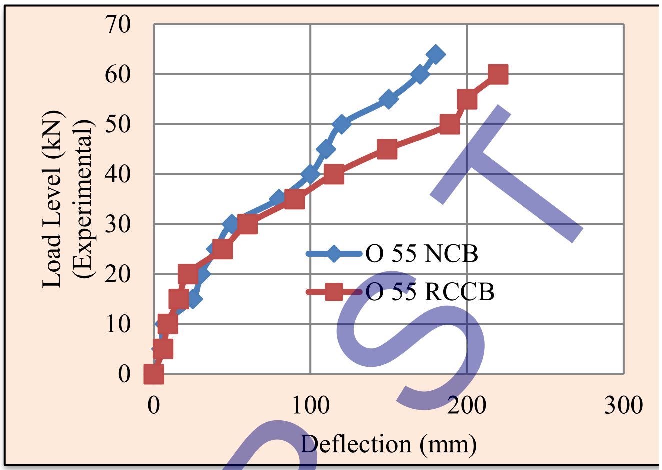


Fig. 19. Load-deflection correlations for HNCB and HRCCB (O55)

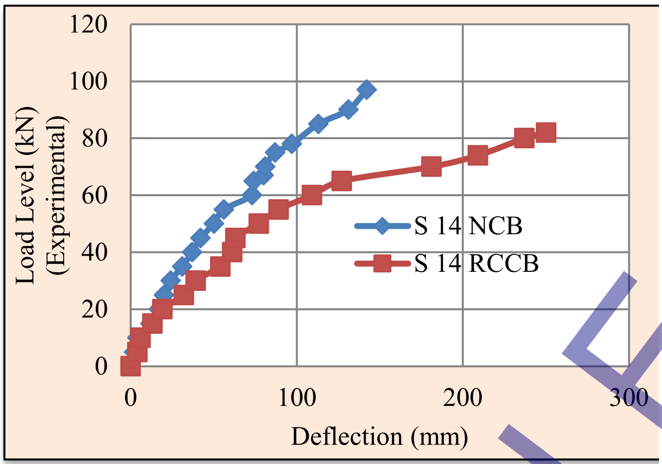


Fig. 20. Load-deflection correlations for SNCB & SRCCB (S 14)

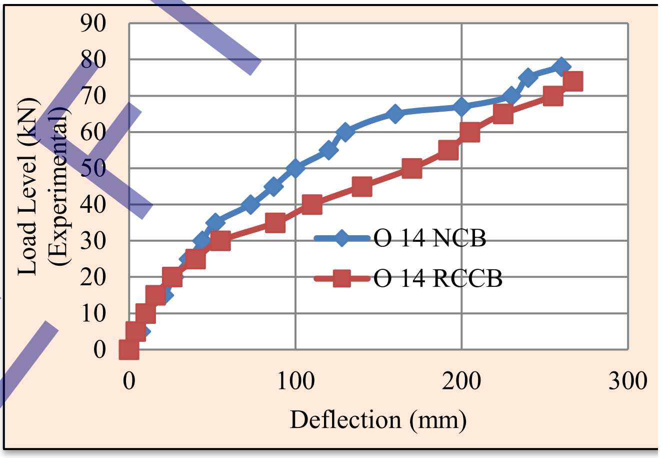


Fig. 21. Load-deflection correlations for HNCB and HRCCB (O 14)

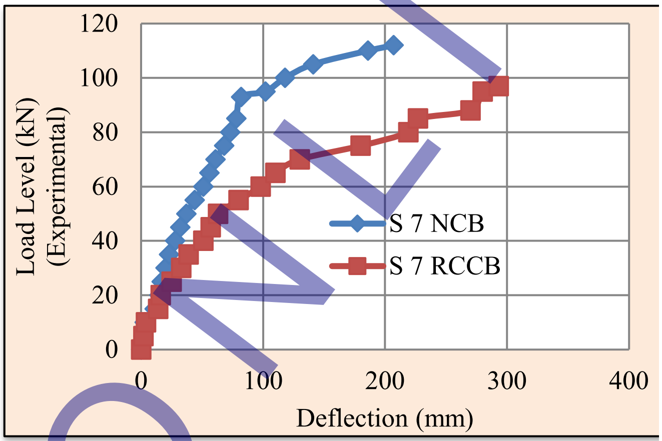


Fig. 22. Load-deflection correlations for SNCB & SRCCB (S7)

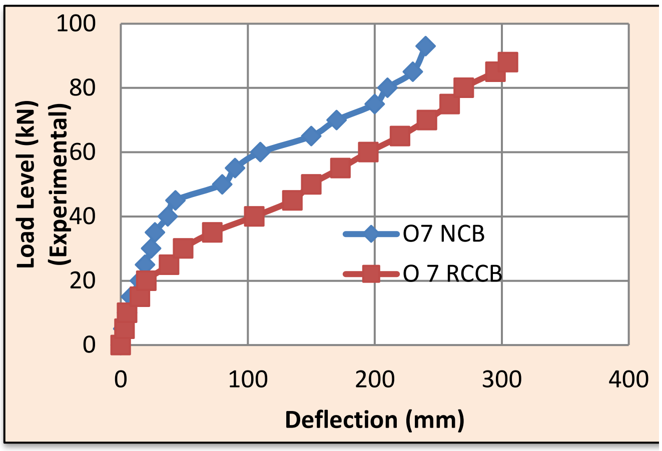


Fig. 23. Load-deflection correlations for HNCB & HRCCB (O7)

3.4 Comparison of shear strength with ACI 318 predictions

3.4.1 Shear strength equations according to ACI 318

According to the provisions of ACI 318, the nominal shear strength of reinforced concrete beams is expressed as sum of concrete contribution and transverse reinforcement contribution [43]:

$$V_n = V_s + V_c \tag{1}$$

where:

- Vn represents nominal shear strength
- Vc represents shear contribution of concrete
- Vs represents shear contribution of transverse reinforcement

For non-prestressed reinforced concrete beams subjected to shear and normal-weight concrete:

$$V_c = 0.17\lambda\sqrt{\mathrm{fc}' \cdot \mathrm{b_w} \cdot \mathrm{d}} \tag{2}$$

where:

- λ = 1 for normal-weight concrete
- b_w represents web width (mm)
- fc' represents concrete compressive strength (MPa)
- d represents effective depth (mm)

The shear resistance provided by vertical stirrups is:

$$V_s = \frac{(A_v \cdot \mathrm{f_y} \cdot \mathrm{d})}{s} \tag{3}$$

where:

- A_v = area of shear reinforcement within spacing s
- f_y = yield strength of stirrups
- s = stirrup spacing

The design shear strength is:

$$\varphi V_n = \varphi(V_c + V_s) \tag{4}$$

where:

- φ = 0.750

3.4.2 Experimental-to-ACI shear strength ratio

The experimental shear capacities of the tested beams have been qualitatively compared to predictions that have been obtained from ACI 318 equations using the ratio [42].: Vu (exp) / Vu (ACI)

- Vu (exp): experimental ultimate shear capacity
- Vu (ACI): predicted shear capacity according to ACI 318

The comparison between experimental and ACI 318 predicted shear capacities (SNCB, HNCB, HRCCB, & SRCCB) is shown in Table 7. The results indicate that the ACI 318 provisions generally provide conservative predictions for beams containing recycled ceramic aggregates. Although the recycled aggregate beams exhibited slightly lower shear resistance than conventional concrete beams, the overall behavior remained reasonably consistent with the assumptions adopted by the code for reinforced concrete beams that have been subjected to shear loading. The hollow beam specimens showed lower experimental shear capacities than solid beams due to the reduction in effective shear area and the modification of stress distribution caused by the longitudinal voids. Nevertheless, the influence of stirrup spacing remained significant and consistent with ACI 318 expectations.

Table 7. Comparison between experimental and ACI 318 predicted shear capacities (SNCB, HNCB, HRCCB, & SRCCB)

Beam designation	f_{cu} (MPa)	Vu (exp) (kN)	Vu (ACI) (kN)	Vu (exp)/Vu (ACI)
S 55 NCB	42	78	70	1.11
S 14 NCB	41.5	97	86	1.13
S 7 NCB	43.5	112	98	1.14
O 55 NCB	43	64	59	1.08
O 14 NCB	42.5	78	71	1.10
O 7 NCB	41	93	84	1.11
S 55 RCCB	38.5	66	61	1.08
S 14 RCCB	37	82	74	1.11
S 7 RCCB	37.5	97	87	1.12
O 55 RCCB	39	60	55	1.09

Beam designation	f_{cu} (MPa)	Vu (exp) (kN)	Vu (ACI) (kN)	Vu (exp)/Vu (ACI)
O 14 RCCB	37.5	74	67	1.10
O 7 RCCB	38	88	79	1.11

The comparison between the experimentally obtained shear capacities and the predictions based on ACI 318 demonstrates that the code equations provide reasonably conservative estimates for reinforced concrete beams incorporating recycled ceramic aggregates. The average Vu(exp)/Vu(ACI) ratios remained greater than unity for all tested specimens, indicating that the code provisions can adequately capture the general shear behavior despite the presence of recycled ceramic aggregates and longitudinal hollow sections.

However, the hollow beam specimens exhibited slightly lower agreement with the code predictions due to the reduction in effective web area and the altered internal stress trajectories induced by the longitudinal cavities. Since the ACI 318 shear design equations were originally developed for conventional solid reinforced concrete members, additional considerations may be required when applying these provisions to hollow structural members containing recycled aggregates.

Furthermore, the recycled ceramic aggregate beams exhibited slightly increased crack widths and reduced stiffness compared with conventional beams, which may be a result of higher porosity and weaker interfacial transition zone that is associated with the ceramic aggregates. Despite these effects, the overall structural performance remained within acceptable engineering limits, supporting feasibility of using recycled ceramic aggregates in sustainable reinforced concrete structural applications.

3.5 Limitations of the study

This study is limited to a short-term experimental investigation under static four-point bending loading conditions. Only one replacement ratio (30%) of recycled ceramic coarse aggregate and one hollow diameter configuration were considered. In addition, the number of tested specimens was limited to laboratory-scale beams. Therefore, the results obtained should be interpreted within the scope of the investigated parameters. Further studies are recommended to examine different replacement ratios, larger-scale structural members, cyclic and fatigue loading conditions, and long-term durability performance. Furthermore, durability characteristics and numerical finite element simulations were not considered in this study.

4 Conclusions

The current work provides the results of an experimental assessment of reinforced HRCCB. With the use of a four-point bending approach, six reinforced recycled ceramic concrete beams were constructed and tested. The reinforced HRCCB beams' size and configuration served as study parameters. The increased ultimate deformation capacity of reinforced SRCCB with the hollow part removed has been compared. The degradation of concrete shear resistance is the primary subject of discussion for the shear resistance mechanism pertaining to HRCCB and SRCCB beams. Based on the experimental investigation conducted in this study, the following conclusions can be drawn:

- Hollow beams exhibited lower shear capacity and higher deflection than solid beams due to the reduction in effective shear area.
- Recycled ceramic aggregate beams showed acceptable structural performance with only moderate reductions in ultimate load compared with conventional concrete beams.
- Reducing stirrup spacing significantly improved crack control, stiffness, and shear resistance.
- The dominant failure mode was diagonal shear cracking followed by concrete crushing in compression zone.
- The experimental behavior generally agreed with the expected trends of ACI 318 provisions for RCBs subjected to shear loading.

The principal reason for this decrease in the shear capacity of the beams made with recycled ceramic aggregates is the increased porosity and poor ITZ characteristics, which leads to a decrease in stiffness and shear resistance of recycled concrete, compared with conventional concrete. Furthermore, the introduction of a longitudinal hollow core will change the stress distribution and decrease the shear area which results in stress concentration and earlier appearance of diagonal shear cracks. Hollow beams, therefore, have less load capacity and more deflection than solid beams. It is also shown that the effect of shear reinforcement is very important, with a decrease in the spacing between the stirrups, which is a measure of crack control, the shear resistance is increased. In general, the performance of the tested beams is in good agreement with that prescribed by design codes (e.g., ACI 318), but the combined use of recycled aggregates and hollow sections needs to be carefully considered in structural design.

The findings of this study contribute to a better understanding of shear behavior of RCBs incorporating recycled ceramic aggregates. Further research is recommended to investigate long-term durability and structural performance of recycled ceramic concrete in other structural elements like slabs, columns, and large-scale structural systems.

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7 Conflict of interest statement

The authors declare no conflicts of interest.

8 Author contribution

Salam Salman Chiad Alharishawi contributed to the conceptualization of the study, experimental program design, specimen preparation, and data collection. Nagham Rajaa carried out experimental investigation, formal analysis, manuscript drafting, language editing, and simulation-related work. Hadi Salih Mijwel Aljumaily contributed to reviewing and revising the manuscript, interpretation of results, and supervision of the final scientific content.

9 Availability statement

The data are contained within the article.

10 Supplementary materials

There are no supplementary materials to include.

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