

Experimental investigation on the structural performance of reinforced concrete deep beams incorporating recycled concrete aggregates

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Abstract

This investigation focuses on exploring the feasibility of using recycled concrete aggregates mix in concrete structures. The objective of the study is to examine the tensile, compressive, and flexural strengths of recycled aggregate concrete, as well as performance of reinforced RAC deep beams by evaluating critical parameters including aggregate replacement ratio, water-to-cement ratio, presence of structural web openings, and layered casting configurations. Concrete incorporating recycled concrete aggregates mix with replacement percentages of (0, 25, 50, 75, and 100%) was utilized and tested after 28 days of curing. The study evaluated 13 reinforced concrete deep beams categorized into solid, with web openings, and layered configurations. Overall, it was observed that an increase in the percentage of recycled aggregates led to a reduction in the compressive, tensile, and flexural strengths of the concrete. Nevertheless, the application of RAC as aggregate concrete can be supported by adjusting the replacement percentage of recycled concrete aggregates and the water-to-cement ratio to achieve the desired performance of reinforced concrete structures. A 25% RCA replacement ratio minimizes the compressive strength loss to just 3.48%.

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1. Introduction

The environmental repercussions of producing the raw materials for concrete (cement, coarse and fine aggregates), are significant [1,2]. The measure of this issue necessitates the exploration of alternative raw material sources to decrease energy consumption and the use of natural resources, ultimately leading to a more sustainable concrete. One common approach to achieving an eco-friendlier concrete is the crushing of concrete to create coarse aggregate for new concrete production. This method reduces the demand for natural resources and minimizes the landfill space required for waste concrete. While there are no current assessments of recyclable waste volumes in Iraq, the Ministry of Environment estimated that in 2010 and 2011, about 58% of the total waste disposed of in municipal dumps was construction debris. A large part of this waste consists of concrete and building rubble. It is crucial to investigate the mechanical properties and durability characteristics of Recycled Aggregate Concrete (RAC) to ensure the appropriate use of recycled materials. Many studies have examined the mechanical and durability properties of RAC [3,4,5]. Findings indicate that the mechanical characteristics are contingent upon the characteristics of the recycled aggregate used to produce the concrete, and the percentage of coarse aggregates replaced in the new concrete [6]. For example, with a 100% replacement of recycled aggregates, Deng, X., & Zhang, H. [7] reported that the compressive strength decreased by 9%, while

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El-Sayed, T. A., & Metwally, I. M. [8] reported a 45% decrease. Likewise, Kakar, A., & Gupta, P [9] assessed a 15% reduction in the modulus of elasticity of RAC, while Khan, M. S., & Ali, M. [10] noted a decrease of up to 40% at a higher water-cement ratio of 0.75, with an insignificant difference at a lower ratio of 0.55. Additionally, Li, J., & Zhang, Y. [11] proposed equations for the modulus of elasticity that suggest an average decrease of 15% for Normal Aggregate Concrete (NAC) and RAC with similar cylinder compressive strength. The structural application of Recycled Concrete Aggregate (RCA) requires a thorough understanding of its fresh and hardened properties. Incorporating RCA typically alters the concrete matrix due to its inherent physical characteristics, such as higher water absorption and lower density compared to natural aggregate. However, adjusting critical mix proportions, particularly optimizing the water-to-cement ratio, can significantly enhance and control the compressive strength development of recycled aggregate mixtures.

In 2020, Xiao et al. stated that during the mechanical crushing of recycled concrete, very tiny cracks are created, which greatly increase its ability to absorb water and reduce its aggregate bonding strength compared to using natural aggregate [12]. In 2018, Knaack and Kurama stated that the weakness in the mechanical strength of recycled aggregate concrete can be compensated by improving the dosages of chemical additives, but its shrinkage performance remains critical when drying because of the highly porous cohesive paste [13]. In 2022 Ahmed, et. al, they showed that the results indicate adding 50% of recycled concrete aggregate when casting deep reinforced beams gives an acceptable structural shear capacity, even though it significantly increases maximum mid-span deflections and the width of diagonal cracks [14]. In 2023 Liu, F., & Sun, X., they studied the shear behavior of deep beams made from recycled concrete and showed that diagonal crack formation happens at relatively lower load levels due to the weak interfacial transition zone around the old cement paste [15].

The primary objective of this research is to evaluate the feasibility and structural performance of utilizing recycled concrete aggregate (RCA) as a partial or full replacement for conventional coarse aggregate in structural concrete. To achieve this goal, the following specific objectives have been established:

- To assess the influence of RCA on the workability and properties of concrete mix.
- To investigate the effect of RCA replacement ratios on the mechanical properties of concrete, specifically compressive, flexural, and splitting tensile strengths.
- To investigate the shear behavior, cracking patterns, and ultimate load capacity of reinforced concrete deep beams under varied configurations, including beams with structural web openings, solid control beams, and beams including layered RCA casting layouts.
- In addition to experimental objectives, this study aims to highlight the environmental and economic advantages of utilizing RCA as a sustainable construction material.

Advanced configuration approaches are important to optimize the performance of Recycled Concrete Aggregate (RCA) deep beams in structural buildings. Applying a layered casting technique strategically enhances the critical shear span region, effectively mitigating strength loss while maximizing structural sustainability. Conversely, the integration of structural web openings significantly alters internal load transfer mechanisms, making it vital to analyze their direct impact on the beam's ultimate load-carrying capacity.

2. Materials

2.1 Cement

The cement used in this study is Iraqi ordinary Portland cement Type (I). It is stored in airtight plastic containers to avoid exposure to different atmospheric conditions. This cement is tested and checked according to the American Standard Specification (ASTM C150). Tables 1&2 show the physical and chemical cement properties, respectively.

Table 1. Physical properties of type (I) cement (According to ASTM C150)

Physical Property Under Test	Laboratory Test Result	ASTM C150 Type I Limits	Compliance Status
Fineness (Blaine Air Permeability)	2850 cm ² /g	≥ 2600 cm ² /g	Pass
Setting Time (Vicat Apparatus)			
— Initial Setting Time	135 minutes	≥ 45 minutes and ≤ 375 minutes	Pass
Soundness (Autoclave Expansion)	0.12%	≤ 0.80%	Pass
Compressive Strength (Standard Mortar Cubes)			
— 3-Day Hydration Age	18.4 MPa	≥ 12.0 MPa	Pass
— 7-Day Hydration Age	26.8 MPa	≥ 19.0 MPa	Pass
— 28-Day Curing Baseline	44.5 MPa	≥ 28.0 MPa (Optional Target)	Pass

Table 2. Chemical composition of type (I) cement (According to ASTM C150)

Chemical Component / Oxide	Abbreviation	Laboratory Test Result (%)	ASTM C150 Type I Limits	Compliance Status
Lime	CaO	62.45%	No explicit limit	—
Silica	SiO ₂	20.80%	No explicit limit	—
Alumina	Al ₂ O ₃	5.12%	No explicit limit	—
Iron Oxide	Fe ₂ O ₃	3.25%	No explicit limit	—
Magnesia	MgO	2.15%	≤ 6.0%	Pass
Sulfur Trioxide	SO ₃	2.38%	≤ 3.0%	Pass
Loss on Ignition	LOI	1.85%	≤ 3.5%	Pass
Insoluble Residue	IR	0.62%	≤ 0.75%	Pass
Main Mineral Phases (Bogue Calculation)				
Tricalcium Silicate	C ₃ S	51.40%	No explicit limit	—
Dicalcium Silicate	C ₂ S	21.15%	No explicit limit	—
Tricalcium Aluminate	C ₃ A	8.10%	No explicit limit	—
Tetracalcium Aluminoferrite	C ₄ AF	9.88%	No explicit limit	—

2.2 Fine Aggregate

The quantity and grading of fine aggregate have a significant influence on concrete production. Natural fine aggregate from Safwan city (Jabal Senam) was used. Table 3 shows the fine aggregate grading and the limits of the ASTM C33/C33M-18. It has a fineness modulus of 2.68 and a specific gravity of 2.62.

Table 3. Grading of the fine aggregate

No.	Sieve size (mm)	% Passing by weight	
		Fine aggregate (% Passing by weight)	Limits of ASTM C33/C33M-18
1	9.50	100.0	100
2	4.75	98.5	95-100
3	2.36	90.3	80-100
4	1.18	72.55	50-85
5	0.60	52.7	25-60
6	0.30	18.45	5-30
7	0.15	1.3	0-10

2.3 Coarse Aggregate

Two types of coarse aggregate are used:

2.3.1 Gravel

Crushed gravel from Senam hill region in Safwan city with grading of (5 - 20) mm was used. The coarse aggregate grading is shown in Table 4. The obtained results show that; the grading of coarse aggregate is within the requirements of ASTM C33/C33M-18. Table 5 shows the specific gravity, sulphate and chloride content and absorption of the used coarse aggregate.

Table 4. Grading of the coarse aggregate

Sieve size (mm)	Passing by weight (%)	ASTM limit (%)	Within limit?
25.0	100.0	100	Yes
19.0	93.7	90–100	Yes
9.5	22.8	20–55	Yes
4.75	0.10	0–10	Yes
2.36	0.03	0–5	Yes

Table 5. Properties of the coarse aggregate

Physical property	Normal Aggregate		Recycle Aggregate	
	Test result	IOS No. 45/1984 limit	Test result	IOS No. 45/1984 limit
Specific gravity	2.65	—	2.62	—
Sulfate content (SO ₃)	0.062%	≤ 0.1%	0.063	≤ 0.1%
Chloride content (Cl)	0.082%	≤ 0.1%	0.084	≤ 0.1%
Absorption	0.65%	—	0.69%	—
Loose bulk density	1500 kg/m ³	—	1490 kg/m ³	—

2.3.2 Recycled Aggregates

Recycled aggregates refer to granular materials that have been processed from sources such as sand, gravel, rock, or concrete from demolished structures. These aggregates are highly versatile and can be utilized in numerous applications, including the production of concrete and asphalt, as well as in drainage projects.

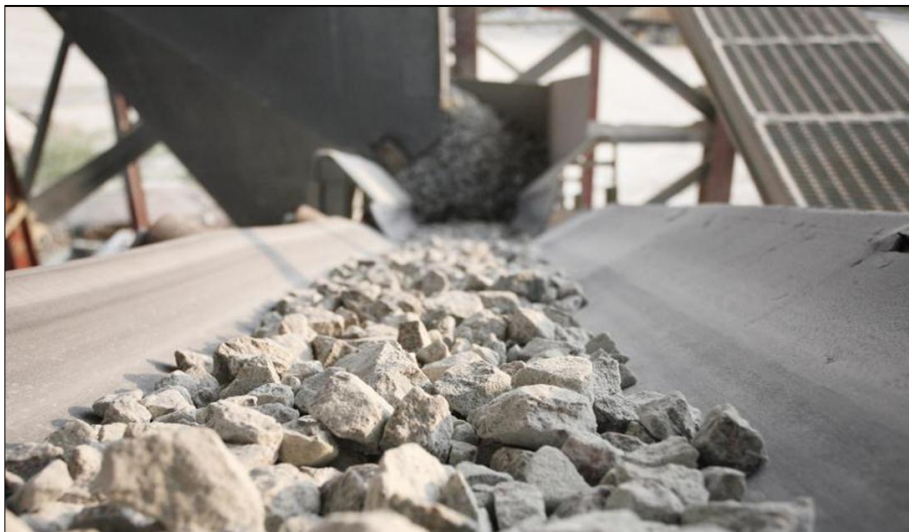


Fig. 1. Recycled aggregate

To enhance the conservation of natural rock resources and support environmental sustainability, recycled aggregates are derived from materials that have been recycled, including concrete, brick, and masonry waste [16]. Figure 1 show the sample of recycled aggregate. The recycled concrete (RCA) was obtained from leftover concrete from previously tested samples, and it was crushed and sieved to reach a maximum aggregate size (MAS) of 20 mm.

Recycled aggregate concrete differs from natural concrete mixes, as it contains hardened cement mortar. The cement mortar on recycled aggregate has higher porosity, water absorption and lower adhesion than natural aggregate. It has negative effects on the mechanical behavior and durability of fresh and hardened recycled aggregate concrete. Therefore, it will enable use the recycled concrete aggregate if the adhered cement mortar can be enhanced. The two main methods for enhancing the properties of recycled aggregate concrete are strengthening, and removing the adhered mortar.

2.4 Water

Regular tap water is applied without any additives for the processes of mixing, casting, and curing. It is necessary to wet the surface of aggregates to improve adhesive quality, as the cement paste adheres more quickly and satisfactorily to a wet surface than to a dry one. Moreover, water is essential for creating a plastic mixture of the various components, which provides workability to the concrete, making it easier to place in the desired position. Ultimately, through its chemical reaction with cement, water plays a vital role in producing the desired properties of the concrete.

2.5 Super Plasticizer

To produce a high strength concrete, super plasticizer is used. One of new materials generation of copolymer-based super plasticizer is the (Sika ViscoCrete Hi-Tech 1316) as shown in Figure 2.



Fig. 2. Super plasticizer



Fig. 3. Specimens of hardened concrete

3. Experimental Work

3.1 Concrete Mix Proportions

The mix proportion was chosen as 1:1.59:2.39 (by weight) cement, sand, gravel respectively and 0.38 water cement ratio, and (1000 g) SP for each 1 m³ concrete, the specific gravity of the polymer (1.08). Table 6 shows recycle aggregate concrete mix proportions in this study depending on recycle aggregate content. Concrete was replaced with absolute volumetric calculations weighted by batches during the design of concrete mixes to adjust the resulting volume and keep the effective cement volume per cubic meter constant.

3.2 Specimen Fabrication and Curing Conditions

All the laboratory specimens for the hardened state tests were cast in molds with manual compaction. According to the standard specification ASTM C192, compaction was carried out in

three equal layers using a standard 16 mm diameter tamping rod with 25 strokes per layer. All samples are demolded after 24 hours, marked and cured in water until testing age. Figure 3 shows the specimens that were cast and tested in this study to assessment the hardened concrete. cubes (150 mm), cylinders (150x300 mm), and prisms (150x150x500 mm) tested at 28 days.

Table 6. Concrete mix proportions

#	Coarse Aggregat e Type	Total Volum e (m ³)	Mixing Proportions					S.P. (ml)	Slum p test (mm)
			Cemen t (Kg)	Sand (Kg)	Aggregat e (Kg)	Water (kg)	Water/Ceme nt Ratio		
First Mix	Normal 100 %	1	447.8 1	712.0 0	1070.00	170.0 0	0.38	100 0	163
Secon d Mix	Recycle 25 %	1	447.8 1	712.0 0	R 267.5 N 802.5	176.2 5	0.39	100 0	165
Third Mix	Recycle 50 %	1	447.8 1	712.0 0	R 535 N 535	180.7 7	0.40	100 0	168
Fourt h Mix	Recycle 75 %	1	447.8 1	712.0 0	R 802.5 N 267.5	188.5 9	0.42	100 0	170
Fifth Mix	Recycle 100 %	1	447.8 1	712.0 0	1070.00	195.0 0	0.44	100 0	170

Note: R: Recycled Concrete Aggregate; N: Natural Coarse Aggregate (Gravel).

3.3 Compressive Strength Test

Standard 150 mm cubes were used according to BS EN 12390-3:2019 and they are opened after one day of casting. Testing was carried out at 28 days. The machine which was used in the tests is one of the hydraulic types of 2000kN capacity as shown in Figure 4. Compressive strength (MPa) is obtained by averaging of the results of three specimens according to the test results. The rate of loading of 0.6 MPa/s (13.5 kN/s) was applied automatically until failure.



Fig. 4. Cube compression test of hardened concrete

3.4 Flexural Strength Test

To calculate the flexural strength of concrete, the prism with ASTM C78 standard parameters are explicitly governed by third-point loading configurations rather than center single-point configurations. The test samples measured 150x150x500 mm. In the same conditions of the specimens of compressive strength, the flexural strength samples were tested. A “third-point loading” mechanism and support details for the 150x150x500 mm prism specimen in accordance with the ASTM C78 standard was used, as shown in Figure 5. Flexural strength (MPa) is obtained from testing. constant loading rate of 1.0 MPa/min (0.15 kN/s) was applied.

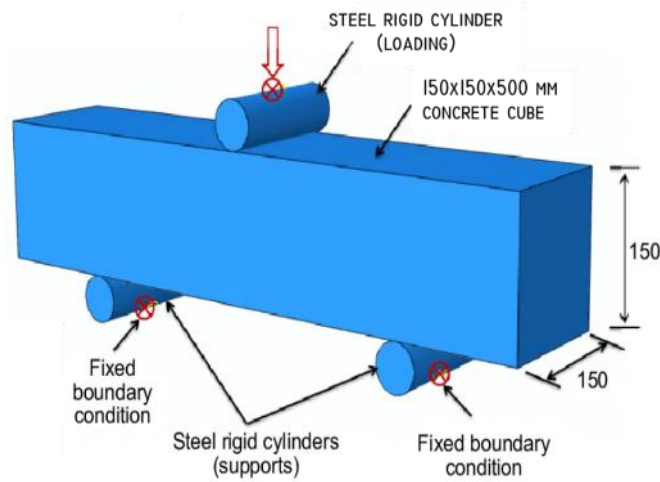


Fig. 5. Flexural strength test of hardened concrete

3.5 Splitting Tensile Strength Test

The splitting tensile strength is determined at 28 days on cylinders with ($h=300\text{mm}$, $d=150\text{ mm}$). The test was carried out in accordance with ASTM C496/C496 - 17. The cylinders are cast and cured at the same conditions for the specimens of the compressive strength tests. The test is carried out by placing a cylinder specimen horizontally between the loading surfaces of a compression testing machine and the load was applied until failure of the cylinder as shown in Figure 6 then the splitting tensile strength is obtained from testing. A loading rate of 1.2 MPa/min was executed. plywood bearing strips were used between the cylinder and the loading platens to prevent local crushing and stress concentrations. The mechanical calculation formula is:

$$f_{ct} = 2P / (\pi * L * d) \quad (1)$$

where: P is the ultimate failure load, L is the cylinder length (300 mm), and d is the diameter (150 mm).



Fig. 6. Splitting tensile strength test of hardened concrete

3.6 Beam Specimens and Details

The investigational program consists of casting and testing of thirteen, simply supported reinforced concrete beams. The beams were designed to fail in shear with different RCA amount. Five mixes were prepared with different RCA replacement ratios (0%, 25%, 50%, 75% and 100 %). Two deep beams were prepared to represent the control beam, which they were with normal aggregate (Normal aggregate 100 % "N-100%" and normal aggregate with opening "N-100% + O"). Four deep beams were prepared with different percentage of RCA (R-25%, R-50%, R-75% and R-100%), without opening. Four deep beams were prepared with different percentage of RCA (R-25%+O, R-50%+O, R-75%+O and R-100%+O), with opening.

Table 7. Deep beam details

Deep beam description	Deep beam Name	Note
Normal aggregate without opening	N-100 %	Control
Normal aggregate with opening	N-100 % + O	Control
Mix Normal aggregate and recycle aggregate ration 25% without opening	Mix-R-25 %	-
Mix Normal aggregate and recycle aggregate ration 25% with opening	Mix-R-25 % + O	-
Mix Normal aggregate and recycle aggregate ration 50% without opening	Mix-R-50 %	-
Mix Normal aggregate and recycle aggregate ration 50% with opening	Mix-R-50 % + O	-
Mix Normal aggregate and recycle aggregate ration 75% without opening	Mix-R-75 %	-
Mix Normal aggregate and recycle aggregate ration 75% with opening	Mix-R-75 % + O	-
Recycle aggregate 100% without opening	R-100 %	-
Recycle aggregate 100% with opening	R-100 % + O	-
Normal aggregate with recycle aggregate ration 25% as layer	L-R-25 %	-
Normal aggregate with recycle aggregate ration 50% as layer	L-R-50 %	-
Normal aggregate with recycle aggregate ration 75% as layer	L-R-75 %	-

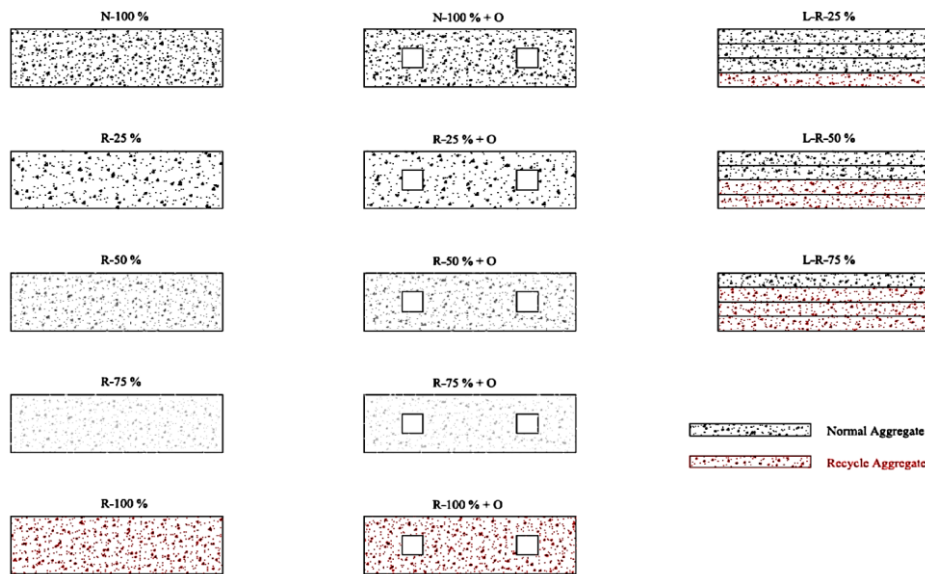


Fig. 7. Details of deep beams

Three deep beams were prepared with putting the RCA in layers (L-R-25%, L-R-50% and L-R-75%). All web openings were square, 100x100 mm, centered vertically within the beam depth, and positioned exactly at 350 mm from supports. The shear height (a) is 350 mm and the effective depth (d) is 310 mm, so the a/d ratio is constant at 1.13, which scientifically confirms its classification as deep beams ($a/d < 2.0$), also there wasn't any extra reinforcement around the openings. All beams above are shown in Table 7 and Figure 7.

3.7 Molds Preparation

Molds of wood were used for the beam's fabrication. The Molds are made of 18 mm thickness plywood; bolts were used to connect the different parts of the Molds. No additional reinforcement steel was placed around the corners of the opening to specifically isolate and secure the effect of raw RCA deterioration on shear capacity. Mineral oil was applied to the inner surfaces of the

wooden panels, and all structural joints were sealed with waterproof silicone to prevent leaks. Details of the reinforcement and molds are illustrated in Figure 8a & b respectively.

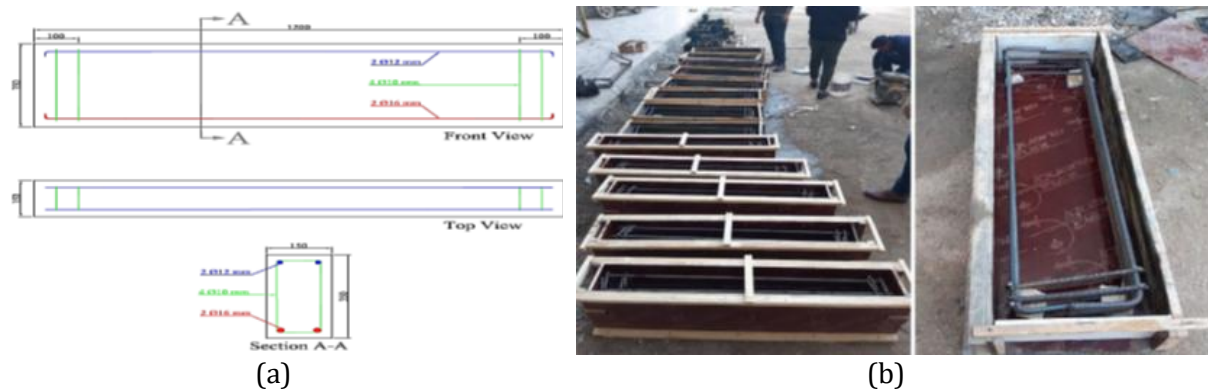


Fig. 8. (a) and (b). Deep beam details

3.8 Casting and Curing of RCA Beams

The casting was done by using a 0.27 m³ drum mixer. All materials were prepared by weight as shown in figure 9. The cast was started with the second mix R-100% so as to start with the layers that is designed to be at the bottom of the deep beam, then the first mix N-100%, R-25%, R-50% and R-75% respectively.



Fig. 9. Materials preparation



Fig. 10. Casting with R-100% at layers

The beams were treated using covers made of burlap cloth that were kept constantly wet for 28 days at an ambient temperature of $25 \pm 2^\circ\text{C}$. Where, 'L-R-25%' means that 100% of the RCA concrete was poured exclusively in the bottom layer, which makes up about 25% of the total beam height (87.5 mm), while the remaining top area, 75%, was poured with normal concrete (N-100%). The casting is shown in figure 10. For a continuous pour, the upper layer placed within 30 minutes of the lower layer to avoid a weak seam.

3.9 Testing of RCA Beams

Before doing the tests, all beams faces were white painted to enable tracing the cracks. The typical procedure, experimental setup, and loading configuration are shown in Figure 11a&b. Where,

Figure 11 (a) show simulation loading configuration, and (b) actual test configuration.' To apply the testing loads a 2000kN capacity Universal Testing Machine (UTM), was used. Mid-span deflection, the first inclined cracking, and ultimate loads were recorded for each beam. The target plate was extended horizontally under the beam, and the spring-loaded plunger in the disc gauge pushes upward against this plate. When the beam experiences a brittle collapse, the beam and the attached plate fall faster than the piston spring's rebound speed, or move sideways. The piston immediately loses contact with the plate. The beam hits the lab's heavy supports below, preventing damage from the failure.

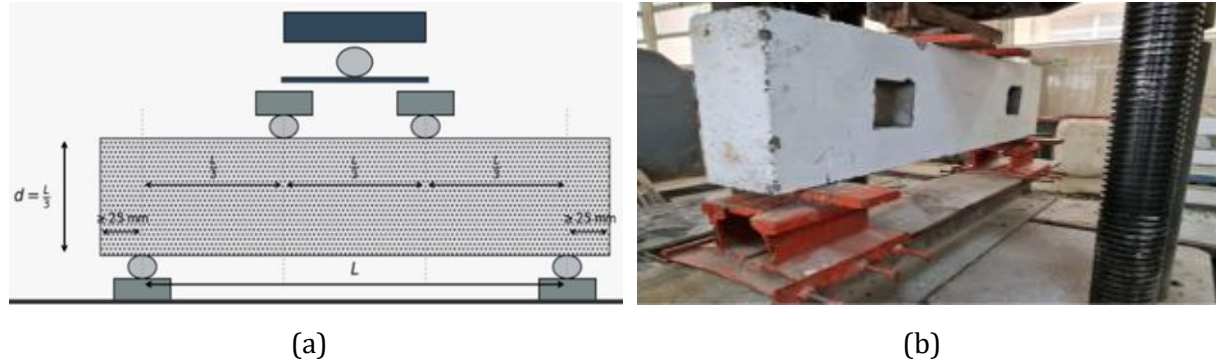


Fig. 11. (a) and (b). Testing deep beam

4. Test Results and Discussion

4.1 Properties of Fresh Concrete

In this study, to investigate the effect of adding recycle aggregate on the concrete workability the amount of superplasticizer in the concrete mixtures was kept constant even when recycle aggregate was added with different quantities, but the amount of water was changed from mix to other. Table 8 and shows the results of the slump test of concrete for all studied mixes. This examination was conducted according to the ASTM C143/C143M – 15a.

Table 8. Slump test results

Mix	Coarse Aggregate Percent	Water Amount	Slump Test Result (mm)
First Mix	N – 100%	170.00	163
Second Mix	R – 25%	176.25	165
Third Mix	R – 50%	180.77	168
Fourth Mix	R – 75%	188.59	170
Fifth Mix	R – 100%	195.0	170

The significant water absorption characteristics of RCA can create challenges. If the RCA is in a dry state, it will draw water from the paste, thereby diminishing the workability of the fresh concrete [17]. This also causes a reduction in the effective water-to-cement (w/c) ratio within the paste. Therefore, it is essential to observe the fluctuations in the w/c ratio for each mix in relation to the quantity of RCA utilized to maintain adequate workability.

4.2 Compressive Strength

In order to examine the effect of incorporating recycled aggregate on the compressive strength of conventional concrete, standard 150 mm cubes were tested in accordance with BS EN 12390-3:2019 at 28 days of age. The results of the concrete compressive strength for all examined mixes are presented in Table 9 and Figure 12. Table 10 details the extent of the reduction in compressive strength resulting from the addition of recycled aggregate to the concrete, where the strength loss to the porous old adhered mortar, high water absorption, and the weak microstructure of the Interface Transition Zone (ITZ).

Table 9. Compressive strength results

Mix	Coarse Aggregate Percent	Compressive Strength at 28 Days (MPa)
First Mix	N – 100%	38.80
Second Mix	R – 25%	37.45
Third Mix	R – 50%	36.59
Fourth Mix	R – 75%	34.69
Fifth Mix	R – 100%	32.54

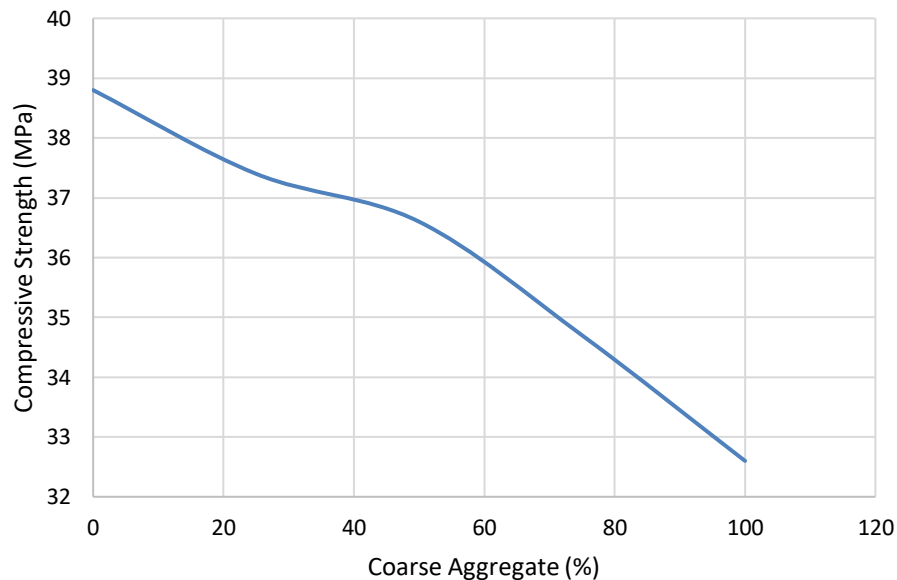


Fig. 12. Compressive strength results

Table 10. Rate of compressive strength decreasing due to adding recycled aggregate

Mix	Coarse Aggregate Percent	Compressive Strength Decreasing (%)
First Mix	N-100%	0.00
Second Mix	R-25%	3.48
Third Mix	R-50%	5.70
Fourth Mix	R-75%	10.59
Fifth Mix	R-100%	16.13

From the results presented above, it can be inferred that the compressive strength of concrete reduces as the volume ratio of recycled aggregate increases. The compressive strengths of concrete containing recycled aggregate were found to be lower than that of conventional concrete by rates of 3.8%, 5.7%, 10.59%, and 16.13%, respectively. The results indicate that incorporating RCA at a level of 100% leads to a more significant reduction in concrete compressive strength compared to other types. This result can be attributed to the stiffness associated with this particular type of recycled aggregate. It can be inferred from the results that the effect of recycled aggregate on decreasing concrete compressive strength intensifies as the volumetric recycled content reaches 100%.

4.3 Flexural Strength

The process of mixing recycled concrete aggregate (RCA) with natural aggregate clearly changes the distribution of internal stresses and the failure configuration in deep beams. According to materials science concepts, it's not just the stiffness of the aggregate that is the main factor for the deterioration of the internal structure, but also the porous nature of the leftover mortar sticking to the surface of the old aggregate and its high ability to absorb large amounts of water, as well as the relatively weak microstructure in the secondary transition zone (ITZ) formed between the new cement paste and the recycled aggregate [12]. As a result of the connection between the material

and the geometry around the openings, the hairline cracks that combine shear and bending spread directly through the weak and porous mortar and the breakable layer between the aggregate particles instead of bending around the aggregate boundaries. This significantly reduces the bonding capability between the aggregate particles and exposes the radial concrete support to early deterioration, leading to sudden and brittle crushing along the compression path [13]. The results regarding flexural strength (modulus of rupture) are displayed in Table 11 and illustrated in Figure 13. Table 12 details the reduction rate of flexural strength resulting from the incorporation of recycled aggregate into the concrete across all examined mixes.

Table 11. Flexural strength results

Mix	Coarse Aggregate Percent	Flexural Strength at 28 Days (MPa)
First Mix	N-100%	14.74
Second Mix	R-25%	13.62
Third Mix	R-50%	13.53
Fourth Mix	R-75%	13.26
Fifth Mix	R-100%	12.50

Table 12. Rate of flexural strength decreasing due to adding recycle aggregate

Mix	Coarse Aggregate Percent	Flexural Strength Decreasing (%)
First Mix	N-100%	0.0
Second Mix	R-25%	7.6
Third Mix	R-50%	8.21
Fourth Mix	R-75%	10.04
Fifth Mix	R-100%	15.20

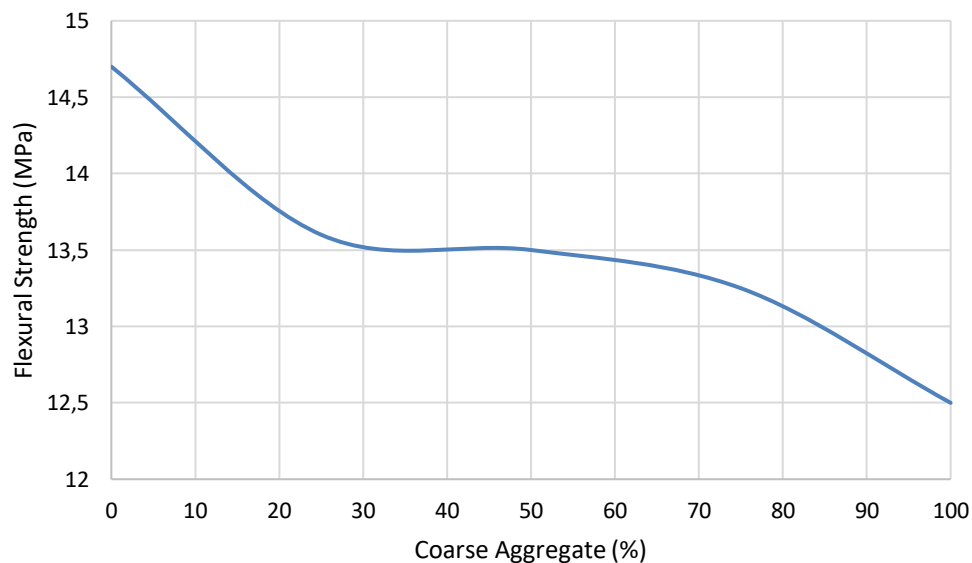


Fig. 13. Flexural strength results

4.4 Cracking and Ultimate Applied Loads of Deep Beams

First inclined cracking and ultimate loads are recorded in Table 13. The first inclined cracking load is defined as the load at which the first visible inclined crack appears in the shear span, the ultimate loads refer to failure loads, furthermore, the development of these diagonal cracks directly reflects the diagonal splitting tension performance in deep beam shear spans [17]. Figure 14 shows some beams at first and ultimate loads stages.

Table 13. First cracking and ultimate loads

Beam Designation	P_{crack} (kN)	$P_{ultimate}$ (kN)	$\Delta_{ultimate}$ (mm)
N-100%+O	120	470	3.99
Mix-R-25%+O	100	440	4.55
Mix-R-50%+O	90	390	5.12
Mix-R-75%+O	75	330	5.74
R-100%+O	70	300	6.62
N-100%+O	55	200	6.20
Mix-R-25+O	50	190	6.52
Mix-R-50+O	45	180	7.19
Mix-R-75+O	40	170	9.07
R-100%+O	40	160	11.21
L-R-25%+O	110	460	4.32
L-R-50%+O	100	420	4.95
L-R-75%+O	80	360	5.38



Fig. 14. Crack patterns and failure profiles of layered RAC deep beams at ultimate load stage

4.5 Effect of RCA on Deep Beams Behavior

The difference in the percentage of RCA ratios significantly affected the first cracking and ultimate failure loads. Both cracking and ultimate loads decrease with the RCA ratio increase. The higher reduction in cracking and ultimate loads are corresponding to the higher RCA content either the present of openings. The behavior of bending and the maximum load-bearing capacity of the deep beams being tested is controlled by arch movement and should be assessed within the strut-and-tie model (STM) framework. In this system, the internal drift of forces is represented as a truss mechanism, where a partial concrete strut (compression portion) transfers the applied loads directly to the strut, supported by a longitudinal steel tie (tension portion) at the bottom chord. Adding recycled concrete aggregate (RCA) significantly reduces the compression efficiency of this partial strut due to the presence of weakly bonded old mortar, the porous nature, and the weak secondary transition zone (ITZ) [18]. Beams with 0% of RCA exhibited higher ultimate load than RCA 25%, 50%, 75%, and 100%. Table 14 shows the comparison of first, ultimate loads and failure mode in the first group specimens.

Table 14. Ultimate load, first crack, deflection and failure mode of deep beam

Beam Designation	P _{Crack} (KN)	P _{Ultimate} (KN)	Δ _{ultimate} (mm)	P _{Cracking} /P _(N 100%+O)	P _{Ultimate} /P _(N 100%+O)	P _{Cracking} /P _{Ultimate}	Failure Mode
N-100%	120	470	3.99	1.00	1.00	1.00	Shear
Mix-R-25%	100	440	4.55	0.83	0.94	0.89	Shear
Mix-R-50%	90	390	5.12	0.75	0.83	0.90	Shear
Mix-R-75%	75	330	5.74	0.63	0.70	0.89	Shear
R-100%	70	300	6.62	0.58	0.64	0.91	Shear

On the other hand, the Tables 15&16, show the comparison of first, ultimate loads and failure mode in the second and third specimen groups, respectively.

Table 15. Ultimate load, first crack, deflection and failure mode of deep beam

Beam Designation	P _{Crack} (KN)	P _{Ultimate} (KN)	Δ _{ultimate} (mm)	P _{Crack} /P _{Crack(N 100%+O)}	P _{Ultimate} /P _{Ultimate(N 100%+O)}	P _{Cracking} /P _{Ultimate}	Failure Mode
N-100%+O	55	200	6.2	1.00	1.00	1.00	Shear
Mix-R-25%+O	50	190	6.52	0.91	0.95	0.96	Shear
Mix-R-50%+O	45	180	7.19	0.82	0.90	0.91	Shear
Mix-R-75%+O	40	170	9.07	0.73	0.85	0.86	Shear
R-100%+O	40	160	11.2	0.73	0.80	0.82	Shear

Table 16. Ultimate load, first crack, deflection and failure mode of deep beam

Beam Designation	P _{Crack} (KN)	P _{Ultimate} (KN)	Δ _{ultimate} (mm)	P _{Crack} /P _{Crack(N 100%+O)}	P _{Ultimate} /P _{Ultimate(N 100%+O)}	P _{Cracking} /P _{Ultimate}	Failure Mode
N-100%	120	470	3.99	1.00	1.00	1.00	Shear
L-R-25%	110	460	4.55	0.90	0.97	0.94	Shear
L-R-50%	100	420	5.12	0.83	0.90	0.90	Shear
L-R-75%	80	360	5.74	0.66	0.80	0.86	Shear

The previous results presented in Tables 14, 15 and 16 offer a comprehensive indication of how Recycled Concrete Aggregate (RCA) replacement ratios and the structural web openings, influence the structural behavior of reinforced concrete deep beams. Where the analysis shows three main specimen groups their cracking, ultimate loads, deflection, and failure modes.

The increase of (RCA) will reduce the first cracking and ultimate loads, but increase the mid span deflection. Also, the structural web opening will reduce the first cracking and ultimate loads.

5. Conclusions

The most important conclusions that can be drawn from the present study are the following:

- The most important conclusion observed in this study when replacing recycled concrete aggregate as an alternative to normal aggregate is that using recycled concrete aggregate in layers is better than mixing recycled concrete aggregate with normal aggregate.
- For all replacement ratios of recycled concrete aggregate as an alternative to normal aggregate in concrete, the concrete compressive, flexural, and splitting tensile strengths decrease with the increase of replacement ratio, and this decrease in the strengths is small.
- The quality and mechanical properties of the recycled concrete aggregate are relatively good when compared to normal aggregate.
- To decrease the cost of concrete, we can replace normal aggregate by an RCA ratio of 25%, due to its minimum effect as observed in this study where the decrease in compressive strength, and flexural strength ratio was 3.48%, and 7.6%, respectively.
- The RCA has water absorption much more than normal aggregate, which has a big effect on workability. So, for the purpose of using RCA, we must adjust the W/C ratio or wet the RCA before using it in the mixers.

- The presence of web openings reduces the ultimate load-carrying capacity of the beam element by nearly 50%. So, if the presence of openings is necessary, we can change the mix design to a high-strength mix design.
- The diagonal tension cracks emerging from the opening corners propagate at a radically accelerated rate through the porous RCA paste. The micro-cracks integral to the old adhered mortar easily coalesce with the macro-cracks induced by the geometric opening, causing a rapid reduction in the aggregate interlocking apparatus.

6. Recommendations

- It's recommended to use recycled concrete aggregate (RCA) in prearranged layers instead of mixing it directly with regular aggregate, because a layered configuration yields better structural performance.
- It is recommended to use a 25% replacement rate of recycled aggregate because it gives strong and eco-friendly concrete.

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