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Flexural behavior of reinforced recycled concrete coarse aggregates rectangular beams with and without splice bars

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HIGHLIGHTS

- Flexural tests involve sixteen beams with varying recycled coarse aggregate ratios and different lap splice lengths.
- Beams containing RCA exhibit behavior similar to those without RCA.
- The load-bearing capacity declines as the RCA content in the concrete mix increases.
- An RCA ratio of 50% is more suitable compared to other ratios.
- Concrete strain distribution across the beam cross-section decreases with higher RCA

Keywords:
recycled coarse aggregate; recycled concrete; splice length; concrete strain; flexural behavior.

ABSTRACT

Interest in using recycled concrete aggregate (RCA) as a partial or full replacement for natural coarse aggregate (NCA) in concrete production has increased significantly in recent years. This shift contributes to reducing landfill usage and conserving natural resources. This study presents an experimental investigation into the behavior of sixteen rectangular beams cast with varying RCA ratios to examine the effects on ultimate load capacity and concrete strain. The beams, each measuring 1600 mm in length, 170 mm in width, and 260 mm in height, were reinforced with two longitudinal 12 mm steel bars, and 8 mm stirrups spaced at 75 mm intervals. The beams were categorized into four groups, with each group consisting of four beams containing RCA at replacement levels of 0%, 25%, 50%, and 75%, respectively. Group one beams were cast without rebar splice lengths, while the remaining three groups incorporated splice lengths of 10, 20, and 30 times the bar diameter (db), respectively. The experimental results indicate that RCA has a marginal impact on the ultimate load capacity. Specifically, for beams with a splice length of 10 db, RCA replacement at 25%, 50%, and 75% led to ultimate load reductions of 3.19%, 6.53%, and 11.7%, respectively. For beams with a 20 db splice length, the reductions were slightly lower at 2.78%, 5.05%, and 9.99%, respectively. In contrast, for beams with a 30 db splice length, the reductions were almost identical to those observed in beams without any splice length, measuring at approximately 1.59%, 2.82%, and 6.64%, respectively.

1. Introduction

Concrete waste presents a significant environmental challenge, as it is non-biodegradable and requires landfill space. Consequently, recycling concrete waste and using it as aggregate in concrete has become a crucial practice [1]. Research has shown that replacing a portion of natural aggregate with recycled concrete aggregate (RCA) can reduce the strength of the resulting concrete. For instance, Sayhood et al. [2], examined the behavior of circular short columns reinforced with ties and spirals, incorporating a 50% replacement of natural aggregate with RCA. They tested ten columns with dimensions of 150 mm in radius and 600 mm in height. Their findings indicated a decrease in strength metrics, with reductions of 30% in flexural strength, 10% in compressive strength, 22% in the modulus of elasticity, and 30% in splitting tensile strength.

Furthermore, Hadi et al. [3], explored the use of RCA in producing self-compacting concrete and investigated its impact on the shear behavior of concrete box girders. Their study revealed that the ultimate load capacity decreased by 32%, 25%, and 19% for RCA content levels of 100%, 75%, and 50% respectively, when compared to a control specimen. Fiol et al. [4], studied the effect of using 100% recycled coarse aggregate (RCA) in self-compacting concrete (SCC) mix on maximum load capacity. Scaled beams (120 ×240×1800 and 240 × 240 × 1300 mm) were tested to fail by bending. The experimental results showed that the maximum load capacity of beams without (RCA) was 1.5 and 3 times higher than the others with 100% (RCA). Abdullah [5], presented an investigation using a database of sixty studies to identify the main parameters affecting the shear strength of recycled concrete beams without mesh reinforcement. He concluded that the shear failure pattern is similar for the beams regardless of the RCA replacement ratio. Meanwhile, the difference in the physical properties of RCA leads to a decrease in compressive strength by 10%.

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Several researchers have improved concrete containing recycled coarse aggregate by adding some materials. For example, Tobeia et al. [6], enhanced the compressive and tensile strength of concrete content in the recycled concrete aggregates by adding Styrene Butadiene-Rubber (SBR). The compressive and tensile strength of concrete was enhanced by about 92.566%, and 197.894%, respectively, to replace the ratio of recycled concrete aggregates by 50% and 100%. However, Sayhood et al. [7], reduced the strength reduction of the concrete mix due to recycled coarse aggregate using different proportions of steel fibers and tested this in eight beams. Anike et al. [8], study the effect of adding steel fibers (SF) to the concrete mix containing recycled fine and coarse aggregate (RFA and RCA) on the maximum bending load of beams. The results showed that the maximum bending load of the beams increased by 8% to 13% when using a mix containing 100% (RFA and RCA) and 1% (SF), compared to similar beams without (SF) of the reference mix.

On the other hand, the bond between concrete and reinforcement bars is a significant issue in reinforced concrete structures, impacting their strength and safety. The main parameters that influence the bond strength of development or spliced bars in concrete include, the concrete compressive strength, bar diameter, bar spacing (concrete cover), development splice length, bar surface deformation, and stat (with or without coating) [9]. The maximum load that may be transferred by steel bars in overlapped regions represents splice strength and refers to the load that may be assigned by overlapped intermittent reinforcement steel bars via bond action [10]. Kadhem et al. [11], investigated the bond strength and slip relationship by testing twelve concrete beams using reactive powder. The experimental results show that the bond strength increased by 12.67%, whereas the slip decreased by 67.411%.

In contrast, an increment of concrete cover from 25 mm to 50 mm leads to a slight reduction of slip and an increase in bond strength by 17.54%. Al-Hassani et al. [12], tested the seven-beam content lap splice of the reinforcing bar to study structural performance when exposed to repeated loading. The test results showed that resistance to repeated loading can be enhanced by increasing the rebar splice length and using stirrups at the splice region to provide confinement to concrete.

This research's main parameter is the ratio of recycled coarse aggregate extracted from concrete waste. In addition, study its effect on the ductility index, the lap splice steel bars' bond strength, and the concrete strain at the middle of beams in the tension and compression zone.

Comprehending the behavior of splice bars and accurately measuring the splice strength in recycled aggregate concrete is essential for ensuring the safe use of this type of concrete in structural applications. Contrary to pullout tests, which have limited usefulness in design, testing splice specimens provides data that may be utilized to calibrate descriptive bond strength equations that apply to structural design. The experiment tested the performance of scaled beam specimens made of recycled aggregate concrete to measure splice strength. The focus was on length splices lap, with different replacement ratios of recycled aggregates.

2. Experimental work

2.1 Materials

The materials used in concrete mixes are as follows: ordinary Portland cement conforming to IS 8112-1989 [13], sand from the Al-Ukhaydir area as fine aggregate, crushed gravel from the Al-Sudur area as natural coarse aggregate (NCA), and recycled coarse aggregate (RCA).

The recycled coarse aggregate was obtained from the demolished concrete of an old house and then crushed using a jaw crusher. The natural and recycled coarse aggregate was sieved to a size between 4.75 and 14 mm to match the specified limits of gradation of I.S.: 383-1970 [14]. Because the (RCA) has a high ability to absorb water, it was immersed in water for 24 hours, then extracted from the water and exposed to the air by spreading it on a dry, clean floor and stirring it from time to time for approximately three hours to obtain a (RCA) as saturated surface dry (SSD) to meet the requirements of ASTM. $C33/C33M$ [15]. The content of residual mortar in (RCA) was found according to the (hydrochloric acid dissolution) method of SSW Nagataki et al., [16]. The procedure in I.S.: 2386 (Part IV) - 1963 [17], was applied to obtain values of crushing and impact for both (NCA) and (RCA). Table (1) lists fine and coarse aggregate's physical and mechanical properties.

The concrete mix included clean tap water, a superplasticizer (Visco Crete-180 G) classified as Type F in compliance with ASTM C494 [18], and silica fume, added at 10% of the cement's weight, with a specific gravity of 2.3 in accordance with ASTM C1240-03 [19]. Longitudinal reinforcement consisted of deformed steel bars with a nominal diameter of 12 mm, while 8 mm bars were used as stirrups. Testing conducted at the University of Technology's Department of Production and Mineral Engineering in Baghdad confirmed that the steel bars met ASTM A615/615M-14 standards for Grade 60 steel [20].

Table 1: The physical and mechanical properties of fine and coarse aggregate

Characteristics	Fine Aggregates	Natural Coarse Aggregates (NCA)	Recycled Concrete Aggregates (RCA)
Grading	Zone III	4.75 to 14 mm	4.75 to 14 mm
Fineness modulus	2.5	-	-
Bulk specific gravity	2.54	2.62	2.4
Water absorption (%)	0.74	0.75	5.4
Crushing value (%)	-	21.3	21.4
Impact value (%)	-	17.3	22.3
Residual mortar content (%)	-	-	31.8

2.2 Concrete mix proportions

Four types of concrete mixes are produced using the absolute volume method. These mixes depend on the ratio of replacing recycled coarse aggregate in each mix instead of natural coarse aggregate. The reference mix is a conventional concrete using 100% natural coarse aggregate without RCA. The recycled coarse aggregate ratios for the other three types were 25%, 50%, and 75%, respectively. The volumetric method replaced recycled coarse aggregate instead of natural coarse aggregate, while other mixed components kept the same amount. On the other hand, adding a viscocrete 180 G superplasticizer reduced the water/cement ratio to 0.3 and achieved the required workability.

The recycled coarse aggregate was soaked in water for 24 hours to overcome the problem of water absorption, and then it was spread on a clean floor to dry its surface. In this way, the recycled coarse aggregate was at the surface saturated dry (SSD) state and ready for use in concrete production. Table (2) shows the proportions of materials used in producing the four types of concrete mixes and the compressive strength of each mixture measured by finding the average compressive strength of three cylinders with dimensions (150 mm diameter and 300 mm height). The cylinders were tested after 56 days of casting.

Table 2: Materials proportions and compressive strength of concrete mixes

Mix type	f'c (MPa)	C (kg/m^3)	S.F. (kg/m^3)	F.A. (kg/m^3)	NCA (kg/m^3)	RCA (L/m^3)	W (kg/m^3)	HRWRA (mL/m^3)
Mix without RCA	47.51	500	50	686.4	1045.4	0	149.4	4380
Mix with 25% RCA	46.15	500	50	686.4	784.11	230.34	149.4	4380
Mix with 50% RCA	45.88	500	50	686.4	522.73	460.67	149.4	4380
Mix with 75% RCA	41.26	500	50	686.4	261.38	690.97	149.4	4380

f'c= Cylinder compressive strength, C= Ordinary Portland cement, SF= Silica Fume, FA= Fine aggregate, NCA= Natural coarse aggregate, RCA= Recycled coarse aggregate, W= Tap water, HRWRA= High-Range Water Reducer Admixture.

2.3 Beam specimens details

In this research, a total of 16 scaled beam specimens were cast and cured with water for 28 days. The splice beam specimens were designed taking into account the recommendations of ACI 408R-03 [21]. The beams were divided into four groups. Four beam specimens were cast in the first group, representing reference beams for other groups, including continuous rebar without lap splice. Each beam used a mix type with a different percentage of recycled coarse aggregate (0%, 25%, 50%, 75%). As for the other three groups, four beams were cast in each group using different replacement ratios of recycled coarse aggregate (0%, 25%, 50%, 75%), respectively. The splice length of the splice lap in specimens of the three groups was equal to 120 mm (10 db) in group two, 240 mm (20 db) in group three, and 360 mm (30 db) in group four.

On the other hand, for all beams, the minimum concrete cover was 30 mm, the longitudinal bottom bar diameter was 12 mm, and the top bar was 8 mm. To prevent shear failure close, rectangular stirrups of 8 mm were used at 75 mm in the shear span, while no stirrups were provided at the lap splice to prevent concrete confinement in this region.

The dimensions of the rectangular cross-section of the beam specimen are a width of 170 mm and a height of 260 mm. The length of the specimen is 1600 mm, while after the beam was supported, the effective length of the span was 1500 mm. According to the recommendations of Harajli and Abouniaj [22], the beam was designed to achieve the splice length of rebar into the region of maximum moment so that the area of the maximum constant moment is greater than the length of the lap splice plus half the height of the beam to prevent interfere of the bending cracks with the cracks resulting from the end of splice region.

The splice length was initially chosen as 120 mm (10 db), which is significantly less than the requirements of ACI 318-19 [23], for development length in tension to ensure that failure occurs in rebar lap splice before bending failure. Then, the splice length was increased to 240 mm (20 db) and finally 360 mm (30 db) to determine the effect of the replacement ratios of recycled coarse aggregate on the splice length by compared with the reference beams. The end of the longitudinal rebar was bent at a 90-degree angle at each end to act as a mounting hook with a length equal to 144 mm (12 db) to ensure adequate anchorage. The details of beam specimens are illustrated in Table (3).

The Longitudinal cross sections and all details of beam specimens of groups one, two, three, and four were illustrated in Figures 1(a - d). Moreovere the cross sections of group one (reference beams) specimens are shown in Figures 2(a and b). The cross sections of group two, three, and four beam specimens are shown in Figures 3(a and b).

Table 3: Lap splices length and recycled coarse aggregate of beam specimens

Group	Beam Symbol	d_b (mm)	NCA(%)	RCA(%)	Ls (mm)	Ls/d_b
Group one	B1	12	100%	0%	-	-
	B2	12	75 %	25%	-	-
	B3	12	50 %	50%	-	-
	B4	12	25%	75%	-	-
Group two	B5	12	100%	0%	120	10
	B6	12	75%	25%	120	10
	B7	12	50%	50%	120	10

Table 3: Continued

Group	Beam Symbol	d_b (mm)	NCA(%)	RCA(%)	Ls (mm)	Ls/d_b
	B8	12	25%	75%	120	10
Group three	B9	12	100%	0%	240	20
	B10	12	75%	25%	240	20
	B11	12	50%	50%	240	20
	B12	12	25%	75%	240	20
Group four	B13	12	100%	0%	360	30
	B14	12	75%	25%	360	30
	B15	12	50%	50%	360	30
	B16	12	25%	75%	360	30

db = Bar diameter, Ls = Overlap splice length

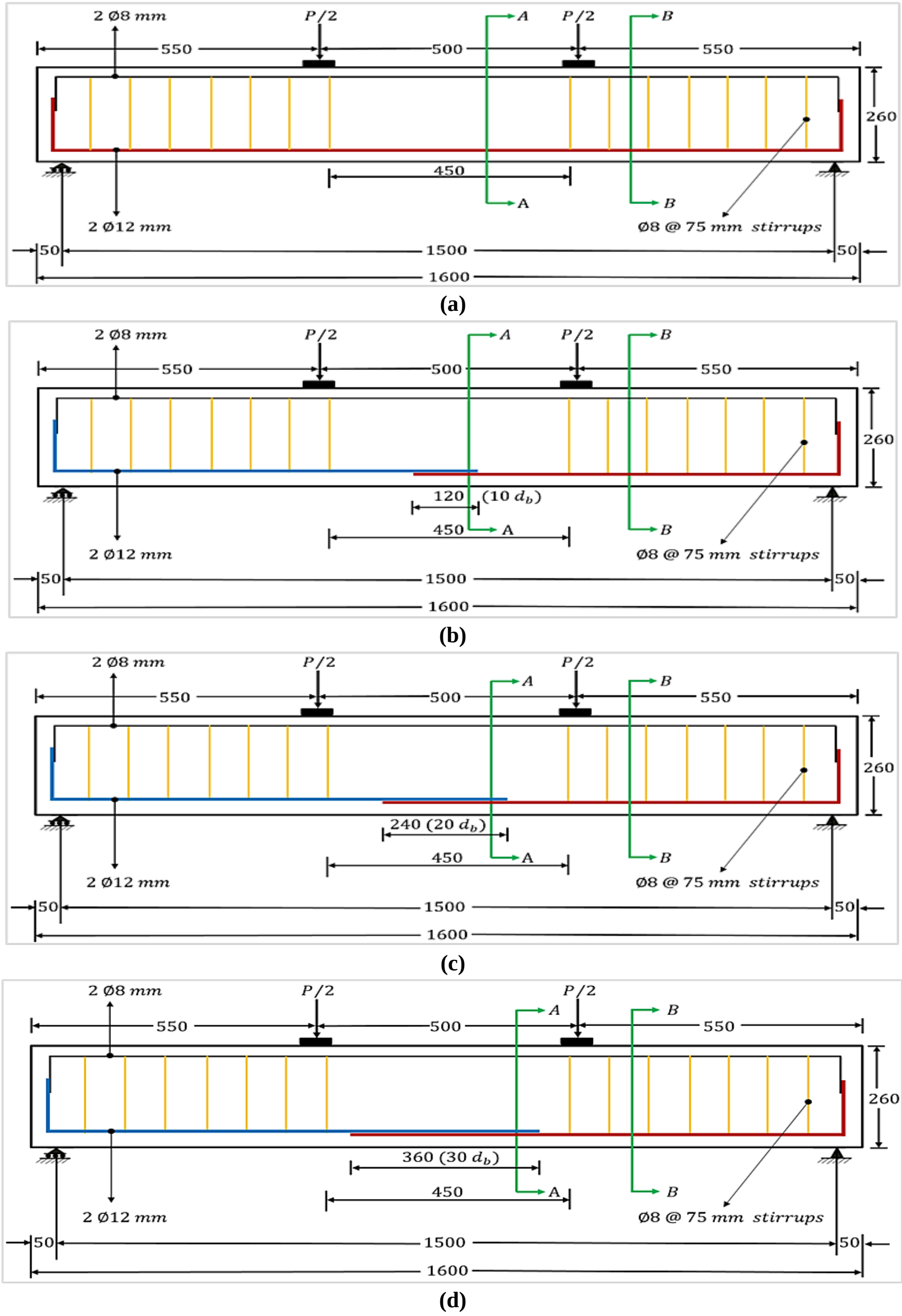
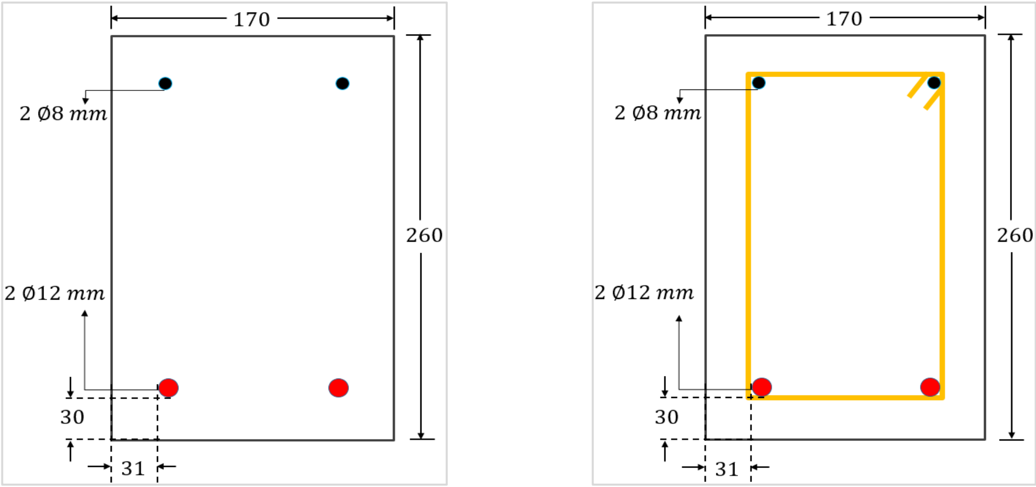
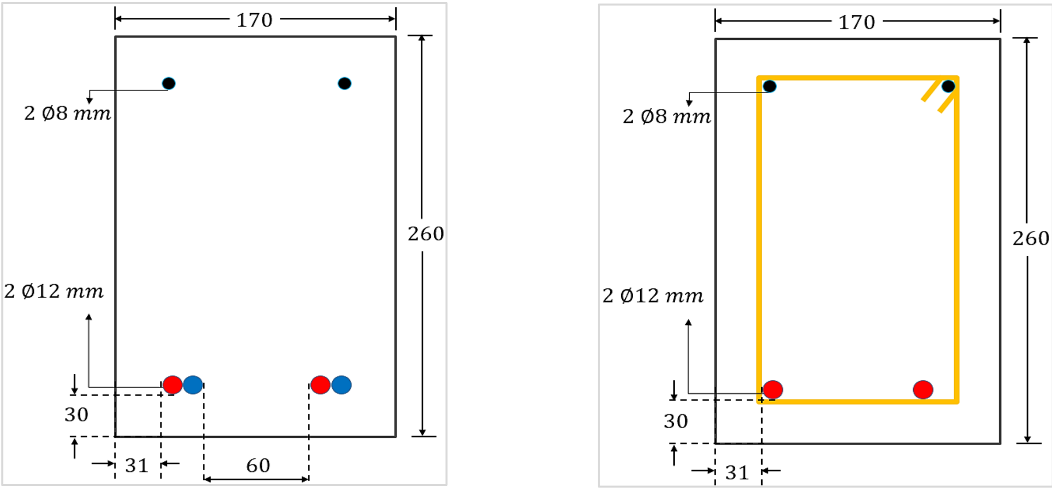


Figure 1: Longitudinal cross-section of beams (a) group one (beams: B1, B2, B3 and B4) (b) group two (beams: B5, B6, B7 and B8) (c) group three (beams: B9, B10, B11 and B12) (d) group four (beams: B13, B14, B15 and B16)



(a) **(b)**

Figure 2: Cross sections of beams of group one (a) Cross–section $A - A$, b) Cross–section $B - B$



(a) **(b)**

Figure 3: Cross sections of beams of groups two, group three, and group four (a) Cross–section $A - A$ (b) Cross–section $B - B$

3. Concrete strain

This study measured strain in concrete beams using foil electrical strain gauges. These strain gauges are manufactured by the Japanese company TML, type (PL-30-11-3L). Installing strain gauges on concrete is to measure the stress in concrete on the front surface at the mid-span. In each beam, three strain gauges were installed on the concrete front surface at mid-span, distributed at dista 90, a. n d , 150 close parens 50 mm measured from the top of the beam. Strain gauges were installed on concrete after the curing process was completed and one day before the beams were tested. Figure (4) shows the locations of the strain gauges on concrete.

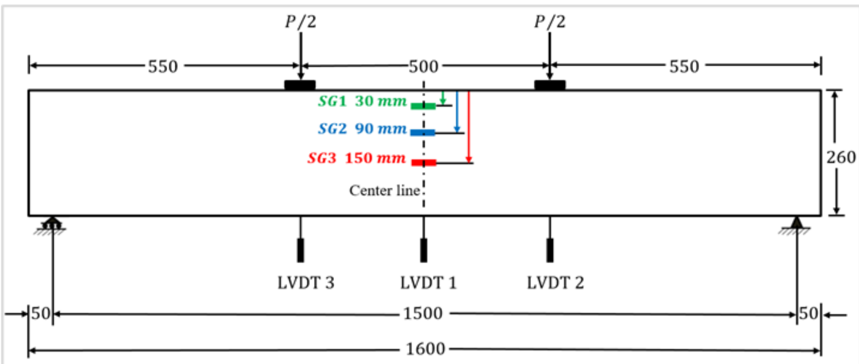


Figure 4: Testing beam diagram

4. Test SETUP

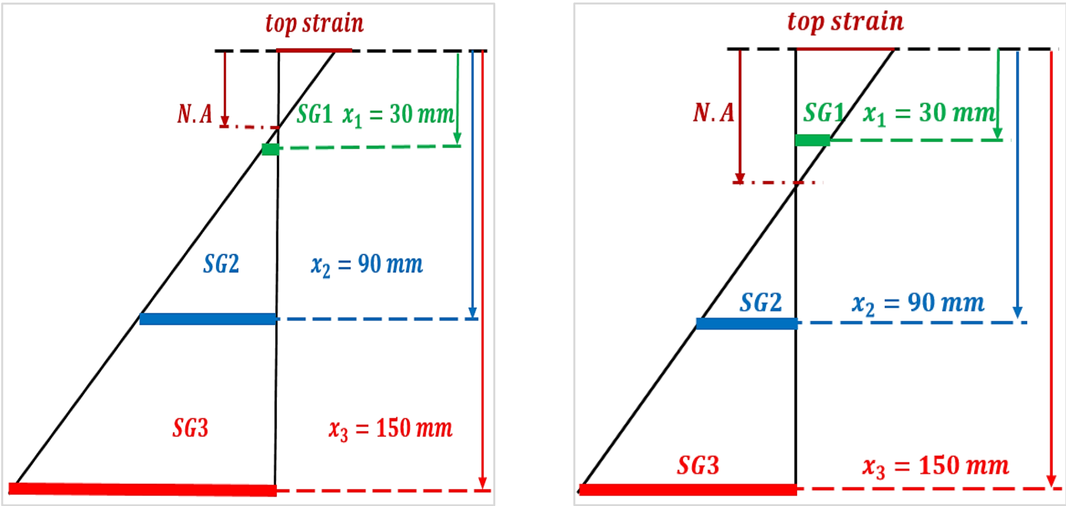
The splice beam specimens were tested by flexural test using a four-point test under load control by a compression testing machine named AVERY with a 2500 kN compression loading capacity. The vertical deflection was measured at three points at mid-span, and the projection line of two-point loads utilized digital LVDTs with an accuracy of 0.000001 mm, and a capacity of 50 mm. The compression load was measured by a load cell with a capacity of 500 kN. The reading of results was obtained from the load cell, concrete strain gauges, and deflection LVDTs by 10 channels digital data logger. All beams were tested 56 days after casting day to ensure that the splice beam specimen got the most compression strength.

One of the basic steps on the testing day was to label the beams based on differences in the splice length and the percentage of recycled coarse aggregate replacement.

5. Neutral axis and top concrete strain calculations

Strains of concrete at the top and neutral axis were calculated, depending on the reading of strain gauges one and two ($SG1$ and $SG2$), using the triangles similarity method. There are two cases for strain gauge one:

The first case is that strain gauge one is below the neutral axis and has a positive value, such as beams in group one, as shown in Figure (5-a). In the second case, strain gauge one is above the neutral axis and has a negative value, such as rest beams, as shown in Figure (5-b).



(a) (b)

Figure 5: Concrete strain gauge locations and neutral axis a) Positive value of strain gauge one b) Negative value of strain gauge one

For the two cases, the neutral axis was calculated using Equation (1), and the top concrete strain was calculated using Equation (2):

$$N.A = \frac{30\ (\varepsilon_{90} - 3 \times \varepsilon_{30})}{\varepsilon_{90} - \varepsilon_{30}} \quad (1)$$

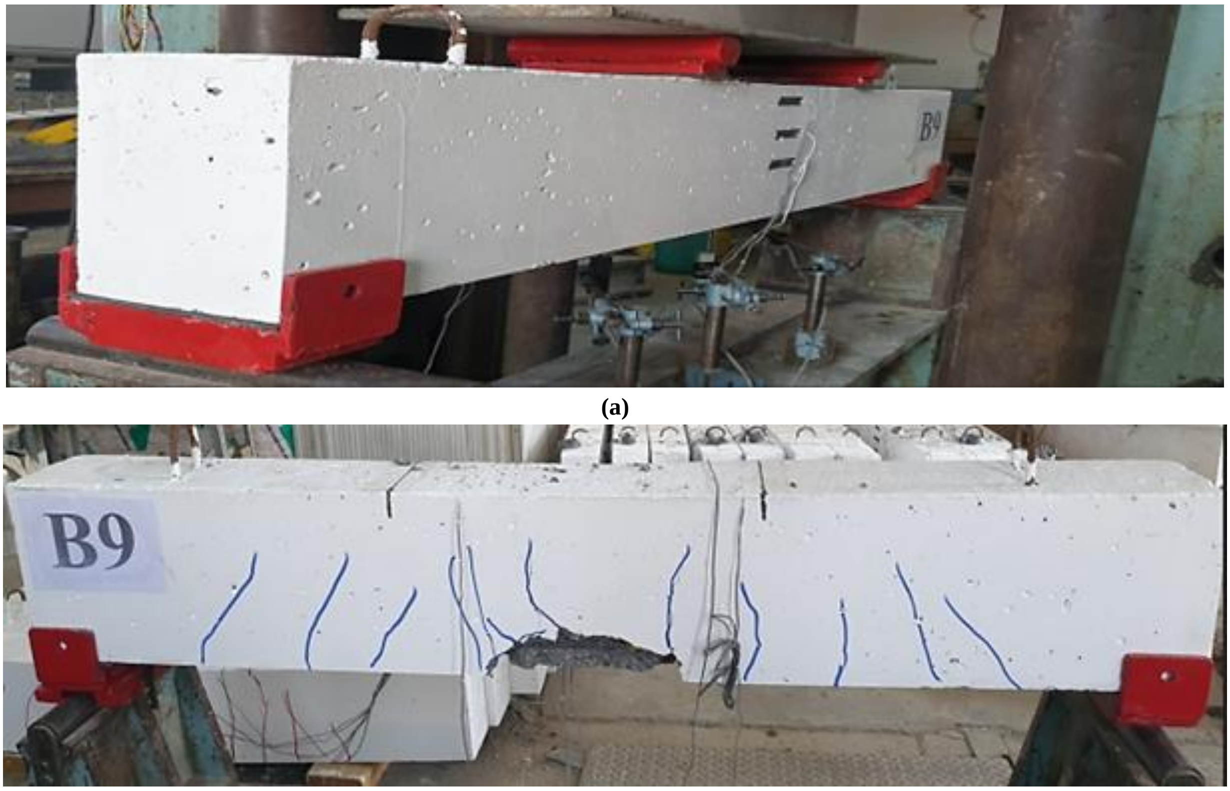
$$\varepsilon_{top} = \frac{\varepsilon_{30} \times N.A}{N.A - 30} \quad (2)$$

6. Results and discussion

6.1 Beams Behavior

During the tests, it was noted that cracking behavior was similar across all the specimens irrespective of their splice length or concrete type according to recycled coarse aggregate ratio. Flexural cracks first formed in the constant moment region, specifically just outside the splice length, and as the applied load increased, these cracks developed in number and size, and their width increased in the rest of the flexural area and the shear period when the applied load reached 60% of the maximum load, horizontally oriented splitting cracks began on the side faces of the beam (lateral splitting cracks) at both ends of the splice length. As the applied load increased, these cracks spread towards the mid-span and developed into sub-splitting cracks.

As a result of the sudden bond failure of beam specimens, loss of concrete cover sometimes occurs, accompanied by rapid propagation of subsurface splitting cracks along approximately the length of the splice, as in beam 9. Selected examples of beam under-test and failure cracking patterns are shown in Figures (6-a) and (6-b) respectively.



(a)

(b)

Figure 6: Test and failure pattern of beam B9 a) Beam B9 underloading b) Mode failure of beam B9

6.2 Ultimate load results

Table (4) summarizes the experimental ultimate load results of beams. These results showed that the percentage of replacing recycled coarse aggregate RCA with natural coarse aggregate NCA has a slight effect on the ultimate load.

For beams of group one without rebar splice length, increasing the ratio of RCA in the following manner (25, 50, and 75)% in beams (B2, B3, and B4) compared to the reference beam B1 without RCA leads to a decrease in the ultimate load by (1.93, 3.42 and 7.7)%, respectively. Comparing beams (B3 and B4) (containing 50 and 75)% RCA with beam B2, which has 25% RCA, decreases ultimate load by 1.53% and 5.82 respectively. For beams of group two with rebar splice length 120 mm (10 db), increasing the ratio of RCA in the following manner (25, 50, and 75)% in beams (B6, B7, and B8) compared to the reference beam B5 without RCA leads to decrease in the ultimate load by (3.19, 6.53 and 11.7)%, respectively. Comparing beams (B7 and B8) contain (50 and 75)% RCA with beam B6, which has 25% RCA decreases ultimate load by 3.45% and 8.79 respectively. For beams of group three with rebar splice length 240 mm (20 db), increasing the ratio of RCA in the following manner (25, 50, and 75)% in beams (B10, B11, and B12) compared to the reference beam B9 without RCA leads to decrease in the ultimate load by (2.78, 5.05 and 9.99)%, respectively. Comparing beams (B11 and B12) containing 50 and 75)% RCA, beam B10 has 25% RCA, decreasing ultimate load by 2.33% and 7.42 respectively. For beams of group four with rebar splice length 360 mm (30 db), increasing the ratio of RCA in the following manner (25, 50, and 75)% in beams (B14, B15, and B16) compared to the reference beam B13 without RCA leads to decrease in the ultimate load by (1.59, 2.82 and 6.64)%, respectively. Comparing beams (B15 and B16) containing 50 and 75)% RCA with beam B14, which has 25% RCA, decreases ultimate load by 1.25% and 5.14 respectively.

In general, the splice length of 360 mm (30 db) is most suitable for practical use, and the percentage of ultimate load reduction using RCA is very close to that of reference beams without splice length. On the other hand, using 25% RCA in the concrete mix instead of NCA reduces the ultimate load by a small amount, about 1.59%, but the economic benefit is also low. However, using 50% RCA is practical and economical because it reduces the ultimate load by almost as close a percentage as using 25% RCA, which is about 2.82%. While using 75% RCA is very economical. However, it reduces the ultimate load by a more significant amount than using 50% RCA, which is about 6.64 %, and it is still an acceptable percentage of reduction in return for many economic and environmental benefits.

P_Cr= Crack load, P_y= Yield load, P_u= Ultimate load, P_(u B_((R)))= Ultimate load of reference beam with (RCA=0%) for each group (B1, B5, B9, and B13) for groups one, two, three, and four, respectively, (-)% of P_(u B_((R)))= Reduction percentage of ultimate load for beams of each group than beam with (RCA=0%) for the same group, P_(u B_((r)))= Ultimate load of beams from group one that corresponds with other beams from rest groups in RCA ratio (B1, B2, B3, and B4 for beams with RCA ratios of 0%, 25%, 50%, and 75%, respectively).

Table 4: Load test results and mode failure

Group	Beam Symbol	RCA (%)	P_{Cr} (kN)	P_y (kN)	Pu (kN)	$\frac{P_u}{P_{u\,B_{(R)}}}\%$	(−)% of $P_{u\,B_{(R)}}$	$\frac{P_u}{P_{u\,B_{(r)}}}\%$	Failure mode
Group one	B1	0%	35.8	108.3	140.4	100	-	-	Yield
	B2	25%	35.2	104.8	137.7	98.07	1.93	-	Yield
	B3	50%	35.1	103.2	135.6	96.58	3.42	-	Yield
	B4	75%	33.4	100.2	129.6	92.30	7.7	-	Yield
Group two	B5	0%	33.9		65.8	100	-	46.87	Slip
	B6	25%	33.7	-	63.7	96.81	3.19	46.26	Slip
	B7	50%	33.5	-	61.5	93.47	6.53	45.35	Slip
	B8	75%	31.9	-	58.1	88.30	11.7	44.83	Slip
Group three	B9	0%	34.8		97.1	100	-	69.16	Slip
	B10	25%	34.3	-	94.4	97.22	2.78	68.55	Slip
	B11	50%	34.1	-	92.2	94.95	5.05	67.99	Slip
	B12	75%	32.5	-	87.4	90.01	9.99	67.44	Slip
Group four	B13	0%	35.4	106.9	138.5	100	-	98.65	Yield
	B14	25%	35.1	101.7	136.3	98.41	1.59	98.98	Yield
	B15	50%	34.9	103.4	134.6	97.18	2.82	99.26	Yield
	B16	75%	33.7	105.8	129.3	93.36	6.64	99.77	Yield

On the other hand, the results showed that beams with 120 mm (10 db) lap splice length give an average ultimate load of about 45.83% of the ultimate load of the corresponding beams without a lap splice length. Meanwhile, beams with 240 mm (20 db) lap splice length give an average ultimate load of about 68.29% of the ultimate load of the corresponding beams without a lap splice length. Moreover, beams with 360 mm (30 db) lap splice length give an average ultimate load of about 99.17% of the ultimate load of the corresponding beams without a lap splice length. Figure (7) shows the effect of RCA on the ultimate load, while Figures (8-a), (8-b), (8-c), and (8-d) illustrates the load-deflection relationship of beams in the four groups.

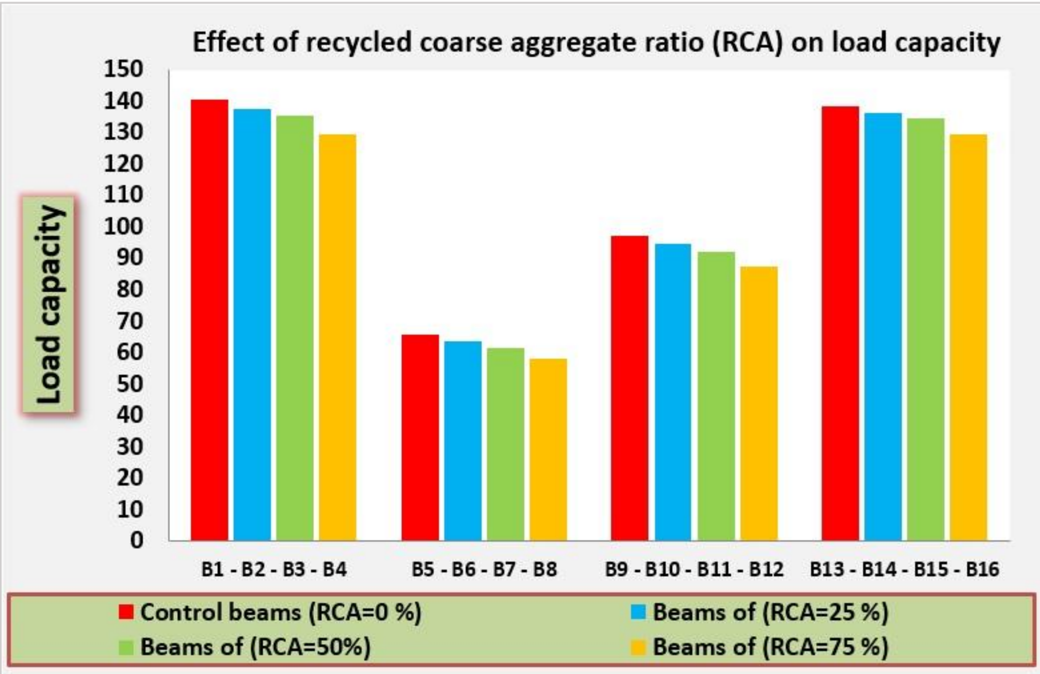
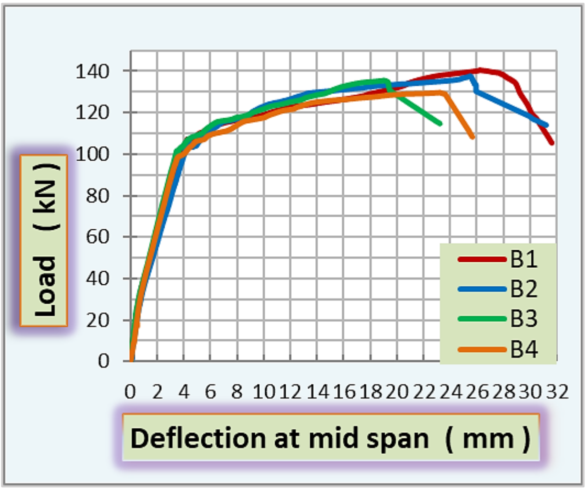


Figure 7: Effect of recycled coarse aggregate on load capacity

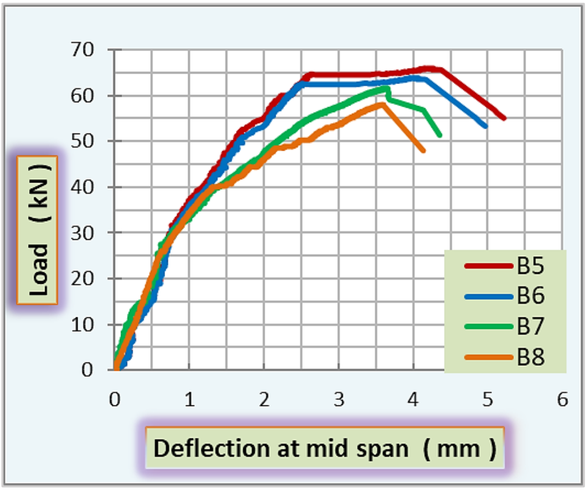
During loading concrete structures with the designed loads, the concrete elements go through several stages. The first stage is the stage of uncracked concrete, and when the load increases, the concrete performance is in the second stage, which is the stage of cracked concrete in the tension zone and the distribution of stresses linearly in the compression zone. In contrast, the third stage occurs after the load reaches 70% of the maximum load, the concrete is cracked in the tension zone, and the distribution of stresses in the compression zone is non-linear [24]. In the second and third stages, concrete contributes to bearing a small part in the tension zone, but the presence of concrete in that zone is necessary to transfer stresses to the reinforcing steel bars, which resist tensile stresses [25].

This study reveals that the ratio of RCA in concrete used in structural elements subjected to a flexural load shows lower strength than conventional concrete, especially when using high percentages of RCA [26-28]. provided convergent explanations about the reason for this effect, which is attributed to the performance of recycled concrete in bonding being worse compared to conventional concrete, as its cracking is early and the crack width is more significant, which leads to a decrease in bonding. In addition, increasing the ratio of RCA replacement instead of NCA causes a decrease in the values of cracking moment due to the decrease in the tensile splitting forces [29]. All these factors lead to a decrease in the performance of structural elements to resist flexure with increasing the ratio of RCA.

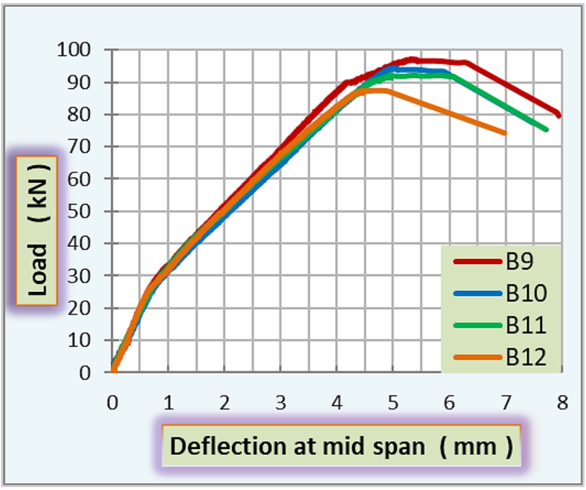
The decrease in the load-bearing capacity of concrete in structural elements in using RCA ratios of 25%, 50%, and 75% is slight and at a rate of 2.5%, 4.5%, and 9%, respectively. These ratios are better than those shown in previous studies regarding the ability to reduce [2]. Reported a decrease of 12% when using 50% of RCA, and [6], reported a reduction in strength of 15% and 20% when using 50% and 100% of RCA, respectively [7]. Also explained a decrease in strength of 15% when using 75% of RCA. The significant reduction in the rate of strength deterioration observed in this study can be attributed to the incorporation of silica fume into the concrete mixture. This material, characterized by its fine particle size, effectively enhances the filling of voids within the concrete matrix, thereby improving its overall density and performance. This is reflected in slowing down the cracking process resulting from tensile stresses inside the concrete and increasing the bond between the reinforcing steel and the concrete. On the other hand, using steel fiber, as mentioned by Sayhood et al. [7], certainly increases the strength of the structural element. Still, it does not significantly affect the prevention of microscopic cracks responsible for weakening the bond between the reinforcing steel and the concrete.



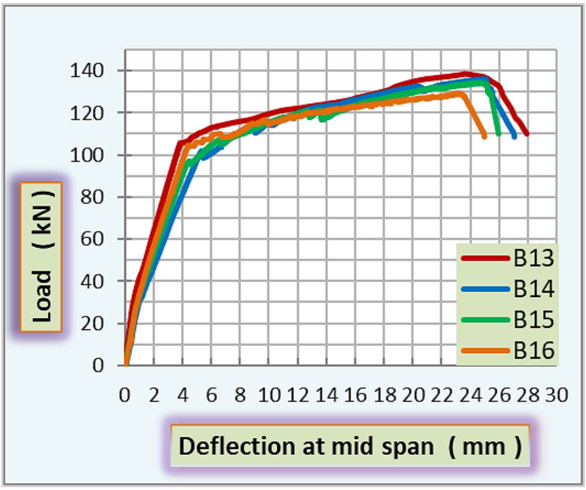
(a)



(b)



(c)



(d)

Figure 8: Load deflection relationship of beams (a) group one (beams: B1, B2, B3, and B4) (b) group two (beams: B5, B6, B7, and B8) (c) group three (beams: B9, B10, B11, and B12) (d) group four (beams: B13, B14, B15 and B16)

6.3 Concrete strain results

The experimental results of concrete strain were obtained from three strain gauges installed at 30 mm, 90 mm, and 150 mm from the top of the beam. Moreover, concrete strain at the top of the beam and the location of the neutral axis are calculated by using Equations (1 and 2) respectively. The neutral axis locations are calculated from the top of the beam. Concrete strain results and neutral axis calculations are listed in Table (5).

The calculation results of the neutral axis showed that the average distance of the neutral axis measuring from the top surface of beams without lap splice length was about 28.48 mm. However, the average distance of the neutral axis of beams with 120 mm (10 db) lap splices length is about 34.64 mm. While the average distance of the neutral axis of beams with 240 mm (20 db) lap splice length is about 33.6 mm. Moreover, the average distance of the neutral axis of beams with 360 mm (30 db) lap splices length is about 31.68 mm. These results indicate that the neutral axis is closer to the middle of the beam's cross-section in group two (beams with 10 db due to their low flexural strength capacity). As the lap splice length increases to 20 db in group three beams, the neutral axis's location increases upwards. It continues to rise in the beams with 30 db in group four because increasing the lap splice length leads to an increase in the flexural strength capacity and, consequently, an increase in the stress on the concrete in the compression zone. It is worth noting that the effect of recycled concrete is slight on the location of the neutral axis due to its slight effect on the flexural strength capacity.

The concrete strain results of beams in group one without lap splice length measuring at 30 mm, 90 mm, 150 mm, and top surface ranged from (120 to 142), (4522 to 6125), (9249 to 10850), and (-1991 to -2850), respectively. Furthermore, the concrete strain results of beams in group two having 120 mm (10 db) lap splice length measuring at 30 mm, 90 mm, 150 mm, and top surface ranged from (-195 to -328), (2763 to 3438), (6281 to 7042), and (-1874 to -2011), respectively. However, the concrete strain results of beams in group three having 240 mm (20 db) lap splice length measuring at 30 mm, 90 mm, 150 mm, and top surface ranged from (-157 to -282), (3219 to 3675), (6585 to 7225), and (-2033 to -2073), respectively. Moreover, the concrete strain results of beams in group four having 360 mm (30 db) lap splice length measuring at 30 mm, 90 mm, 150 mm, and top surface ranged from (-79 to -143), (3848 to 4432), (8013 to 8493), and (-2139 to -2335), respectively.

Table 5: Concrete strain test results

Group	Beam Symbol	RCA (%)	Ls (mm)	$\frac{L_S}{d_b}$	$\varepsilon_{30} \times 10^{-6}$	$\varepsilon_{90} \times 10^{-6}$	$\varepsilon_{150} \times 10^{-6}$	$\varepsilon_{top} \times 10^{-6}$	$N.A$ (mm)
Group one	B1	0%	-	-	142	6125	10850	-2850	28.58
	B2	25%	-	-	132	5417	10345	-2510	28.50
	B3	50%	-	-	125	4970	9759	-2298	28.46
	B4	75%	-	-	120	4522	9249	-1991	28.36
Group two	B5	0%	120	10	-328	3438	7042	-2011	35.23
	B6	25%	120	10	-284	3201	6812	-1962	34.89
	B7	50%	120	10	-241	2981	6528	-1917	34.49
	B8	75%	120	10	-195	2763	6281	-1874	33.96
Group three	B9	0%	240	20	-282	3675	7225	-2073	34.28
	B10	25%	240	20	-243	3412	7099	-2000	33.99
	B11	50%	240	20	-196	3327	6832	-2028	33.34
	B12	75%	240	20	-157	3219	6585	-2033	32.79
Group four	B13	0%	360	30	-143	4432	8493	-2335	31.88
	B14	25%	360	30	-135	4163	8285	-2262	31.89
	B15	50%	360	30	-120	4071	8142	-2238	31.72
	B16	75%	360	30	-79	3848	8013	-2139	31.21

ε_{30} = Concrete strain at 30 mm from the top of the beam measured by strain gauge one (SG1), ε_{90} = Concrete strain at 90 mm from the top of the beam measured by strain gauge two (SG2), ε_{150} = Concrete strain at 150 mm from the top of the beam measured by strain gauge three (SG3), ε_{top} = Concrete strain calculated at the top of beam (at mid-span), N.A= Neutral axis calculated from the top of beam (at mid-span).

The concrete strain showed that the strain at 150 mm, and 90 mm are positive values because it is located under the neutral axis in the tension area. In contrast, concrete strain at 30 mm is positive in the reference beam of group one and negative in other beams of group two, group three, and group four.

The strain distribution along the cross-section of the beams is shown in Figure 9 (a - d). The results of the strain distribution generally show that the strains in the reference beams in group one are greater than the rest of the groups that contain a lap splice length. Furthermore, increasing the lap splice length in the beams increases the straines along the cross-section. On the other hand, increasing the RCA ratio for the reference beams or beams that are identical in lap splice length leads to decreased concrete stress. The reason for all of the above is that the concrete strain distribution based on the stress distribution in the cross-section of the beams is directly related to the load-bearing capacity of the beams. Beams with a higher load-bearing capacity have a higher concrete strain, as in the reference beams, or a longer lap splice length than others.

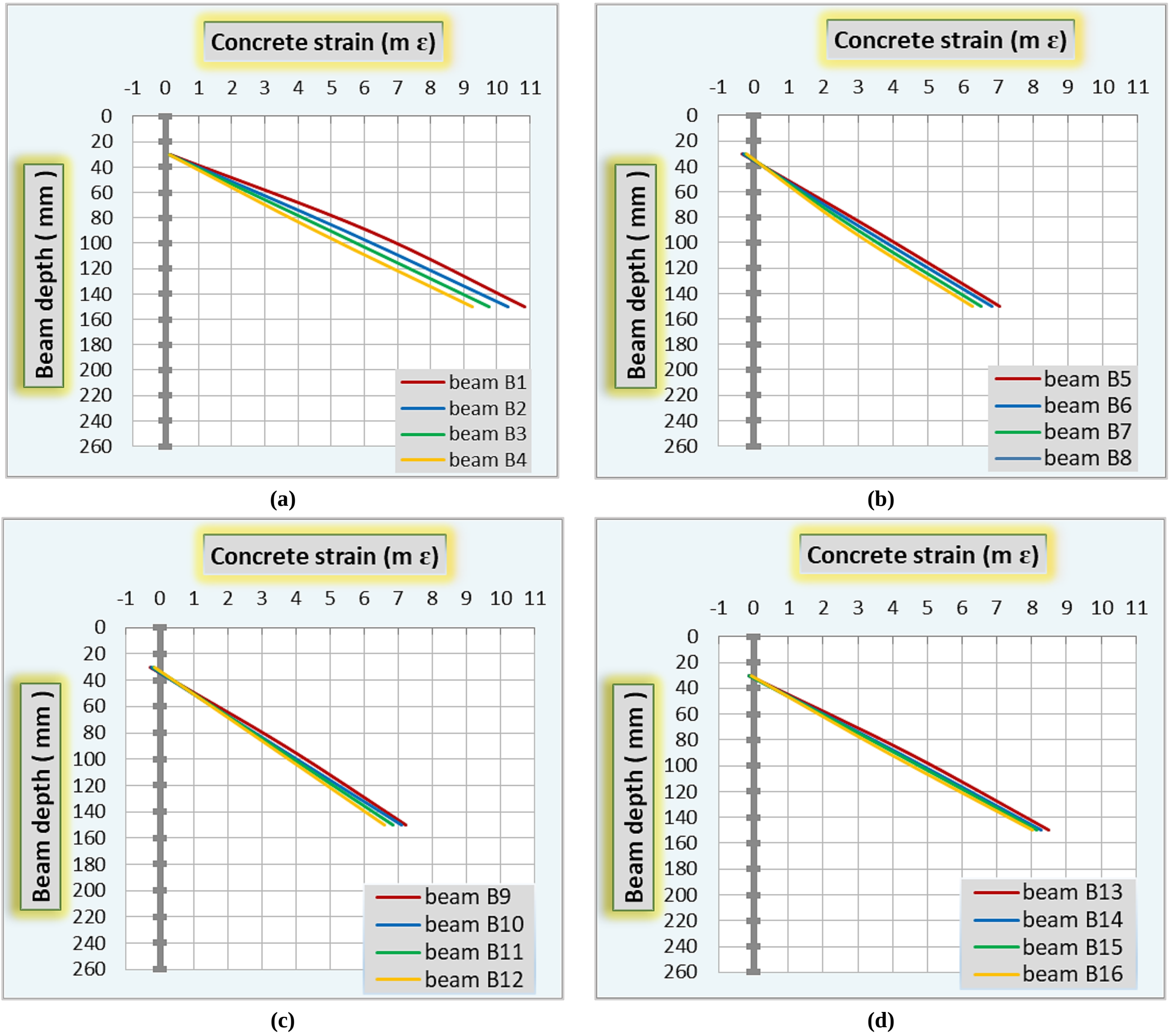


Figure 9: Concrete strain of beams (a) group one (beams: B1, B2, B3, and B4) (b) group two (beams: B5, B6, B7, and B8) (c) group three (beams: B9, B10, B11, and B12) (d) group four (beams: B13, B14, B15, and B16)

7. Conclusion

Based on the experimental results obtained from sixteen beams, both with and without varying ratios of recycled coarse aggregate (RCA) and incorporating splice lengths, the following conclusions can be drawn:

1. The behavior of beams that contain a ratio of RCA is similar to that of beams in which the RCA is absent, and the relationship between the RCA ratio and the ultimate load is slightly inverse.
2. The RCA ratio of 50% is more appropriate than the rest ratios since it reduces the ultimate load slightly less than the RCA ratio of 25%, and the difference increases when using the RCA ratio of 75%.
3. The ultimate load in beams of splice length 120 mm (10 d_b) reaches about (45%) of the ultimate load of corresponding beams without splice length, while in beams of splice length 240 mm (20 d_b) reaches about (68%) of the ultimate load of reference beams.
4. The ultimate load in beams of splice length 360 mm (30 d_b) reaches about (99%) of the ultimate load of corresponding beams without splice length. This indicates that using splice length (30 d_b) in beams is adequate and makes the behavior of these beams similar to the behavior of reference corresponding beams without splice length.
5. The increment of the RCA ratio caused a slight decrease in concrete strain. This indicates that concrete strain has a slightly inverse relationship with the RCA ratio.

Author contributions

Conceptualization, **M. Attab**, **S. Abdulqader**, and **M. Mohsen**; data curation, **M. Attab**; formal analysis, **M. Attab**; investigation, **M. Attab**; methodology, **M. Mohsen**; project administration, **M. Attab**, resources, **S. Abdulgader**; supervision, **S. Abdulgader**, and **M. Mohsen**; validation, **M. Attab**, **S. Abdulgader**, and **M. Mohsen**; visualization, **M. Attab**; writing—original draft preparation, **M. Attab**; writing—review and editing, **M. Attab**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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