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NEW MODEL OF ECO-FRIENDLY HYBRID DEEP BEAMS WITH WASTES OF CRUSHED CONCRETE

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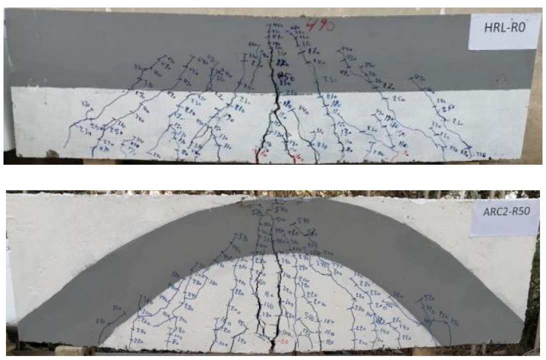
Graphical abstract



Abstract

This paper presents a new model of hybrid sustainable deep beams that include crushed coarse aggregates (RCA) in place of natural aggregates. RCA was in three replacement ratios: 0%, 50%, and 100%. Six specimens of deep beams have been tested experimentally under static loads and were divided into two groups: the first group contains three specimens made with conventional hybrid deep beam models with a top layer of normal strength concrete including steel fibers (SFC) and a bottom layer of RCA with the three replacement ratios. In addition, the second group contains three specimens made with the proposed arched hybrid model SFRC within the arch region and RCA in other regions of the beam. Results revealed that when adopting the proposed model rather than the conventional hybrid model, the capacity improved by 13.5%, 19.7%, and 19.1% for the three replacement ratios, respectively. While the flexural toughness improved by 25.2%, 51.1%, and 62.1%, respectively. Moreover, results showed that for the conventional model, the mode of failure changed from flexure to diagonal with increasing RCA content. Whereas for the proposed model, the mode was kept to a flexural trend regardless of the RCA content in the bottom layer. The suggested arrangement of hybridization may be utilized to produce sustainable precast deep beams that minimize the impact of the waste of construction materials on the environment.

Keywords: Eco-friendly, Hybrid deep beam, Precast, Recycled aggregate, Steel fibers reinforced concrete, Construction and demolition waste

1.0 INTRODUCTION

Sustainable construction refers to utilizing recycled waste materials as an alternative to concrete components to have a lower impact on the environment [1]. One of the benefits of using and recycling waste is reducing gas emissions during the manufacture of concrete components, as well as reducing the consumption of natural resources and preserving the environment by reducing landfill waste and reusing it. Thus, the applications of sustainable concrete are increased dramatically [2]. Construction and demolition waste is a huge source of waste in most countries. In the European Union, it represents more than 35% of the waste rate, as shown in the Figure 1. Construction wastes, such as ceramics, crushed glass, concrete, chopped rubber tires, bricks, wood, and plastic, may be used as recycled aggregate [3].

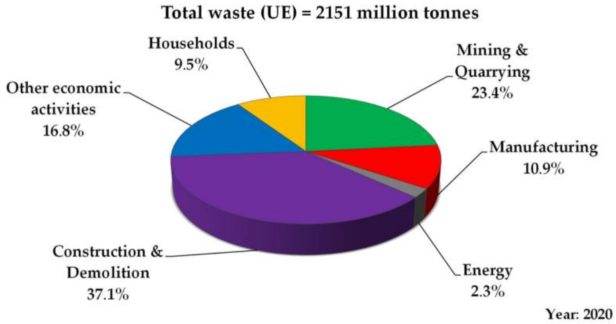


Figure 1 Distribution of waste in the European Union in 2020 [3]

Many researchers have studied the effects of construction waste on the behavior of concrete structural members, including beams, columns, deep beams, etc. Deep beams are considered as one of the D-regions [4-9], which are characterized by relatively high turbulence of the stress contour line that makes using the conventional Bernoulli equation result in unsafe prediction performance. Deep beams are used in multistory buildings and bridges in the form of "transfer beams". Due to the relatively short spans and high loads transferred by such beams, high shear forces are induced. Thus, large cross-sections are used, which results in increasing the self-weight of beams. Many studies have been conducted on improving the shear capacity with keeping the self-weight as small as possible. Some proposals included using high-strength concrete, including steel sections within deep beams, and adopting hybrid deep beams. Regarding the first proposal, Sahoo *et al*. [10] observed that steel-fiber concrete deep beams experienced less crushing than normal concrete deep beams and that the required strength of the strut and tie model was attained before failure. Moradi and Esfahani [11] studied the use of steel fiber-reinforced concrete (SFRC) and how it affected the behavior of deep beams with openings. Results show that the load-bearing capacity of SFRC specimens was maintained while also dramatically increasing the final deflection. Additionally, the specimens' first crack load increased twice after the addition of steel fiber. Yousef *et al*. [12] studied ultra-high-performance fiber-reinforced concrete deep beams with minimum shear reinforcement. It was concluded that the steel fibers have the rate of contribution to the predicted ultimate shear strength for the tested deep beams. Sagi *et al*. [13] studied the effects of steel fibers with different volume fractions (0.5%, 1%, and 1.5%) on shear behavior. Results showed that the behavior of deep beams was greatly improved by the incorporation of steel fibers in concrete in terms of initial cracking load, failure load, and the ductility. However, the failure load was not increased when the content of the tested specimens of excess of 1.0% volume fraction.

Regarding the second proposal, Chen *et al*. [14] studied the behavior and shear strength of steel-shaped reinforced concrete deep beams. Observed that the steel-reinforced concrete (SRC) deep beams showed more ductile behavior compared to the reinforced concrete (RC) deep beams.

In the last few decades, sustainable deep beams have been proposed by using recycled construction materials. Liu *et al*. [15] concluded that the shearing behavior of the tested deep beams was also impacted by the compressive strength of recycled aggregate concrete (RAC). Kachouh *et al*. [16] found that the stiffness, shear cracking load, and shear capacity of concrete deep beam specimens with a 100% RCA were decreased. Soltanabadi and Behfarnia [17] reported that the shear resistance of tested specimen reduced significantly when the replacements of RCA and recycled asphalt pavements (RAP) were 50% and that RAP specimens had more flexural and diagonal cracks than RCA specimens.

It is clear that using recycled material led to a reduction in capacity. Thus, to control such problems, steel fibers are used in RCA. Chaboki *et al*. [18] investigated the influence of several parameters on the shear behavior, such as the RCA replacement ratio and the volume fraction of steel fibers. Results showed that the steel fiber improved the shear behavior of recycled aggregate concrete beams in comparison to control specimens. Zaid *et al.* [19] reported that the mechanical characteristics of RAC are considerably improved by the addition of double-hooked-end steel fibers.

Hybrid deep beams is another proposal to control the cost and performance of such beams. Such model was based on constant distribution of concrete material in the top and bottom parts of the section. Hassan [20] conducted a series of experimental tests to study the effect of the behavior of hybrid deep beam made of top layers of ultra-high performance concrete (UHPC) and bottom layer of normal concrete (NSC). Results showed that for hybrid beams with UHPC in compression, load-deflection behavior with relatively high stiffness was achieved by increasing the thickness of the UHPC layer and steel fiber volumetric ratio. Hassan and Mhebs [21] studied the hybrid deep beams containing two types of concrete: Steel fiber concrete at shear spans for improve the shear resistance and conventional HSC at the mid-portion. Saad and Rasheed [22] studied the behaviors of hybrid deep beams using normal strength concrete (NSC) and reactive powder concrete (RPC) in the compression layer and the tension layer, respectively. The results showed that the ultimate load increased more with increasing RPC layer thickness. Shakir and Hanoon [23] proposed a new arrangement of the hybrid beams that used a variable distribution of concrete between the top and bottom layers in the successive cross section according to stresses induced in a section. This models is called as "curved hybrid deep beams". The SFC was used in the strut's region and NSC or LWC was used within the bottom layer. According to the results, the capacities for the two loading systems (one- and two-point loads) increased by 23% and 27%, respectively, for the conventional hybrid model. The conventional hybrid model's toughness was also improved by 44.7% and 143.7%, respectively, and ductility was enhanced by 11.5% and 32.5% for the horizontal hybridization, compared to 12% and 37.4% for the arched model of hybridization. The study was improved by Shakir and Hanoon [24] by using RPC instead of SF to test the extent of behavior improvement by applying RPC in the top layer. With a one-point system, it was found that the failure load of the conventional hybrid and arched system of hybridization increased by 27.6% and 39%, respectively, while for testing with two-point loads, the capacity increased by 34% and 36.9%, respectively. the proposed hybrid model has been improved by the same authors [25] by adopting the arched hybrid model which is considered to have negligible contribution of the top corners of deep beams in resistance. Recently, Qasim and Farooq [26] incorporated the sustainability aspect into the curved hybrid deep beams by using the RCA instead of the NSC or LWC. RCA was obtained from waste of construction materials, that is added to the concrete mixes at 100% to find the optimum costly-effective distribution of concrete material.

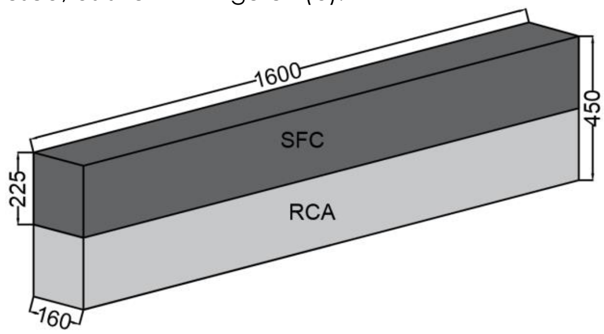
The current research aims to expand and develop the arched model proposed by Shakir and Hanoon [23] by using recycled aggregate concrete with normal-strength concrete. By adding recycled aggregate into the concrete out of the stress transfer channel, the suggested model aims to generate deep beams that meet the requirements of high performance, low cost, and sustainability. As a result, the significance of the present work can be summarized in the following form:

1. Sustainability is promoted in order to provide a safe and healthy environment. For this reason, use sustainable concrete with recycled aggregates.
2. It is possible to reduce the cost through the optimal distribution of materials and thus reduce the construction cost while maintaining the structural performance of the deep beam.

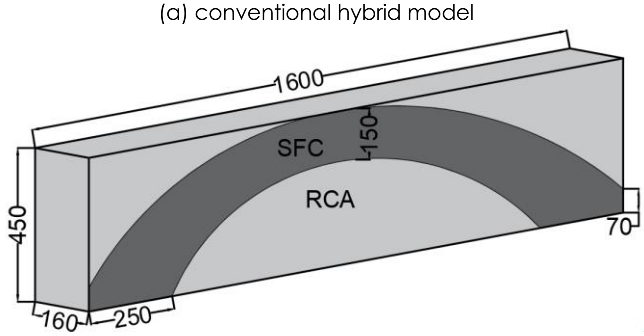
2.0 METHODOLOGY

2.1 Specimens Description

Six deep beams with a total depth of 450 mm, width of 160 mm, clear span of 1400 mm, and total span of 1600 mm were tested. Under one point load applied at mid-span and increased gradually up to failure. The test specimens are groups in two sets based on the model of hybridization with three specimens for each group. The first group represents the conventional horizontal model as shown in Figure 2(a), which consisted of steel fiber concrete (SFC) at the top half layer and recycled concrete aggregate (RCA) at the bottom half layer, with values of replacement of 0%, 50%, and 100%. The second group represents the proposed arched model by which the main two types of concrete mixes are used, as shown in Figure 2(b).



(a) conventional hybrid model



(b) Arched hybrid model

Figure 2 Geometry of the specimens (All units in mm)

Regarding the steel reinforcement detailing, for the main tensile (tie) element reinforcement, bars of 2Ø12 and 2Ø16 are used. While bars of 2Ø10 are used as top reinforcement. For stirrups and strut reinforcement, Ø8@160 is used. For the second group, there is additional steel reinforcement in the strut region of Ø8 @ 160 mm. It is to be mentioned that stirrups in group G2 are inclined (close to be normal on the struts as possible). The coding used for the tested specimens is shown in Table 1.

Table 1 Coding of deep beams.

	Coding	Ratio of replacement
G1:Horzontal Hybridization	HRL-R0	R= 0% within the lower half
	HRL-R50	R= 50% within the lower half
	HRL-R100	R= 100% within the lower half
G2: Arched Hybridization	ARC2-R0	R= 0% out of the arch
	ARC2-R50	R= 50% out of the arch
	ARC2-R100	R= 100% out of the arch

2.2 Materials

In the present study, Portland Cement (IV) has been adopted, and sample were tested to check the conformity with the Iraqi Specification No. 5, 1984

[27]. In the recycled concrete mix, recycled concrete aggregates have been used as a coarse aggregate replacement for natural crushed gravel with a maximum size of 20 mm, in addition to natural sand as the fine aggregate. The steel-fiber concrete mixture contains natural crushed gravel with a maximum particle size of 14 mm. The grain size analysis for both fine and coarse aggregates is indicated in Table 2 which was checked to satisfy the Iraqi specification No. 45/1984 [28]. Limestone powder is used as a low-cost filler material to increase the fine content. Micro-steel fibers of the straight shape having a diameter of 0.3 mm and, 13 mm in length have been used. the super plasticizer EPSILONE HP 580 was used and increase workability of the mix to reduce the water content. It is used in both concrete mixtures. Reinforcing steel samples were tested at the construction materials Laboratory at the University of Kufa, and the test results were consistent with ASTM A615 [29], as depicted in Table 3.

Table 2 Grading size distribution of the aggregate

	Size of Sieve (mm)	%Passing	Limits% Zone(2)[28]
Coarse aggregate	20	99.10	95-100
	14	86.45	80-90
	10	36.10	30-60
	5	2.30	0-10
	Sieve Size (mm)	**%Passing**	**Limits% Zone(2)[28]**
Fine aggregate	4.75	98	90-100
	2.36	87	75-100
	1.18	74	55-90
	0.6	55	35-59
	0.3	22	8-30
	0.15	4.6	0-10

Table 3 Test results of steel bars

Diameter (mm)	Yield stress (MPa)	Tensile strength (MPa)
8	580	733
10	560	712.77
12	590	696.7
16	610	699

2.3 Strength Tests of the Hardened Concrete Mixes

Three cylinders of 100 mm diameter and 200 mm length were tested to determine the splitting tensile strength (ft) in accordance with ASTM C496-11 [30], and three cubes of 100 mm by 100 mm by 100 mm were tested to determine the cube compressive strength (fcu) in accordance with BS 1881-116 1983 [31] for each mix. The tests are shown in Figure 3, and the results of the tests for the various concrete mixtures are shown in Table 4.

(a) (b)

Figure 3 Mechanical properties of hardened concrete (a) Cube compressive strength tests (b) Tensile Splitting Test

Table 4 Properties of concrete mixes of hardened concrete

Mix	(fcu) strength MPa	(f_t) strength MPa
SFC	67.75	5.9
NC-R0%	50	3.9
NC-R50%	45.7	3.18
NC-R100%	42	2.29

R0%: Non-replacement, R50%: Replacement recycled concrete aggregates 50% with natural aggregates, R100%: Full replacement recycled concrete aggregates

2.4 Instrumentation and Testing Machine

A 2000 kN universal testing device depicted in Figure 4(a) was used in testing the deep beams specimens. Mid-span deflection was measured by dial gage. A crack meter with a 0.5-mm range was used to measure the width of crack. A digital Verna was used to measure the crack's width when it was greater than 0.5 mm. Tools for measuring response are shown in Figure 4 (b, c, d).

(a) (b)

(c) (d)

Figure 4 (a) Loading machine(b) Crack meter(c) Vernia(d) dial gage

3.0 EST RESULTS AND DISCUSSION

A. Conventional Horizontal Hybrid

This group is a well-known conventional hybrid deep beam whose aim is to increase the compressive strength of the top half where the top nodal point is located (the CCC node). For such specimens, steel fiber concrete (SFC) was only utilzed in the top layer, and RCA concrete was used in the bottom layer with various rate replacements for different specimen.

The cracking map for specimen HRL-R0 is shown in Figure 5(a). It is clear that the first cracking initiated at mid span as a flexural crack at a load of 60 kN. Further loading resulted in the propagation of the flexural crack upward. However, the high resistance of the top layer to crack propagation due to the inclusion of steel fibers pushed the cracks to develop on both sides towards the supports at which the bottom nodal points are located. At a load level of 210 kN, the diagonal cracking developed with an angle of 44° along the strut line connecting the location of the point load with the support reactions. It may be observed that the cracking propagated along the full shear span. This may reduce the rigidity of the member and result in increased curvature. Moreover, the propagation of cracking with this trend may reduce the efficiency of the strengthening (or repairing) process for damaged beams. Furthermore, it can be observed that the ends of the top layer (dashed) are free from cracking and are then ineffective in resisting the stresses. Thus, using NSC or RCA within such regions may not affect performance significantly and produce more economic beams.

Figure 5(b) shows the crack propagation for HRL-R50, in which concrete contains 50% recycled concrete aggregates instead of coarse natural aggregates. No significant difference from specimen HRL-R0 can be observed. because the difference between the tensile strengths of the two types of concrete is negligible (18%). This makes the use of concrete at 50% replacement more economical and effective in reducing the environmental impact of the waste from the construction materials. It may be noted that the first cracking appeared at the mid-span and started at a 50 kN loading. Further loading caused cracks to move to the supports at a steeper angle, resulting in a diagonal cracking appearance at a load of 120 kN with an angle of 37°. The effect of SFC seems clear from the slow rate of propagation of cracks within the top layer. Thus, at a load level of 460 kN, the specimen failed in the flexural mode of failure. Compared to the specimen HRL-R0, the failure load of the proposed system of hybrid deep beam decreased by 6.1%. It can be concluded that the intensity of cracks for specimen HRL-R50 was similar to that of specimen HRL-R0. The ends of the top layer are also free from cracking, referring to their minor contribution to resisting stresses. Thus, it can be found out that the utiliazation of RCA within these regions may result in reduce the cost of production of beams and support sustainability.

For specimen HRL-R100, RCA concrete was used with 100% replacement at bottom layer. The map of the crack propagation at the failure is shown in Figure 5(c). At a loading of 50 KN, the first crack initiated as a flexural crack in the middle of the span, which corresponds to that of specimen HRL-R50 and is slightly less than that of specimen HRL-R0. This reveals that the ratio of replacement has no significant effect on the first cracking load. Further cracking developed with the progress in loading. The effect of steel fibers included in the concrete of the top layer is clear by the slow rate of development of cracking within the SFC layer. However, the intensity and width of cracks increased with increasing rates of replacement. Vertical cracking developed from increasing loading. In addition, at a load of 150 kN, the diagonal crack initiated with an angle of 47°.

For the three specimens, it can be seen that the mode of failure transferred from the flexural to the flexural-shear type, revealing that a gradual reduction in shear strength occurred based on the shear-friction approach and that the bottom nodal points became weaker according to STM models, which may result in a premature failure at supports. The flexural-shear mode failure occurred at 450 kN of load. Compared to the specimens HRL-R0 and HRL-R50, the capacity of the hybrid deep beam decreased by 8.9% and 2.2%, respectively.

B. Arched Hybrid

This group has the same steel reinforcement as group one, with additional strut reinforcement 4Ø8 as longitudinal bars and stirrups of Ø8@160 (c/c) that are fixed normal to the strut direction. For such specimens, steel fiber concrete was only used in the compression strut region, and RCA was used above and below the arch compressive zone with various rate replacements for each specimen, as shown in Figure 2(b). Figure 5(d,e, and f) represents the results of crack propagation for the proposed sustainable hybrid deep beams. Three replacement ratios were considered (0%, 50%, and 100%) for the sake of comparison with the corresponding specimens of the conventional horizontal model.

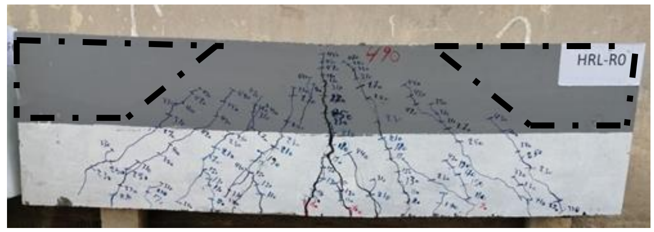
This proposal was considered the results of the previously tested specimens that showed the ends of the top layers do not affect the response, and it is worth studying the performance when these regions are made of RCA. Moreover, it can be seen that most of the cracks within the mid span are vertical, revealing that the STM action controlled the response. i.e., the compression struts represented the compression elements of the vertical truss while the main steel reinforcement provided the tie elements. The concrete out of the compression struts had a minor effect on response. Furthermore, it is clear from the results that making the angle of the stirrups normal to the strut line yielded the optimum resistance to the diagonal cracking and tendency to splitting due to the tensile stresses along the strut elements. Moreover, it is obvious that the high-strength strut elements restricted the development of cracks in this region towards the supports, i.e., close to the bottom nodal points.

Consequently, no premature failure due to the crushing of the supports may occur. There was no significant difference between specimen CRV2-R0, which included a natural coarse aggregate, and specimen CRV2-R100, which included a full RCA. Therefore, it can be concluded that specimen CRV2-R100 plays an essential role in reducing the environmental impact of the waste of construction materials while maintaining performance without a significant drop.

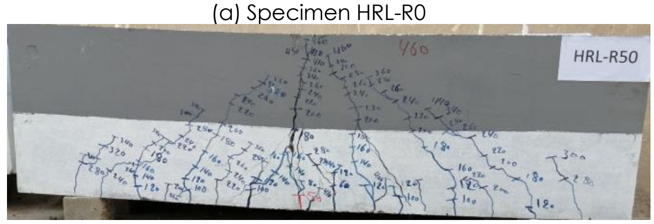
For specimen ARC2-R0, normal strength concrete was used with the recycled concrete aggregate, and the map of the crack pattern is shown in Figure 5(d). Results revealed that the first cracking appeared as a flexural at 40 kN of load in the center of the span and developed in a vertical direction toward the point loads. At 460 kN, a crack with symmetry on both sides appeared near the supports and slowly spread out with increasing loading. The width of the flexural cracks grows as the load increases, and it reaches the failure stage at a load of 556kN with a flexural mode failure. The increment in beam capacity by 13.5% compared to the HRL-R0 specimen was recorded.

Figure 5(e) depicts the map of crack propagation for the ARC2-R50 specimen. The first crack appeared at a load of 60 kN at mid span, and cracks spread within the normal concrete at the tensile zone. However, the excessive lateral crack propagation was reduced by the use of steel fiber concrete and arching action. The failure occurred in a flexural mode under a 550 kN load. When compared to the conventional hybrid specimens HRL-R50 the specimen's capacity increased 19.6%. The failure load of the tested specimen decreased by 1.1% in comparison with the specimen ARC2-R0, referring that the use of normal concrete and the replacement of coarse aggregate by 50% have no significant effect on load capacity.

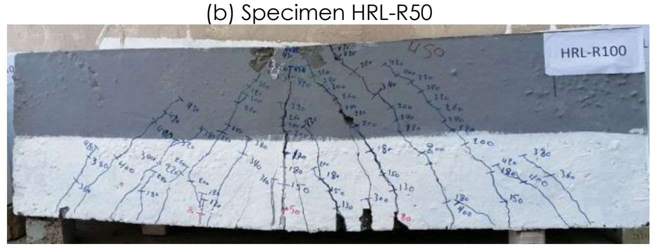
In ARC2-R100, the history of the crack pattern is shown in Figure 5(f), where it may be observed that the first cracking appeared at 50 kN of loading in the mid-span. Diagonal cracks started to form at 160 kN, and more cracks started to appear on both sides of the mid-span and spread upward. A flexural mode failure with a 536 kN load controlled the failure stage. The failure load of the deep beam enhanced by 19% if compared with the conventional hybrid specimens HRL-R100. While it decreased by 3.7% and 2.5% compared to ARC2-R0 and ARC2-R50, respectively.



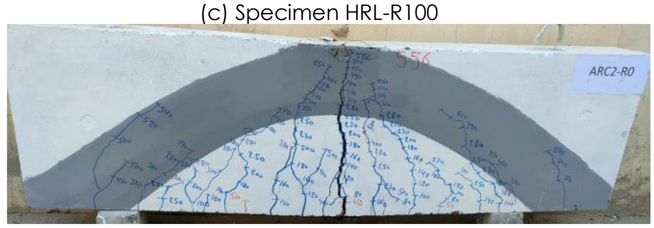
(a) Specimen HRL-R0



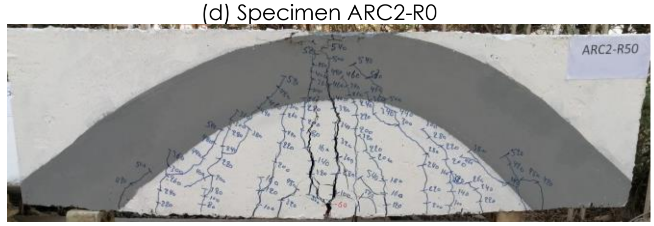
(b) Specimen HRL-R50



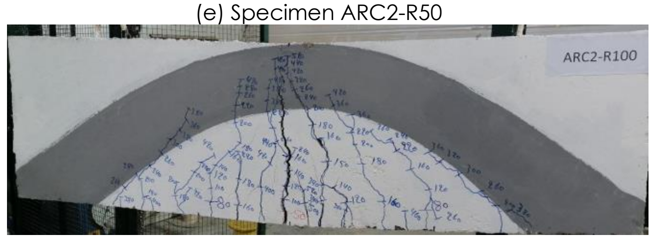
(c) Specimen HRL-R100



(d) Specimen ARC2-R0



(e) Specimen ARC2-R50



(f) Specimen ARC2-R100

Figure 5 Crack patterns of the tested deep beams

3.2 Load-deflection Curves

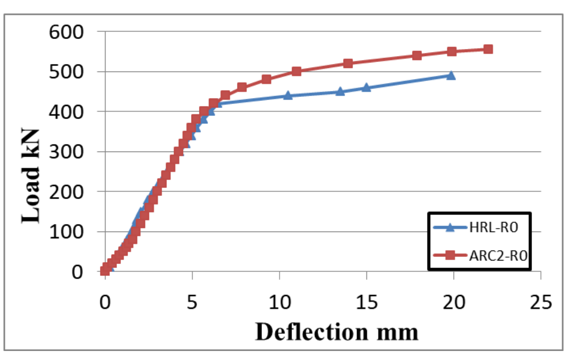
Figure 6 shows the load-deflection curve of the tested specimens. For all the tested samples, it can be noted that the load-deflection curve for two specimens has the same rate of coarse aggregate replacement, but the difference in the hybrid model is that their stiffness is similar in 50%–75% of the load; after that, the stiffness of the conventional hybrid is less than that of the arched hybrid model. The stiffness of conventional hybrid specimens was about zero (horizontal) for the second part of the load-deflection curve, but it gradually increased in the arched hybrid beam, recording the highest value for specimens. No significant difference between the results for the three replacement ratio. Thus, the use of the proposed hybrid model with full replacement may represent the optimum figure in terms of sustainability, cost and structural performance.

It can be seen that there is no significant difference between the results for the conventional hybrid model. This may refer to several aspects, which are:

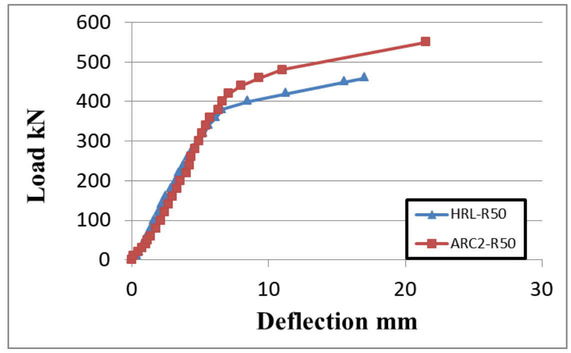
1) The quantity of reinforcement that was calculated by STM may result in ductile failure that is controlled mainly by excessive deformation of main steel reinforcement.

2) The STM model is not affected largely by concrete strength out of the STM system. Thus, the replacement ratio (less than 50%) may not affect significantly the rate of crack widening, crack propagation and mode of failure. However, higher ratio of replacement may reduce the resistance to the diagonal cracking. Thus, resulting in more brittle failure which can be observed by the deflection values recorded at failure 22 mm,17mm.and 16 mm for the replacement ratios of 0%, 50% and 100%, respectively

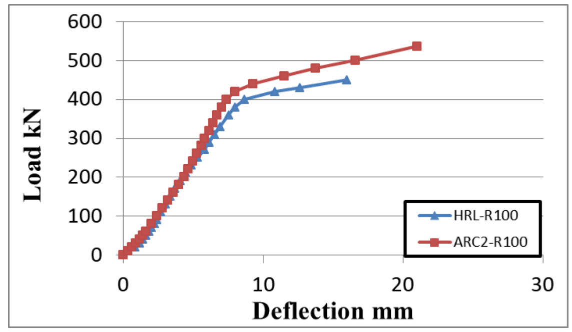
3) For the arched model, behavior that is more ductile was obtained regardless the replacement ratio. This insures that the STM path of stress transfer controls the mechanism of resistance. Thus, no significant differences between the three specimens in failure load and maximum deflection. This gives indication that no significant difference may be obtained in ductility for the arched model compared to that of the conventional hybrid model.



(a) Specimens HRL-R0 and ARC2-R0



(b) Specimens HRL-R50 and ARC2-R50



(c) Specimens HRL-R100 and ARC2-R100

Figure 6 Load-deflection curve of the tested specimens

3.3 Crack Width

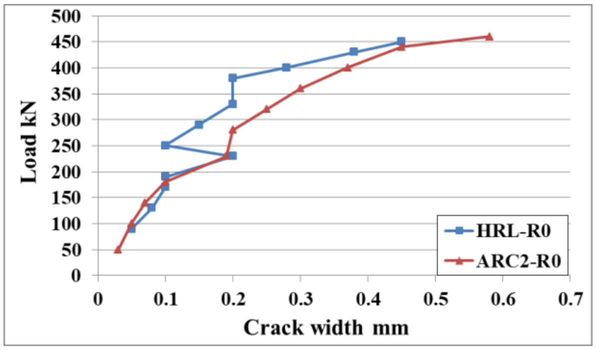
Figure 7(a) shows the rate of widening of the diagonal cracking for the HRL-R0 and ARC2-R0 specimens. It can be observed that the rate of crack width increase for the two samples is almost equal until load 220. Beyond which, the crack width for specimens are slightly irregular. The diagonal crack width for HRL-R50 is greater than the diagonal crack width for ARC2-R50, as shown in Figure 7(b). Figure 7 (c) the rate of increasing the crack width for the specimens HRL-R100 and ARC2-R100.

For the replacement R0, Figure 7(a), it can be seen that the diagonal crack for the conventional hybrid model, HRL-R0, is less than that for the arched model due to the high resistance for diagonal cracking. However, the propagation of the flexural cracking affected the response leading to this change in in rate of cracking and width of the diagonal cracking.

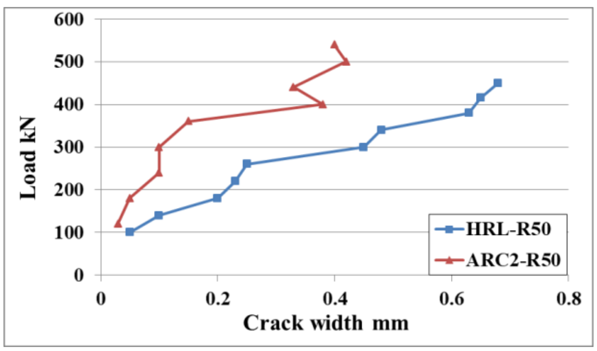
For the specimen ARC2-R0, it is clear that the arch action (STM mechanism) controlled the behavior gradually and that the width of the diagonal crack reduced at the final stages and that the flexural crack controlled the response.

For Figure (7b) with replacement of 50%,it can be observed that the conventional hybrid beam,HRL-R50 was controlled by the diagonal cracking due to the reduction of the shear resistance. While, the transfer from diagonal to the flexural is less clear than specimen ARC2-50.

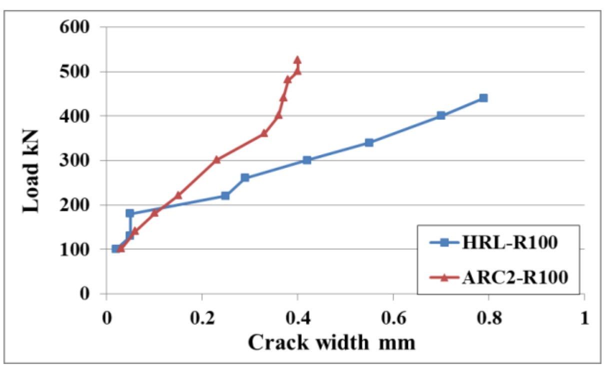
For the replacement R100, Figure 7(c), it can be seen that the diagonal crack controlled the behavior of specimen HRL-R100.While, the flexural crack controlled at earlier stages the specimen ARC2-R100.This can be concluded from the slow rate of development of diagonal crack beyond load level of 350 kN.



(a) Specimens HRL-R0 and ARC2-R0



(b) Specimens HRL-R50 and ARC2-R50



(c) Specimens HRL-R100 and ARC2-R100

Figure 7 Width of diagonal crack mm

3.4 Toughness

The ability of a member to absorb deformations before failing is measured by its toughness. Graphically, it is the region under the load-deflection curve, which represents the energy that has been lost as a result of member deterioration until failure [32]. The values of toughness for the testing of hybrid deep beams are shown in Figure 8. For the first group (conventional hybrid deep beams), the lowest toughness is HRL-R100, while HRL-R0 has the highest toughness. As for the second group, the ARC2-R0 has a toughness of 9380.5, while the ARC2-R50 and ARC2-R100 have the lowest toughness of 7.9% and 16.3% relative to the ARC2-R0, respectively. For both groups, the toughness decreases with an increasing rate of recycled aggregate replacement. The proposed hybrid models are observed to have toughness values that are higher than those of the corresponding conventional hybrid specimens. The reason for that may be related to the arching action within the hybrid beams made using the proposed model, which restricts failure and provides an efficient path for load transfer to the supports.

It can be seen the difference between successive ratio of RCA for the conventional model is higher than that for the arched model. This may be attributed that the lower nodal points and some of the struts are affected significantly by the variation of RCA. Whereas, the arched hybrid model is controlled within most of the range of loading by the tied arch action. Putting in mind that such arch is not affected by the ratio of RCA. Thus, the failure for such specimens (with tied arch action), occurred within higher loads and recording higher values of deflection compared to that of the horizontal model.

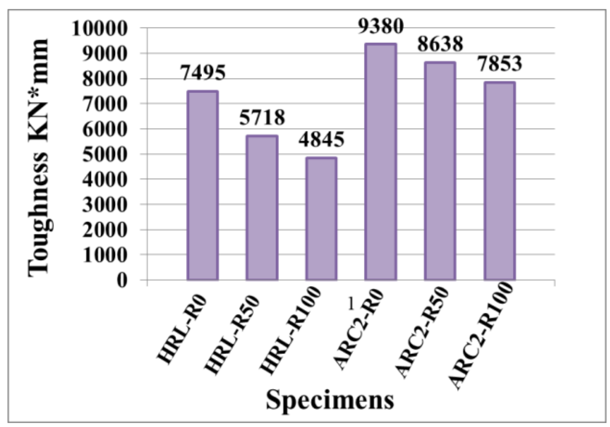


Figure 8 Toughness for specimens

4.0 CONCLUSION

In this study, new models of hybrid sustainable deep beams and conventional hybrid deep beams that include recycled coarse aggregates (RCA) in place of natural aggregates. The key findings may be summarized as follows:

The ultimate capacity decreased by 3.7% and 8.9% for the arched hybrid and conventional hybrid, respectively, when changing the ratio of replacement from 0% to 100%. In addition, the ultimate loading capacity for proposed hybrid specimens (arched) enhanced by 13.4%, 19.7%, and

19% compared to the conventional hybrid specimens (HRL-R0, HRL-R50, and HRL-R100), respectively, at the same rate of replacement RCA. Moreover, The flexural toughness was enhanced by 25.2%, 51.1%, and 62.1% for the arched hybrid compared to the conventional hybrid specimens (HRL-R0, HRL-R50, and HRL-R100), respectively, at the same rate of replacement RCA.

Regarding the mode of failure, it was noticed that for the conventional hybrid model it changed from flexural to the diagonal type by increasing the substitution, but it remained of the flexural type in the case of the proposed arched hybrid model.

It is recommended to examine arched deep beams with low strength concrete out of the arch region by using waste of construction materials as tiles, bricks, etc. to produce light weight sustainable beams and to investigate the structural and service performance with changing the replacement RCA ratios.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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