Journal of Engineering Science and Technology
Special Issue on Development of Sustainability Systems - III, 269 - 283

SHEAR BEHAVIOR INVESTIGATION OF STEEL-FIBER-REINFORCED RECYCLED AGGREGATE CONCRETE DEEP BEAMS

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Abstract

Usually, scrap tyres and deteriorated concrete are discarded in landfills. Building construction is seeing increased use of recycled steel fibre from scrap tyres and recovered coarse aggregate from discarded concrete garbage from landfills. Employing recycled materials in buildings is beneficial since it preserves the environment and natural resources. The current study investigated the effect of using recycled aggregate with three percentages of substituting, 20%, 40%, and 60%, with recycled tyres steel fibre in two percentages, 1%, and 2% from the weight dry mixture. The shear resistance of ten specimens, in which the deep beam specimens were fabricated and tested using two-points vertical load bending test. Deep beams containing recycled aggregates with replacement ratios of 20%, 40%, and 60%, along with steel fibres of 1% and 2%, demonstrated a greater ultimate load of 10.5%, 8.1%, and 5.4%, and 13.2%, 10.8%, and 8.2%, respectively, than those with recycled aggregate alone. Furthermore, when coarse aggregate was replaced by 20%, 40%, and 60%, and recycled steel fibres were introduced by 1% and 2%, it was found that the peak deflection dropped about 2.9%, 1.2%, and 1.73 %, and 1.99%, 1.47%, 5.58%, respectively, relative to those beams with recycled aggregate without any addition.

Keywords: Deep beams, Recycled aggregate, Recycled steel fibres, Replacement ratios, Shear Strength.

1. Introduction

Concrete has long been one of the world's foremost widely used building materials. Concrete requires sufficient shear and tensile strength to ensure its structural reliability and safety in various applications. Adequate shear strength is essential to withstand lateral forces and prevent sudden shear failures, while proper tensile strength is vital to resist bending and stretching forces. Inadequate shear strength can lead to brittle shear failures, and insufficient tensile strength can result in cracking and structural compromise [1, 2].

Deep concrete beams are structural elements with a significantly greater depth than their span length. This unique proportion allows them to carry heavy loads and resist shear forces more effectively than regular beams. One of the primary purposes of deep beams is to transfer loads from upper levels to lower ones, especially in areas where the presence of columns might be impractical or undesirable [3]. On structural behaviour, the increased depth of these beams allows for a more efficient distribution of shear forces and bending moments. This is essential in regions where the risk of shear failure is significant. As a result of deep beam geometry, the strength of such beams will often be governed through shear instead of flexural [4].

Construction products like concrete have been widely utilized throughout the world owing to their affordable price and the availability of materials. Throughout the global region, concrete has been made at a rate of over ten billion tons annually. To produce 10 billion tons of concrete, ten billion tons of concrete ingredients will be needed. Consequently, such a situation suggests that the manufacture of concrete uses up and depletes a great deal of natural substances, thus contributing to energy saving, environmental safety, and economic gains [5].

There is an increasing focus on making use of leftover materials and by-products as part of building operations. The use of waste substances not only assists with having them redirect it to use but also provides many indirect advantages, for instance, energy savings and environmental safety. As a result of the challenges of getting rid of concrete debris and built-up waste, a growing lack of natural aggregate has generated the need for waste concrete to be recycled back into virgin aggregate for freshly cast concrete [6].

The recycling of aggregates refers to the method that transforms a waste substance reclaimed as a supplier. As a result, using damaged substances as an alternative to natural substances might be a good way of supporting environmental safety. Among the methods employed in recycling represent the replacement partially or entirely of regular aggregate in new concrete production. The blocks of concrete that have no parts of wood, steel reinforcement rebars, or plaster materials can be broken down to an extent equal to the natural gravel and then cleaned by wash and classified according to size following sifting using sieves [7].

Adding fibres, such as steel fibres (SF), will improve concrete's brittle behaviour and considerably enhance its tensile strength and strain, the value of toughness, and the ability to be energy-absorbing. Thus, fibres can diminish the effect of cracks in a structure and enhance their deformation properties [2]. Given its distinctive contribution to enhancing concrete behaviour, concrete reinforced using steel fibre has been extensively and commonly employed compared to many kinds of concrete [8].

Recycled steel fibre (RSF) is attracting the concern of scientists globally due to their minimal influence on the environment besides their affordable recovery expenses [9]. Regarding sustainability, using recycled steel fibres aligns with the principles of circular economy and resource efficiency by reusing materials that would otherwise be discarded. This approach reduces the demand for virgin steel production, which is energy-intensive and contributes to greenhouse gas emissions. The fibres act as reinforcement within the concrete matrix, providing a distributed network that helps control and inhibit crack propagation. Achieving this is particularly important in mitigating the formation and widening of cracks caused by shrinkage, thermal effects, and external loads [10].

Wanas et al. [11] analysed the shear behaviour of a deep beam of concrete made from recycled aggregates (RA). The current investigation compares recycled aggregate concrete's strength and capacity for loading to that of concrete that contains naturally occurring aggregates. Generally, there has been a noticeable reduction in strength in the concrete samples that contain recycled aggregate. Sagheer et al. [12] investigated the possibility of using regionally sourced coarse aggregate recycled from demolished building debris for structural purposes.

The findings demonstrated that the recycled aggregates provided a reduction in Los Angeles abrasion and crushing of 18%–28% and 40%, in that order, while their ability to absorb between 40% and 300% was greater relative to the non-recycled aggregate. Hamzenezhadi et al. [13] performed experimental work using eight deep beams made of reinforced concrete. According to three points of loading, two categories of specimens containing 2% steel fibres and fibre-free were tested. The outcomes of the test revealed that the load-carrying capacity in specimens with deep beams could be raised by 84.8% while maintaining similar dimensions if regular concrete were substituted with composites comprising cementitious materials that contain steel fibres at 2%.

Su et al. [14] compare the workability, mechanical characteristics, and durability of reinforced concrete with recycled-tyre steel fibre (RTSF) relative to those that contain commercial industrial steel fibre (ISF). The findings demonstrate that recycled steel fibre concrete possesses more excellent flowability than by using a similar ratio of fibres. Regarding mechanical characteristics, RTSF modestly boosts compressive strength after 28 days. Splitting tensile strength has also been raised to 15.4% after the addition of RTSF, almost near that of ISF 16.9%. Regarding flexural behaviour, RS15 specimens exhibit an almost nearly improved influence for IS05 specimens accompanied by increased residual strength and energy of fracture.

Kachouh et al. [15] developed four models of finite elements in a three-dimensional state in the present work by employing the ATENA program to make a simulation and assess the nonlinear performance of deep reinforced concrete beams constructed from recycled steel fibres (RSF) and recycled concrete aggregates (RCA). According to the findings of the numerical study, it has been deduced that utilizing a 100% RCA substitution led to a substantial shear strength decline of around 37%. The addition of SF significantly improved the strength of the model based on RCA to a degree that was higher relative to a model based on NA. The maximum load of the model with SF was 84% higher than that of the free from SF. Using 1% SF was more effective than using minimum shear reinforcement in improving the performance of the RCA-based models.

Kachouh et al. [16] investigated the influence of steel fibres on the shear performance of deep concrete beams constructed using 100% RCA. Beams of RCA reinforced contain steel fibres with volume fractions equal to 1% and 2%, which recover 80% and 90% of the shear strength of an equivalent beam having the minimum reinforcement in shear. It was found that the RCA specimen response for volume fraction, VF equal to 3% overachieved that of the reference beam based on NA using the minimum reinforcement in shear, suggesting that steel fibres can be employed in deep RCA beams to serve as an alternative for minimum reinforcement in shear. However, only 2 and 12% declines in the shear capacity and cracking load have been measured in the existence of the conventional shear reinforcement.

The beams based on RCA containing VF of 1%, 2%, and 3% demonstrated corresponding shear capacity increases of about 22%, 40%, and 107% versus the reference based on the RCA that matched free of fibres. Sani et al. [17] study investigates the compressive strength of fibre-reinforced concrete (FRC) incorporating recycled waste hybrid steel fibres as a sustainable alternative to conventional reinforcement materials. The experimental results indicate that the inclusion of 0.2% waste hybrid steel fibres enhances the compressive strength of FRC by approximately 6.58%, demonstrating the potential of recycled steel fibres to improve concrete performance while addressing environmental concerns.

Muttashar and Najah [18] investigated the effectiveness of internally embedded steel functional plates in enhancing the flexural behaviour and ductility of FRC beams through experimental and numerical analyses. The results indicate that the proposed strengthening technique significantly improves flexural performance, delaying initial cracking and increasing the ultimate load by up to 45%, with notable enhancements in ductility and stiffness.

The main initiative to perform this study is to produce and characterize a sustainable and environmentally friendly construction material. Tyres, from one hand, are a hard and harmful waste. RCA, on the other hand, is cost-effective alternative to natural aggregate. However, the consequences of using as additives in the concrete constructions is not understood yet.

The current study investigated the response of deep beams to introducing recycled concrete aggregate and recycled steel fibre from tyres. It assessed the influence of a combined action to include recycled aggregate with three ratios of replacement, 20%, 40%, and 60%, and recycled steel fibre with two ratios of 1% and 2% on the shear behaviours of deep reinforced concrete beams.

2. Materials and Methods

2.1. Materials

The materials employed in this study are characterized according to standard procedures that is aligns with Iraqi Standard Specifications. The materials resources and characterization are presented, with the measurement results, in the following sections.

2.1.1. Cement

Ordinary Portland cement was chosen for the casting process for the deep beam specimens. The cement was tested to confirm compliance with Iraqi Standard Specifications I.Q.S, No.5, 2019 [19]. Table 1 displays the measurement results for both chemical and physical properties.

Table 1. Results of the chemical and physical tests conducted on cement.

Chemical Properties		
Oxides Composition	**Content %**	**I.Q.S. No.5, 2019 [19]**
CaO (Free Laminate)	1.4	---
SiO_2	17.4	---
Al_2O_3	3.29	---
Fe_2O_3	3.77	---
Lime Saturation Factor (L.S.F)	0.76	0.66-1.02
MgO	2.14	<5
C3A	4.1	---
SO_3	3.74	< 5
Loss on Ignition (L.O.I)	3.3	< 4.0
Insoluble Residue	1.36	< 1.50
Physical Results		
Specific Surface Area (Blaine Method) (m^2/kg)	332	≥ 230
Initial Setting Time (min)	89	≥ 45 min
Final Setting Time (hr: min)	4:25	< 10 Hr
Compressive Strength at Three days (MPa)	22.4	≥ 15 MPa
Compressive Strength at seven days (MPa)	27.6	≥ 25 MPa
Soundness (Autoclave method)	0.63	≤ 0.8

2.1.2. Fine aggregate

Native sand from the Al-Najaf government was used in this study, where the aggregate of fine particles, which had the largest dimension, passed through sieve number 40 (450 µm) and remained on sieve number 100 (150 µm) (single-grading). The fine aggregate was subjected to various tests, including grading, chemical analysis, and physical analysis. Tables 2 and 3 list the main characteristics of the fine sand used which corresponds to the Iraqi specifications NO. 45/1984 [8] Guides for Zone II.

Table 2. Results of the grading for fine aggregate.

Sieve Size (mm)	Passing %	I.Q.S. No.45, 1984 [8]
10	100%	100
4.75	94.5	90-100
2.36	85.5	75-100
1.18	79.3	55-90
0.6	57.4	35-59
0.3	26.5	8-30
0.15	7	0-10

Table 3. Results of chemical and physical tests for fine aggregate.

Property	Passing percentage	I.Q.S.No.45,1984
Specific Gravity	2.32	---
Absorption	0.79%	---
Sulphate Content	0.31%	≤ 0.5%

2.1.3. Coarse aggregate

Natural and recycled aggregate are used in this work. The natural one was brought from the Al-Nibaai site with a max size of 14 mm. The gravel has been passed through a sieve at a size of 14 mm. Gradation of coarse aggregate was satisfied according to Iraqi specification number 45/1984, which is the requirement for Zone [8] illustrates the physical properties and grading of the coarse aggregate.

Table 4. Physical properties and grading of the coarse aggregate.

Grading Results		
Sieve Size (mm)	**Passing %**	**I.Q.S. No.45, 1984 [8]**
20	100	100
14	98.6	90-100
10	55.1	50-85
5	4.95	0-10
Physical Results		
Specific Gravity	2.54	---
Absorption	0.43	---
Sulphate Content %	0.07	≤ 0.1%
Clay Content %	0.48	≤ 2%

Coarse aggregate from recycled concrete was sieved, ensuring the maximum size was not greater than 14 mm, as illustrated in Fig. 1. Table 5 demonstrates the physical characteristics and grading of recycled concrete coarse aggregates.

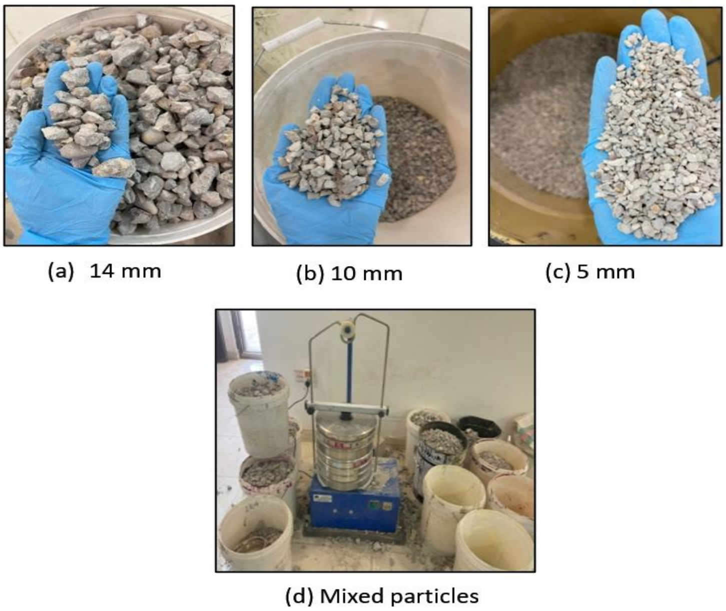

Fig. 1. Recycled concrete coarse aggregate particles passing from sieves; a. 14 mm, b. 10 mm, c. 5 mm, d. mixed particles for a grading test.

Table 5. Coarse aggregate recycled concrete grading results.

Sieve Size (mm)	**Passing %**	**I.Q.S. No.45, 1984**
20	100	100
14	93.8	90-100
10	75.4	50-85
5	6.5	0-10

2.1.4. Recycled steel fiber

Recycled tyre steel fibres were incorporated into the concrete mix for six deep beam specimens. The dimensions of steel fibres are (25 mm) in length and 1.43 mm in diameter. Table 6 summarizes the physical characteristics of recycled tyre steel fibres according to the test report provided by the tensile test, and Fig. 2 shows the adopted recycled steel fibre. The present study shows the magnitude of adding recycled steel fibres (1% and 2%) from the dry weight of the concrete mix.

Table 6. Characteristics of recycled tyre steel fibre steel fibre.

Property	Specification
Tensile Strength	1943 MPa
Average Length	25 mm
Normal Diameter	1.43 mm
Aspect Ratio	17.5

Fig. 2. Recycled steel fibre extracted from end life use tyres.

2.1.5. Steel reinforcement bar

Deep beam specimens were reinforced with 16mm steel bars as longitudinal reinforcements in the tension region. At least three specimens from the steel reinforcement bars used in the beams were tested according to ASTM A615-16 [20] specifications to determine their mechanical properties (yield and ultimate stress). A Tensile test was done in the University of Kufa laboratory, and the results of the test of mechanical properties are presented in Table 7.

Table 7. Mechanical properties of steel bars.

Steel Bar Size (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	ASTM Requirements		
			Grade	Min Yield Strength (MPa)	Min Ultimate Strength (MPa)
16	530	610	60	240	620

2.1.6. Design mix of concrete

Several trial mixes have been performed to verify from getting the appropriate mix that meets the requisite average compressive Strength of three cubes of approximately 36 MPa of the normal concrete (N.C.), as prescribed by ACI 211-91 [21]. The predominant mix design of N.C. by weight was employed in only one of the reference deep beam specimens as a first mix. The component distribution of the four mixes considered in the current study is listed Table 8. Also, some mixtures were mixed by replacing the coarse aggregate with recycled coarse aggregate in three percentages of 20%, 40%, and 60%, and adding recycled steel fibres in some mixtures in two percentages (1% and 2%) of the weight of the dry mixture.

Table 8. Mix the proportion of CB.

Ingredient	Quantity
Cement	450
Fine Aggregate	571
Coarse Aggregate	1148
w/c	0.5

2.2. Experimental work

Details of experimental specimens

Three groups for deep beam specimens were conducted in the present study. The first specimen with normal coarse aggregate was adopted as the control specimen. The first group of specimens had different percentages 20%, 40%, and 60% of recycled concrete as a replacement for coarse aggregate. In the second and third groups, the same ratios of substituted for coarse aggregate in the first group but in addition of recycled steel fibre by 1% in the second group and with a ratio of 2% in the third group.

The deep beam specimens were fabricated and tested using a two-point vertical load bending test. All tested deep beam specimens have an overall length equal to (1400 mm) and a clear distance between applied loads amounted to 1,200 mm. The specimens contain a main longitudinal reinforcement of three steel bars of 16 mm diameter bent on both ends upward to extend along the beam height to the vertical distance of 250 mm. All tested deep beam specimens lack shear reinforcement according to their design, allowing them to fail in shear. Figure 3 illustrates the deep beam specimen dimensions and their reinforcement. Table 9 lists the labelling system for all deep beams tested.

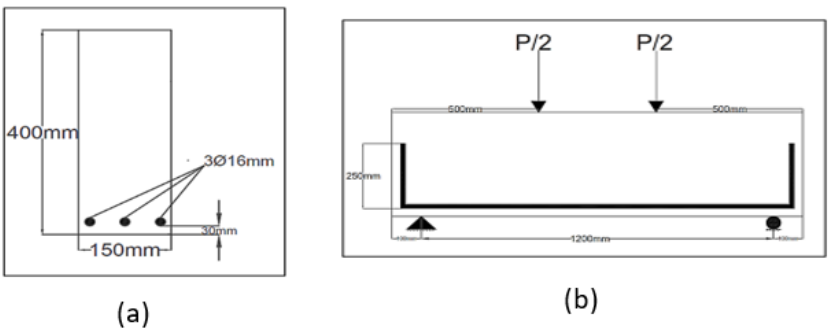

Fig. 3. Specimens' details: a. cross-section, b. side view, and applied load.

Table 9. Labelling of specimens.

Specimens	Description
CB	Control Beam
RA 20%	Recycled Aggregate 20%
RA 40%	Recycled Aggregate 40%
RA 60%	Recycled Aggregate 60%
RA 20% SF 1%	Recycled Aggregate 20% and Recycled steel fibre 1%
RA 40% SF 1%	Recycled Aggregate 40% and Recycled steel fibre 1%
RA 60% SF 1%	Recycled Aggregate 60% and Recycled steel fibre 1%
RA 20% SF 2%	Recycled Aggregate 20% and Recycled steel fibre 2%
RA 40% SF 2%	Recycled Aggregate 40% and Recycled steel fibre 2%
RA 60% SF 2%	Recycled Aggregate 60% and Recycled steel fibre 2%

2.3. Test setup

Once the deep beams had finished the curing process, the beams were transferred to Al-Kufa University structural laboratory to undergo testing in a state of static load. The load was subjected to steel-bearing plates to transform into concrete beams to obviate local failures. Before the experimental test, beams have been painted white with paint that had been emulsified so that the cracks turned out to be visible. Linear variable differential transformer was placed on the lower face of the beam for the mid-extent of the specimen to record the deflection at this location. The deep beam specimens were tested with accredited electrohydraulic apparatus having a peak capacity of two thousand kN, as clarified in Fig. 4.

Fig. 4. Deep beam specimen under test machine.

3. Results and Discussion

3.1. Harding concrete properties results

The compressive strength test describes the features of concrete strength and the inherent importance of the compressive strength of concrete in structural design, as well as the tensile and flexural strength test. This test was obtained by averaging three specimens cast for each concrete mix and testing them at the same age as the beams. The results are presented in Table 10. The best properties are obtained in the concrete specimen with 20% RA+2% steel fibre, where it showed the highest splitting tensile stress, f_r, with value of 9.25, Modulus of Rupture, f_t, with value of 3.95, and Cube compressive strength, f_{cu} with value of 36.3.

Table 10. Harding concrete properties results.

Mix	Cube compressive strength of concrete, f_{cu} (MPa)	Modulus of Rupture, f_t (MPa)	Splitting tensile strength, f_r (MPa)
CB	36.7	2.76	8.73
RA 20%	34.7	2.65	8.15
RA 40%	31.4	2.59	7.66
RA 60%	30.8	2.47	7.25
RA 20% SF 1%	35.4	3.47	9.06
RA 40% SF 1%	32.6	3.12	7.93
RA 60% SF 1%	31.9	3.06	7.86
RA 20% SF 2%	36.3	3.95	9.25
RA 40% SF 2%	33.4	3.26	8.36
RA 60% SF 2%	33	3.19	8.06

3.2. Deep beams experimental results

The results relate to specimens that contain different percentages of recycled aggregate of 20%, 40%, and 60%, with the addition of recycled steel fibres in two percentages of 1% and 2% from the weight of the dry mixture. Table. 11 shows the results of the tested specimens.

Table 11. Result of tested specimens.

Specimens	First crack load (kN)	Service Deflection (mm)	%	Ultimate load (kN)	%	Ultimate deflection (mm)	%
CB	140	3.88	---	425	---	6.18	---
RA 20%	150	3.74	3.6	380	10.6	5.51	10.8
RA 40%	140	3.61	7	370	12.9	5.43	12.1
RA 60%	150	3.62	6.7	365	14.1	5.19	16
RA 20% SF 1%	140	4.12	6.2	420	1.2	6.06	1.9
RA 40%-SF 1%	140	3.9	≈ 0	400	5.9	5.6	9.4
RA 60%-SF 1%	140	3.78	2.6	385	11.3	5.44	12
RA 20%-SF 2%	150	4.35	12.1	430	1.2	6.46	4.5
RA 40%-SF 2%	150	4.09	5.4	410	3.5	5.97	3.4
RA 60%-SF 2%	140	3.71	4.4	395	3.5	5.7	7.8

3.3. Deep beams with 1% recycled steel fiber

Figure 5 illustrates the load versus deflection curve for specimens with RA 20% and RA 20%-SF 1% samples compared to the CB specimen. The first shear crack occurred at 140 kN of load and 2.59 mm of deflection for the RA 20%-SF 1% specimen, while the ultimate load reached 420 kN with an ultimate deflection of 6.06 mm.

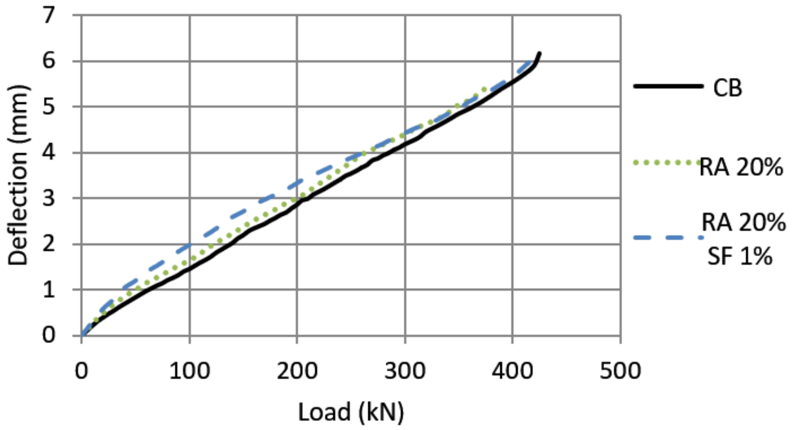

Fig. 5. Results of load vs. deflection comparison between C.B. and R.A. 20% SF1%

The load versus deflection curve results for R.A. 40%-SF 1% and R.A. 40% specimens compared with C.B. The first shear crack appeared with 140 kN load and a deflection of 2.2 mm, while the ultimate load reached 400 kN with a maximum deflection of 5.6 mm for the RA40%-SF 1% specimen, with a reduction of 5.9 % for ultimate load and 9.4% for maximum deflection compared to the CB. sample. Figure 6 illustrates the load versus deflection curve for specimens with R.A. 40% and R.A. 40%-SF 1% samples compared to the CB specimen.

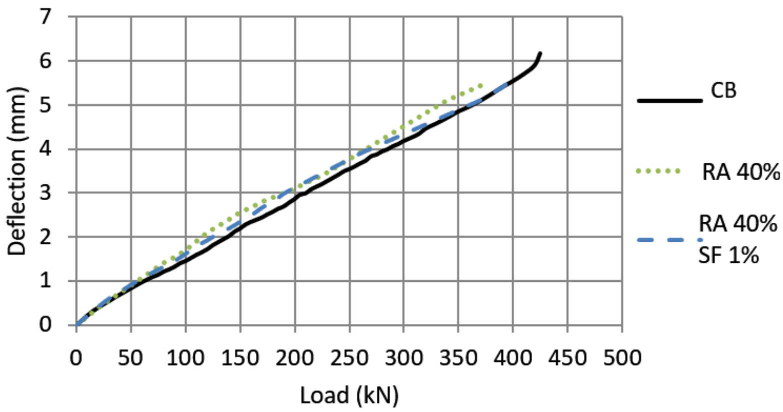

Fig. 6. Results of load vs. deflection comparison between CB, RA 40%, RA 40%-SF1%.

Figure 7 shows the results of the load versus deflection curve for RA 60% and RA 60%-SF 1% specimens compared to the CB specimen. The first shear crack was recorded as 140 kN with a deflection of 2.3 6mm, while the ultimate load reached 385 kN with a deflection of 5.44 mm for RA 60%-SF 1%. The reduction percentage in the failure load reached 11.3% less than CB, but it is still better than RA 20% specimen.

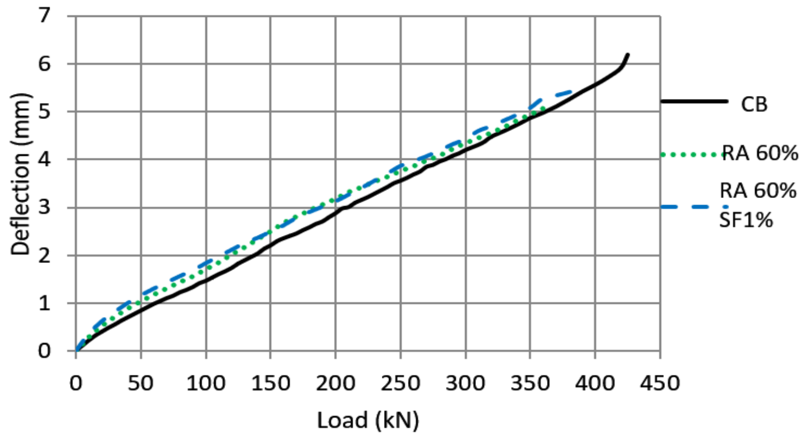

Fig. 7. Results of load vs. deflection comparison between CB, RA 60%, and RA60%-SF 1%.

3.4. Deep beams with 2% recycled steel fiber

Figure 8 clarifies the load versus deflection curve for the R.A. 20%-SF 2%, CB, RA 20%, and R.A. 20%-SF1%. The first shear crack appeared with a 150 kN load and a deflection of 2.64 mm, and the ultimate load reached 430 kN with an ultimate deflection of 6.46 mm for the RA 20%-SF 2% specimen, with an enhancement percentage of 1.2 % for load and 4.5% for deflection more than that found in the CB specimen.

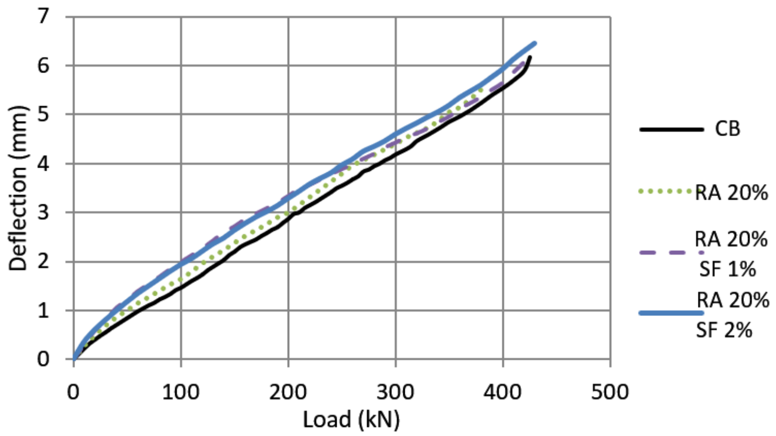

Fig. 8. Load vs. deflection comparison between CB, RA 20%, RA.20% -SF 1%, and RA20%-SF 2%.

Figure 9 illustrates the load versus deflection curve for the CB, RA 40%-SF 2%, RA 40%, and R.A. 40%-SF 1% specimens. The first shear crack occurred with a 150 kN load and 2.53 mm of deflection, while the ultimate load reached 410 kN with an ultimate deflection of 5.97 mm for the R.A. 40%-SF 2% specimen.

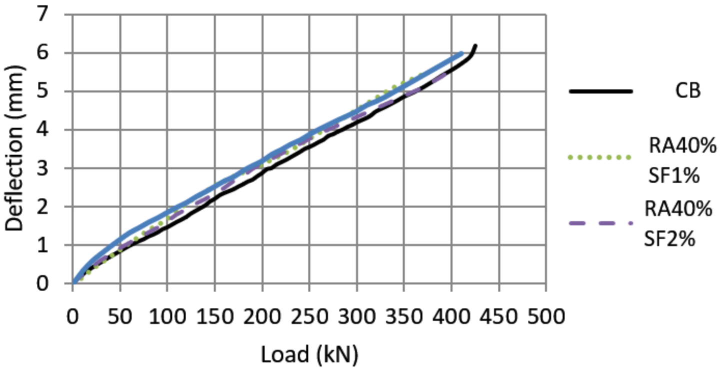

Fig. 9. Load vs. deflection comparison between CB, RA 40%, RA40%-SF 1%, and RA40%-SF 2%.

The results of the load versus deflection curve for RA 60%-SF 2%, CB, RA 60%, and RA 60%-SF 1% specimens are demonstrated in Fig. 10. The first shear appeared with a 150 kN load and a deflection of 2.27 mm, and the ultimate load reached 395 kN with an ultimate deflection of 5.52 mm for the RA. 60%-SF 2% specimen. In the future the structural member made of recycled concrete can be strengthened by adding CFPR [22].

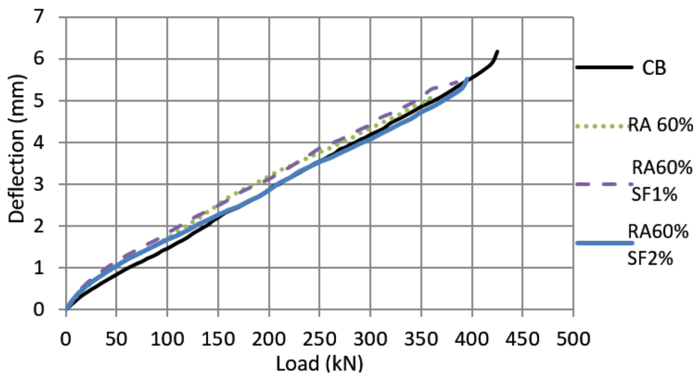

Fig. 10. Load vs. deflection comparison between CB, RA 60%, RA 60%-SF 1%, and RA 60%-SF 2%.

4. Conclusion

This work investigated the characteristics of a material for sustainable construction using recycled aggregate and waste tyres steel fibre as additives to the cement concrete. Based on experimental test of 10 reinforced concrete deep beams made of normal aggregate, recycled aggregate, recycled aggregate with recycled steel fibre, the following was concluded.

- Concrete made from recycled steel fibres has higher compressive, tensile, and flexural strength than concrete made without recycled steel fibres since the fibres make concrete harder and increase the material's ductility.
- The best sample of deep beam is RA 20% SF 2% which processed load failure higher than the control sample by 1.2.

- The load-to-deflection curves for deep beam specimens exhibited a linear pattern in all instances. The arching action and high stiffness also contribute to this linearity. Additionally, the geometric properties reduce complex bending effects, ensuring a proportional relationship between load and deflection.

Nomenclatures

Symbols

f_{cu}	Cube compressive strength of concrete, MPa
f_r	Flexural strength of concrete (modulus of rupture), MPa
f_t	Tensile strength (splitting tensile strength), MPa

Abbreviations

CB	Control Deep Beam
FRC	Fibre-reinforced concrete
ISF	Industrial steel fibre
RA	Recycled aggregate
RSF	Recycled steel fibres
RTSF	Recycled-tyre steel fibre
SF	Steel fibre
VF	Volume fraction

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