Jilin Daxue Xuebao (Gongxueban)/Journal of Jilin University (Engineering and Technology Edition)
ISSN: 1671-5497
E-Publication: Online Open Access
Vol: 42 Issue: 10-2023
DOI: 10.5281/zenodo.10052476

FLEXURAL BEHAVIOR OF TWO-LAYER BEAM MADE WITH LIGHT WEIGHT STEEL FIBRE CONCRETE AND RECYCLED AGGREGATE CONCRETE

WADHAH M. TAWFEEQ
Faculty of Engineering, Sohar University, 311 Sohar, Oman.

AHMED W. AL ZAND
Department of Civil Engineering, Universiti Kebangsaan Malaysia (UKM), Bangi 43600, Malaysia.

MALEK AL-RUSHDI
Faculty of Engineering, Sohar University, 311 Sohar, Oman.

SALEH MAZEN
Faculty of Engineering, Sohar University, 311 Sohar, Oman.

ABDUL AZIZ AL-BADI
Faculty of Engineering, Sohar University, 311 Sohar, Oman.

HAMDAN AL JABRI
Faculty of Engineering, Sohar University, 311 Sohar, Oman.

Abstract

In structural design, it is extremely desirable to use as low-material as possible while keeping integrity and usefulness. Reducing the structure's weight is one strategy for achieving this objective. Steel fibres have recently been added to reinforced concrete beams to increase flexural and shear strength. Fibre reinforcement in structural elements has drawn considerable interest from the building sector. Steel fibre has received the greatest attention and utilization among all fibre types. When compared to plain concrete, incorporating fibres into concrete may result in better crack management and greater strength. This study examines how two-layer beams made of lightweight steel fibre concrete and recycled aggregate concrete flex under bending loads. Twelve distinct beams with cross sections measuring 100 mm, 150 mm, and 1500 mm (width, depth, and length) are prepared and tested as part of the study. These beams are evaluated under four-point bending. In the tension zone of the lightweight concrete layer, different percentages of steel fibre ranging from 0% to 1.5% by volume were introduced. In the concrete compression layer, recycled block aggregate was substituted for natural coarse aggregate in varying percentages (0%, 25%, and 50%). According to the findings, the flexural strength of beams with a higher steel fibre percentage is higher than that of beams with a higher recycled aggregate component. The study also shows that two-layer beams with higher steel fibre content have superior crack management and deflection behavior than those with lower steel content. The results of the flexural reinforced concrete beam test were contrasted with the calculated design strength determined using British Standards.

Keywords: Light-Weight Concrete, Flexural, Recycled Aggregate, Two-Layer Beam, Displacement, Fiber.

1. INTRODUCTION

The use of sustainable and durable construction materials is crucial in the world of civil engineering and construction. In recent years, new materials have become available that offer superior structural performance and environmental sustainability, such as lightweight steel fibre concrete (LSFC) and recycled aggregate concrete (RAC) [1–3]. Due

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to the amalgamation of the benefits of these materials, the two-layer beam exhibits impressive flexural behavior [4,5]. Recycled aggregate concrete and lightweight steel fibre concrete. As a general rule, LSFCs incorporate steel fibres into a lightweight concrete matrix to improve the composite's mechanical properties [6,7]. By adding steel fibers to concrete, cracking resistance and flexural strength are improved. As an added benefit, LSFC has a lower density than traditional concrete, which reduces dead loads on structures. In addition, the RAC contributes to the environmental sustainability of the construction industry [8]. RAC uses recycled aggregates derived from construction and demolition waste, thereby reducing the demand for natural resources and mitigating the environmental impacts of waste disposal. Additionally, RAC demonstrates a commendable level of strength and durability.

The composite two-layer beam made from LSFC and RAC displays distinct flexural behavior due to the unique properties of each layer. The top layer, composed of RAC, as the top surface of a beam is subjected to compressive stresses when the beam is loaded. While the LSFC is sufficient to be placed at the lower-half of the beam, since the steel fibres in the LSFC layer significantly increase the cracking resistance and carrying high tensile strength [9]. The composite two-layer beam's flexural behavior is significantly affected by the interlayer bond strength. Strong interlayer bonding is crucial to ensure composite action between the layers under flexural load. If the bond is weak, the layers may act independently, undermining the structural advantages of the composite beam. In addition to the structural benefits, the two-layer beam made from LSFC and RAC is highly durable and environmentally friendly [10–12]. The use of RAC promotes the recycling of construction waste, reducing the environmental footprint of construction activities.

Accordingly, the action of beams composed of two layers of different materials has been the subject of considerable research over the last few years [13–18]. In addition, the flexural performance of the RC beams that made from normal concrete and lightweight concrete had been compared by Al-Farttoosi et al [19]. Where the bending strength was decreased of about 0.13%, 0.44%, 3.4%, and 8.65% with increases of light weight aggregate content in the layer located at the tension zone from 25%, 50%, 75%, and 100%, respectively. The bending strength of the lightweight aggregate concrete beams reinforced with glass fibre bars with varied contained of steel bars had been experimentally investigated by Wu et al. [16]. Where it was proven that using LSFC was shown to be effective in enhancing the deflection and crack width of GFRP-reinforced beams at low load levels.

Based on the above literature, the discussed composite beams remain limited despite their tremendous potential. The presented researches had been mainly focused on a continuous two-layer beam with two-layer containing high-strength concrete with steel fibre in the compression zone. While adopting the recycled concrete at the compression zone and the lightweight concrete strengthened with steel fibre at the tension zone (bottom-half of the beam’s cross-section) has still very limited researches. Based on that, in this study, coarse aggregate in compression zone was replaced by recycled concrete block (with a weight change, ranging from 0% to 50%) to save the natural aggregate and

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to protect the environment. While steel fibre was added to lightweight concrete in tension zone (0% to 1.5%) to improve the tensile strength of lightweight concrete.

2. Experimental Program

The study involved casting twelve beams in two layers. After casting the first layer, the second layer was cast after 24 hours. During the load application and beam bending, the shear steel reinforcement prevented the two layers from sliding. Lightweight concrete was used in the first layer, which is allocated in the tension zone, with different addition percentages of steel fiber ranging from 0% to 1.5%. The proportions of the trial mix for the tension zone are shown in Table 1. For the second layer in the compression zone, normal concrete was used with varying replacement percentages of coarse aggregate ranging from 0% to 50%. Compression zone proportions are shown in Tables 2. Table 3 shows the list of tested beams and their designation names.

Table 1: Trial Mix Proportions for the Tension Zone

Beam No	Cement (kg)	Sand (kg)	Poly (kg)	SF (kg)	Water (L)	SF % (by volume)
B1	10.4	26.74	0.67	0	13.0	0
B2	10.4	26.74	0.67	0	13.0	0
B3	10.4	26.74	0.67	0	13.0	0
B4	10.4	26.74	0.67	2.76	13.0	0.5
B5	10.4	26.74	0.67	2.76	13.0	0.5
B6	10.4	26.74	0.67	2.76	13.0	0.5
B7	10.4	26.74	0.67	5.52	13.0	1.0
B8	10.4	26.74	0.67	5.52	13.0	1.0
B9	10.4	26.74	0.67	5.52	13.0	1.0
B10	10.4	26.74	0.67	8.28	13.0	1.5
B11	10.4	26.74	0.67	8.28	13.0	1.5
B12	10.4	26.74	0.67	8.28	13.0	1.5

Table 2: Trial Mix Proportions for the Compression Zone

Beam No	Cement (kg)	Sand (kg)	Aggregate 10 mm (kg)	RA 10 mm (kg)	Aggregate 20 mm (kg)	RA 20 mm (kg)	Water (L)	Replacement Percentage (by weight)
B1	10.4	34.4	14.2	0	24.8	0	5.8	0 %
B2	10.4	34.4	10.66	3.55	18.6	6.2	5.8	25%
B3	10.4	34.4	7.1	7.1	12.4	12.4	5.8	50%
B4	10.4	34.4	14.2	0	24.8	0	5.8	0 %
B5	10.4	34.4	10.66	3.55	18.6	6.2	5.8	25%
B6	10.4	34.4	7.1	7.1	12.4	12.4	5.8	50%
B7	10.4	34.4	14.2	0	24.8	0	5.8	0 %
B8	10.4	34.4	10.66	3.55	18.6	6.2	5.8	25%
B9	10.4	34.4	7.1	7.1	12.4	12.4	5.8	50%
B10	10.4	34.4	14.2	0	24.8	0	5.8	0 %
B11	10.4	34.4	10.66	3.55	18.6	6.2	5.8	25%
B12	10.4	34.4	7.1	7.1	12.4	12.4	5.8	50%

Table 3: List of Tested Beams and Their Designation Names

Beam No.	Beam Designation*	Zone	Description
B1	LWC-0%-SF	Compression	Normal concrete with 0% recycled aggregate
	NC-0%-RA	Tension	Light-weight concrete with 0% steel fiber
B2	LWC-0%-SF	Compression	Normal concrete with 25% recycled aggregate
	NC-25%-RA	Tension	Light-weight concrete with 0% steel fiber
B3	LWC-0%-SF	Compression	Normal concrete with 50% recycled aggregate
	NC-50%-RA	Tension	Light-weight concrete with 0% steel fiber
B4	LWC-0.5%-SF	Compression	Normal concrete with 0% recycled aggregate
	NC-0%-RA	Tension	Light-weight concrete with 0.5% steel fiber
B5	LWC-0.5%-SF	Compression	Normal concrete with 25% recycled aggregate
	NC-25%-RA	Tension	Light-weight concrete with 0.5% steel fiber
B6	LWC-0.5%-SF	Compression	Normal concrete with 50% recycled aggregate
	NC-50%-RA	Tension	Light-weight concrete with 0.5% steel fiber
B7	LWC-1.0%-SF	Compression	Normal concrete with 0% recycled aggregate
	NC-0%-RA	Tension	Light-weight concrete with 1.0% steel fiber
B8	LWC-1.0%-SF	Compression	Normal concrete with 25% recycled aggregate
	NC-25%-RA	Tension	Light-weight concrete with 1.0% steel fiber
B9	LWC-1.0%-SF	Compression	Normal concrete with 50% recycled aggregate
	NC-50%-RA	Tension	Light-weight concrete with 1.0% steel fiber
B10	LWC-1.5%-SF	Compression	Normal concrete with 0% recycled aggregate
	NC-0%-RA	Tension	Light-weight concrete with 1.5% steel fiber
B11	LWC-1.5%-SF	Compression	Normal concrete with 25% recycled aggregate
	NC-25%-RA	Tension	Light-weight concrete with 1.5% steel fiber
B12	LWC-1.5%-SF	Compression	Normal concrete with 50% recycled aggregate
	NC-50%-RA	Tension	Light-weight concrete with 1.5% steel fiber

* LWC: Light-Weight Concrete

SF: Steel Fiber

NC: Normal Concrete

RA: Recycled Aggregate

This project used a beam with a span of 1500 mm. The cross-section had a height of 150 mm and a width of 100 mm. concrete crushing can be prevented by ensuring that the ultimate moment of the beam is equal to or less than the ultimate moment of the steel reinforcement [20-22]. Two steel reinforcement bars of 8 mm diameter with 460 MPa yield strength were used as reinforcement providing 101 mm^2 in the tension zone. To prevent any shear failure, 6 mm diameter stirrups were placed at 150 mm intervals along the entire beam length. Stirrups were mounted on two hanger bars of 6 mm. The beam utilized is shown in detail in Figure 1.

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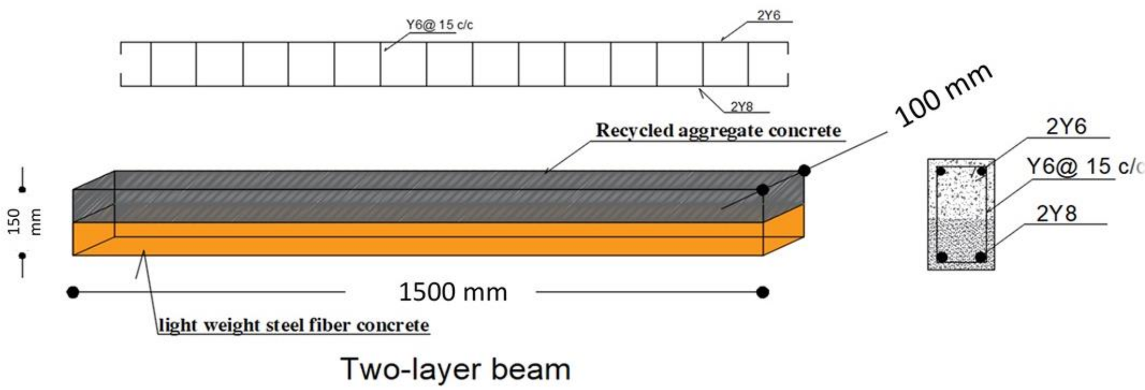

Figure 1: Beam Details

During the testing process, all beams were simply supported, and two-point loads were applied to the middle third of the beams, as shown in Figure 2. Loads were applied by a hydraulic press machine to rigid beams, where the load was applied as a two-point load. Load measurements and data were recorded on computers using a load cell. In addition, an electronic dial gauge was used to measure the vertical displacement at the middle of the beam's span.

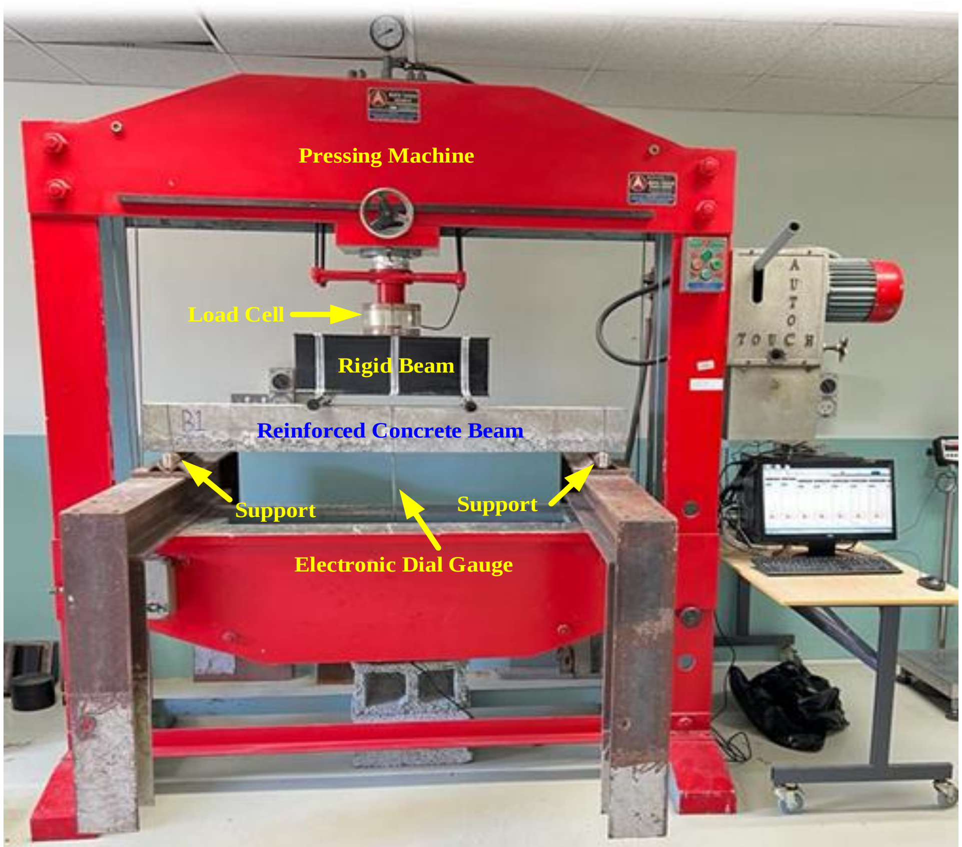

Figure 2: Setting up the Beam for Testing

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3. MATERIALS

3.1 Cement

In this study, an ordinary Portland cement from UAE was used. Al-Fujairah-OPC Type (I) adheres to the standards set in BS EN 197-1:2000 [23].

3.2 Fine Aggregate

Natural sand, completely washed, was provided by an Omani crusher from the Wilayat of Suhar. According to BS 882:1992 [24], fine aggregate grades are tested as shown in Figure 3. This study used fine aggregates according to BS EN 993-1:1997 [25]. According to BS 812-2:1995 [26] and BS EN 1097-3:1998 [27], the water absorption capacity of the sand being used is 2%. The clay content in the utilized sand is below 3% and measures approximately 2%.

3.3 Coarse Aggregate

In this research, locally crushed natural aggregates with 20 mm and 10 mm size from the Wilayat of Suhar, Oman were employed. The coarse aggregate underwent sieve analyses in accordance with BS 882:1992 [24]. To assess the grade of the utilized gravel, the methodology outlined in reference [25] was utilized, and the results are illustrated in Figures 4 & 5. The experimental investigation indicated that the water absorption capacity and specific gravity of the gravel were found to be 1.5% and 2.6 respectively.

3.4 Recycled Aggregate (RA)

To achieve the same size as natural coarse aggregate, crushed blocks were crushed again to reach a size of 20 mm and 10 mm. For crushing, a jaw crusher was used, as shown in Figure 6. A sieve was used after crushing the RA in order to comply with BS 882:1992 [24]. A sieve analysis result for RA is shown in the Figures 4 & 5. Experimental results indicated that the RA had a water absorption capacity of 4.5% and a specific gravity of 2.4.

3.5 Water

Drinking water was used for mixing and curing of concrete cubes and beams.

3.6 Steel Fiber (SF)

The SF used was made in Oman, with dimensions of 30 mm in length and 1 mm in diameter (see Figure 7). This material has an ultimate tensile strength of 370-500 MPa, a yield tensile strength of 235 MPa, and a density of 7840 kg/m^3.

3.7 Polystyrene (Poly)

During this study, polystyrene round shapes with diameters of 1.5 to 3 mm were used (see Figure 8). The styrene monomer is used in the manufacture of polystyrene, also known as Styrofoam. In terms of material, polystyrene is a lightweight (95% air) and rigid cellular foam. Moisture resistance, corrosion resistance, and resistance to mildew and rot are all excellent characteristics of polystyrene [28, 29].

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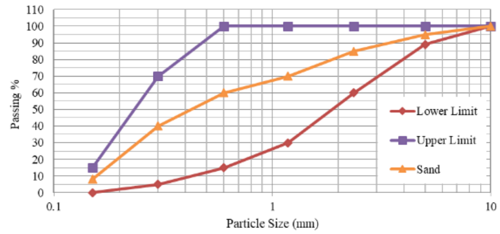

Figure 3: Grading Of Fine Aggregate

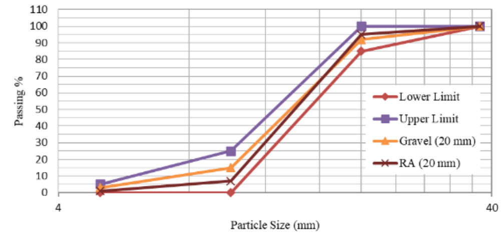

Figure 4: Grading Of Coarse Aggregate (20 Mm)

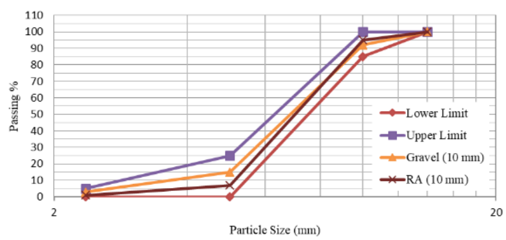

Figure 5: Grading of coarse aggregate (10 mm)

Figure 6: Jaw Crusher

Figure 7: Steel Fiber

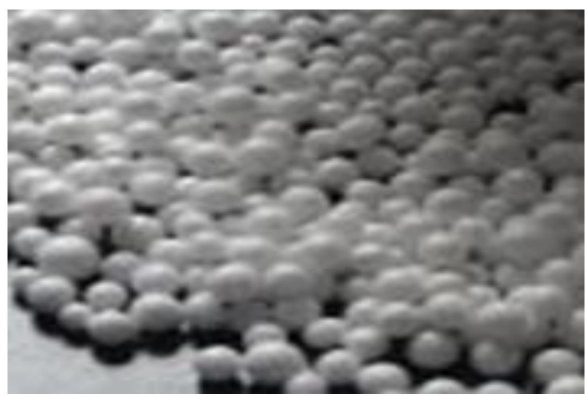

Figure 8: Polystrene

4. RESULTS AND DISCUSSION

4.1 Compressive Strength and Weight

The concrete's compressive strength was measured according to BS EN 12390-3 [30] with cubes size of 150 × 150 × 150 mm. The compression tests were conducted with an ADR-Auto 2000 compression machine with a 2000 kN capacity and a 13.5 kN/sec load rate. For each trial mix, three cubes were measured for their average compressive strength after 28 days. The compressive strength of concrete used in the compression

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zone ranged from 44.5 MPa when the trial mix had 0% RA to 32.5 MPa when the mix had 50% RA. Due to the use of RA, the compressive strength has been reduced. RA is obtained from demolished concrete structures that may have already degraded and worn over time. Because of this, RA is generally weaker than natural aggregates in terms of mechanical properties. Natural aggregates tend to have a lower porosity than RA. Increasing porosity reduces the density of concrete and reduces its strength due to more voids within the aggregates. There are possible contaminants in RA, such as mortar residues or other construction debris. As a result, these contaminants can negatively affect cement paste-aggregate bonding, reducing concrete strength. When compared to natural aggregates, RA often has a higher water absorption capacity. The higher water absorption can increase the amount of water needed during mixing, altering the water-cement ratio and reducing concrete strength. As a result of their irregular shapes and surface textures, RA may not compact as well as natural aggregates, resulting in voids in concrete.

Figure 9 shows that using 25% RA reduced the concrete compressive strength by 13.5% whereas using 50% RA reduced it by 27%. Other researchers have also reported reduced compressive strength [21, 31, 32]. Considering the environment when designing concrete mixes and implementing quality control measures, using recycled aggregates can provide an environmentally friendly approach while maintaining the desired strength and durability of the concrete.

In terms of weight, the average weight of three concrete cubes with 0% RA is about 8.67 kg. Using 25% RA reduces concrete cube weight by about 1.6% while using 50% RA reduces it by about 2.4%. See Figure 9. Different types of aggregate have different specific gravity, which results in a weight reduction. RA's specific gravity is less than the natural aggregate's.

The compressive strength of lightweight concrete can be improved by adding SF in tension zones. After 28 days of curing, the average compressive strength of three cubes of lightweight concrete without SF was 2.5 MPa. Figure 10 shows that adding 0.5%, 1.0%, and 1.5% SF by volume increases the compressive strength of lightweight concrete by 1.68, 2.32, and 3 times, respectively. Concrete's compressive strength can be improved by adding SF. The ability of SF to enhance concrete's post-crack performance is one of its significant advantages. Concrete cracks when subjected to tensile stress. These cracks, however, can be bridged by SF, preventing them from propagating. As a result of this bridging action, concrete's strength is improved even after cracking. Concrete cracks can be reduced in width by adding SF. In turn, smaller crack widths lead to better load distribution and improved load-carrying capacity, resulting in higher compressive strength. Previous studies [2] have reported an increase in the compressive strength of lightweight concrete with the addition of SF.

Lightweight concrete is used in tension zones of beams to reduce their weight. Three lightweight concrete cubes weighed an average of 3.23 kg. Based on Figure 10, adding SF to lightweight concrete results in a slight increase in weight for the cube samples. By adding 0.5%, 1%, and 1.5% of SF to lightweight concrete, the weight increases by 11.2%,

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24.8%, and 37.2%, respectively. SF increases the weight of lightweight concrete. This is due to the fiber's high specific of gravity [2].

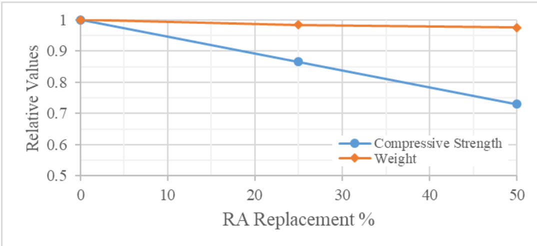

Figure 9: Concrete properties at different replacement percentages of RA

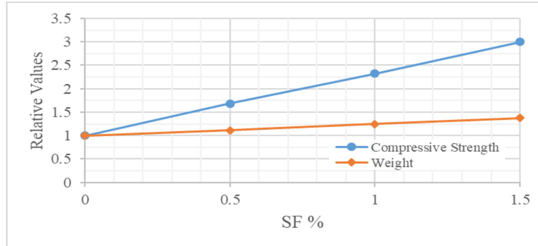

Figure 10: Concrete properties at different percentages of SF

4.2 Flexural behavior of two-layer Beam

Using twelve two-layer reinforced concrete beams, the flexural behavior of these beams was investigated. In order to measure the load, we manually applied the load over the beam and recorded the result on the computer. Beams behave linearly until they develop their first crack. Figures 11 & 12 show that the displacement increased dramatically after that. There was a noticeable expansion of the cracks until there was a complete disappointment. There are cracks observed near the midpoint of a beam, throughout its depth, and at its greatest flexural moment. A comparison of the effects of SF in lightweight concrete in the tension zone and RA replacement percentages in the compression zone is shown in Figure 11.

By adding the SF, the two-layer beams perform better. It can be seen from Table 4 that both the ultimate experimental load and ultimate experimental moment have improved. A comparison of the ultimate experimental load to the theoretical value derived from BS8110 [33] was also conducted. The measured maximum load exceeded the theoretical value by approximately 20%. This outcome was attributed to the beam's composition, which consisted of two distinct layers with varying properties. One layer was composed of normal concrete, while the other layer utilized lightweight concrete. Additionally, RA was observed in the compression zone of the concrete, and SF was incorporated into the lightweight concrete within the tension zone.

Plain lightweight concrete exhibits lower flexural strength compared to normal-weight concrete with the same compressive strength. However, when fibers are added to lightweight concrete, its flexural strength is enhanced. The rationale behind this improvement lies in the behavior of the fibers after matrix cracking occurs. The fibers effectively bear the load that the concrete carried before cracking due to the strong interfacial bond between the fibers and the matrix. Consequently, the fibers impede the propagation of cracks and exhibit a gradual failure, leading to an increased load-carrying capacity [2].

Traditional reinforced concrete beams tend to exhibit a brittle behavior once the first crack appears, which can be problematic, especially if the structure must support additional loads after cracking. However, the addition of steel fibers improves the post-crack

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behavior of concrete by effectively bridging the cracks, enabling the beam to carry higher loads even after cracking. Steel fibers contribute to enhancing the overall toughness of the concrete beam and facilitate a more uniform distribution of applied loads, resulting in a more efficient load-carrying capacity.

In Figure 12, the effect of replacing different percentages of natural aggregate with RA - at levels of 0%, 25%, and 50% - along with varying percentages of added SF - at levels of 0%, 0.5%, 1%, and 1.5% - on the flexural behavior of two-layer beams is demonstrated. Replacing natural aggregate with recycled aggregate from used blocks leads to a decrease in the compressive strength of the concrete, which in turn affects the ultimate load the beam can withstand. By incorporating steel fibers into the tension zone of lightweight concrete, it effectively offsets the reduction in compressive strength experienced in the compression zone. This inclusion of steel fibers empowers the beam to withstand higher loads, despite the challenges posed by the reduced compressive strength in the compression zone.

Analyzing Table 4 and Figure 12, it becomes apparent that an increase in the replacement percentage results in a decrease in the flexural behavior of the two-layer beam. In all tested beams, the failure mode observed was flexural failure, and the main cracks were predominantly located in the middle third of the beams, as depicted in Figure 13.

Table 4: Trial Mixes' Test Outcomes

Beam No.	Ultimate Experimental Load (P_{EX}) [kN]	Ultimate Theo. Load (P_{TH}) [kN]	Yield Stress (Steel Bar) [MPa]	P_{EX} / P_{TH}	Deflection of Beam at Ultimate Load [mm]	Exp. Ultimate Moment [kN.m]
B1	11.20	10.00	460	1.12	4.04	2.52
B2	10.00	8.65	460	1.16	4.80	2.25
B3	8.00	7.30	460	1.10	4.99	1.80
B4	12.00	10.00	460	1.20	4.40	2.70
B5	10.50	8.65	460	1.21	4.70	2.36
B6	8.80	7.30	460	1.21	4.70	1.98
B7	13.50	10.00	460	1.35	3.96	3.04
B8	11.60	8.65	460	1.34	4.30	2.61
B9	9.10	7.30	460	1.25	4.60	2.05
B10	14.00	10.00	460	1.40	3.55	3.15
B11	12.20	8.65	460	1.41	4.20	2.75
B12	10.01	7.30	460	1.37	4.30	2.25

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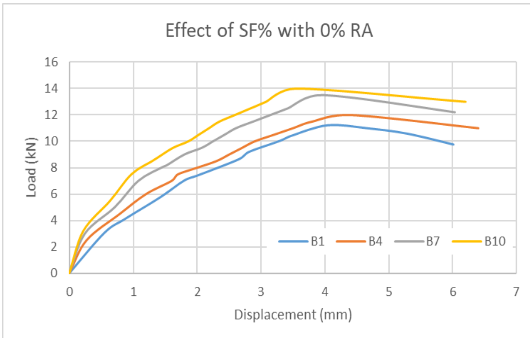
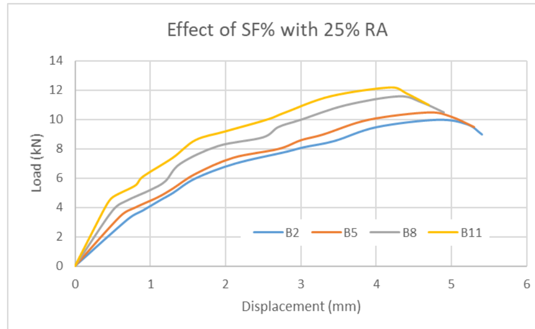
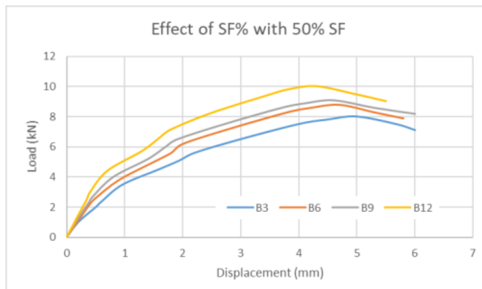


(a) 0% RA

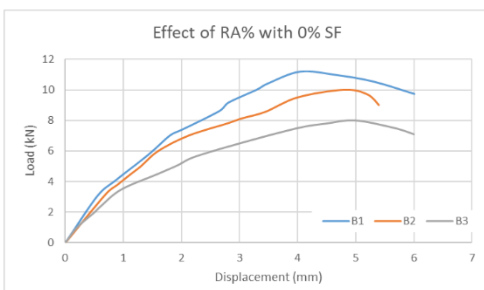


(b) 25% RA

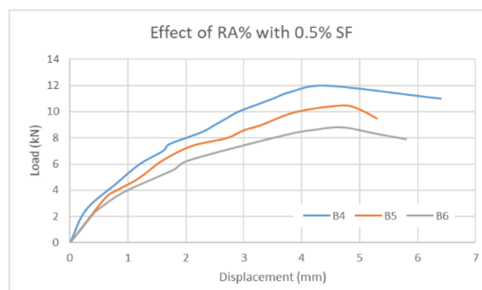


(c) 50% RA

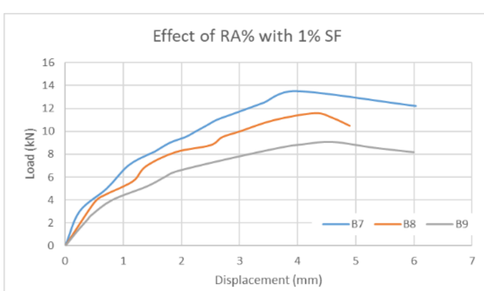
Figure 11: For various SF%, the Load-Displacement at the Mid-Span of the Beam



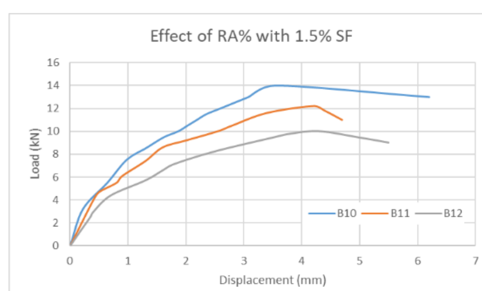
(a) 0% SF



(b) 0.5% SF



(c) 1% SF



(d) 1.5% SF

Figure 12: For various RA%, the Load-Displacement at the Mid-Span of the Beam

Jilin Daxue Xuebao (Gongxueban)/Journal of Jilin University (Engineering and Technology Edition)
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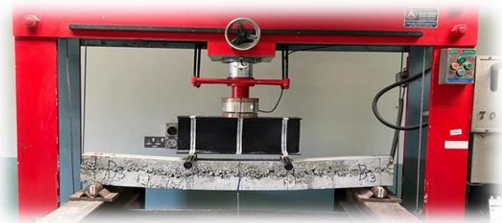
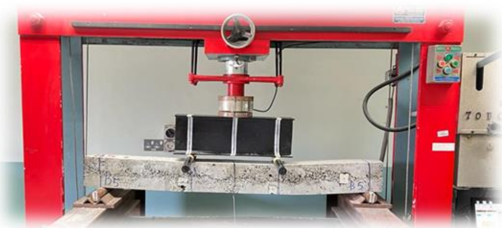
DOI: 10.5281/zenodo.10052476


(a) B1


(b) B2


(c) B3


(d) B4


(e) B5


(f) B6


(g) B7


(h) B8


(i) B9


(j) B10

Jilin Daxue Xuebao (Gongxueban)/Journal of Jilin University (Engineering and Technology Edition)
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(k) B11 (l) B12

Figure 13: Failure Mode of two-layer Reinforced Concrete Beams

5. CONCLUSIONS

This study examined twelve beams cast and tested under four bending points, comparing the failure load to the theoretical value calculated according to BS 8110 [33]. In order to measure the mechanical properties of concrete, material tests were conducted. Summarizing the study's findings, we can draw the following conclusions:

1) As the amount of steel fiber in the concrete mixture increases, its compressive strength tends to increase. The steel fibre increase the compressive strength 27% from the actual value when added 1.5%
2) Using light weight concrete has a significant reduction in the weight of concrete cube more than 50%.
3) Using recycled aggregate reduce the strength of concrete with the increase of replacement percentage. In general, the value of compressive strength was accepted.
4) Adding steel fiber improve the flexural behavior of reinforced concrete beams.

Acknowledgement

It is the authors' sincere gratitude to Sohar University for supporting the project during its implementation. The civil engineering lab technician deserves our appreciation and thanks for her support, assistance, and encouragement.

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