Flexural Behavior of Zero Coarse Aggregate Concrete Beams reinforced with Glass Fibers: An Experimental Comparative Study

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ABSTRACT

In recent decades, engineers have focused on finding solutions to reduce the weight of concrete structures. Undoubtedly, the coarse aggregate weight in concrete is important. This study examined the flexural behavior of zero coarse aggregate concrete with Glass Fiber (GF) added to the steel reinforcement. Also, normal-weight fine aggregate was substituted with autoclaved aerated concrete (Thermostone) by 50% and 75% by weight. The process involved comparison of the test results of two groups. The first group comprised normal reinforcement Lightweight Aggregate Concrete (LWAC), while the second group comprised fiber-reinforced LWAC and a specimen of Lightweight (LW) mortar. Fiber addition boosts energy absorption and slows down the rapid development of crack formation. GFs by 1.5% of concrete weight were added. The results revealed a decrease in the failure load of beams reinforced with GF compared to those reinforced with steel bars. The decrease amounted to 54%, 50%, and 59% for aggregate replacement percentages of 0%, 50%, and 75%, respectively. Replacing steel reinforcement with GF reduced the ultimate load by almost half. All beams with steel reinforcement experienced flexural failure, while the beams with GF reinforcement underwent shear failure.

Keywords-flexural behavior; lightweight aggregate concrete; glass fiber; fiber reinforced concrete; sustainable improvement; thermostone

I. INTRODUCTION

Utilizing Lightweight Concrete (LWC) in construction has contributed to the rapid evolution of progressing states. Engineers' typical objective is to create safe and affordable structures. Furthermore, environmental protection and sustainability are becoming more and more important. Engineers are more obliged than ever to select eco-friendly materials and blend the best resources to enhance their mechanical properties and fire resistance [1-4]. Since LWC has a lower modulus of elasticity, cracks are more likely to form and spread [5-8]. However, improving LWC's mechanical and tensile qualities is now possible with various additives. LWC has been made to function better structurally when using GFs [9, 10]. GFs have high strength, excellent resistance, thermal performance, and good bonding to the matrix [11]. The disadvantages of GFs are water sensitivity and weakness against alkalis in alkaline conditions [12]. However, much more research is still required despite the benefits documented in this field. This is due to the wide range of fiber types and options accessible within each kind, as well as the variety of sources that may provide Lightweight Aggregates (LWAs). No type of fiber can offer complete reinforcement in terms of strength, flexibility, and durability [13]. It has been demonstrated that it is possible to increase a variety of fiber-reinforced concrete qualities by combining different types and sizes of fibers [14]. Also, it has been proven that GFs enhance the strength and durability of concrete while decreasing its flowability. A lack of workability may occur, causing a decrease in concrete mechanical properties when implementing high GF dosages. A dosage of 2% was found to be the best one, especially with a high amount of plasticizer [15]. According to [16], at service load levels, LWC beams with reinforcement ratios of 0.52% and 3.9% satisfied the maximum allowable deflection limitations specified by the BS code. In [17], six under-reinforced beams with a cross-section of 150 mm to 225 mm and various ratios of reinforcing steel were built and analyzed. Specimens with a reinforcement ratio of 1.13% exceeded the maximum deflection limit. In [18], an experimental investigation was conducted to examine the flexural behavior of cement mortars reinforced with hybrid mixtures of Recycled Postconsumer Tire Steel Fibers (RTSF) and Recycled Plastic Fibers (RPF). According to the test results, at 0.5% RTSF and 0.5% RPF by volume, there was a noticeable improvement in the pseudo-strain hardening response and flexural toughness of the mortars studied due to the fiber blends.

II. PRACTICAL APPROACH

The study variables include the type of concrete aggregate, namely normal aggregate or recycled LWA, and the type of reinforcement material in experimentally investigating the flexural behavior of concrete beams made with recycled LWA reinforced by steel bars or GF.

A. Specimens' Morphology

The mix design is based on the ACI code Method III. Seven mixtures were used, including control concrete, with different proportions of LWA, GF, and admixture. The GF and Styrene Butadiene Copolymer (SBR) admixture were added separately, according to the concrete mix design. The Thermostone replaced the fine aggregate by 50% and 75% by weight. All the specimens were free from coarse aggregate.

1) Compressive Strength Testing

Six cube specimens with dimensions of 100 mm × 100 mm × 100 mm were cast for compressive strength testing. At ages of 7 and 28 days, three specimens from each age and from each mixture were tested. Manual mixing was used to pour the cubes. Materials were added in the following sequence with continuous mixing: Cement, Fine Aggregate, Water, Fiber, and SBR (Figure 1).

Fig. 1. Cubic casting operation.

2) Flexural Testing

Two groups of LWAC specimens with dimensions of 1500 mm × 250 mm × 150 mm were considered. Each group consisted of three specimens. The first group was LWAC of 0%, 50%, and 75% replacement ratios of fine aggregate reinforced with normal reinforcement (steel bars). The other was LWAC of 0%, 50%, and 75% replacement ratios of fine aggregate and reinforced with GF by 1.5% of concrete weight. The specimens were cast using wood molds designated for this purpose, as illustrated in Figure 2.

3) Reinforcing Bars

Following a precise design procedure, high-yield strength deformed steel bars complying with ASTM [19] were used for longitudinal and transverse reinforcement, as depicted in Table I. Two 12 mm diameter bars were used as tension reinforcement, while two 8 mm diameter bars were employed as compression reinforcement. Lastly, as seen in Figure 3, 8 mm 2-legged stirrups at 80 mm c/c spacing were deployed as shear reinforcement.

Fig. 2. Wooden mold.

TABLE I. TENSILE TEST OF REINFORCEMENT STEEL BAR

Bar diameter (mm)	Cross section area (mm²)	Fy (MPa)	Fu (MPa)	Total elongation (%)
8	50.3	540	672	12.3
12	113	610	722	11.1

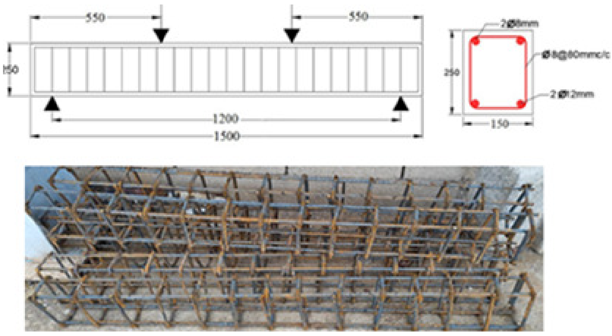

Fig. 3. Beams setup.

4) GFs

A Cem-FIL® 54 Straight Pattern GF was used to reinforce the beams. It is composed of delicate GFs, resembling silk in appearance and texture, which may be several times finer than human hair. Rigid fiber is not as robust as flexible GF. It does not rust, burn, or expand. It is a lightweight and incredibly durable material. The fibers were divided into segments with a length varying from 3 cm to 4 cm, as portrayed in Figure 4.

Fig. 4. The process of cutting GF to the required length.

III. MATERIALS

In this research, locally available materials were used to prepare all the tested specimens. Local ordinary Portland cement was utilized. The cement-test procedure followed the ASTM specifications [20]. Distilled water, free of salts, acids, bases, and organic materials, was employed for mixing, pouring, and curing. Natural river sand from the city of Tikrit with 2.65 specific gravity was used.

A. Lightweight Aggregates

BS EN 206-1 defines LWC as having an oven-dry density of not less than 800 kg/m^3 and not more than 2000 kg/m^3. The LWA utilized in this research was a waste construction material, known as Thermostone [22], originated in northwestern Iraq. It was chosen due to its low cost and availability. In the laboratory, the aggregates' physical characteristics were assessed under the ASTM guidelines [23]. The LWA Thermostone, used as a recycled material, was ground by a grinding machine, and the resulting aggregate passed through a 1.18 mm sieve [24]. The aggregate was moistened and allowed to absorb water for 24 hours to reduce its water absorption. The moistened Thermostone aggregate was dried to obtain the SSD condition. Fibers a rate of 1.5% by concrete weight and SBR additive at a rate of 3% by cement weight were added. Table II lists the quantities of the components needed to prepare one 1 m^3 of concrete.

TABLE II. CONCRETE MIXTURES

Group	Mix ID	Sand (kg/m^3)	Thermo stone (kg/m^3)	Cement (kg/m^3)	W/C Ratio	Glass (% of concrete volume)	SBR (% of cement weight)
No reinforcement	B0	620	0	620	0.4	0	3
Normal reinforced LWAC	N0	620	0	620	0.4	0	3
	N50	310	310	620	0.4	0	3
	N75	150	470	620	0.4	0	3
GF reinforced LWAC	G0	620	0	620	0.4	1.5	3
	G50	310	310	620	0.4	1.5	3
	G75	150	470	620	0.4	1.5	3

IV. RESULTS AND DISCUSSION

All the tests were conducted in the Civil Engineering Department laboratories at the University of Tikrit.

A. Compressive Strength

Concrete is known to resist compressive stresses. Therefore, replacing any of its components should not decrease its basic strength. The compression strength of the different mixtures is depicted in Figure 5.

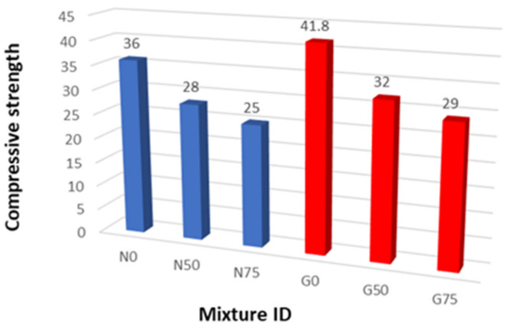

Fig. 5. Specimens' compressive strength.

The results exhibit that when replacing normal aggregate with refractory aggregate results in LWC, its basic strength is lost. With the specific aim of building compressive strength, SBR was added. In the case of normal concrete, the decrease in the compressive strength was about 22.2%, and 30.6% for mixtures containing 50%, and 75% Thermostone, respectively. In the case of GF concrete, the decrease in the compressive strength was about 23.4%, and 30.6% for mixtures containing 50%, and 75% Thermostone, respectively. This decrease is due to the presence of a cellular structure in LWC, unlike normal-weight concrete.

B. Performance of Beams subjected to Flexural Test

Figure 6 shows the specimen testing procedure. The ultimate load of each specimen is displayed in Figure 7.

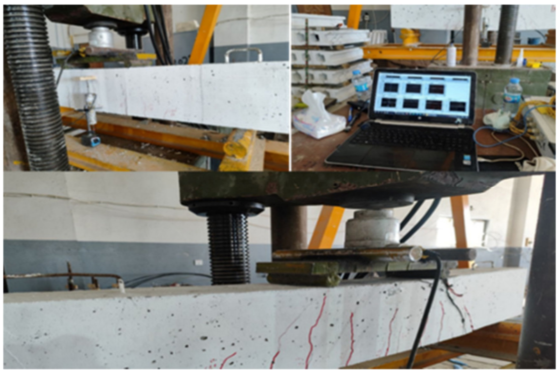

Fig. 6. Flexural test setup.

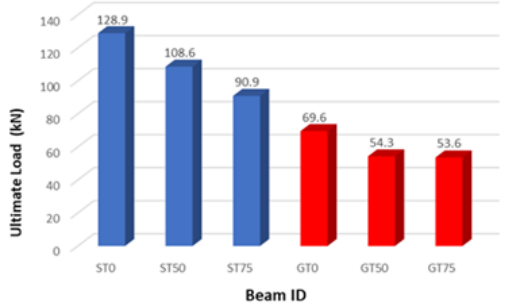

Fig. 7. Ultimate load according to the type of rainforcement.

Figure 7 demonstrates that the failure load of the regular steel reinforcement group decreased by 15.7% and 29.5% for replacement ratios of 50% and 75%, respectively. Considering the GF group, the decrease percentage reached 21.9% and 22.9%, when the replacement ratio was 50% and 75%, respectively. This behavior is caused by the presence of Thermostone, which leads to reduced compressive strength. However, changing the aggregate replacement ratio gave less decrease at a ratio of 75% in the GF group compared to the same ratio in the steel bar group. This means that having increased the Thermostone ratio did not significantly change the decline rates when the reinforcement was GF. There was a decrease in the failure load of beams reinforced with GF compared to those reinforced with steel bars. The decrease amounted to 54%, 50%, and 59% for the aggregate replacement percentages of 0%, 50%, and 75%, respectively, as shown in Figure 8. This means that replacing steel reinforcement with GF reduced the ultimate load by almost half.

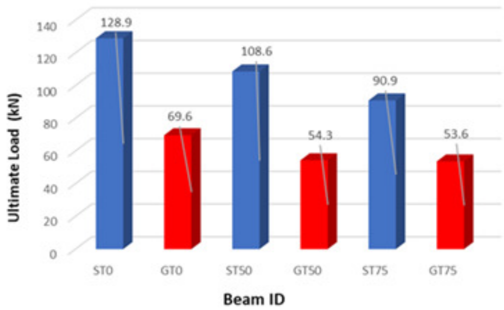

Fig. 8. Ultimate load according to the type of fine aggregate.

C. *Cracking Load*

Figure 8 illustrates the ultimate and cracking loads for each specimen. For the beams with normal steel reinforcement, the cracking load to the ultimate load percentage was about 16%, while for the beams with GF reinforcement, the ratio was 21.2%, because GFs work from the beginning to increase the tensile strength of the concrete, unlike the reinforcing steel, which starts working after cracking occurs. That is, GFs improve the resistance of concrete to cracking.

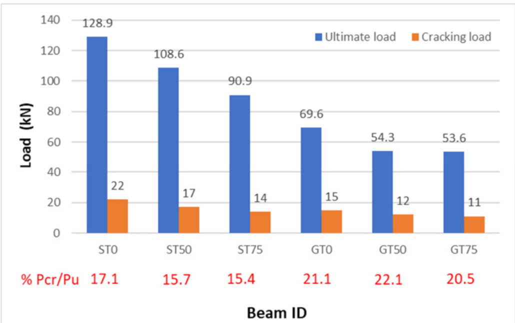

Fig. 9. Ultimate and cracking load.

D. *Deformability of the Beams*

The term deformability can be used to describe a member's deflection, rotation, or strain in a body. The relationship between the applied load and mid-span deflection from zero loading to the failure stage is depicted in Figure 10.

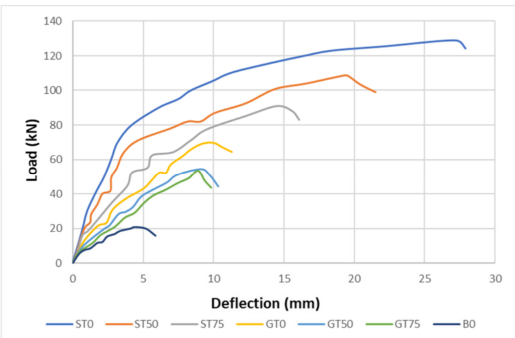

Fig. 10. Load–deflection relationship.

The deflection values of GF specimens are very close compared to the steel bar group specimens, where there is a large difference between normal and LWA specimens. This fact indicates that the deflection is insignificantly affected by the type of concrete in steel absence. Also, the elastic region in the GF group is less than that of the steel bar group, this is due to the lower ductility of glass and its high brittleness compared to steel. Figure 11 shows the load-deflection relationship for beams with normal steel reinforcement, while Figure 12 portrays the load-deflection relationship for beams without normal steel reinforcement.

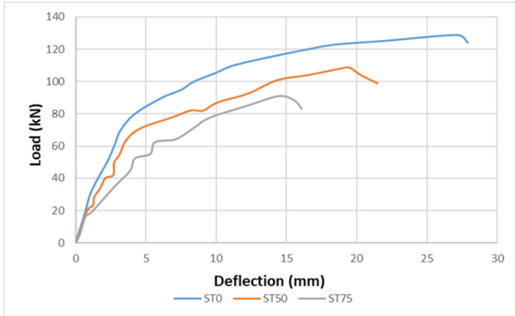

Fig. 11. Load–deflection relationship of steel bars reinforcement group.

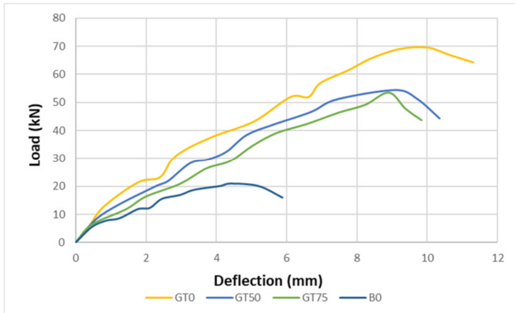

Fig. 12. Load–deflection relationship of GF reinforcement group.

E. *Ductility*

A structure's ductility is its ability to support a load while withstanding deformation that occurs beyond the point of the first yield deformation. Ultimate deflection equals the ductility index. Table III exhibits that having increased the replacement percentage, Thermostone slightly reduced the value of the ductility index, and that having replaced the steel reinforcement with GFs caused a significant decrease in ductility index.

TABLE III. DUCTILITY INDEX OF THE TESTED BEAMS

Beam	Pu kN	def-u mm	p-y kN	def-y mm	Duc-Index
ST0	128.9	27.2	90.2	6.12	4.44
ST50	108.6	19.5	76	6.9	2.83
ST75	90.9	14.5	63.6	5.66	2.56
GT0	69.6	10	48.7	5.7	1.75
GT50	54.3	9.1	38	5.3	1.72
GT75	53.6	8.9	37.5	5.4	1.65
B0	20.9	4.4	14.63	2.7	1.62

F. *Absorbed-Energy*

The region covered by the load-displacement curve up until the maximum load is attained constitutes the concrete beam's energy absorption capacity. This area displays the amount of energy absorption that the concrete beam may endure before showing a noticeable decline in load-carrying capacity. Table IV demonstrates that having increased the Thermostone replacement percentage, slightly reduced the absorbed energy value, and having replaced the reinforcing steel with GFs caused a significant decrease in the absorbed energy value because of the significant decrease in the ultimate load.

TABLE IV. ABSORBED ENERGY OF THE TESTED BEAMS

Beam ID	Pu kN	Def-u	Absorbed energy
ST0	128.9	27.18	2817.919483
ST50	108.6	19.5	1556.906754
ST75	90.9	14.5	878.5794906
GT0	69.6	10	423.4309072
GT50	54.3	9.1	303.2564554
GT75	53.6	8.9	264.3786209
B0	20.9	4.4	57.05739218

G. Cracking Mode

All specimens experienced flexural cracks beginning in the middle third and extending toward the supports. Cracking failure modes are depicted in Figure 13.

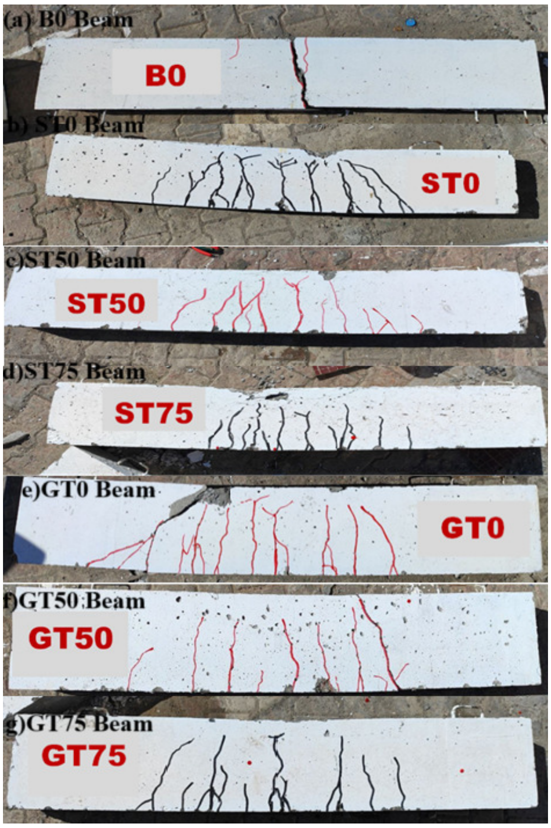

Fig. 13. Mode failure pattern of the tested beams.

It can be seen that the number of cracks and the extending area decrease with the increase of Thermostone ratio. The LWA maintains specimen integrity regardless of the reinforcement type, which is consistent with the results in [25].

All beams with steel reinforcement experienced flexural failure, while the beams with GFs experienced shear failure.

V. CONCLUSIONS

The goal of this study was to address the lack of raw concrete components and eliminate the poor properties of steel reinforcement, especially its heavy weight and rust. Although the literature includes numerous studies on Lightweight Concrete (LWC) reinforced with fibers, few studies were able to produce concrete material that is of as high-quality as normal concrete and entirely free of coarse aggregate and steel reinforcement. Based on the data gathered, the following conclusions may be drawn:

- Increasing the Thermostone ratio from 50% to 75%, led to the same influence of fibrous concrete and normal concrete on compressive strength reduction, which occurs due to the cellular structure of Thermostone concrete. The fibrous concrete reduction value increased by roughly 1.2% compared to that of ordinary concrete with 50% Thermostone. The decrease value was the same for both normal and fibrous concrete at 75% Thermostone percentage.
- Compressive strength significantly impacts flexure load, which is reduced as it lowers. The study's findings indicate that, as aggregate replacement increased from 50% to 75%, this drop was less pronounced in fibrous concrete than in regular concrete. When the replacement was 50%, the reduction in fibrous concrete was 6.2% more than that of conventional concrete, but when the replacement was 75%, the reduction was 6.8% smaller. This behavior demonstrates that using Glass Fiber (GF) instead of steel reinforcement improves the bond with the Thermostone. Additionally, when the Thermostone percentage increased, the known aggregate distraction when utilizing fibers was reduced.
- In general, replacing reinforcement steel with GF reduced the ultimate load by almost half.
- According to the data gathered, GF strengthened the concrete's crack resistance, as seen by the 5.2% rise in the cracking to ultimate load ratio in GF beams as opposed to steel reinforcement beams. This is because, unlike steel reinforcement, which begins to boost tensile strength after cracking, GF increases concrete tensile strength from the moment loading begins.
- The ductility index decreased marginally when the Thermostone replacement ratio increased, and it significantly decreased when GFs were employed in place of the reinforcing steel.
- As the Thermostone replacement percentage increased, the value of the absorbed energy was slightly reduced. When GFs were used instead of steel reinforcement, the ultimate load decreased substantially, resulting in a significant decrease in the absorbed energy value.
- All steel-reinforced beams experienced flexural failure, whereas GF-reinforced beams experienced shear failure.

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