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RESEARCH ARTICLE
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Retrofitting Reinforced Concrete Beams with Eco-friendly Ferrocement Mortar

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Abstract:

Introduction: This study investigated the effect of using eco-friendly materials such as silica fume, crumb rubber, and waste plastic fiber in ferrocement mortar. It is also compared with their performance against traditional mortals. The effect of using two types of reinforcement, welded wire mesh and glass fiber mesh, in ferrocement to retrofit beams with full or U-shape wrapping was also studied.

Methods: The experimental program consists of casting ten reinforced concrete beams with dimensions of 150×250×1800 mm. Two beams served as reference beams. The other eight beams were preloaded to 70% of the failure load, then retrofitted using ferrocement with two layers of mesh and a thickness of 25 mm.

Results: The results showed that the highest increase in ultimate load was 13.6% for the beam retrofitted using traditional mortar and reinforced with welded wire mesh in full wrapping. For eco-friendly mortar, the highest increase was 7.7% for the beam retrofitted with welded wire mesh and 6.2% with glass fiber mesh, both in U-shaped wrapping. Beams retrofitted using eco-friendly mortar exhibited higher ductility than those with traditional mortar, by 3.6% with welded wire mesh and 5.4% with glass fiber mesh in full wrapping. However, their stiffness was lower compared to traditional mortar.

Discusion: The increase in ultimate load for welded wire mesh is due to higher tensile strength compared to glass fiber mesh. Eco-friendly mortar causes an increase in ductility and reduces stiffness due to weak bonding between materials, resulting in more deformation.

Conclusion: Ferrocement is an effective method for retrofitting RC beams due to its availability, low cost, and effectiveness in improving beam behavior.

Keywords: Ferrocement mortar, Eco-friendly mortar, Welded wire mesh, Glass fiber mesh, Retrofitting, Ultimate load.

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1. INTRODUCTION

Concrete has many useful qualities and attributes that make it an excellent choice for construction. It is one of the most widely used building materials. Apart from its extremely useful capacity to be molded into nearly any shape or form, this composite material has several other advantages, like strength, adaptability, durability, economy, and good compression resistance [1]. Reinforced concrete, which is a composite material consisting of concrete and steel, gets damaged due to various reasons, such as overloading, corrosion of steel, earthquake, high wind loads, poor design, and poor building materials. Therefore, the retrofitting of deficient structural members is necessary to increase the load-carrying capacity and prevent spalling [2]. Retrofitting applications aim to increase the ultimate load capacity of older structures, which were initially designed for lower loads than they currently support. Other uses include seismic retrofitting, alterations in building usage, reducing wear and tear, and repairing damaged structures [3]. Ferrocement is a form of thin-walled reinforced concrete with a thickness of 25 mm, typically composed of cement mortar reinforced by multiple layers of continuous, relatively small wire mesh. The mesh can be constructed from metal or any other material [4].

Much research has identified ferrocement as an effective retrofitting material for the rehabilitation of various reinforced concrete elements. Wang *et al*. [5] suggested and tested various methods to improve the surface properties of rubber aggregate using solutions made from polyethylene glycol-200, polyvinyl alcohol, and hydroxypropyl methylcellulose through copolymerization and drafting techniques. They examined the flexural strength and pore size distribution of steel fiber-reinforced rubberized mortar. Significant improvements were observed in the surface microstructure and hydrophilic characteristics of the rubber aggregate. Živkovic *et al*. [6] examined the flexural capacity of RC beams strengthened with glued ferrocement strips. Fifteen beams were tested under two-point loads. Reinforcement was applied to four types of ferrocement on the tension side, each with varying wire mesh layers and thickness. The results show that the flexural capacity of strengthened beams increased by about 21.4% compared to the reference due to an increase in the number of layers and thickness. Taha *et al*. [7] evaluated different wrapping forms in terms of angle of rotation, torsional strength, and crack development. Six beams were cast with a concrete compressive strength of 25 MPa. Two beams served as control beams, while the remaining four were divided into two groups, strengthened using ferrocement on either three or two sides. The study found that the three-sided wrapping form is a viable approach to improving torsional behavior. The U-shaped wrapping technique resulted in a substantial increase in stability, along with a decrease in both the ultimate twist and crack formation. Soundararajan *et al*. [8] investigated ten reinforced concrete beams strengthened with ferrocement using a square weld wire mesh with volume fractions of 1.76% and 2.35%. Steel slag replacement ratios of 0% and 30% by weight of fine aggregate were used. The beams were tested for bending. The results showed that the first crack load and the ultimate load were higher in beams strengthened with ferrocement at a volume fraction of 2.35% (Vr) and a 30% replacement of steel slag.

The objective of this research is to investigate the effect of using eco-friendly materials (silica fume, crumb rubber, and plastic fiber) in ferrocement mixtures and compare their performance with that of traditional ferrocement. It also **e**xamines the effectiveness of employing two layers of different types of mesh reinforcement, such as steel wire and glass fiber mesh.

Furthermore, this study investigates the effect of wrapping configurations, including full and U-shape wrapping, on strengthening damaged reinforced concrete beams by measuring the improvement in ultimate load and deflection resistance compared to control beams.

2. MATERIALS AND METHODS

2.1. Traditional Materials

2.1.1. Cement

Ordinary Portland Cement (OPC) of the type I (Sinjar), manufactured in Iraq, was used in this study. The physical properties of used cement, meeting the IQS: No. 5/2015 [9], are listed in Table **1**, conducted in the University of Mosul, Civil Engineering Laboratory.

Table 1. Cement physical properties.

Properties	Results	Limits of Iraqi Specification [9]
Standard ductility	0.295	--
Initial Setting Time (minutes)	120	≥ 60
Final Setting Time (minutes)	300	≤600
3 days Compressive Strength MPa.	20	≥15
7 days Compressive Strength MPa.	30.6	≥23
Fineness Sieve no. 170 (%)	2.2	≤10

2.1.2. Coarse and Fine Aggregate

Locally available gravel with a 19 mm maximum aggregate size and sand passing sieve No. 4 were used in this study. The physical properties of coarse aggregate meet ASTM C127-15, and fine aggregate meets ASTM C128-22, as shown in Table **2** [10, 11].

Table 2. Physical properties of fine and coarse aggregates.

Physical Properties	Coarse Aggregate	Fine Aggregates
Specific gravity (S.S.D)	2.69	2.60
Absorption	0.66%	2.46%
Compact unit weight kg/m³	1625	1822
Fineness modulus	6.71	2.61

2.1.3. Water

Potable water was used following IQS: 1703/ 1992 [12].

2.2. Eco-Friendly Materials

2.2.1. Silica Fume

Micro silica (SF) is a byproduct of the manufacture of silicon metal and ferro-silicon alloys from CONMIX Company, as shown in Fig. (1). The Pozzolanic Activity Index (P.A.I.) of silica fume, based on a test conducted at the University of Mosul/ Materials Testing Laboratory, was 108%, which meets ASTM C1240-20 [13].

Fig. (1). Silica fume.

2.2.2. Waste Tire Rubber

Crumb Rubber (CR) is generated from recycled tires and processed by removing metal and fiber components, followed by mechanical shredding of discarded vehicle tires (Fig. 2). The particle sizes of crumb rubber used in this study ranged from 0.03 mm to 3.5mm.

Fig. (2). Crumb rubbers.

2.2.3. Waste Plastic Fiber Bottle

The waste Plastic Fiber bottle (PF), which is locally available (known as polyethylene terephthalate), is used in this study. The plastic bottles were first washed with water to remove dust, then each bottle was shaped as a sheet by removing the neck and base. Finally, the sheet was cut into strips, as shown in Fig. (3a-c), to produce plastic fiber. The dimensions and physical properties of PF are given in Table 3.

Table 3. Physical properties of PF.

Property	Description
Type	Polyethylene Terephthalate (PET)
Average Length (mm)	25
Average Width (mm)	5
Average Thickness (mm)	0.15
Aspect Ratio	25.588
Density (kg/m^3) *	1375

Note: *According to previous studies [14].

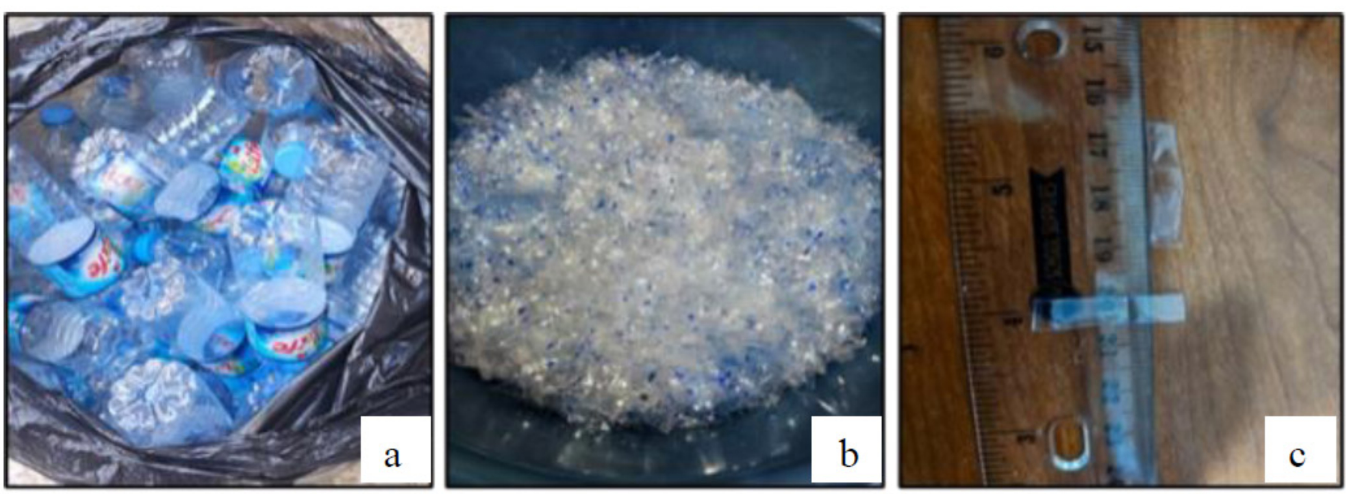


Fig. (3). Process to produce waste plastic fiber.

2.3. Mortar Types and Mix Proportions

2.3.1. Traditional Mortar

Traditional mortar consists of cement, sand, and water. These materials were mixed with a mixing ratio of 1:1.906:0.47 (Cement: Sand: w/c).

2.3.2. Eco-friendly Mortar

Eco-friendly mortar consisted of cement, sand, and water with a mixed ratio of 1:1.906:0.47 (Cement: Sand: w/c). Eco-friendly materials were added to this mix to make it sustainable. 8% silica fume as a replacement ratio of cement weight, 5% crumb rubber replacement of sand weight, and 0.75% volumetric ratio of waste plastic fiber were used. These replacement percentages were selected after conducting and testing several mixtures to determine the optimum mixture.

2.4. Reinforcement

2.4.1. Steel Reinforcement

Deformed reinforcing steel bars under the brand name “Mass” were used to reinforce the beams. The main longitudinal bars for tension, compression, and stirrups were 10 mm in diameter. Samples of the three bars were tested to specify their properties of yield strength, ultimate strength, and elongation as given in Table 4. Fig. (4) demonstrates the stress-strain relation of the tested bar.

Table 4. Properties of reinforcing steel bars.

Properties	Value	Requirements ASTM [15]
Nominal Bar Diameter (mm)	10	-
Actual Diameter (mm)	9.75	-
Yield Stress (MPa)	580	Min. 550 MPa
Ultimate Stress (MPa)	695	Min. 690 MPa
Elongation (%)	8	Min. 7%

2.4.2. Mesh Reinforcement

Two types of mesh reinforcement were used in this study, including welded steel wire mesh and glass fiber mesh, as shown in Fig. (5a, b). The properties of both types of mesh are listed in Table 5. Fig. (6a, b) shows stress-strain relations for welded wire and glass fiber mesh.

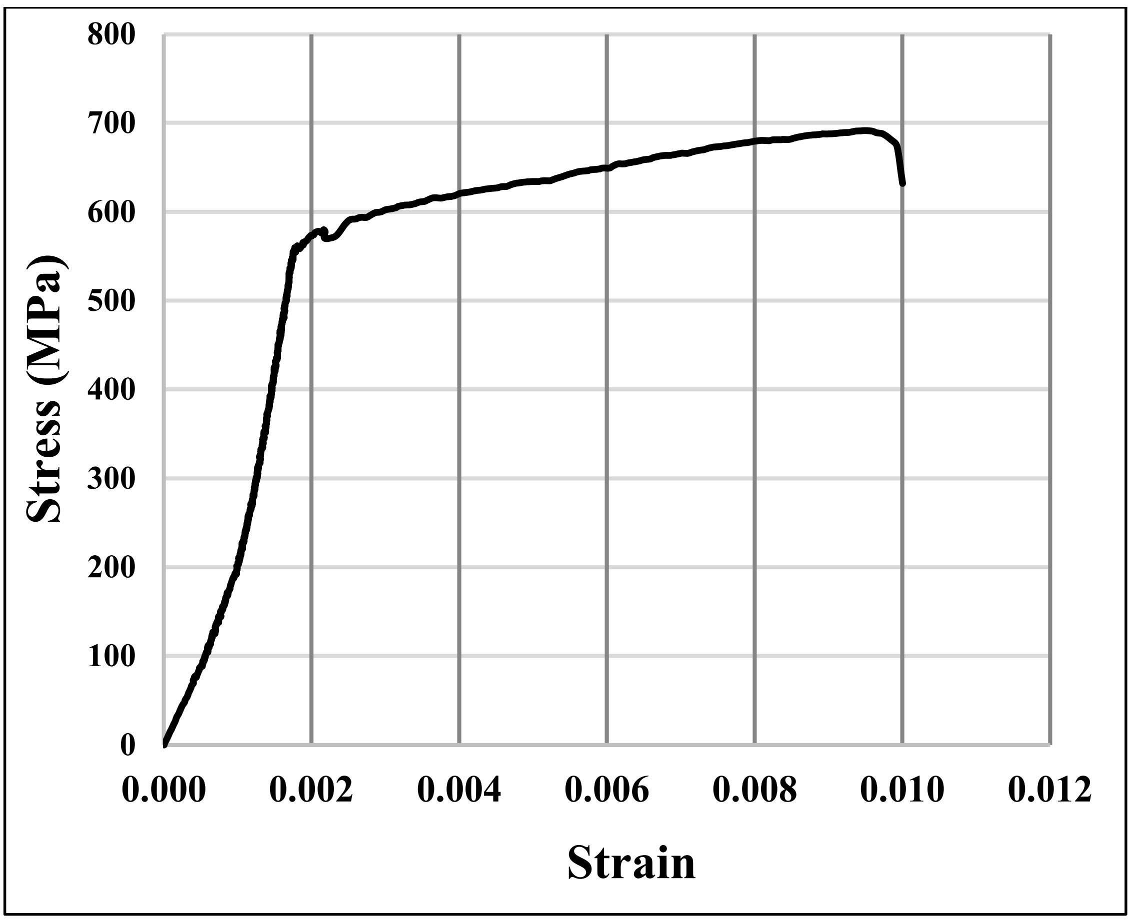


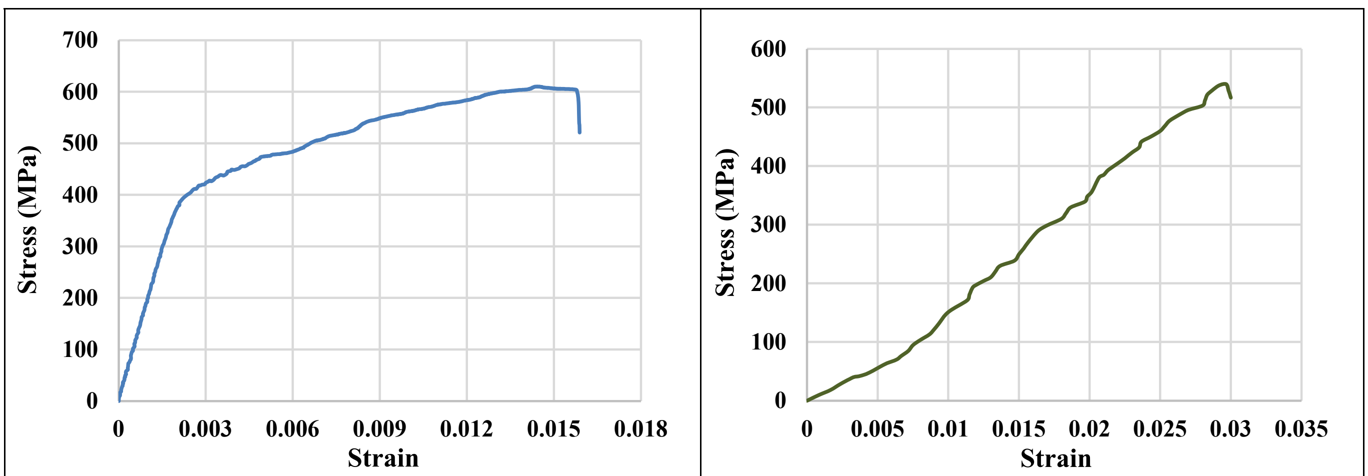
Fig. (4). Stress-strain relation of steel bars.

Table 5. Properties of welded wire mesh and glass fiber mesh.

Specifications	Welded Wire Mesh	Glass Fiber Mesh
Opening Size (mm)	12.5 x 12.5	4 x 4
Size of Wire (mm)	0.6	0.3 x 0.3
Yield Strength (MPa)	395	---
Ultimate Strength (MPa)	610	540
Weight (g/m^2)	340	160

a. Welded Wire Mesh and b. Glass Fiber Mesh.

Fig. (5a, b). Type of mesh used.



A. Stress-Strain Relation of Welded Wire Mesh.

B. Stress-Strain Relation of Glass Fiber Mesh.

Fig. (6a, b). Stress *versus* strain relation of wire mesh.

2.5. Preparation of Specimens

Fig. (7) demonstrates the details of the beams used in this study. These beams were designed according to the Building Code Requirements for Structural Concrete (ACI 318M-19) [16]. These beams were tested by applying center-point loading as shown in Fig. (7).

Two wooden formworks were prepared and placed on the ground in an equilibrium status. The steel cages were fixed inside the formworks as shown in Fig. (8a). The concrete was then poured as shown in Fig. (8b). A total of ten reinforced concrete beams were cast using concrete with a mix ratio of (1: 1.906: 2.787/0.47). After 24 hours, the outer side of the wooden formwork was removed.Afterward, the specimens were cured for 28 days using wetted jute bags and covered with plastic sheets as shown in Fig. (8c).

2.6. Preloading of Specimens

The testing of the beams was carried out at 28 days after moist curing. The ten specimens were tested under center-point loading using a flexure and compressive testing machine, and measuring tools, as shown in Fig. (9). Two specimens (CB1 and CB2) were tested to failure and considered as reference beams. The remaining eight specimens were loaded up to 70% of the ultimate load of the reference beams and represent the preloaded beams.

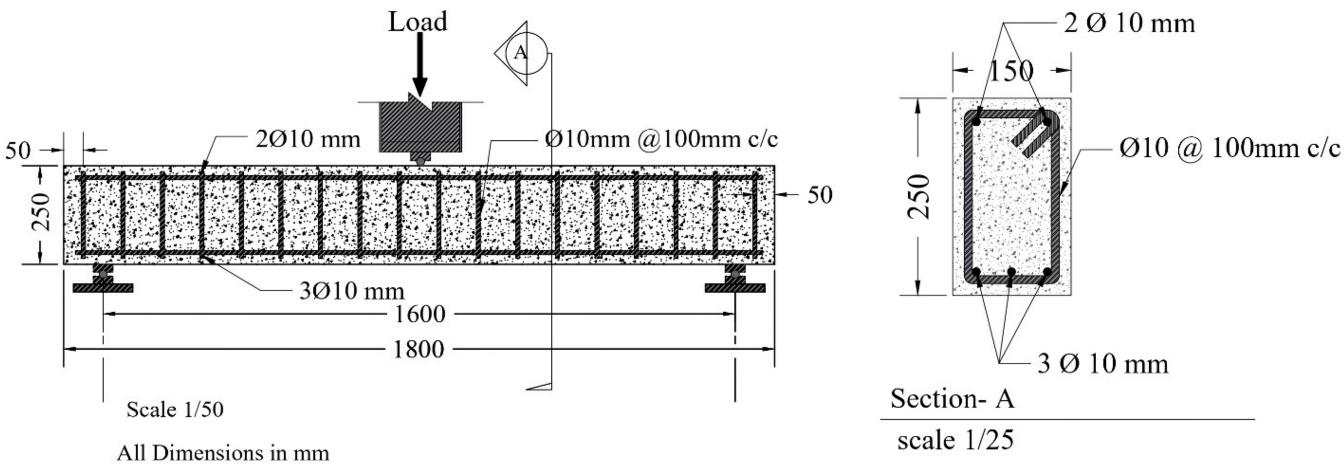
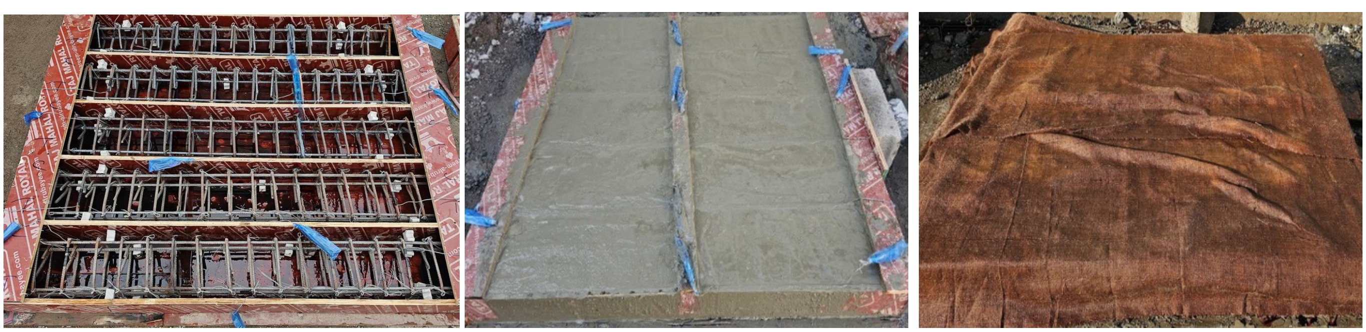


Fig. (7). Longitudinal, cross-section, and centre point load test of beam.



a) Formwork preparing and fixing reinforcement. b) Casting the Specimens. c) Curing the specimens.

Fig. (8a-c). Fixing steel bars, casting and curing the specimens.

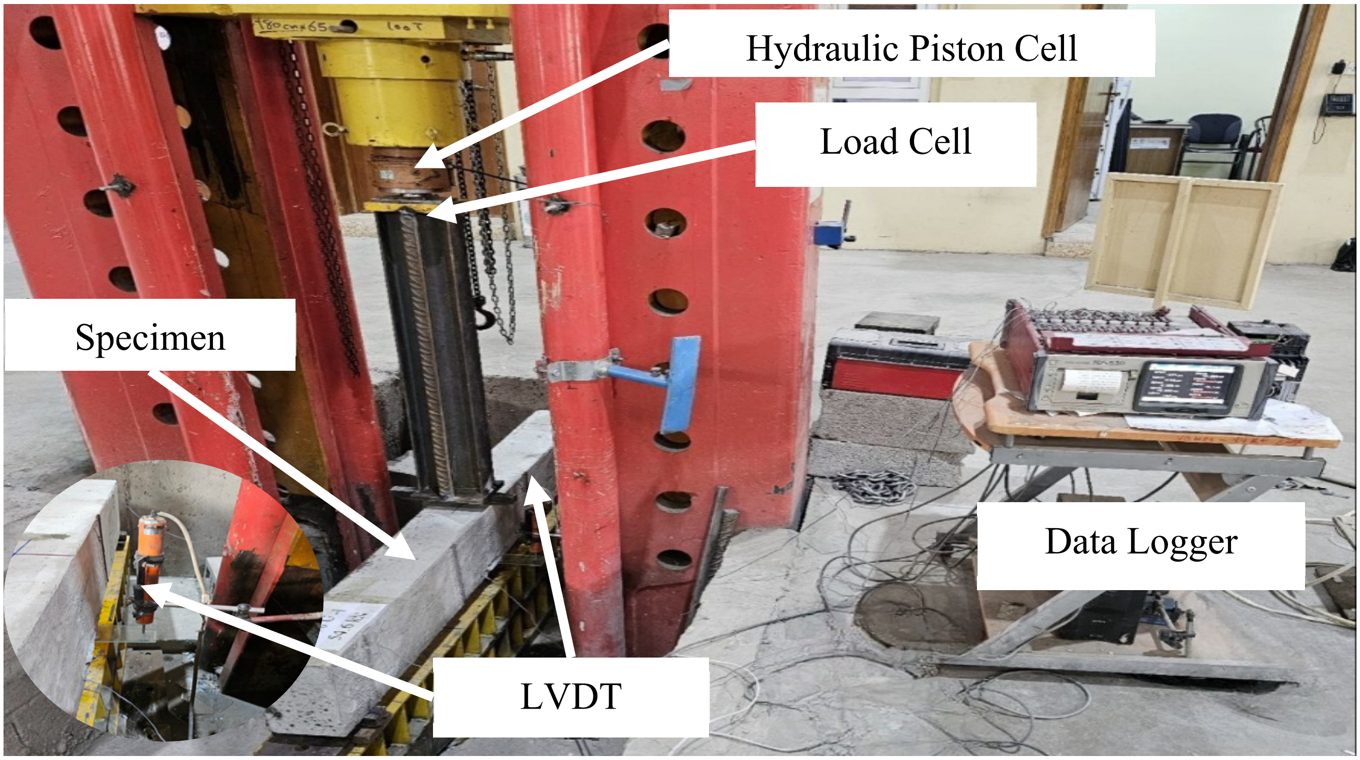


Fig. (9). Test setup.

2.7. Retrofitting Reinforced Concrete Beams

2.7.1. Description of Beams

The preloaded beams (mentioned above) were divided into four groups, based on the materials used in retrofitting and the wrapping method, as shown in Fig. (**10a** and **b**).

- Group 1 contains two beams, both of which have been retrofitted using traditional mortar and reinforced with welded wire mesh. One of them was retrofitted for full wrapping, while the other was retrofitted for U-shaped wrapping.
- Group 2 contains two beams, both retrofitted using traditional mortar and reinforced with glass fiber mesh. One of them was retrofitted for full wrapping, while the other was retrofitted for U-shaped wrapping.
- Group 3 contains two beams, both retrofitted using eco-friendly mortar and reinforced with welded wire mesh. One of them was retrofitted for full wrapping, while the other was retrofitted for U-shaped wrapping.
- Group 4 contains two beams, both retrofitted using eco-friendly mortar and reinforced with glass fiber mesh. One of them was retrofitted for full wrapping, while the other was retrofitted for U-shaped wrapping.

The symbols used in the study are listed in Table **6**. The details of the reference and the four groups of specimens are shown in Table **7**.

Table 6. Define the symbol used in ferrocement.

Symbol	Definition	Symbol	Definition
C	Control	B	Beam
T	Traditional mortar	E	Eco-friendly mortal
F	Full wrapping	U	U-shape wrapping
W	Welded wire mesh	G	Glass fiber mesh

Table 7. Details of the specimens.

Groups	Specimen's Code	Type of Mortar	Type of Mesh	Type of Wrapping	Preloaded Percentage	No. of Specimens
CB	CB	Beams without any jacketing			100%	2
Group 1	BTWF	T	W	F	All these beams were preloading to 70% of the ultimate load	1
	BTWU	T	W	U		1
Group 2	BTGF	T	G	F		1
	BTGU	T	G	U		1
Group 3	BEWF	E	W	F		1
	BEWU	E	W	U		1
Group 4	BEGF	E	G	F		1
	BEGU	E	G	U		1

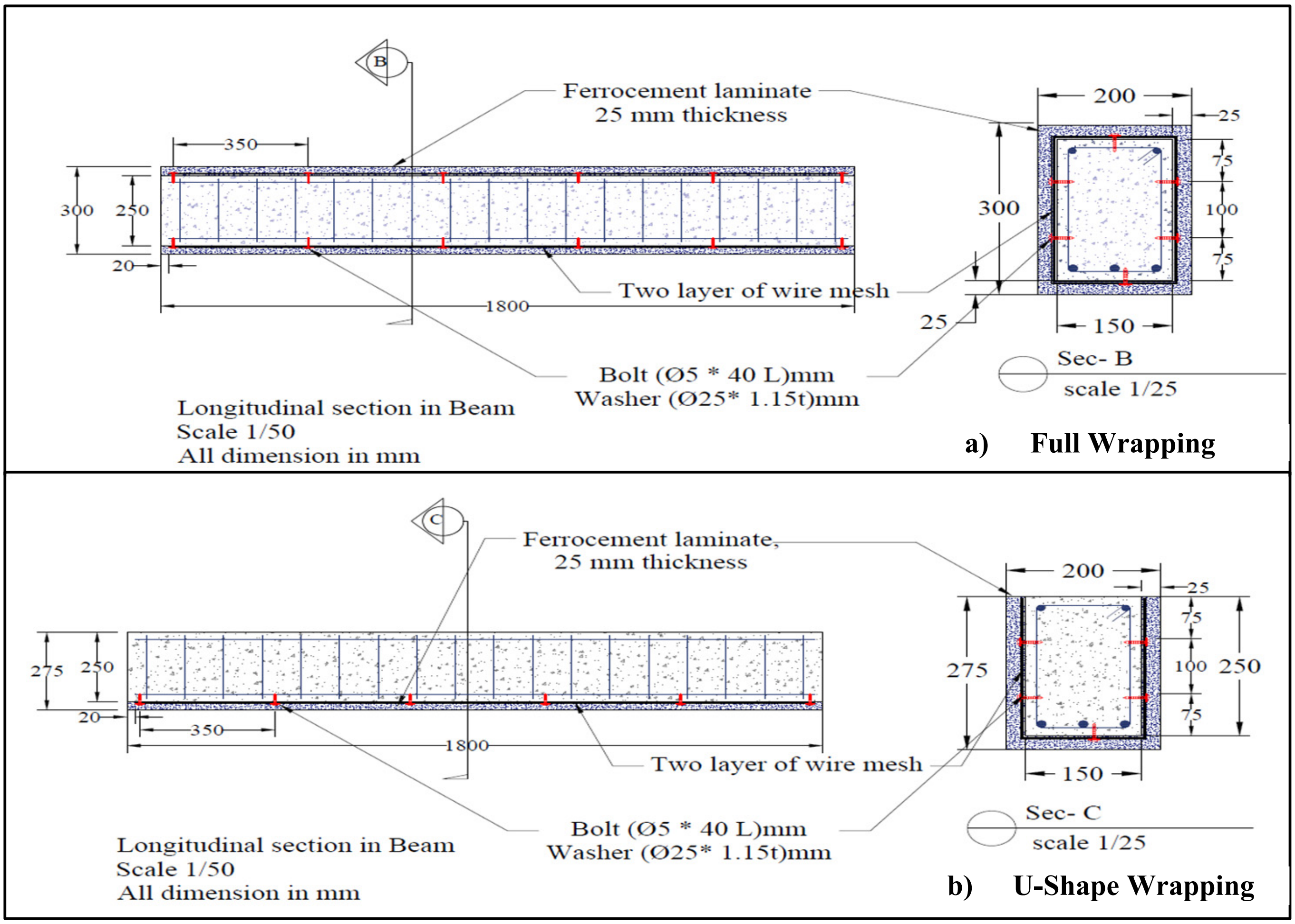


Fig. (10a, b). Longitudinal and cross-section of beams show types of wrapping.

2.7.2. Retrofitting Process

2.7.2.1. Wrapping the Mesh Reinforcement

The preloaded beams were wrapped in a U-shape and fully wrapped using two layers of two types of mesh reinforcement: steel wire mesh and glass fiber mesh, as shown in Fig. (**11a** and **b**). Each layer exhibits an overlap of at least two mesh opening sizes [4] or 50 mm, and with a cover of 2 mm. The reinforcing mesh was fixed using bolts with dimensions (Ø5×40 length) mm and washers (Ø25×1.15 thickness) mm to prevent debonding and achieve the maximum tensile strength of the mesh.

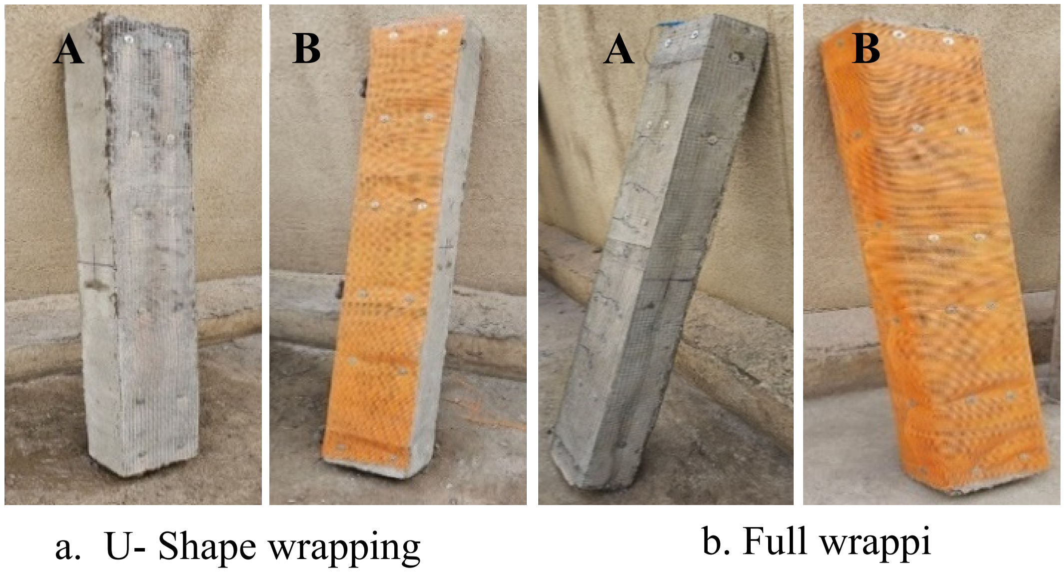


Fig. (11a, b). Wrapping of beams using steel and glass fiber mesh.

The fixing process involves:

- Cleaning: Cleaning the beam surface.
- Drilling the holes: Each hole measures 8 mm, equal to the Fischer diameter.
- Spacing: Holes were placed at 350 mm intervals at the top, bottom, and sides of the beam, with two rows on each side.
- Bolt insulation: Bolts were inserted into each Fischer with washers placed on the mesh, and the bolts were tightened to achieve a secure fit of the mesh on the beam's sides.

2.7.2.2. Plastering the Specimens Using Mortar

2.7.2.2.1. Using Traditional Mortar

The process of plastering the beams includes: Preparing and cleaning surfaces of the beams from dust and dirt, weighing and mixing all the required materials, filling the gaps of the mesh with mortar, installing wooden rulers to maintain uniform thickness, and continuing plastering to achieve the final appearance of the beams as shown in Fig. (**12a-c**).

Fig. (12a-c). Process of retrofitting using traditional mix mortar.

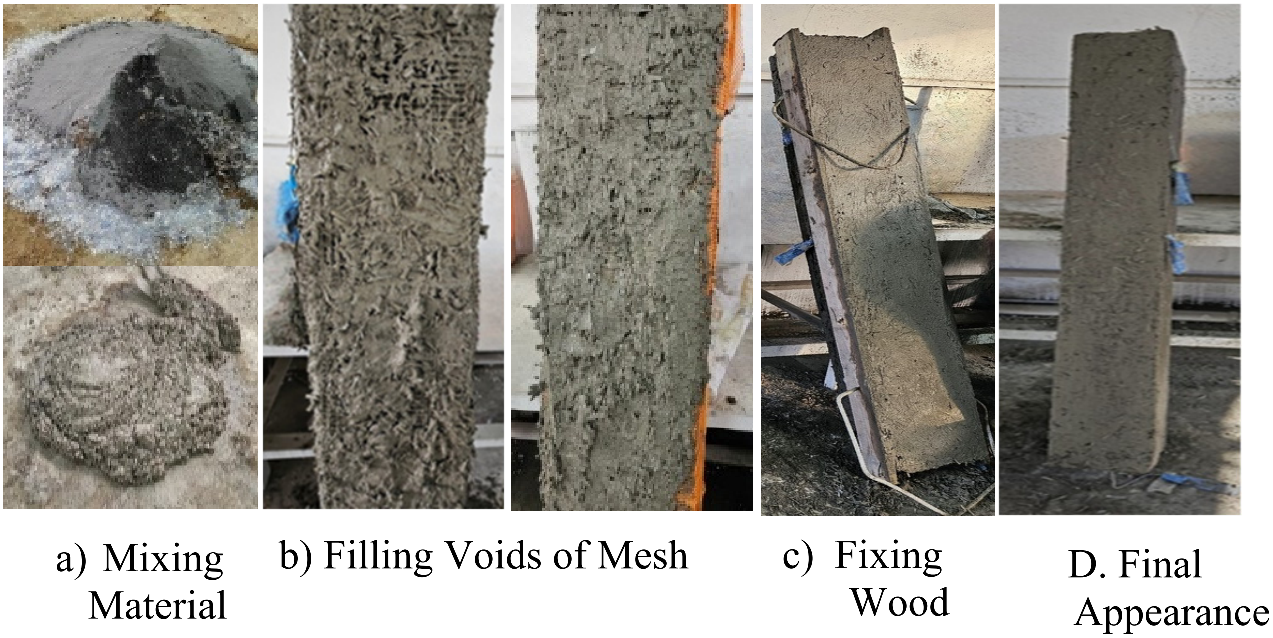


Fig. (13a-d). Process of retrofitting using eco-friendly mortar.

2.7.2.2.2. Using Eco-Friendly Mortar

The optimal mixture, along with the basic materials, was used to prepare the eco-friendly mortar. Welded wire mesh or glass fiber mesh was used for the reinforcement. The same plastering process described in traditional mortar was applied, as shown in Fig. (**13a-d**).

2.7.2.3. Curing and Painting

The retrofitted specimens were cured by covering them with burlap bags to retain moisture for 28 days. The burlap was moistened daily. After the curing period, the specimens were painted white to make the cracks visible during the test, and then the beam code was recorded on them.

2.7.2.4. Testing Set-Up

After the 28-day curing period, four groups of specimens containing eight retrofitted beams were tested under center point load up to failure using the same test setup and following the same process mentioned in Section 2.6.

3. RESULT

3.1. Load-Deflection Curve of the Control and Preloaded Beams

Fig. (**14**) shows the load-deflection curve for the control beams (CB1 and CB2). The ultimate load of two control beams (CB1, CB2) was equal to 77.9 and 75.8 kN and the mid-span maximum deflection was equal to 14.15, 15.21 mm, respectively as shown in Fig. (**14**). The average ultimate load and deflection of the control beams were 76.85 kN, 14.68 mm. these values were used for comparison with other beams under the name CB. The eight preloaded beams were preloaded to 70% of the Control Beam (CB) failure load, which equals 53.8 kN.

3.2. Results of Retrofitted Specimens

Table **8** presents the experimental results of the retrofitted beams, including first cracking load, yield load, ultimate load, and the corresponding mid-span deflection.

Table 8. Test results for the retrofitted beams.

Group	Beam Code	First Cracking Load		Yielding Load		Ultimate Load		
		Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	% Increase in Ultimate Load
CB	**CB**	16.5	0.75	73.45	7.17	76.85	14.68	---
Group1	**BTWF**	32.1	1.7	84.3	6.7	87.3	20.53	13.6
	BTWU	29	2.7	78.9	6.85	82.8	19.45	7.7
Group2	**BTGF**	28	2	81	7.2	84.8	20.10	10.3
	BTGU	24.5	1.9	75.1	7.1	81.61	19.00	6.2
Group3	**BEWF**	27	2.4	78.2	7.8	81.3	24.70	5.8
	BEWU	29.5	2.7	82.8	8.5	82.8	8.50	7.7
Group4	**BEGF**	24	2.28	74	8.1	78.5	23.83	2.1
	BEGU	28	2.44	76.6	8.4	81.6	24.24	6.2

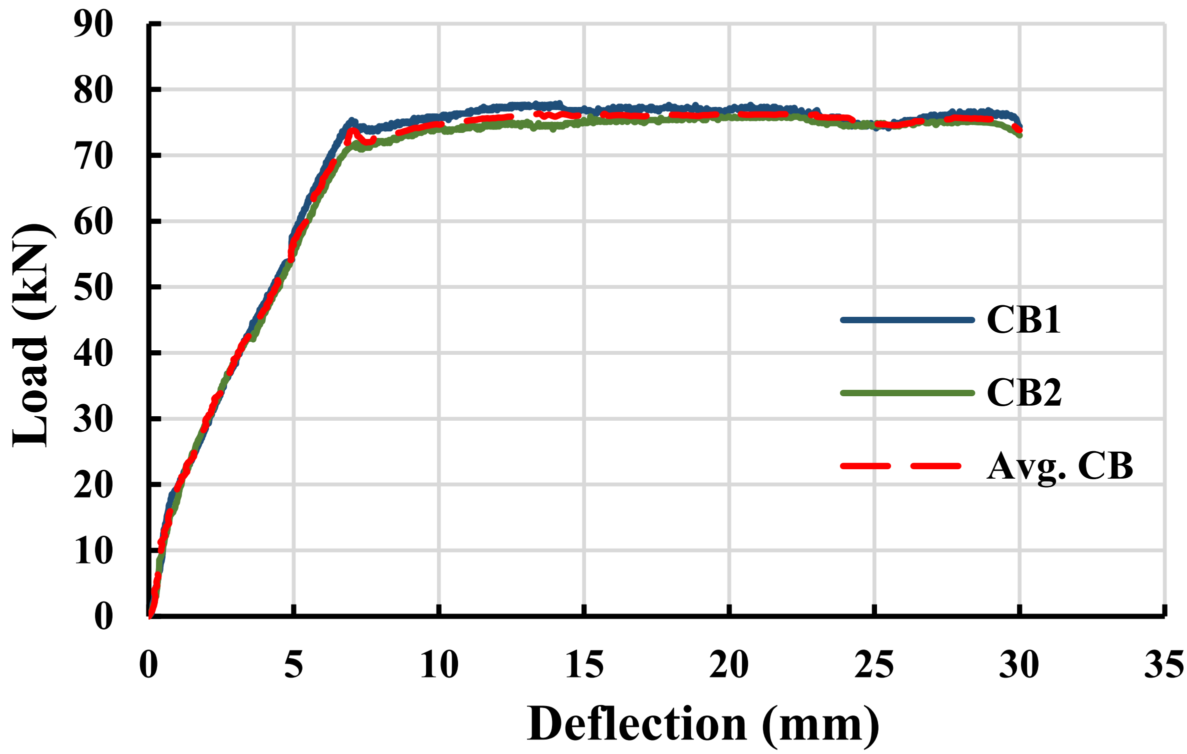


Fig. (14). Mid-span load deflection curve for control beams.

3.2.1. Mid-Span Load Deflection Curve

3.2.1.1. Group 1

Fig. (**15a**) shows load-deflection curves of the specimens in group 1 compared to the control beam. The result indicates that applying ferrocement with traditional mortar enhances the load-deflection curve of the strengthened beams. These results agree with those found by [17, 18]. The results also show that applying ferrocement with full wrapping (BTWF) increases the ultimate load by 13.6% and 5.4%, as compared to the control and BTWU beams. The U-shape wrapping (BTWU) exhibited an increase by 7.7% in the ultimate load compared to the control beam. It is also observed that the deflection of the retrofitted beam (BTWF, BTWU) in terms of yield load reduced by 6.6% and 4.5%, respectively, compared to the control beam. The reduction was due to the ferrocement increasing the beam's effective depth. At ultimate load, the deflection in the retrofitted beams was higher than that of the control beams by 39.8 and 32.5%. This is due to ferrocement, which allows the beam to deform more before failure, improving its ductility.

3.2.1.2. Group 2

Similar behavior to that of the specimens in Group 1 was observed in this group. Fig. (**15b**) shows that the increase in the ultimate load and deflection at ultimate load was (10.3, 6.2) % and (36.9, 29.4) % for beams BTGF and BTGU, respectively, compared with the control.

3.2.1.3. Group 3

Fig. (**15c**) demonstrates that the beam BEWF exhibits an increase in ultimate load by 5.8% compared with control beams. Beam BEWU also shows an increase in ultimate load by 7.7% compared with control beams and by 1.85% compared with beam BEWF.

Beam BEWF exhibited a drop in load-carrying capacity as shown in Fig. (**15c**), indicating that the beam is failing or collapsing. This behavior may be due to weak bonding between the eco-friendly mortar and the beam surface, leading to partial debonding of the ferrocement with the beam. This resulted in a sudden failure, characterized by a wide crack in the beam. Fig. (**15c**) also shows that at the ultimate load, the full wrapping specimens exhibited less deflection compared to the control beams, while the U-shape wrapping specimens exhibited higher deflection.

3.2.1.4. Group 4

Fig. (**15d**) demonstrates the load-deflection curve of beams in group 4 compared to the control beam. This figure shows that the ultimate load of the beams (BEGF and BEGU) increased by 2.1% and 6.2% respectively, compared to the control beam. Additionally, the ultimate load of beams BEGU increased by 3.95% compared to beam BEGF. Additionally, the deflection at ultimate load of the specimens in group 4 was higher compared to the control beam.

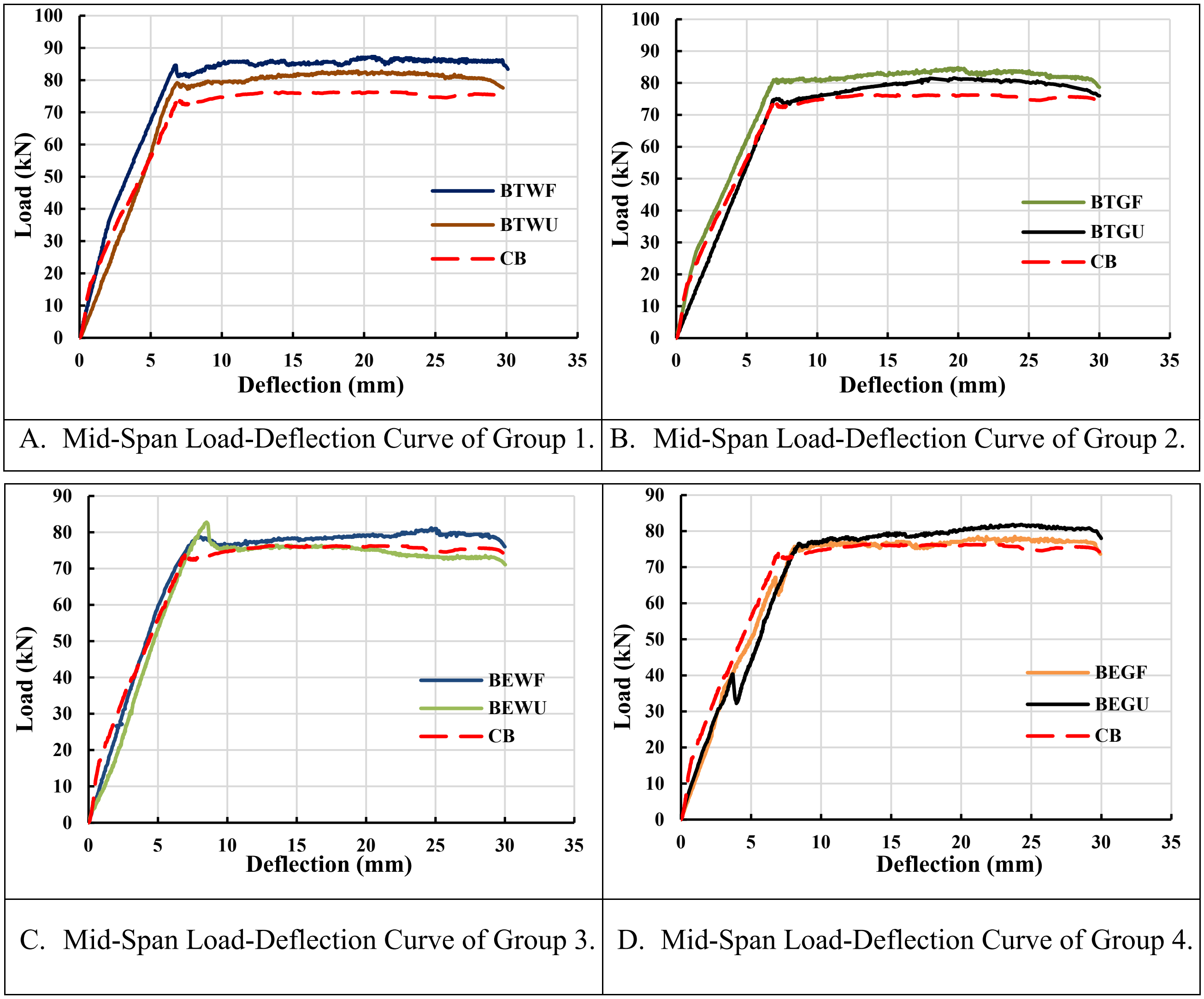


Fig. (15a-d). Mid span load deflection curve for all groups.

3.2.2. Comparison Between Mid-Span Load Deflection Curve

Fig. (**16a**) shows the load-deflection curve of the beams in group 1 and group 2, in addition to the control beam. From this figure, it is noted that the specimens in Group 1 (reinforced with steel wire mesh) exhibited a higher ultimate load and less deflection compared to the specimens in Group 2 (reinforced with glass fiber). The reduction in ultimate load for group 2 as compared to group 1 was (2.86, 1.4) % for full and U-shape wrapping, respectively.

Fig. (**16b**) shows the load-deflection curve of beams in Group 1 and Group 3, in addition to the control beam. From this figure, it is noted that the ultimate load of the beams (BEWF and BEWU) retrofitted with ferrocement using eco-friendly mortar exhibited a reduction of 6.87% and 0%, compared to the beams retrofitted with ferrocement using traditional mortar (BTWF and BTWU). However, the value of deflection in these beams was more than that of the beams in Group 1 due to lower stiffness and bonding between the mortar itself and the beam surface.

Fig. (**16c**) demonstrates the load-deflection curves of beams in Group 3, Group 4, and the control beam. The ultimate load of the beams BEGF and BEGU in group 4 decreased by 3.44% and 1.45% respectively, compared to the beams BEWF and BEWU in Group 3. Additionally, the beams in Group 3 exhibited lower deflection compared to the beams in Group 4. This is due to the use of welded wire mesh, which resists more deformation compared to glass fiber.

Fig. (**16d**) illustrates the load-deflection curves of beams in Group 2, Group 4, and the control beam. The ultimate load of beams in group 4 (BEGF, BEGU) decreased by 7.43% and 0% compared to Group 2 (BTGF and BTGU), respectively. Additionally, beams in Group 2 exhibited lower deflection compared to those in Group 4, due to the use of traditional mortar.

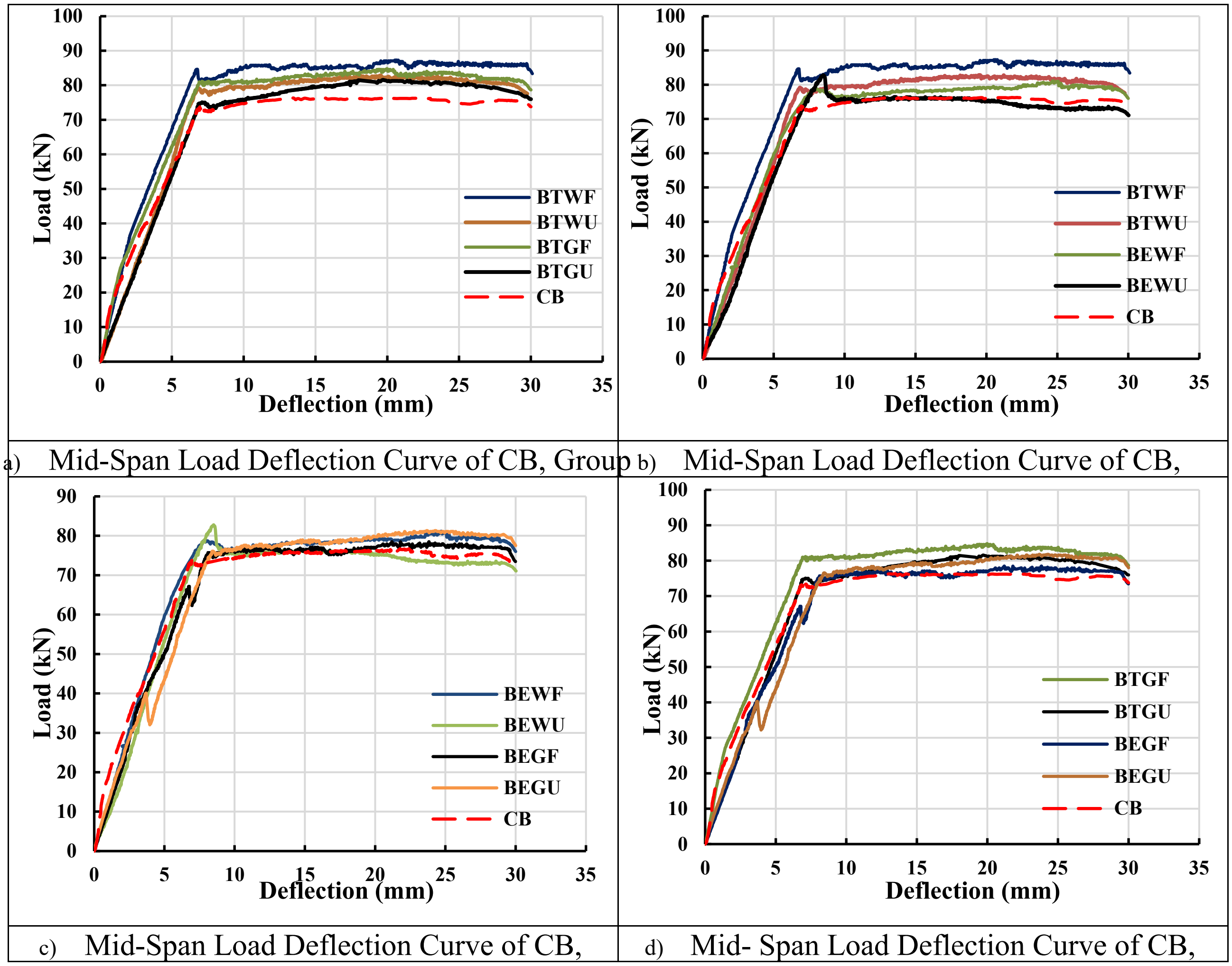


Fig. (16a-d). Comparison between mid-span load deflection of various groups.

3.3. Ductility Index

Ductility refers to the ability of the structure to sustain applied loads after yielding without experiencing critical failure, indicating how much plastic deformation it can endure before fracturing. The ductility index (μ) is defined as the deflection ratio at the ultimate load to the deflection at yield [19]:

$$\mu = \frac{\delta_{\text{ult. load}}}{\delta_{\text{yielding}}}$$

Fig. (**17**) shows the ductility index, along with its increase and decrease percentages, for all tested beams. All the retrofitted beams showed an increase in ductility index compared to the control beam, except for beam (BEWU). This beam exhibited a decrease in ductility index due to the sudden failure that occurred as a result of using eco-friendly materials.

Additionally, from Fig. (**17**), note that the ductility index of a beam retrofitted using eco-friendly mortar for full or U-shaped wrapping was higher than that of traditional mortar. Beams retrofitted for full wrapping cause an increase in ductility compared to U-shaped wrapping. In addition to beams reinforced with welded wire mesh, it has more ductility than those reinforced with glass fiber mesh.

3.4. Stiffness

Stiffness refers to the ability of a structural member to resist deformation within an approximately elastic range. In this study, stiffness was determined as the slope of the load-deflection curve at the yield load condition.

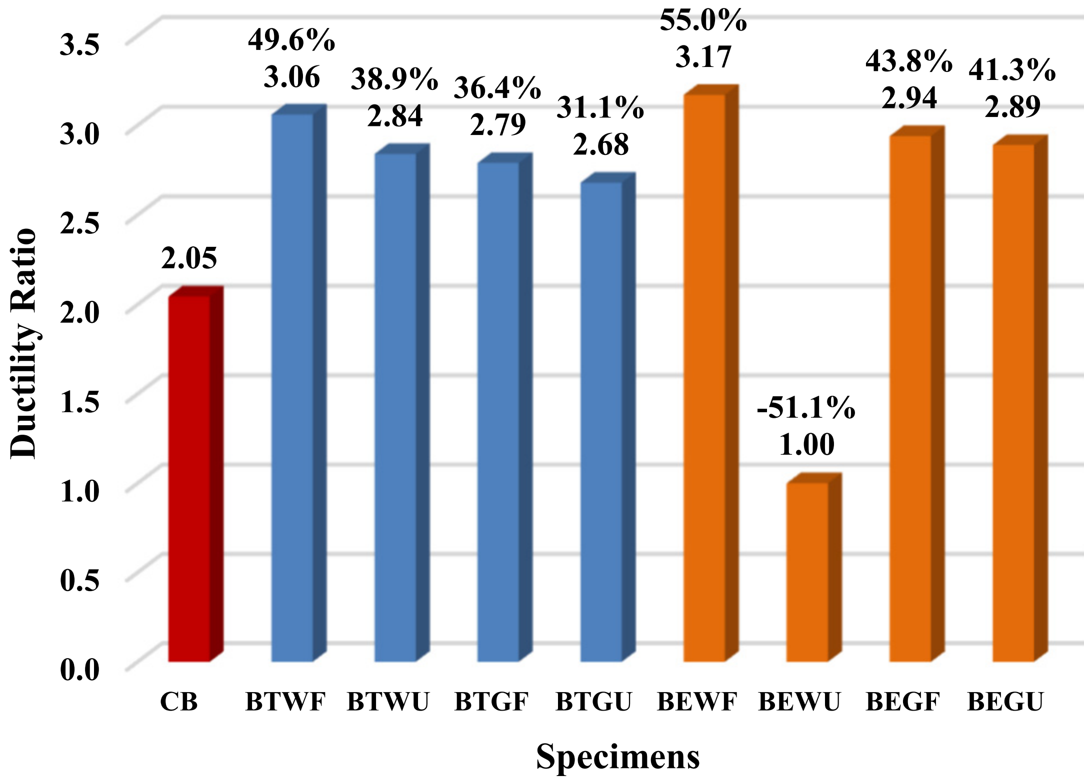


Fig. (17). Ductility index and increase or decrease ratio for all tested beams.

The results of stiffness for each beam are listed in Fig. (**18**). The results indicate that the beams retrofitted using traditional mortar exhibited higher stiffness values compared to the control beam. In contrast, the stiffness of beams retrofitted using eco-friendly mortar was lower than that of traditional mortar and control beams. The highest increase in stiffness was observed in the BTWF beam, with a 22.9% rise compared to the control beam. The greatest decrease in stiffness was found to be 10.9% for the beam BEGU compared to the control beam.

4. DISSCUSION

4.1. Effect of Wrapping Type On

4.1.1. Load-Deflection Curve

Using ferrocement with traditional mortar for a full wrapping configuration provided better confinement and improved the ultimate load, as shown in Table **8**, compared to the U-shaped wrapping configuration. Additionally, the deflection in terms of yield load for beams with full wrapping was less compared to U-shaped wrapping. This behavior is due to the increase in the effective depth of retrofitted beams. Further, the full wrapping beams prevent the debonding of the ferrocement layer. These results agree with the findings of the studies conducted by Zisan and Sirimontree *et al*. [20, 21].

When using eco-friendly materials, full-wrapping beams showed a lower ultimate load compared to U-shaped wrapping beams. This is due to the use of eco-friendly mortar, which has lower compressive and flexural strength, as well as weak bonding to the beam surface. This behavior may lead to an increase in stress concentration at the edges, causing early failure due to either cracking or debonding.

U-shaped wrapping exhibited better performance by improving the stress redistribution. The free upper surface allows natural deformation, while the three wrapping sides enhance tensile strength.

4.1.2. Ductility Index

Beams retrofitted with ferrocement jacketing, which was fully wrapped, exhibited higher ductility compared to those with U-shape wrapping. This is due to the better confinement provided by the full wrapping configuration and higher plastic deformation. These results agree with the findings of previous studies [22, 23].

4.1.3. Stiffness

Beams retrofitted using ferrocement with full wrapping exhibited higher stiffness compared to U-shaped wrapping. Full wrapping provides more uniform distribution of stresses, better bonding with the beam surfaces, and better confinement. These results align with the findings of a previous study [24].

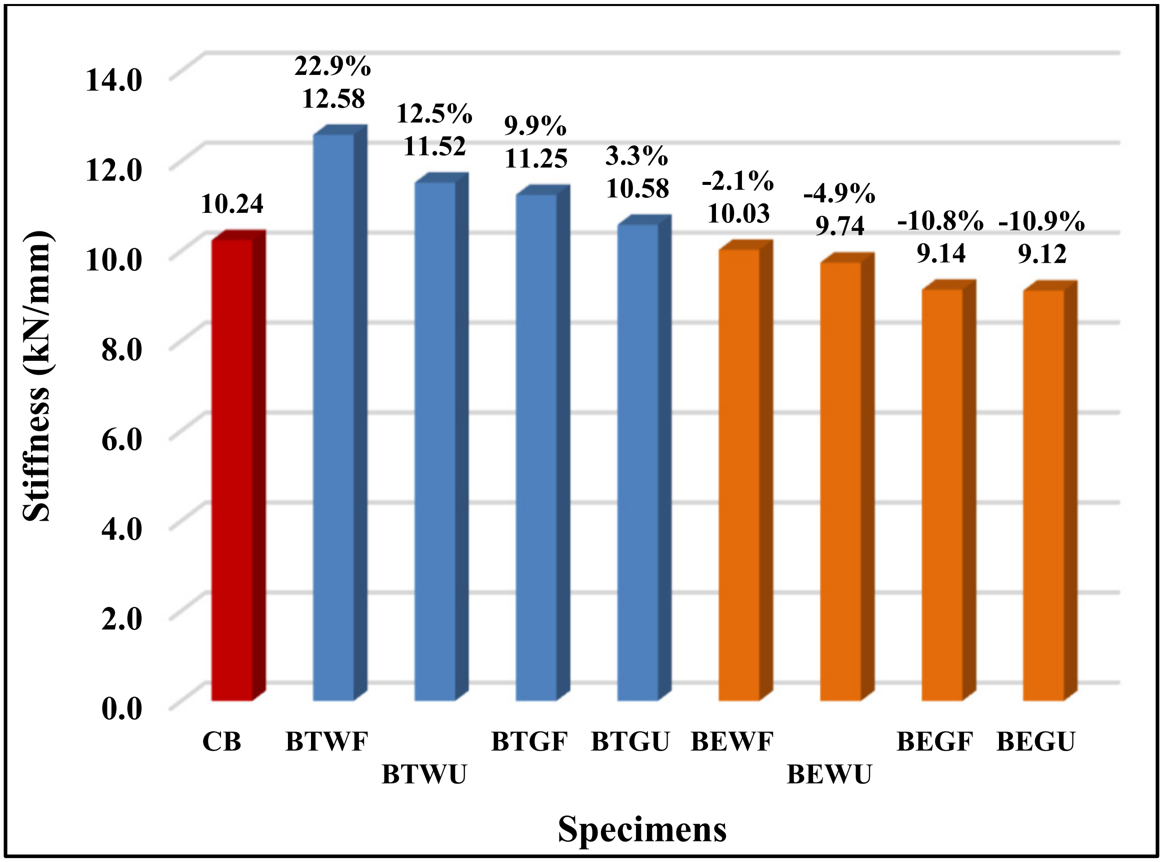


Fig. (18). Stiffness and increase or decrease ratio for the tested beams.

4.2. Effect of Mortar Type on

4.2.1. Load-Deflection Curve

Using traditional mortar resulted in delaying the first crack, increasing ultimate load, and reducing deflection at the corresponding load levels. These results agree with the findings of previous studies [18, 25]. Using eco-friendly mortar exhibited lower ultimate loads, more cracks, smaller crack widths, and higher deflections compared to the beams retrofitted with traditional mortar. The lower ultimate load is due to the weak bonding between eco-friendly materials, which caused strength loss. In addition, eco-friendly materials have a smooth surface, which causes weak bonding with the beam surface. These results align with the previous studies [26].

4.2.2. Ductility Index

Eco-friendly mortar exhibited higher ductility compared to traditional mortar. This is due to the inclusion of crumb rubber and plastic fibers, allowing more deformation before failure. These results align with the findings of previous studies [27-29].

4.2.3. Stiffness

Beams retrofitted using traditional mortar exhibited higher stiffness than eco-friendly mortar. This behavior is due to the presence of crumb rubber and plastic fiber, which increase the voids and gaps in the mixture as well as reduce the cohesion between the mixture components and the beam surface. These results are consistent with those of previous studies [30, 31].

4.3. Effect of Reinforcement Type on

4.3.1. Load-Deflection Curve

A beam retrofitted using ferrocement reinforced with welded wire mesh exhibited a higher ultimate load and less deflection compared to a beam retrofitted with ferrocement reinforced with glass fiber mesh. The reason is that the welded wire mesh has a higher ultimate stress (610 MPa) compared to glass fiber mesh (540 MPa). These results agree with the findings of previous studies [32, 33]. The lower deflection is due to several reasons, such as the high stiffness and young modulus of the welded wire mesh, and the weak bonding between the mortar and the glass fiber mesh, which is attributed to its small opening size. This behavior is consistent with the findings of a previous study [34].

4.3.2. Ductility Index

Beams retrofitted with ferrocement reinforcement and welded wire mesh exhibited higher ductility compared to those reinforced with glass fiber mesh. Welded wire mesh allowed for gradual yielding and better energy absorption, enabling the beam to carry load after yielding. Unlike glass fiber, which lacks a yield point, its behavior remains linear until failure. These results are consistent with the results in section (2.4) and findings of a previous study [35].

4.3.3. Stiffness

Beams retrofitted with either traditional or eco-friendly mortar and reinforced with welded wire mesh exhibited higher stiffness than those reinforced with glass fiber mesh. Welded wire mesh provides higher tensile strength, stronger bonding to the mortar, and more uniform stress distribution, which reduces deformation and increases stiffness.

5. STUDY LIMITATIONS

The current study has some limitations that should be addressed:

1. Only ten beams were tested, which is a relatively small sample size that may affect the generalizability of the results.

2. A particular eco-friendly material and retrofitting configurations were investigated. Findings may change when using different materials or configurations.

The following recommendations are proposed to address these limitations:

1. Study the effect of using a glass fiber mesh with the same opening size as the welded wire mesh in the ferrocement for retrofitting RC beams.

2. Investigate the behavior of the RC beam retrofitted using eco-friendly ferrocement mortar under two-point load on the ultimate strength.

3. Develop an enhanced eco-friendly mixture by adding SBR to improve the bonding strength of the mixture components.

4. Conduct a theoretical and experimental evaluation of RC beams retrofitted using eco-friendly ferrocement under center-point loading.

CONCLUSION

Retrofitting of the RC beams using traditional mortar, reinforced with either welded wire mesh or glass fiber mesh in a full wrapping or U-shape wrapping configurations, effectively increased their ultimate load by 13.6, 7.7, 10.3, and 6.2%, respectively, compared to the control beams. Additionally, beams retrofitted using ferrocement reinforcement with welded wire mesh exhibited lower deflection compared to those with glass fiber mesh. This is due to the higher stiffness and modulus of elasticity of the welded wire mesh compared to glass fiber mesh. Retrofitting beams using traditional mortar reinforced with either welded wire mesh or glass fiber mesh, in full wrapping configuration, resulted in increased ductility by 7.75% and 4.1% and increased stiffness by 9.2% and 6.33%, respectively, compared to U-shaped wrapping. Also, it is noted that welded wire mesh has higher ductility and stiffness compared to glass fiber mesh. The highest increase in ultimate load for beam retrofitting using eco-friendly mortar was 7.7% for BEWU as compared to the control. The stiffness of the beams retrofitted using eco-friendly mortar reinforced with welded wire or glass fiber mesh was lower than that of the beams retrofitted using traditional mortar by 20.3% and 18.8% for full wrapping and by 15.5% and 13.8% for U-shape wrapping, as well as the control beam. This was due to the presence of crumb rubber and plastic fiber, which increase voids and gaps in the mix and reduce the cohesion between the mixture components and the beam surface. In contrast, the ductility of beams retrofitted for full wrapping using eco-friendly mortar with welded wire and glass fiber mesh increases by 3.6 and 5.4%, respectively, compared to traditional mortar. Additionally, U-shape wrapped beams retrofitted with eco-friendly mortar exhibited higher ductility than those retrofitted with traditional mortar, as the eco-friendly mortar allows for greater deformation before failure.

AUTHORS' CONTRIBUTIONS

The authors confirm their contributions to the paper as follows: M.M.A.H. and S.M.A.H.: Acted as supervisors; J.M.F.: Responsible for writing the paper. All authors reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

S. F	=	Silica Fume
C.R	=	Crumb Rubber
P. F	=	Plastic Fiber
O.P.C	=	Ordinary Portland Cement
ACI	=	American Concrete Institute
ASTM	=	American Standards Testing Materials
FE	=	Finite Element
F.M	=	Fineness Modulus
GFRP	=	Glass fiber-reinforced polymer
WWM	=	Welded Wire Mesh
GPa	=	Gigapascal
IQS	=	Iraqi Standard Specifications
kN	=	Kilonewton
LVDT	=	Linear Variable Differential Transducer
M.A.S	=	Maximum Aggregate Size
mm	=	Millimeter
MPa	=	Megapascal
RC	=	Reinforced Concrete
S. G	=	Specific Gravity
w/c	=	Water/Cement ratio

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data supporting the findings of this study are available upon request from the corresponding author.

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None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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