Enhancing the flexural performance of lightweight concrete slabs with CFRP Sheets: an experimental analysis

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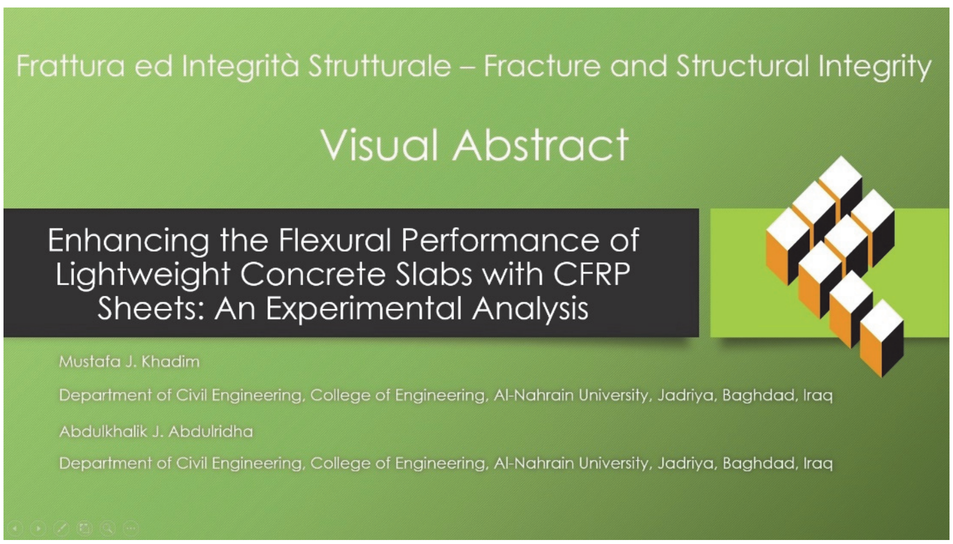

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INTRODUCTION

The ductility and stiffness of rehabilitated LWC members with completely wrapped CFRP sheets have improved over the original members. One promising strategy for preventing corrosion in concrete structures is to use fiber-reinforced polymer (FRP) as reinforcement rather than more conventional materials. The remarkable strength-to-weight ratio of FRP materials results from their resistance to corrosion. Their lightweight design, excellent tensile strength, and remarkable flexibility have made them famous worldwide. Their qualities make them an excellent choice for extending the life of concrete flat slabs. Because of its efficacy in shear reinforcement, fiber-reinforced polymer (FRP) has grown in popularity. These factors contribute to FRP's benefits, which include its lightweight construction, flexibility, and tensile solid properties. Fiberglass-reinforced plastic (FRP) rods, sheets, laminates, and sheets significantly reinforce and strengthen concrete buildings. The combination of glass fiber and light expanded clay aggregate (LECA) in this concrete produces exceptional results that are both long-lasting and environmentally friendly. Tests that would be difficult, costly, or impractical without a solid grasp of the mechanical characteristics of composite materials, as elucidated by analytical models. The elastic characteristics of Lightweight Aggregate Concrete (LWAC) have been the subject of a great deal of theoretical and computational research. Lightweight aggregate concrete, aerated concrete, and no-fines concrete are three ways to make lightweight concrete. It can get these aggregates from the ground or make them. Lightweight aggregate composites reinforced with fibers are an attractive material for this application. Among LECA composite constructions' many lauded qualities are their remarkable lightweight, fire resistance, and sound insulation [1–12].

Most lightweight aggregate-reinforced concrete parts are less intense than heavy ones. When adding FRP to RC parts, they can hold a lot more weight, even more than what the ACI standards allow. Since it is clear that the code needs to be changed, the best way to improve the performance of a structure might be to change the amount of FRP reinforcement carefully used. As the FRP strengthening level goes up, resistance to movement and energy flexibility decrease. Tensile compression stress on beam supports has gone down since CFRP was used. Several studies [13–19] have shown that CFRP may improve how well it absorbs energy, holds loads, and bends in the middle. The study showed that rebar-reinforced plastic sheets made lightweight concrete slabs more resistant to bending. Researchers Golham and Al-Ahmed (2024) [20] say that adding CFRP strips to concrete slabs with holes makes them more robust and able to handle more weight. It was found that CFRP laminates changed the strength and breakdown mode of the slabs, which is similar to what Abed and Medhlom found in 2023 [21]. All of our results together show that CFRP sheets might make thin concrete slabs much more potent when they are pulled apart. Flat surfaces made of reinforced concrete and strengthened with CFRP sheets were less likely to bend and could hold more weight [22]. Studies have shown that CFRP sheets could strengthen lightweight concrete bases.

Lack of weight in concrete, or LWC, is becoming more famous since it can be used in many ways in the building business. Loose-weight concrete (LWC) usually has a density of between 300 and 2000 kg/m^3 after being baked. Adding lightweight materials (LWA), which can be artificial or found naturally, is a popular way to improve the binding matrix. LWAC is a beneficial material that can be used in many ways because it has a great mix of low density and high strength. Because of a drop in self-weight, straight parts like slabs or beams may feel lower maximum moments and shear forces. Because of this, it is now possible to build buildings with either considerable lengths or small cross-sections. In places where shocks are standard, LWAC has extra benefits. When applied to moving concrete buildings, LWAC can make them much lighter and less stiff, making them work better; when limited base space, lightweight composite (LWAC) houses are often the most cost-effective choice. Changing things about houses usually makes money [23–34].

Thus, the decrease in mechanical strength of LWA is expected also to affect the punching shear resistance. This is because the aggregates may break, resulting in a decrease in friction stress along the cracks. Several production methods are available for classifying different types of Lightweight Concrete (LWC). There are two types of concrete: Aggregate Lightweight Concrete and Concrete with bubbled voids, also referred to as aerated, cellular, foamed, or gas concrete. c) Concrete without fine aggregate, known as no-fines concrete. Various forms of lightweight concrete have distinct applications. A type of concrete known as structural lightweight concrete possesses both strengths and falls within a specific density range. Another type, masonry concrete, serves structural and insulating purposes and possesses a specific compressive strength and density. Finally, insulating concrete has its own specific compressive strength and density requirements. It stands for Light Expanded Clay Aggregate. Expanded Clay aggregate is a ceramic product known for its consistent pore structure, which enables excellent porosity. This is made in rotary kilns using raw materials that contain clay minerals. Once the raw material is meticulously prepared, it is subjected to a high-temperature firing process, usually between 1100 °C and 1200 °C. This process significantly increases volume, resulting in the desired outcome [35-42].

Carbon fiber reinforced plastic (CFRP) sheets were used at the bottoms of the slabs in this work to restore the resistance of lightweight concrete that had been cracked. This was the original contribution of this work. Damage can be of varying degrees and percentages. To achieve the primary aim of this work, the flexural behavior of two-way reinforced lightweight concrete slabs that have been strengthened or repaired with carbon fiber reinforced polymer (CFRP) sheets that have been bonded to their exteriors will be investigated by experimental means. While the experiment was being conducted, five reinforced lightweight concrete slab samples measuring 1000 mm by 1000 mm by 120 mm were examined and evaluated. One reinforced slab and three repaired slabs were constructed using damage ratio treatments at 50%, 60%, and 70% of the ultimate load on a single layer of carbon fiber-reinforced polymer (CFRP). The slabs were damaged in the same way. The reinforced slab was the portion of the structure that was damaged the most. It can evaluate the performance of carbon fiber-reinforced plastic (CFRP) slabs that have been strengthened or repaired, and it may also use a control specimen that has not been reinforced under any circumstances. They must meet particular flexure failure requirements since the specimens are of a consistent size and the reinforced concrete slab is used. When the primary support conditions were met, a weight was introduced and dispersed across the middle of each section.

OUTLINE OF THE EXPERIMENTAL SECTION

This research investigates the behavior of reinforced lightweight concrete slabs subjected to varying degrees of damage, ranging from five% to seventy%. The carbon fiber-reinforced plastic (CFRP) strengthens or mends anything. A monotonic one-point focused load was applied to five two-way slab specimens to evaluate the flexural behavior of reinforced lightweight concrete slabs. The results were taken into consideration. The slab's dimensions being examined were 1,000 mm, 1,000 mm in breadth, and 120 mm in height. A square stub column had dimensions of 150 mm in width, 150 mm, and 100 mm in height. In every direction, the foundation layer contained tension reinforcement with a thickness that ranged from nine to twelve mm. The effects of applying heating and shrinking to the top layer are depicted in Figure 1. These processes reinforced the top layer of 4 Ø 10 mm in both directions. The slab specimens are described in Tab.1, the chemical properties of the cement are described in Tab. 2, and the physical characteristics of the cement are discussed in Tab. 3. According to Tab. 4, the experiment used natural sand with a maximum particle size of 4.75 mm. This was done under the grading rules established in the Iraqi standard specification I.Q.S. No. 45-1984. The lightweight aggregate (LECA) was used in the laboratory to conduct the experiment as an alternative to the coarse aggregate. The maximum diameter of the LECA was 8 mm. Testing was performed on this sand under the Iraqi standard I.Q.S. No.45-1984, as seen in Tab. 5

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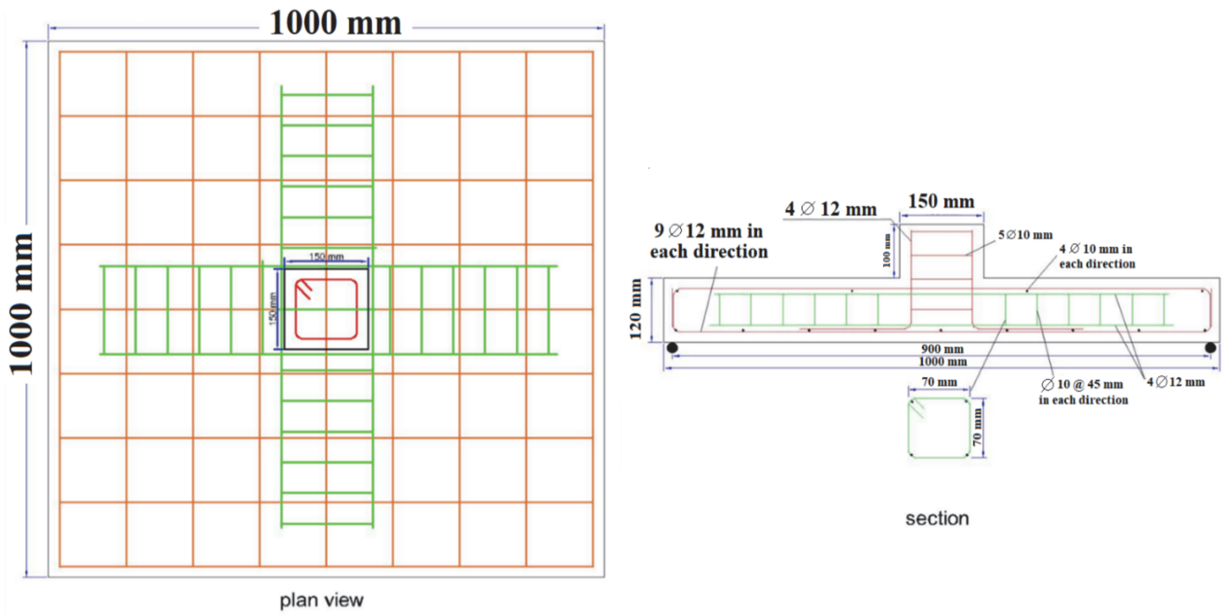

Figure 1: Dimensions of the specimen used in this investigation.

Specimen designation	Description
SC-Control	slab without CFRP
SF-S-0	Carbon fiber-covered reinforced concrete slab without any previous damage
SF-R-70	damaged slab under 70% damage with a full layer of CFRP sheet
SF-R-60	damaged slab under 60% damage with a full layer of CFRP sheet
SF-R-50	damaged slab under 50% damage with a full layer of CFRP sheet

Table 1: Characteristics of beam specimens.

Composition of the Compound	Chemical composition	%(weight) test results	I.Q. S. No. 5/2019 Limitations
Loss on ignition	L.O.I	3.71	≤ 4%
Non soluble substances		0.62	≤ 1.5
Sulfate content	SO3	2.36	2.5 if C3A ≤ 3.5 2.8 if C3A ≥ 3.5
Tricalcium Aluminates	C3A	2.91	Not Specified
Magnesium Oxide	MgO	1.83	5.0
Chloride content		0.04	0.1

Table 2: Chemical analysis of cement.

Physical Characteristics		Test results	I.Q. S. No. 5/2019 Limitations
Finesse (Blaine)	m^2/kg	366	≥ 280
Initial Setting Time	minute	135	≥ 45
Final Setting Time	hours	2:54	≤ 10
Soundness (expansion)	mm	0.52	≤ 10
Compressive strength is not less than (N/mm^2)	2d	24.9	≥ 20.0
	28d	48.9	≥ 42.5

Table 3: Cement Physical Analysis.

Sieve Size	% Passing by weight
10 mm	100
4.75 mm	94
2.36 mm	83
1.18 mm	57
600 µm	46
300 µm	11
150 µm	3

Table 4: Analyses of sand sieves.

Declared performance: Essential characteristics	Performance	
Particle shape	Semi-Round/cracked	
Aggregate size	0 -8mm	
Aggregate size distribution (Dry Sieving)		Passing
	Sieves	
	25 mm	100 %
	19 mm	100 %
	12.5 mm	100 %
	9.5 mm	90 %
	4.75 mm	42 %
	2.36 mm	13 %
	1.18 mm	7 %
	0,3 mm	0-1%
	0.15 mm	0-0.5 %
Loose bulk density Limits Typical	700 kg/m^3	

Table 5: sieve analyses of LECA.

This study used a super-plasticizer known as PC600 to ensure excellent workability with a low (water/cement) ratio. Its specific gravity is 1.22, and its properties satisfy ASTM C494 and BS 5075 standards. Tap water was used to mix and cure concrete. The water used in this investigation was as pure and straightforward as feasible. This study used deformed steel bars with 10 mm and 12 mm diameters. Tensile tests were conducted on the steel reinforcement according to the specifications outlined in ASTM A615M-16 at the Laboratory of the Civil Engineering Department at Al-Nahrain University. The primary data collected are presented in Tab. 6. The slabs have been externally reinforced with CFRP BASF MasterBrace, which consists of unidirectional, woven, carbon-fiber textiles. Tab. 7 shows the CFRP laminates' mechanical properties. MasterBrace epoxy resin SAT 4500 is specifically designed to be used with MasterBrace FIB sheets. This adhesive substance consists of a base (Part A) and a reactor (Part B) mixed in a 2A:1B ratio. The mechanical and physical characteristics of the bonding resin are presented in Tab. 8. The mix design lists presented in Tab. 9 measured in (kg/m^3), and a W/C ratio of 0.3 was utilized in this experimental work with a Dry density of 1713.4 kg/m^3 and cube compressive strength of 37 MPa determined at 28-day.

Bar size(mm)	Area mm^2	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)	Elongation (%)	Es (GPa)
10	76.0	435.2	536.1	12.45	200
12	113.1	502.0	676.6	13.21	200

Table 6: Steel bar test.

Properties	CFRP sheet
Thickness (mm)	0.166
Width (mm)	500
Tensile Strength (MPa)	4900
Fiber Weight (g/m²)	300
Elasticity (GPa)	230

Table 7: Technical features of CFRP.

Properties	MasterBrace SAT 4500
Composition	Two parts (A & B)
Mixed density	1.06 kg / Lt
Color	Blue
Bond strength	>2.5 N/mm² (Failure in concrete)
Full cure	7 days at 20°C

Table 8: The bonding materials' properties.

Material	Cement(kg/m³)	Sand (kg/m³)	LECA (kg/m³)	Water (kg/m³)	Admixture (Liter/m³)
Quantity	465	600	490	139.5	4.65

Table 9: Ratios of concrete ingredients.

THE TECHNIQUE FOR REHABILITATION

Fig. 2 shows the procedure for installing CFRP sheets to cover the slab specimen's tension bottom, which has dimensions of 850 x 850 mm. As illustrated in Fig. 3, the three specimens with damage of 50%, 60%, and 70%, respectively, were restored using a complete layer of CFRP sheets.

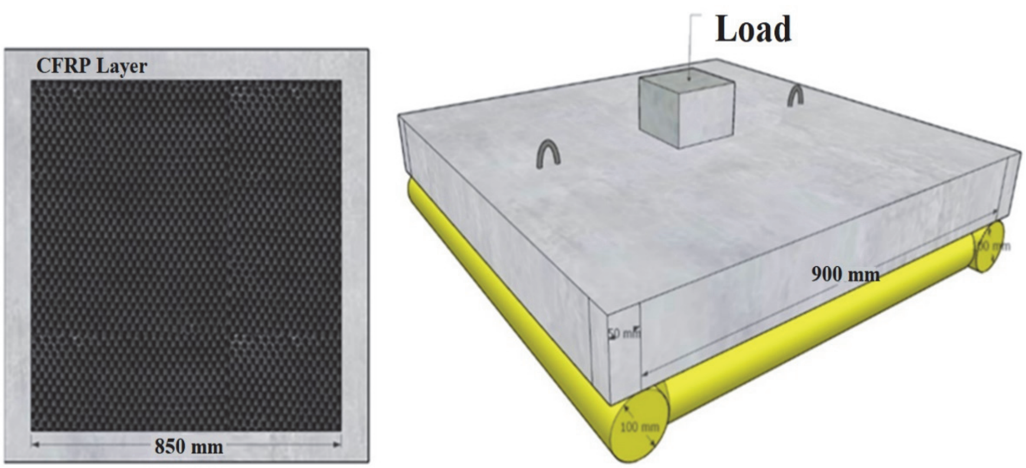

Figure 2: Full layer of CFRP sheet.

REHABILITATION PROCEDURE

The CFRP strip is cut to appropriate lengths and cleaned to ensure the carbon fiber-reinforced polymer (CFRP) is installed correctly and does not come off during lab tests. The slab specimens are prepared using an angle grinder to remove dust and grease. Once prepared, two epoxy parts (MasterBrace SAT 4500) are mixed and applied to the slab's tension face. Any air voids between the CFRP strips and epoxy are removed using a plastic roller. After seven days of curing, the slab reaches its full strength and is ready for testing. The mechanical repair with CFRP sheet, as shown in Fig. 4

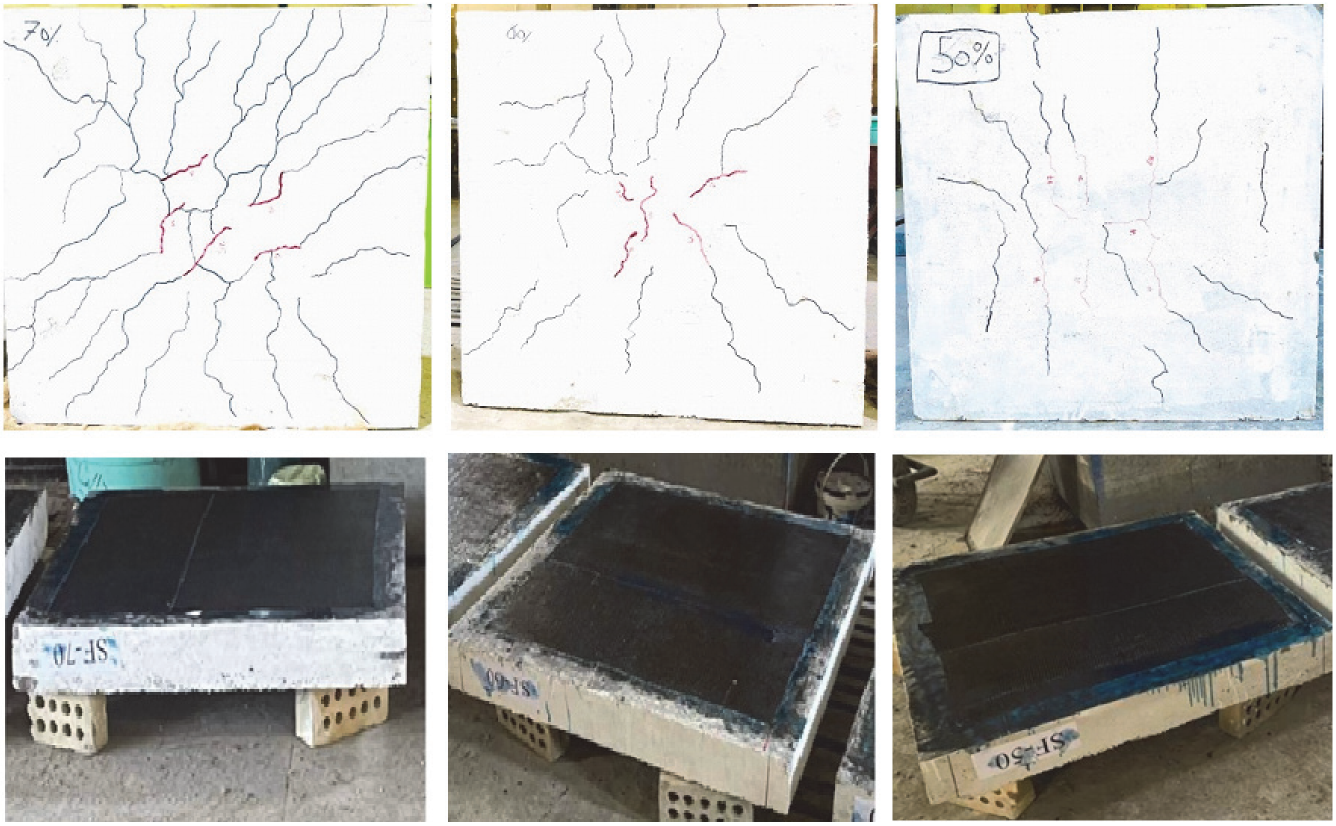

Figure 3: Specimens with damage of 50%, 60% and 70%.

Figure 4: Mechanical repairing with CFRP sheet.

Results and discussion

Load capacity

The load capacity of LWAC slabs was rehabilitated using one CFRP sheet layer. The results and discussion of the experiment are presented below. Tab. 10 demonstrate the extent and magnitude of damage to the ultimate load capacity (Pu). Changing the degree of damage from 70% to 50% increased the ultimate load capacity by 10.9%, 12.6%, and 17.7% for SF-70, SF-60, and SF-50, respectively. Further, this increase resulted in a 30.2% improvement in the strength of the strengthened specimen (SF-S-0). It is worth noting that the slab (SF-S-0), after rehabilitation, exhibited the most significant enhancement in ultimate load capacity by over 330 kN on average compared to slabs with other damage ratios. This outcome indicates that the CFRP layer effectively improved the slab's strength. This means that the CFRP layer contributed to the strength of the slab effectively. The size and extent of the damage to the Ultimate deflection (Δu) are shown in Tab. 10. As compared to the ultimate deflection of the control slab specimen that is not strengthened, the deflection of the center section of the slabs (SF-S-0 strengthened, SF-R-70, SF-R-60, and SF-R-50) decreases by about 15.6%, 13.3%, 20.9%, and 31.4%, respectively. All specimens' load-deflection curves are shown in Fig. 5. According to the results, the CFRP-Epoxy composite's rigidity mitigated all damage grades, thanks to its outstanding mechanical properties throughout the initial reaction phases. There was a gradual decrease as the damage progressed because the concrete fragments were crushed to varying degrees before repair. This is similar to what was obtained from previous researchers Atefatdoost et al. (2022) [21], Abed and Medhlom (2023) [22] and Shabestani et al. (2022) [43]. They found that the most optimal array of the retrofitting material increases the capacities for two-way slabs by 18-30%.

Specimen symbols	Ultimate load (Pu) (KN)	Ultimate deflection Δu (mm)	Changing ultimate load Pu %	Decreases ultimate deflection Δu %
SC	254.1	16.3	----	----
SF-S-0	330.8	13.7	30.2	15.6
SF-R-70	281.8	14.1	10.9	13.3
SF-R-60	286.1	12.9	12.6	20.9
SF-R-50	299.2	11.2	17.7	31.4

Table 10: Results of load and displacement.

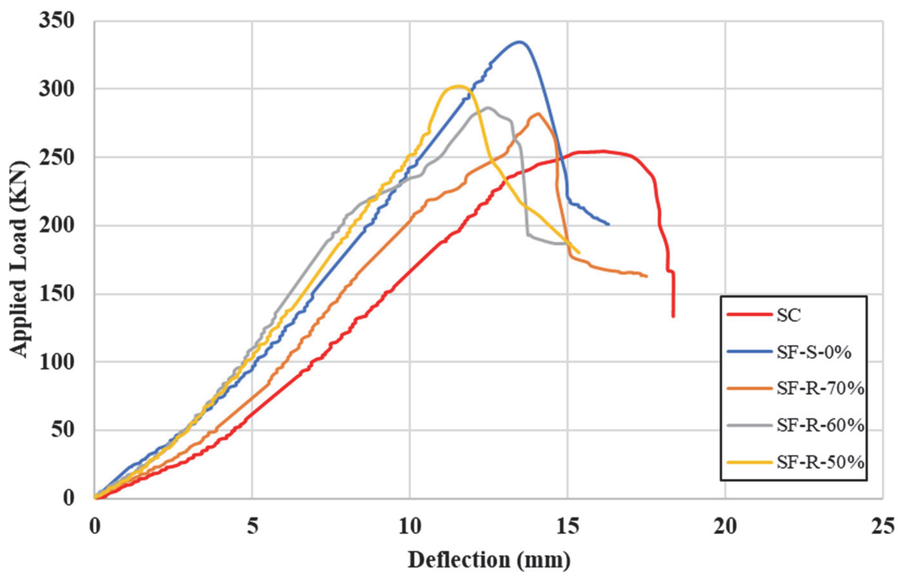

Figure 5: Load-deflection curve.

Compared to the repaired slabs, the damaged ones could support more weight when the repairs were completed. In contrast to the restored slabs, the mended ones had several advantages and disadvantages. According to the data, carbon fiber reinforced polymer (CFRP) significantly affected the slab. Several approaches were also used to ascertain how the process affected the Ultimate shift (Δu). The research led us to believe that the combination of epoxy and CFRP provides superior protection when exposed to harmful elements. Since the repair of the concrete caused the degrees of damage to reduce over time, it had likely been crushed in various ways in the past. The findings suggest that coating LWAC slabs with carbon fiber-reinforced plastic (CFRP) might improve their strength and load-bearing capacity. Due to this, costly repairs and maintenance may be needed less often. Because LWC slabs progressively lose strength as they decay, an immediate solution is necessary to address this problem. The stiffness and flexibility of LWC beams must be maintained when they are faced with destruction. There has to be an emphasis on this. A possible solution to the problem of weak LWC slabs and the structures underneath them might be to thicken them with an extra layer of carbon fiber-reinforced plastic (CFRP). It would be mutually beneficial. Previous researchers Atefatdoost et al. (2022) [21], Abed and Medhlom (2023) [22], and Shabestani et al. (2022) [43] obtained identical results. This technique is effective for repairing the mentioned slabs. CFRP sheets can considerably restore the slab's flexural rigidity, and in certain cases, it can even surpass that of a homogeneous slab.

Failure mode

The failure manner of the control specimen may be seen visually in Fig. 6. The usual mechanism of tension failure, flexure failure, was observed in the control specimen. The expectation was that cracks would spread. None of the fractures have reached the extreme compression face. As seen in Fig. 7, the fissures widened in (SF-R-50), (SF-R-60), and (SF-R-70) as the severity of the damage increased. At all damage levels indicated, crushing failure and debonding became the failure mechanism after rehabilitation. The reinforced slab (SF-S-0) failed in the same way. The CFRP sheet strengthening and repairing can enhance the strength of reinforced concrete members. Also, the CFRP sheet is suitable for repairing RC members due to its ease of installation and other characteristic values. The CFRP sheets resist cracking, corrosion, and temperature, making them the best choice for concrete production. Externally bonded CFRP sheets significantly contributed to repairing the beams, refreshing the initial shear capacity, and increasing the ultimate capacity. Reinforced concrete slabs repaired by composite materials (CFRP) sheets significantly increase failure load compared to unreinforced slabs and prevent crack propagation compared to unreinforced slabs. Using CFRP sheets to repair lightweight concrete slabs is a promising repair method.

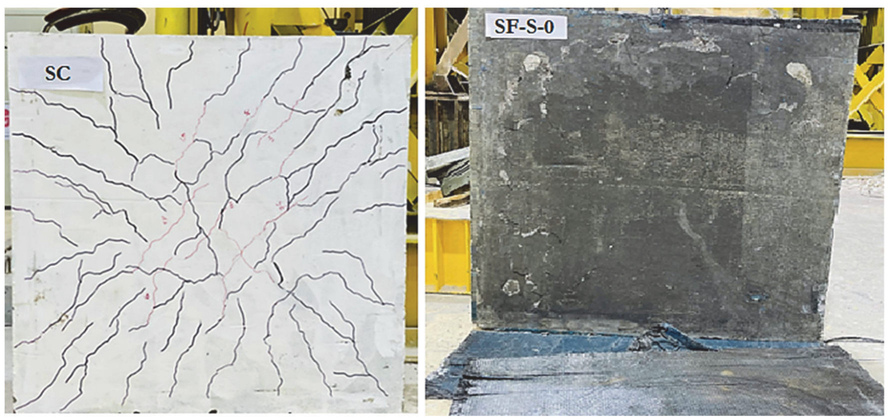

Figure 6: The mode of failure for control slab and strengthened slab.

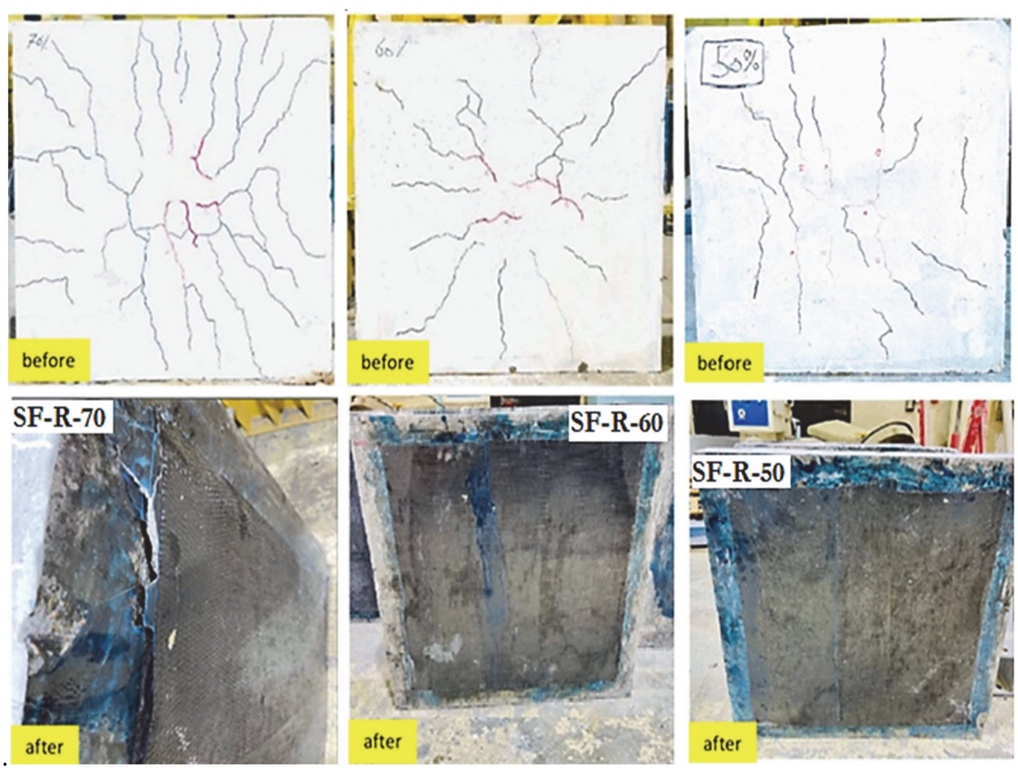

Figure 7: The mode of failure for the one layer of CFRP sheets rehabilitation technique.

Conclusions

An experimental analysis of the flexural behavior of two-way reinforced lightweight concrete slabs that have been repaired or strengthened with carbon fiber reinforced polymer (CFRP) sheets that have been bonded to their exteriors is the primary objective of this work. In the course of the experiment, five samples of reinforced lightweight concrete slabs were examined and evaluated. Using a single layer of carbon fiber-reinforced polymer (CFRP), damage ratio treatments at 50%, 60%, and 70% of the ultimate load resulted in one reinforced slab and three repaired slabs. Based on the study, the following conclusions can be drawn:

1. Repairing the specimens with CFRP sheets increased the failure load of reinforced concrete slabs and effectively prevented crack propagation. A possible solution to the problem of weak LWC slabs and the structures underneath them might be to thicken them with an extra layer of carbon fiber-reinforced plastic (CFRP).
2. The CFRP strengthening has good mechanical properties, making it suitable for enhancing the strength of reinforced concrete slabs and efficiently repairing them.
3. The application of CFRP strips significantly increases the load-bearing capacity of the reinforced concrete damaged slabs by about 17.7% and improves their stiffness. However, the increase in the damage ratio reduces the effectiveness of rehabilitation.
4. The ultimate displacement capacity of the rehabilitated structures decreases by an average of 31.4%. The CFRP sheet technique significantly enhanced the flexural capacity of pre-cracked reinforced concrete two-way slabs.
5. The performance characterization parameters of the proposed approaches, including service load and load-bearing capacity, exhibit a discernible decline with increasing damage in the LWC beams. Nevertheless, the ultimate load capacity climbed by 30.3% at the strengthened specimen, 17.7% at the 50% damage level, 12.6% at the 60% damage level, and 10.9% at the 70% damage level.
6. The ultimate deflection decreased by 31.4% at a damage level of 50%, 20.9% at a damage level of 60%, and 13.3% at a damage level of 70%, while it decreased by only 15.6% at a strengthened specimen.
7. The carrying capacity of LWC slabs decreases as deterioration increases and the degree of damage incurred by LWC slabs affects their ductility and stiffness.
8. Compared to the repaired slabs, the damaged ones could support more weight when the repairs were completed. In contrast to the restored slabs, the mended ones had several advantages and disadvantages. According to the data, carbon fiber reinforced polymer (CFRP) significantly affected the slab.
9. The research led us to believe that the combination of epoxy and CFRP provides superior protection when exposed to harmful elements. Since the repair of the concrete caused the degrees of damage to reduce over time, it had likely been crushed in various ways in the past. The findings suggest that coating LWAC slabs with carbon fiber-reinforced plastic (CFRP) might improve their strength and load-bearing capacity.

Future research recommendations

To improve the load capacity of reinforced concrete beams, it is recommended that future studies and professional engineers work on improving design standards and regulations for optimal amounts of FRP reinforcement. Also, FRP-strengthened beams must reduce the delamination and deboning of FRP laminates so that they last longer and are more resilient. To make informed decisions when designing and analyzing FRP-reinforced structures, it is essential to improve predictive modelling techniques that consider material nonlinearity, interface behavior, and failure mechanisms. This will allow for more accurate predictions of structural behavior.

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LIST OF SYMBOLS

CFRP	Carbon fiber-reinforced polymer
LWC	Lightweight concrete
RC	Reinforced concrete
FRP	Fiber-reinforced polymer
LECA	Light expanded clay aggregate
I.Q.S.	Iraqi standard specification
fy	Yield strength
fu	Ultimate strength
Es	Modulus of elasticity for steel
Pu	Ultimate load
Δu	Ultimate deflection