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Abstract

Among many manufacturing industries, civil engineering sectors have been more involved in incorporating fiber reinforced polymer (FRP) composites. These composite materials have been selected as an appropriate solution for strengthening reinforced concrete structural elements because of their excellent tensile strength, high strength to weight ratio, and simplicity of implementation. This experimental study aims to evaluate the flexural behaviors of structural light-weight reinforced concrete (SLWC) one-way slabs strengthened with different patterns of CFRP. The proposed material in the current study is using pumice aggregate as a full replacement of natural coarse aggregate. Four structural light-weight concrete (SLWC) slabs with the dimensions of 1200 mm long, 450 mm wide, and 80 mm thick were cast and tested to failure. One slab has been taken as a control and the other samplesare strengthened with five strips in one layer, ten strips in two layers and full wrap CFRP. The samples are tested under a four-point load bending test setup until failure. Each of the ultimate loads, mid-span deflection, cracking loads, crack patterns, and failure modes were well evaluated. The results showed that, strengthening with CFRP composites significantly increases load-carrying capacity. Strengthening with five strips, ten strips, and full wrap with CFRP increased the ultimate capacity by 115%, 138%, and 170% respectively and decreased mid-span deflection by 43%, 58%, and 55% compared to the reference specimen respectively.

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Strengthening, Structural light-weight concrete, FRP composites, One-way slabs, Flexural behavior

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RESEARCH ARTICLE

Utilization of Carbon Fiber Reinforced Polymer for Strengthening of Structural Light-weight Reinforced Concrete One-way Slabs

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ABSTRACT

Among many manufacturing industries, civil engineering sectors have been more involved in incorporating fiber reinforced polymer (FRP) composites. These composite materials have been selected as an appropriate solution for strengthening reinforced concrete structural elements because of their excellent tensile strength, high strength to weight ratio, and simplicity of implementation. This experimental study aims to evaluate the flexural behaviors of structural light-weight reinforced concrete (SLWC) one-way slabs strengthened with different patterns of CFRP. The proposed material in the current study is using pumice aggregate as a full replacement of natural coarse aggregate. Four structural light-weight concrete (SLWC) slabs with the dimensions of 1200 mm long, 450 mm wide, and 80 mm thick were cast and tested to failure. One slab has been taken as a control and the other samples are strengthened with five strips in one layer, ten strips in two layers and full wrap CFRP. The samples are tested under a four-point load bending test setup until failure. Each of the ultimate loads, mid-span deflection, cracking loads, crack patterns, and failure modes were well evaluated. The results showed that, strengthening with CFRP composites significantly increases load-carrying capacity. Strengthening with five strips, ten strips, and full wrap with CFRP increased the ultimate capacity by 115%, 138%, and 170% respectively and decreased mid-span deflection by 43%, 58%, and 55% compared to the reference specimen respectively.

Key words: Strengthening, Structural light-weight concrete, FRP composites, One-way slabs, Flexural behavior

INTRODUCTION

Whenever structural dead-loads are required to be reduced, lightweight concrete (LWC) is commonly utilized as a substitute to conventional concrete (Liu, Chia and Zhang, 2010). According to the ACI building code, light-weight concrete is classified into two main types: non-structural light-weight concrete (NSLWC) and structural light-weight concrete (SLWC) (ACI 213R-03, 2003). Whenever the minimum 28-day compressive strength and density of a mixture are 17 MPa and (1120 - 1920 kg/m^3) respectively, the mixture is considered as structural lightweight concrete (SLWC) (ACI 213R-03, 2003). The reduction in the overall dead load of the structural system is extremely significant because it permits longer span to be cast, thus saving the construction time for each floor. Moreover, reducing structural dead load makes savings in foundations and reinforcements. The most heavyweight structural element in reinforced concrete buildings is slab, due to its large volume and high unit weight of normal concrete. Utilizing light-weight concrete allows designers to minimize column, beam and footing dimensions. Strengthening agents have a massive effect on the capacity of flexural members. Numerous theoretical and experimental investigations have been conducted to investigate the effect of these strengthening agents on the structural response and capacity of different structural members. The main purpose of strengthening is to increase, maintain, or restore the desired structural capacity of reinforced concrete members, whether they are made of normal or lightweight concrete (Faria, Lúcio and Ramos, 2011). Cement grout, epoxy injection, different types of fiber reinforced polymers (FRP), ferrocement, and steel jacketing are a few of the alternatives provided for strengthening and reinforcing different reinforced concrete structural members (Shbeeb *et al.*, 2012).

FRP composites have multiple uses in structural engineering, such as strengthening reinforced concrete elements. One of the best strengthening technics is using FRP composite to improve flexural, shear and torsional strength of different reinforced concrete structural members. The main reason that strengthening with FRP composites are one of the best technique is FRPs are incredibly strong, eight times more durable than conventional steel reinforcement bars (Gdoutos,

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Pilakoutas and Rodopoulos, 2000). Strengthening is required for many reasons, such as underestimating the loads added to the members because of simple design errors, building (implementation) errors leading to the formation of a weak member and increasing loads on the part because of change in application. In the case of structural lightweight slabs, strengthening is required to compensate the eliminated strength capacity due to the utilization of lightweight aggregates. FRP composites are available in various shapes and forms, such as FRP bars that are suitable as internal reinforcements for new buildings. Another form of FRP is sheet or plate form for externally strengthening purposes (Ehsani, 2005). The widely used fibers in civil and structural engineering can be divided into four main types: Carbon, Glass, Aramid, and Basalt. Each of these fibers has its own properties and exhibits a substantial role in the enhancement of structural efficiency (Blanksvärd and Täljsten, 2008).

Carbon fibers are one of the strongest types and the most widely used fibers since they have good tensile strength approximately 2.7 GPa to 3.9 GPa and a high Young module about 120 GPa (ACI 440.6M-08, 2008). The diameter of micro-fibers of CFRP sheets is approximately five to ten micrometer. The fibers consist of carbon atoms that bind both in crystals, the crystal structure gives a high strength to volume ratio (Breña *et al.*, 2001). CFRP composites consist of reinforcement which is carbon fiber providing strength and durability and a matrix for holding fibers together, this matrix usually is a polymer resin, such as epoxy (Mugahed Amran *et al.*, 2018).

Widely known failure modes that have been observed from literature studies on strengthened RC elements with different types of FRP composites are rupture of FRP sheet, debonding of FRP sheet from the concrete, and separation of concrete cover(ACI 440.2R-17, 2017). The externally attached FRP would collapse if the FRP strain exceeds the final strain while the concrete does not reach its crush strain in the top compression fiber. FRP debonding typically takes place where the axial force cannot be supported by concrete in bended FRP reinforcement. The splitting of the concrete cover is another kind of failure mode that normally produces cracks near the end of the FRP at high stress levels, which extracts the concrete cover from the FRP composites that are attached externally (Naser, Hawileh and Abdalla, 2019). The effects of CFRP on the behavior of SLWC one-way slabs have only been investigated in a limited number of studies. Shbeeb *et al.*, 2012 evaluated the effects of CFRP strengthening on the flexural behaviors of pre-loaded SLWC slabs. The length of the slabs was 1200 mm, and their cross sections measured as 70 * 500 mm in both depth and width, respectively. All specimens were reinforced with 3 Φ 10 mm as main reinforcement. The specimens strengthened with CFRP Sheets and strips and loaded until failure under four-point loading setup. As a result, a significant decrease in the amount of deflections at the mid-span (% 40 on average) was observed. Additionally, the increment in the maximum capacity was more than double compared to the control specimen, and a substantial improvement in stiffness was also observed. Therefore, the main purpose of the present study is to gain a better understanding of the influence of externally CFRP strengthening on the behavior and capacity of structurally light-weight reinforced concrete one-way slabs.

EXPERIMENTAL PROGRAM

Materials and concrete mixes

The light-weight concrete made with natural fine aggregate and pumice stone as a light-weight coarse aggregate. Ordinary Portland cement (OPC) was used. The chemical and physical properties of used cement are presented in Table 1. Throughout the whole of the experimental work, the cement was kept in nylon bags so that it would remain in excellent condition and the effects of humidity would be reduced as much as possible.

Natural fine aggregate and pumice stone as a lightweight coarse aggregate were utilized for producing structural light-weight concrete. The maximum aggregate size of pumice was 12.5 mm. The particle size distribution curves for fine and coarse aggregates are presented in Figure 1 and Figure 2, respectively. Table 2 presents specific gravity and water absorption (%) for both types of aggregate according to (ASTM C127-7, 2009).

Table 1. Chemical and physical properties of used cement

Physical Properties			Chemical compositions		
Properties	Test result of used cement	ASTM limit	Item	Test result of used cement (%)	ASTM limit
			SiO_2	19.13	---
Setting time by Vicate (ASTM C191–04, 2007)			Al_2O_3	5.16	---
Initial (min.)	110	Min 45	Fe_2O_3	2.43	---
			CaO	62.68	---
			MgO	6.17	6.0 Max
Compressive strength (paste) (ASTM C150, 2015)		Min (MPa)	SO_3	2.19	3.0 Max
3 days	37.2	7	K_2O	2.02	---
7 days	39.06	12			
28 days	43.55	28	MnO	0.22	---

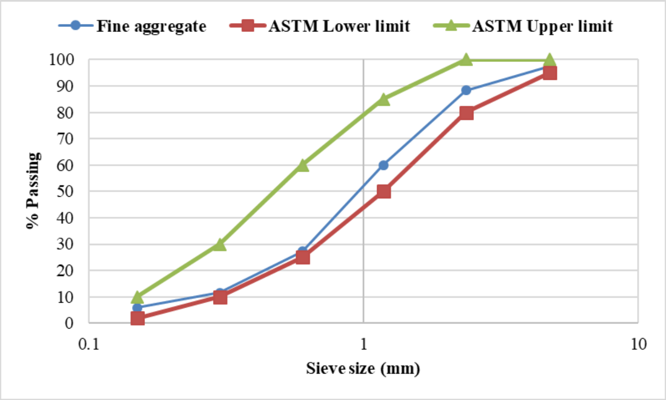


Figure 1. Gradation curve for natural fine aggregate (ASTM C33, 2001)

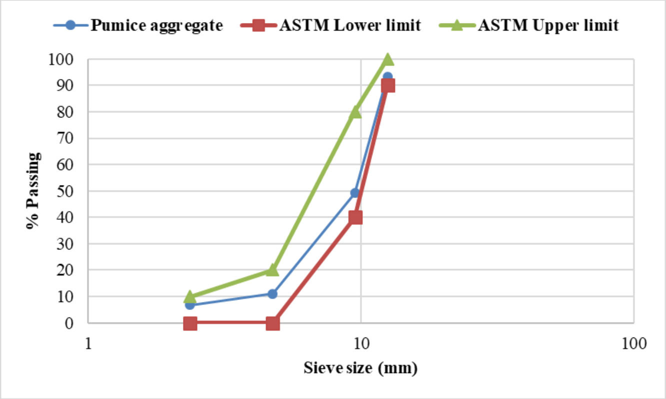


Figure 2. Gradation curve for lightweight coarse aggregate (ASTM C330, 2011)

Table 2. Properties of used aggregates

Type of Aggregate	Average SG	Apparent SG	Water absorption (%)
Natural fine aggregate	2.68	2.8	1.67
Lightweight coarse aggregate (Pumice)	0.79	1.34	51.75

A graded 60 steel bars with 8 mm in diameter and a yield strength of 420 MPa were imbedded in all slab specimens as the main reinforcement, as well as temperature and shrinkage reinforcement. In order to assess the steel bars tensile strength and other mechanical characteristics, tensile tests were performed using a standard testing machine. Three samples were tested and the outcomes of average yield strength, ultimate strength, and elongation percentage are shown in Table 3.

The utilized CFRP in this experimental investigation was unidirectional Sika Wrap 300C and installed by Sikadur-330 epoxy. The physical properties of CFRP is presented in Table 4.

Table 3. Mechanical properties of steel bars

Bar diameter	Cross-sectional area (mm2)	Elongation at failure (%)	Yield strength (MPa)	Ultimate tensile strength (MPa)
8 mm	50.27	20.6	473.1	671.4

Table 4. Physical properties of Sika Wrap 300C

Type of fiber	High strength carbon fibers
Fiber orientations	0° (unidirectional)
Weight	300g/m2 ± 5 %
Density	1.80 g/cm3
Thickness	0.17 mm
Tensile strength	3900 MPa
Modulus of elasticity	230000 MPa
Rapture strain	1.5 %

In order to fulfil the requirements of ASTM, the SLWC must have a minimum 28-days compressive strength of 17 MPa and a maximum density of 1920 kg/m^3 (ASTM C330-04, 2009). The (ACI 211.1-91, 2002) was used to figure out the first test mix for lightweight concrete. After a few laboratory trails, a lightweight mix designed with a 28 days' compressive strength and density of 24 MPa and 1786 kg/m^3 respectively. The slump value was measured according to (ASTM-C143, 2008) and equals to 130 mm. Table 5 provides an outline of the mix design.

One-way slab specimens

Four structural lightweight reinforced concrete one-way slabs were cast for strengthening purposes. The specimens have a length of 1200 mm, a width of 450 mm and a depth of 80 mm. The reinforcement ratio was 0.0081 (4 Φ 8 mm). The concrete cover was 20 mm at the bottom and 25 mm at the sides. One of the specimens was reference and the other three specimens were strengthened with CFRP to investigate the influence of different FRP layers and patterns on the structural response and capacity of SLWC slabs. The designation and details of specimens are presented in Table 6 and Figure 3.

Table 5. Details of SLWC mix design

Mix	Proportions (Kg)/m3				Design strength (MPa)	Slump (mm)	w/c ratio
	Cement	Natural fine agg	Lightweight pumice agg	Water			
Light-weight mix	556	735	390	200	25	130	0.36

Table 6. The designation of slabs

Label	Reinforcement ratio	Main reinforcement	Transverse reinforcement	Dimensions (mm)	Description	Strengthening details (CFRP)
S1	0.0081	4 Φ 8 mm	5 Φ 8 mm	Length= 1200 Width= 450 Depth= 80	Reference (Un-strengthened)	None
S2					Strengthened with CFRP	5 strips (5 cm) 1 layer
S3					Strengthened with CFRP	5 strips (5 cm) 2 layers
S4					Strengthened with CFRP	Full wrap

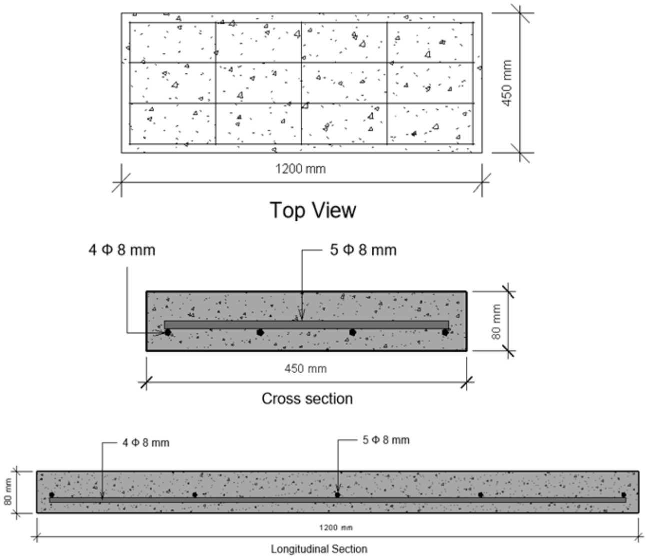


Figure 3. The details of one-way slabs

FRP installation

The surface of specimens was prepared to produce a surface that is profiled and open-textured as well as to remove any cement laitance and any weak and friable elements. Honeycombing, blowholes, and cavities on the surface, along with any other surface defects, have to be thoroughly revealed. Sikadur-330 is a two-component epoxy that used for the resin priming coat and as the impregnating resin. After the surface had been prepared, the appropriate dimensions for the FRP sheets were determined, and the lines were created on the concrete surface according to the designed patterns. As can be seen in Figure 4, the FRP sheets were trimmed by special sharp scissors to the specified dimensions, which were 1000 mm in length and 450 mm in width for full wrap and a width of 50 mm for strips. Then, by using the dry lay-up technique, the FRP was attached to the tension face of the specimens.

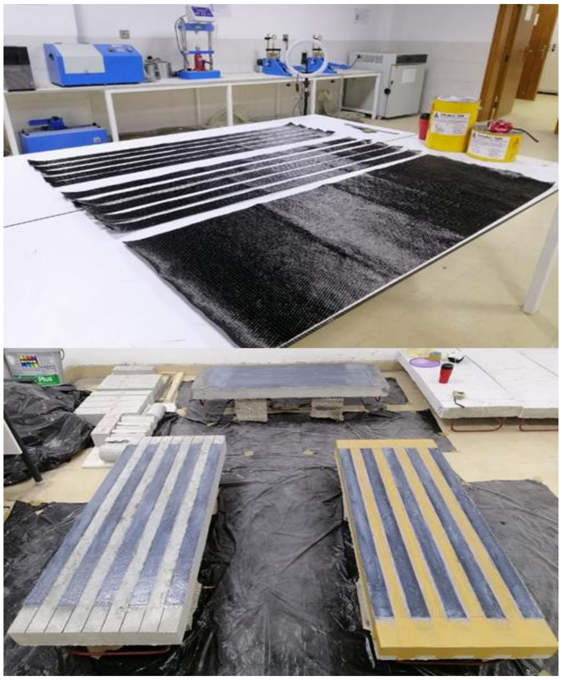


Figure 4. Sika wrap 300C and Sikadur 330 & strengthened specimens

Instrumentation and testing procedure

All four specimens were tested under four-point bending tests after 60 days from casting. All one-way slabs were simply supported at a 1000 mm span and accurately exposed to two-line loads in the L/3 of the span and tested by a hydraulic flexural machine with a capacity of 2000 kN as shown in Figure 5. Deflection at the mid span was recorded throughout loading history using an electrical transformer known as a linear variable differential transducer (LVDT). An electrical strain gauges were attached to the compression zone of the concrete and FRP in the loading direction in order to get an accurate reading of strains. The slab specimens were tested at a constant rate of loading of 0.2 kN/s until failure. On the same day, the compressive strength, flexural strength, and splitting tensile tests were also conducted using the accessories for the compressive testing machine. The last property that was taken into consideration was determining the equilibrium dry density for lightweight concrete in accordance with (ASTM C567-14, 2015).

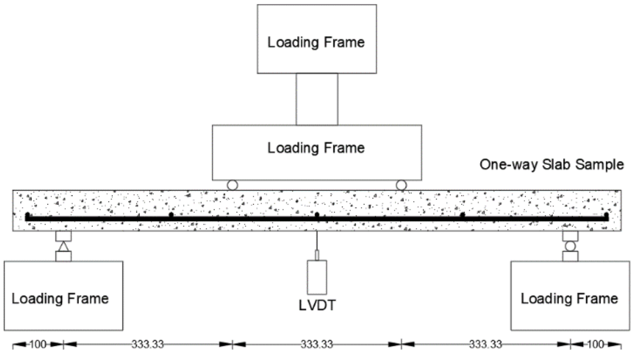


Figure 5. Details of test setup

ACI Procedure for calculating theoretical capacity

The nominal strength capacity of the specimens that externally strengthened with CFRP is determined through the compatibility of strain from equivalent stress block with specifying the related failure mode (Equation 1) (ACI 440.2R-17, 2017). Figure 6 presents the stress-strain distribution profiles for a typical strengthens specimen.

$$M_n = A_s f_s \left(d - \frac{\beta_1 c}{2}\right) + \psi A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2}\right) \qquad \textbf{Equation 1}$$

Where
M_n: nominal moment capacity of strengthened sections
A_f: area of externally bounded FRP
A_s: area of tension steel bars
f_{fe}: effective stress at FRP level
f_s: stress at steel level
d_f: depth of FRP from top of the section
d: effective depth
c: depth of neutral axis
ψ: efficiency factor (ψ = 0.85)
β_1: concrete stress block parameter

Equation 2 determines the depth of rectangular stress block (c) by ensuring that the internal forces are balanced and compatible for measured strains. The stress in steel and FRP level are calculated based on calculated strains (Equations 3 and 4). The α_1 and β_1 are factors that describe the equivalent stress block based on parabolic stress-strain relation. According to Whitney stress block for the concrete compressive strength in between 17 and 28 MPa α_1 =0.85 and β_1=0.85, while for the compressive strength values greater than 28 MPa the ACI Equations 5 and 6 are used (Orlando, Bittencourt and Meneghetti, 2022).

$$c = \frac{A_s f_s + A_f f_{fe}}{\alpha_1 f_c \beta_1 b} \qquad \textbf{Equation 2}$$

$$f_s = E_s \varepsilon_s \le f_y \qquad \textbf{Equation 3}$$

$$f_{fe} = E_f \varepsilon_{fe} \qquad \textbf{Equation 4}$$

$$\alpha_1 = \frac{3\varepsilon_c' \varepsilon_c - \varepsilon_c^2}{3\beta_1 \varepsilon_c'^2} \qquad \textbf{Equation 5}$$

$$\beta_1 = \frac{4\varepsilon_c' - \varepsilon_c}{6\varepsilon_c' - 2\varepsilon_c} \qquad \textbf{Equation 6}$$

Where
f_s: stress at steel level
f_y: yield stress of steel
f_{fe}: effective stress at FRP level
E_s: modulus of elasticity for steel
E_f: modulus of elasticity of FRP

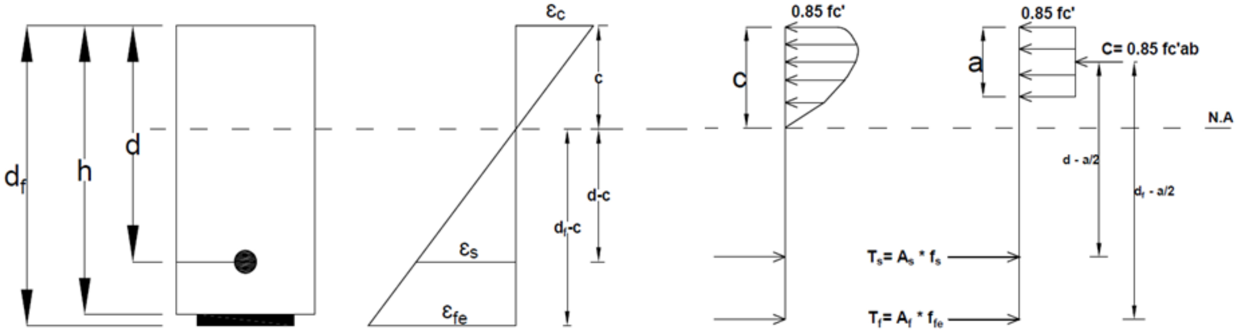
From the strain profile that presented in Figure 6 the effective strain at FRP level is calculated to check if the FRP debonds or the concrete crushes using Equations 7 and 8. If the effective stress (Ɛfe) is lower than or equals to debonding strain then debonding of FRP controls, otherwise the concrete crushes at the compression zone.

$$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c'}{nE_f t_f}} \le 0.9\varepsilon_{fu} \qquad \textbf{Equation 7}$$

$$\varepsilon_{fe} = 0.003\left(\frac{d_f - c}{c}\right) \le \varepsilon_{fd} \qquad \textbf{Equation 8}$$

Where
f_c': characteristic compressive strength of concrete
t_f: thickness of FRP sheets
n: number of FRP layers
ε_{fd}: debonding strain
ε_{fu}: rapture strain
ε_{fe}: effective level of strain in the FRP

Figure 6. Stress-strain distribution profiles for a typical strengthened specimen



RESULTS AND DISCUSSION

Compressive strength

Based on the provisions of British Standard (BS), the cube specimens were casted and tested for the purpose of measuring compressive strength of the slabs (British Standard Institute, 1983). Three 100 * 100 * 100 mm cubes were tested at 7, 14, 28 and 60 days from the casting date under the hydraulic compressive strength machine. A bar chart in Figure 7 presents the average cube compressive strength value for structural light-weight concrete mixture at different ages.

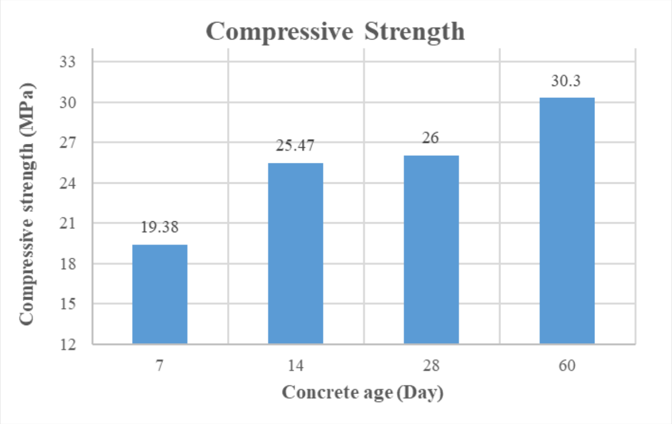


Figure 7. SLWC's compressive strength development

Weight observation

The weight of the samples was determined by using an electronic balance (0.01 precision) in their wet state immediately after being removed from the curing tank and in their air-dried state after being left to dry at room temperature. This was done to evaluate the amount of water loss that occurred among the different ages (14 days, 28 days, and 60 days). Figure 8 shows the different amounts of water that have been lost with age for structural light-weight concrete mixture. The higher amount of water loss indicates higher porosity and water absorption of pumice aggregate compared to natural aggregates.

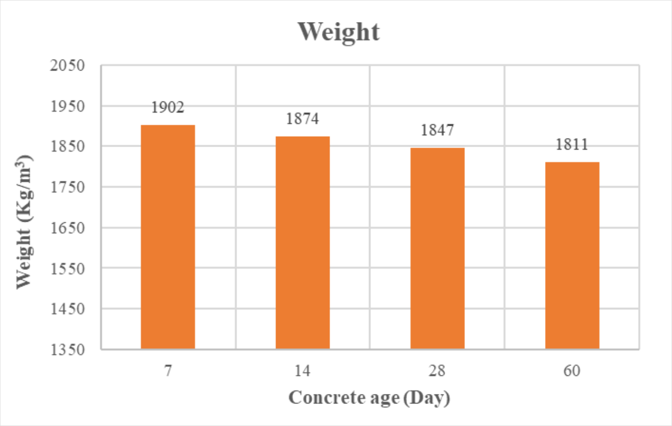


Figure 8. Representation of the amount of water loss

Splitting tensile strength

The splitting tensile test which is also referred to as the Brazilian test is a common test that is utilized in the process of determining the tensile strength of concrete (Denneman, Kearsley and Visser, 2011). It is important to expect that the tensile strength measured using this method will be 10 to 40% more than the actual tensile strength for normal strength concrete (Olesen, Østergaard and Stang, 2006). Moreover, the splitting tensile strength is higher than the direct tensile strength, however it is lower than the flexural strength (ASTM C496/C 496M − 17, 2011). A splitting tensile test was performed on the day of testing slabs. The specimens are cylinders with a diameter and height of 100 mm and 200 mm respectively. The preparation and testing of specimens followed the guidelines outlined in (ASTM C496/C 496M − 17, 2011). The splitting tensile test was carried out by using a splitting tensile accessory with a 2000 kN hydraulic compressive strength machine. The specimens were tested under a constant loading rate of 1.38 MPa/min (within the range of ASTM C496 [0.7 to 1.4 MPa/min]) until failure. The maximum load was recorded and splitting tensile strength was calculated, the outcomes of the test and calculations are presented in Table 7.

Table 7. Results of splitting tensile strength test

Label	Maximum applied load (kN)			Splitting tensile strength (MPa)			Average Splitting tensile strength (MPa)
	I	II	III	I	II	III	
S1	55.6	54.7	61.5	1.77	1.74	1.96	1.82

Flexural strength

This test is conducted in order to determine the flexural tensile strength of SLWC also referred to as the "modulus of rupture". According to the procedures presented in ASTM C78 (ASTM C78/C78M − 18, 2010), three 100 × 100 × 400 mm concrete prisms were tested using a flexural testing machine. This test was carried out by applying two point loads to a simply supported prism in order to evaluate its performance. The loading span is 300 mm and the load applied at a constant rate of 1.2 MPa/min. The maximum load displayed by the machine at fracture is recoded and the modulus of rapture calculated, the outcomes of this test are summarized in Table 8.

Table 8. Results of flexural tensile strength test

Label	Flexural Load (kN)			Flexural strength (MPa)			Average Flexural strength (MPa) III
	I	II	III	I	I	II	
S1	5.4	5.5	4.8	2.16	2.2	1.92	2.1

Load-deflection responses

The load-deflection responses of all specimens were recorded throughout loading history and are presented in Figure 9. As can be seen, the curves generally start linearly and appears in the form of a straight line; the modulus of elasticity (stiffness) of the slab can be calculated from the slope of the straight line. As soon as the first crack appears, the slope of the line decrease. As a result, the stiffness decreases. Then, it continues until it reaches its ultimate load and fails. The load-deflection curves show that the behavior of specimens significantly changes when strengthened with CFRP. The strengthened specimen's maximum load capacity and stiffness increased, and the maximum mid-span deflection decreased simultaneously. On the other hand, a reduction in ductility was observed, and the failures were more abrupt compared to the slab without FRP. The reference specimen showed ductile behavior and gave warnings before fracture, while the strengthened specimens fractured suddenly. This reduction in ductility in strengthened specimens is caused by the higher stiffness of CFRP compared to structural light-weight concrete.

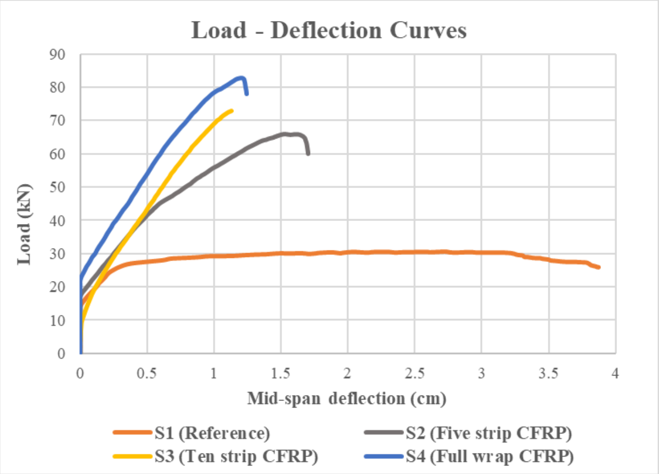


Figure 9. Load vs deflection curves

Influence of strengthening on ultimate load capacity

A broad interpretation of the findings indicates that, the maximum load capacity of all strengthened slabs increased significantly when compared to the un-strengthened specimen. The results of maximum load capacity for strengthened and un-strengthened specimens are presented in Figure 10. The increment percentage of maximum load capacity for S2, S3, and S4 were %115, %138, and %171 respectively. Additionally, utilizing full wrap CFRP in specimen S4 resulted in the greatest improvement in the maximum load capacity compared to other specimens. The theoretical capacity of specimens were predicted based on the specifications and procedure of (ACI 318–19, 2019) and (ACI 440.2R-17, 2017). The results of load carrying capacity and mid-span deflections at first-crack and ultimate load stages are presented in Table 9. The results show that the ACI code procedure can accurately predict the capacity of slab specimens strengthened with one or two layers of strip FRP; however, it is un-conservative for specimen with fully covered tension face with FRP sheet.

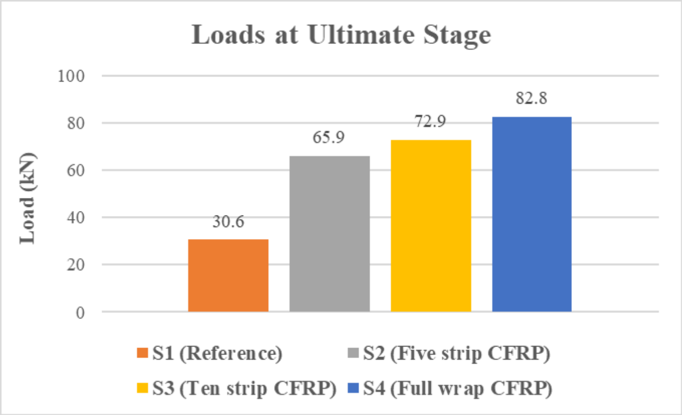


Figure 10. Maximum load capacity for one-way slab specimens

Table 9. The results of load carrying capacity and mid-span deflections in different stages

Label	Experimental first crack		Experimental ultimate stage		Theoretical Capacity (kN)	$\frac{P_{exp}}{P_{cal}}$	$\frac{P_{cr}}{P_{cr\,(S1)}}$	$\frac{P_u}{P_{u\,(S1)}}$
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)				
S1	16	0	30.6	27	26.04	1.2	1	1
S2	43.5	5.5	65.9	15.3	68.28	1.0	2.72	2.15
S3	46	5.48	72.9	11.32	83.69	0.9	2.86	2.38
S4	56.8	5.43	82.8	12.03	106.47	0.8	3.55	2.71

Influence of strengthening on mid-span deflection

There are substantial improvements to the slabs' mid-span deflection after strengthening with carbon fiber reinforced polymers (CFRP). The mid-span deflection at ultimate load was decreased for all strengthened specimens by an average of 43%, 58%, and 55% for S2, S3, and S4 respectively compared to the reference specimen. This reduction may take place due to the behavior of CFRP, since CFRP is a brittle material with a strain at failure of just 0.015, therefore it can only be deformed a limited amount before fracturing. Moreover, the mid-span deflection when subjected to the same load (30 kN) significantly improved. For instance, the mid-span deflection for spacemen S4 that strengthened with full wrap CFRP decrease from 14.5 mm to 1.1 mm (Figure 11).

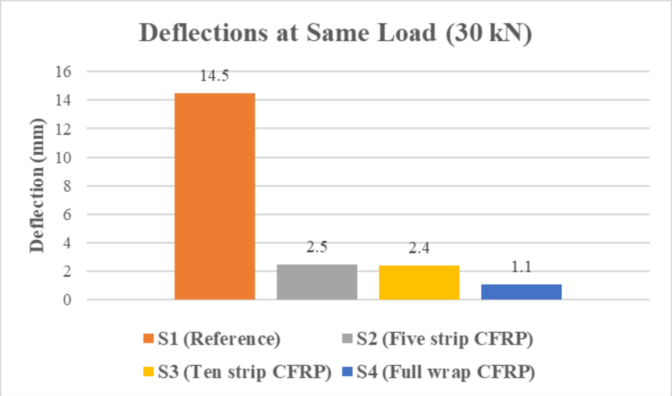


Figure 11. Variation of deflection at the same load

Influence of strengthening on cracking load

Strengthening with CFRP has a considerable improvement in cracking load. According to the findings presented in Table 9, the first-crack load significantly increased for all strengthened specimens. Based on the findings and observations, for the slab specimens S1, S2, S3 and S4, the first crack is appeared at 52.3%, 66%, 63.1%, and 68.6% of the ultimate load capacity respectively. The postponement of the first crack is caused by the high stiffness of the used CFRP that restrict the concrete and minimize the possibility of early cracking. Figure 12 presents the cracking loads for strengthened specimens compared to the reference.

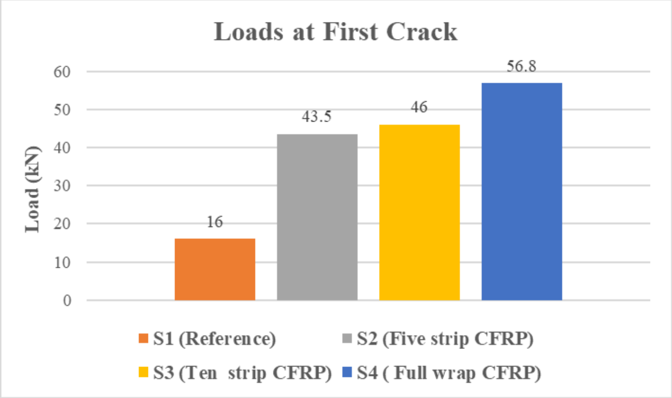


Figure 12. Variation of cracking load

Influence of strengthening on concrete strain

For the purpose of evaluation, strain gauges were attached to the concrete surface and CFRP at the center of the slabs in the direction of loading. The compressive strain of concrete and CFRP strain at different loads were measured and load versus strain curves plotted. According to findings presented in Figure 13, the concrete compressive strain decrease from 0.002 to 0.0015 for all strengthened specimens, the amount of reduction approximately equals for all strengthened specimens. This is because of the substantial amount of stiffness possessed by CFRP. The strains of CFRP strips are presented in Figure 14.

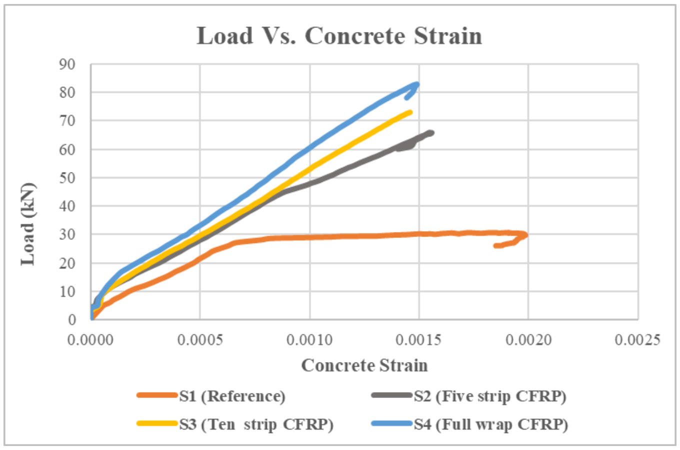


Figure 13. Concrete compressive strain

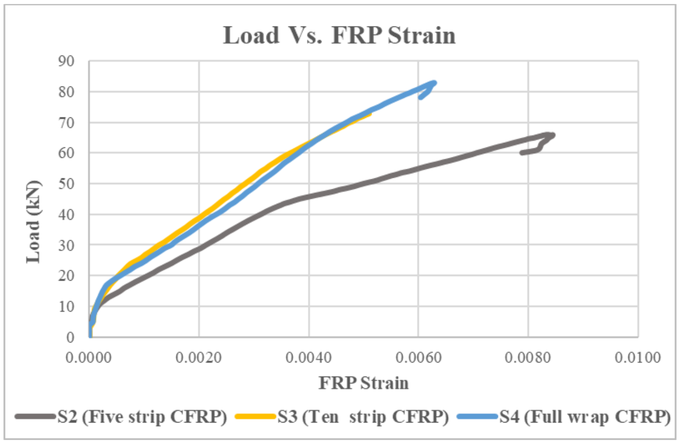


Figure 14. Strain of CFRP

Influence of strengthening on crack patterns

The observations of the tests indicated that the cracking patterns of all SLWC one-way slabs are flexural cracks. Firstly, the reference specimen (S1) that was un-strengthened was put through the test to make a comparison with strengthened specimens. The reference specimen was loaded under a constant loading rate, the first crack appeared in a location of maximum moment, then the cracks started to form in the tension face of the slab. The number of cracks increased and widened gradually until they got closer to the compression zone. The failure took place after the tension steel had yielded and the concrete in the compression zone was crushed. The same behavior was observed from strengthened specimens. However, once the load reaches the point at which the steel yields, the CFRP resists the applied load and prevents failure. As the applied load increased constantly, the failure occurred. The corresponding failure mode was end-interfacial debonding for all strengthened specimens. The CFRP detached from the concrete suddenly, and a brittle failure occurred without any warning. The crack patterns for the tested specimens are presented in Figures 15 and 16. The smaller crack width was noticed from the strengthened specimens and the cracks were distributed along the length of the specimens in a wider range.

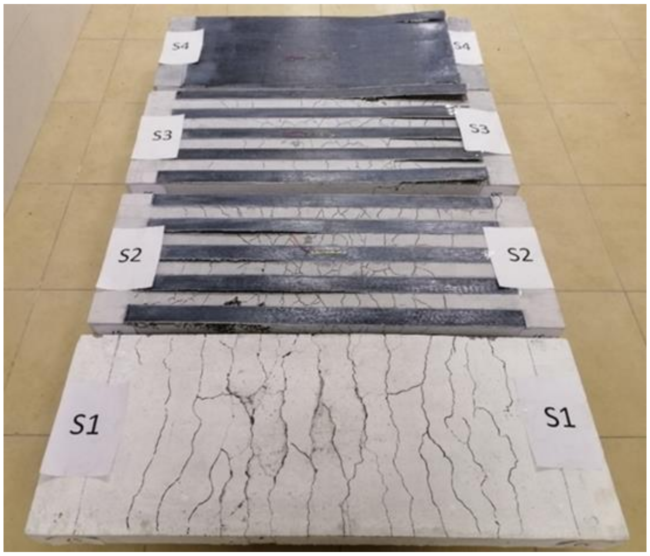


Figure 15. The crack patterns at bottom face of the specimens

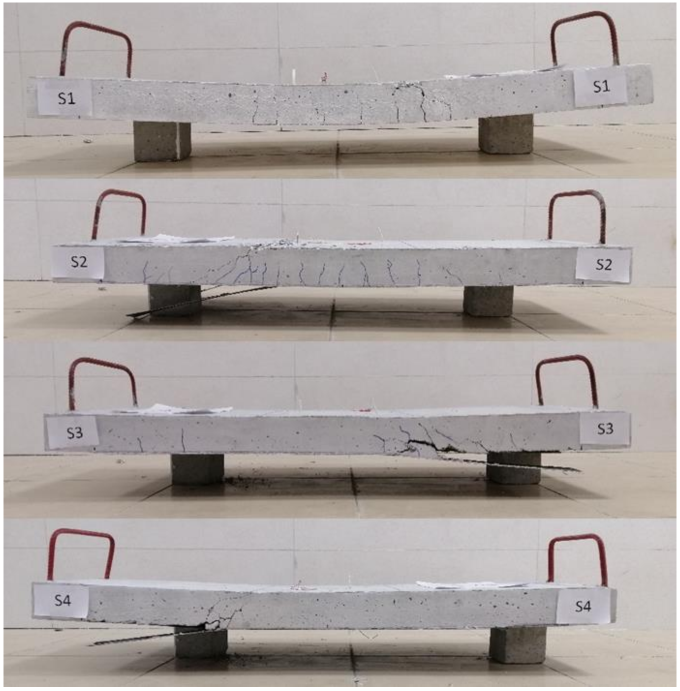


Figure 16. The crack patterns

CONCLUSION

On the basis of the overall findings attained from the experimental results for the strengthened structural lightweight concrete one-way slabs with carbon fiber reinforced polymer (CFRP) compared to the un-strengthened specimen, the following conclusions can be drawn:

1. The use of pumice stone as a totally replacement with natural coarse aggregate satisfies the structural lightweight concrete requirements outlined by ACI code.
2. All strengthened SLWC one-way slabs show a substantial increase in ultimate load. The increment percentage is about 115%, 138% and 171% for specimens S2, S3 and S4 respectively compared to the un-strengthened specimen.
3. Strengthening the specimens with CFRP at the tension faces

increases the stiffness, which makes the mid-span deflection smaller at all stages. The mid-span deflection decreased from 14.5 mm to 2.5, 2.4 and 1.1 mm at the same load and about 43%, 58%, and 55% for S2, S3, and S4 respectively compared to the un-strengthened specimen.

4. Strengthening with CFRP has a substantial effect on crack patterns, since it delays the formation of the first crack, reduces the crack width, and increases the cracking load. For the specimens S1, S2, S3 and S4, the first crack appeared at 52.3%, 66%, 63.1%, and 68.6% of the ultimate load capacity, respectively.
5. Strengthening with a full wrap CFRP exhibited the greatest improvements in terms of cracking loads, ultimate load and mid-span deflection, compared to strengthening with CFRP strips.
6. ACI procedure for predicting failure modes is accurate since the failure mode of all strengthened specimens were debonding of CFRP from the concrete surface.

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