

Flexural Behavior of Damaged Lightweight Reinforced Concrete Beams Strengthened by CFRP

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ABSTRACT

One of the most common methods of strengthening, rehabilitation, or repairing of structural lightweight concrete (LWC) elements is the external carbon fiber reinforced polymer (CFRP) strips. This paper presents an experimental study on the flexural behavior of reinforced concrete beams which comprise lightweight aggregate concrete, in different proportions, strengthened by CFRP sheets. The experimental program included six specimens with a 1500mm effective span. Two of the specimens were normal concrete beams. Another two samples were lightweight beams with a 50% aggregate replacement with pumice. The last two specimens were lightweight concrete beams with a 75% aggregate replacement with pumice. These beams were casted and tested twice under a two-point load application, once before strengthening and the other after that. The experimental results show that full strengthening of the beams along with their entire length, increase in load-carrying capacity by 75%, 113%, and 107% for normal concrete beam, (50% aggregate replacement) LWC beam, and (75% aggregate replacement) LWC beam respectively. While the middle-third strengthening of the beams shows an increase in load-carrying capacity by 64%, 72%, and 57% for normal concrete beam, (50% aggregate replacement) LWC aggregate beam, and (75% aggregate replacement) LWC beam respectively. The strength of the two types of LWC beams was almost the same and it is about 85% of the concrete beam with normal weight.

Key words: Pumice; Strengthening; Lightweight Concrete; CFRP; Flexural Behavior.

INTRODUCTION

The world is currently moving towards developing a new form of concrete using green-technology to reduce pollution and construction costs (Hussein et al., 2016). Lightweight concrete LWC considered to be eco-friendly. It has a lower density than normal-weight concrete NWC and therefore reduces the construction cost by reducing the applied dead loads (Omer & Mohamed, 2002). Lightweight concrete structures have many advantages such as giving the structural elements more efficient strength-to-weight ratio, possessing superior thermal insulation properties and higher fire resistance in compare to normal-weight concrete (Xu et al., 2012). It has various names depending on the way of producing (cellular LWC, lime LWC, and foamed LWC). The density of lightweight concrete ranges from 1400 to 2000 Kg/m³ as compared to the density of the normal-weight concrete which has a range of 2200 to 2400 Kg/m³ (Shabeeb et al. 2012).

One of the lightweight aggregate types that are used in construction is pumice. Pumice is a natural substance of volcanic origin that results from the release of gases during a lava hardening. The cellular structure of the pumice is formed by creating bubbles or air voids while the gases in the molten lava flowing from the volcanoes are trapped during the cooling process (Khandaker & Hossain, 2004). Many investigators have shown that with certain treatments, pumice (lightweight concrete) could be classified as a structural concrete. Al-Rawi (1995), Ghaidan (2018), and Al-Mamoori (2018) have discussed the mixture properties and characteristics of the LWC which varies based on the origin of the aggregates.

There are various techniques available for the rehabilitation and strengthening of deteriorated structures. One of the emerging techniques is the utilize of the fiber-reinforced polymer FRP. Many researchers found that FRP is a reliable, effective, and cost-efficient way

for strengthening reinforced concrete structures (Ziraba et al., 1994). FRP laminates have many advantages such high stiffness to weight ratio, high tensile resistance, high resistance to fatigue ratio, corrosion resistance, and easy to handle in construction. Furthermore, the FRP strengthening techniques are becoming competitive with conventional strengthening techniques using steel plates (Nanni, 1999, as cited in Benjeddou et al., 2007).

One of the most challenging applications of FRP materials is the flexural strengthening of reinforced concrete beams. Comprehensive experimental and theoretical researches have been conducted on the flexural strength of the concrete beams strengthened with different FRP bonded types. Reinforced concrete beams strengthened with FRP sheets have four modes of failure: (1) disassembly failure; (2) rupture of FRP; (3) failure in compression and (4) failure in shear (Bonacci & Maalej, 2001). Among the types of FRP, the research community has given attention to the applications of the CFRP in strengthening and repairing concrete beams. Faza and Ganga (1994) as cited in Benjeddou et al. (2007) showed that when the CFRP laminates are wrapped around beams, the strength increased by 200%.

Carbon Fiber Reinforced Polymers (CFRP) sheets are relatively expensive compared with other FRP composite types, with high electric conductivity, and fail in a brittle manner due to its linear behavior until the failure. CFRP may be a good alternative to traditional materials for rehabilitation and repairing of existent reinforced concrete structures and used in new buildings as a substitute to steel reinforcement (Soudki et al. 2007, Zaman et al. 2013, Kalavagunta et al. 2014, Danraka et al. 2017, & Dushimimana et al. 2018). A good guide for the analysis and design of these types of structural elements can be found in the American Concrete Manual ACI 440.2R (2008).

Limited researches were performed on the use of the FRP laminates in lightweight concrete structures. Yazdani and Goucher (2015) studied the influence of the FRP warps on lightweight

concrete durability improvement, and they concluded that the FRP sheets can reduce the steel corrosion effectively with continuous improvement in the durability.

This research presents an experimental study on the efficiency of external strengthening of lightweight concrete damaged beams using CFRP sheets.

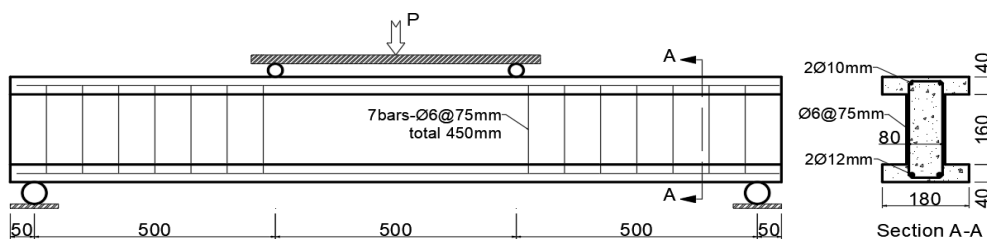
EXPERIMENTAL PROGRAM

The experimental work included six reinforced concrete beams, as summarized in Table 1: Two beams were normal concrete and the others were lightweight aggregate concrete (volumetric replacement of normal aggregate 50% and 75% by pumice respectively). To get the lightweight concrete, the natural aggregate (pumice) was used. Pumice is a natural lightweight aggregate of claystone. It's available as a cellular concrete block. The maximum aggregate size of the pumice was 12.5mm. The lightweight aggregates (pumice) absorb more water than normal aggregates because of the cellular structure of the pumice. To prevent continuous absorption of water by pumice that can cause a fast slump loss, the pumice was submerged in the water for 24 hours to reach saturation. Then, the water has been dripped off and the aggregate left for 24 hours in the laboratory to attain the saturated dry surface condition.

Table 1 Details of specimens

Sample	Description	Strengthening Types
B1F	B1: Normal concrete	Full rehabilitation (for entire beam length)
B2F	B2: Lightweight aggregate concrete 50% replacement	Full rehabilitation (for entire beam length)
B3F	B3: Lightweight aggregate concrete 75% replacement	Full rehabilitation (for entire beam length)
B4P	B4: Normal concrete	Partial rehabilitation (the middle-third of the beam)
B5P	B5: Lightweight aggregate concrete 50% replacement	Partial rehabilitation (the middle-third of the beam)
B6P	B6: Lightweight aggregate concrete 75% replacement	Partial rehabilitation (the middle-third of the beam)

The beam specimen was 1600mm long with a clear span of 1500mm and with the detailed dimensions of ($b_w= 80\text{mm}$, $h= 240\text{mm}$, $b_f= 180\text{mm}$, $t_f= 40\text{mm}$). The I-shape beams were reinforced with $2\phi 12\text{mm}$ longitudinal reinforcing bars at the bottom, with $2\phi 10\text{mm}$ longitudinal bars at the top, and $\phi 6\text{mm}$ stirrups at 75mm center to center. The steel reinforcement was fabricated according to ASTM A615 (2018). The reinforcement details are shown in Figure 1 and the properties of steel are given in Table 2.



The beams have been tested under a two-point load test, as shown in Figure 1. In the first test, the beams were loaded until the theoretical yielding stress of reinforcing bars. In the second test, the beams were strengthened and loaded until failure.

Figure 1 Beam Dimensions and steel details

Table 2 Properties of steel rebar

Diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Steel grade
6	370	540	Grade 40
10	573	675	Grade 60
12	420	627	Grade 60

All the beams are repaired with CFRP sheets in the tension face. The unidirectional carbon fiber reinforced polymer type (DCP-Profiber CW230) was used for rehabilitation of the reinforced concrete beam. The CFRP sheet thickness is 0.0131 mm and it has a modulus of elasticity of 230 GPa and a tensile strength of 4.9 GPa with extreme elongation of 2.1%.

Figure 2 (a&b) shows the strengthening scheme for the reinforced concrete elements, where three beams have full-length sheets along its span, while the remaining specimens rehabilitated using CFRP laminates bonded to the middle-third length bottom face of the beam (partial strengthening). It's worthy to note here that all the beams strengthened with CFRP were completely coated with epoxy. The CFRP sheets have been bonded to the bottom face of specimens as follows: the bottom face was cleaned using an iron brush and blown with air, a primer was applied on the surface and left for 24- hours. After that, the first layer of resin (Quickmast ER350) with the DCP-Profiber CW230 sheet has been applied. Finally, the second layer of resin was applied and left for two days before the test.

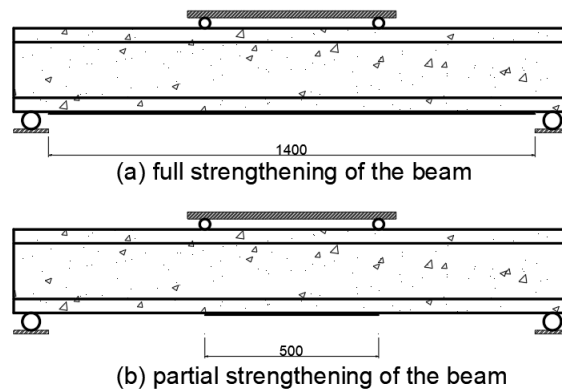


Figure 2 Strengthening sketch

As mentioned before, the specimens were tested under a two-point loading test. The load was applied by using a hydraulic testing machine of capacity equal to 300 kN. The deflection of the beam was measured at the mid-span by using a dial gauge of 0.01mm accuracy. The load was increased slowly where the data was recorded every 2.5 kN load increments until failure occurred.

Many trials-mixed had been tried before starting the cast of the main beams. Finally, the mixed was proportioned to have concrete strength (f_c) for 28 days-age equal to 36.2 MPa. After replacing 50% and 75% of the coarse aggregate with Light pumice, the strength of concrete was dropped to 21.1 MPa and 18 MPa respectively.

The grading of fine and coarse aggregates were lied within the ranges defined by IQS No.45 (1984) while some deviation was recorded when comparing the results with ASTM specification. The results are shown in Tables 3 and 4 respectively, while the physical properties of pumice are given in Table 5.

Table 3 Grading of fine aggregate

Sieve size (mm)	Limit of ASTM C33-09	Limit of Iraqi specification No. 45, 1984	Cumulative passing %
9.5 mm	100	100	100
4.75	95-100	90-100	90.1
2.36	80-100	60-95	63.4
1.18	50-85	30-70	48
0.6	25-60	15-34	29.7
0.3	5-30	5-20	7.7
0.15	0-10	0-10	1.1

Table 4 Grading of coarse aggregate

Sieve size (mm)	Limit of ASTM C33-09	Cumulative passing %
19.0 mm	100	100
12.5 mm	90-100	97.4
9.5 mm	40 to 70	75
4.75 mm	0 to 15	6.1
2.36 mm	0 to 5	1.7

Table 5 Properties of pumice aggregate

Properties	Specification	Test results	Limit of specification
Sulfate content %	Iraqi specification No.45, 1984	0.2	1 (max. value)
Specific gravity	ASTM C127, 2015	1.6	---
Absorption %	ASTM C127, 2015	29	---
Dry loose unit weight, Kg/m ³	ASTM:C29/C29M, 2009	576	---

Table 6 Physical properties of cement

Physical properties	ASTM specification	Limits of Iraqi Specification No.5 (1984)	Test results
Compressive strength (MPa) for: 3-days 7-days	ASTM C150-17		
	Not less than 12 MPa Not less than 19 MPa	Not less than 15 MPa Not less than 23 MPa	17.2 28
Specific surface area (m ² /kg)	Lower limit (280 m ² /kg)	Lower limit (230m ² /kg)	350

Setting time (vacate Test)	ASTM C191-99		
Initial setting (hrs.: min)	Not less than 45min	Not less than 45min	3hr
Final setting (hrs.: min)	Not more than 6hrs:25 min	Not more than 10hrs	4hrs:05min

Table 6 shows the physical properties of the cement that used in this research according to Iraqi and ASTM specifications.

RESULTS AND DISCUSSIONS

To investigate the behavior and rigidity of the lightweight concrete structures strengthened by CFRP sheets, the load-deflection curve is analyzed. All the beams were loaded up to the theoretical failure loads. These loads were calculated according to the simple bending theory of reinforced concrete beams (ACI 318M-19) as shown in Table 7. The effective depth of rebar was 220 mm, and the beam width was 180 mm. The strength reduction factor (ϕ) was ignored in these calculations to quantify the actual strength of specimens.

Table 7 Primary strength of reinforced concrete beams

Concrete Type	Concrete Strength (MPa)	a (depth of Whitney stress block) mm	Moment Capacity of Beams (kN .m)	P_u (kN)
Normal concrete	36.2	17.14	20.07	80.28
Lightweight aggregate concrete 50% replacement	21.1	29.40	19.45	77.80
Lightweight aggregate concrete 75% replacement	18	34.46	19.25	77.04

In the first stage, the beams were loaded until the primary strength of the beams, where sever cracks were developed. These cracks started from the bottom face of the beam near the mid-span region (tension cracks). Moreover, diagonal cracks appear near the support and extended until they reach the top of the flange of the beams (compression zone). In this stage, the loading process was stopped. The load-deflection curved was drawn for all the samples. The recorded loads in this phase were considered as failure load since it is the most reachable value without

causing permanent unfixable damage for the beams. All the beams are designed as under reinforcing condition, therefore the concrete compression failure was avoided in this stage. After removing the applied loads, the specimens restored its original shape with some permanent deformation (deflection) due to concrete cracks and reduction of the rigidity of the samples, as shown in Figure 4. The previously opened cracks were closed partially after removing of loads according to their places and orientation.

Figure 3 cracks in the reference beam, B1

In the second stage, all the beams were rehabilitated using carbon fiber sheets. Three beams were rehabilitated along their entire length (B1F, B2F, and B3F), while the rest were strengthened through their middle-third span (B4P, B5P, and B6P). The results show that CFRP sheets assist to achieve a large percentage of the member's ductility concerning the deflection features, (Figure 4).

Concerning failure mode, the entire length strengthened beam with CFRP showed flexural cracks and debonding failure mode at a later stage of loading. Those cracks prolonged from the main cracks occurred in the original tested beam and continued until the failure. At the final loading steps, the CFRP sheets began to separate from the beams at its endpoints. For the partial strengthening beams (B4P, B5P, and B6P), the cracks developed at the region behind the sheets, where the moment and corresponding stresses are still at a high level, leading to typical flexural failure, as shown in Figure 5.

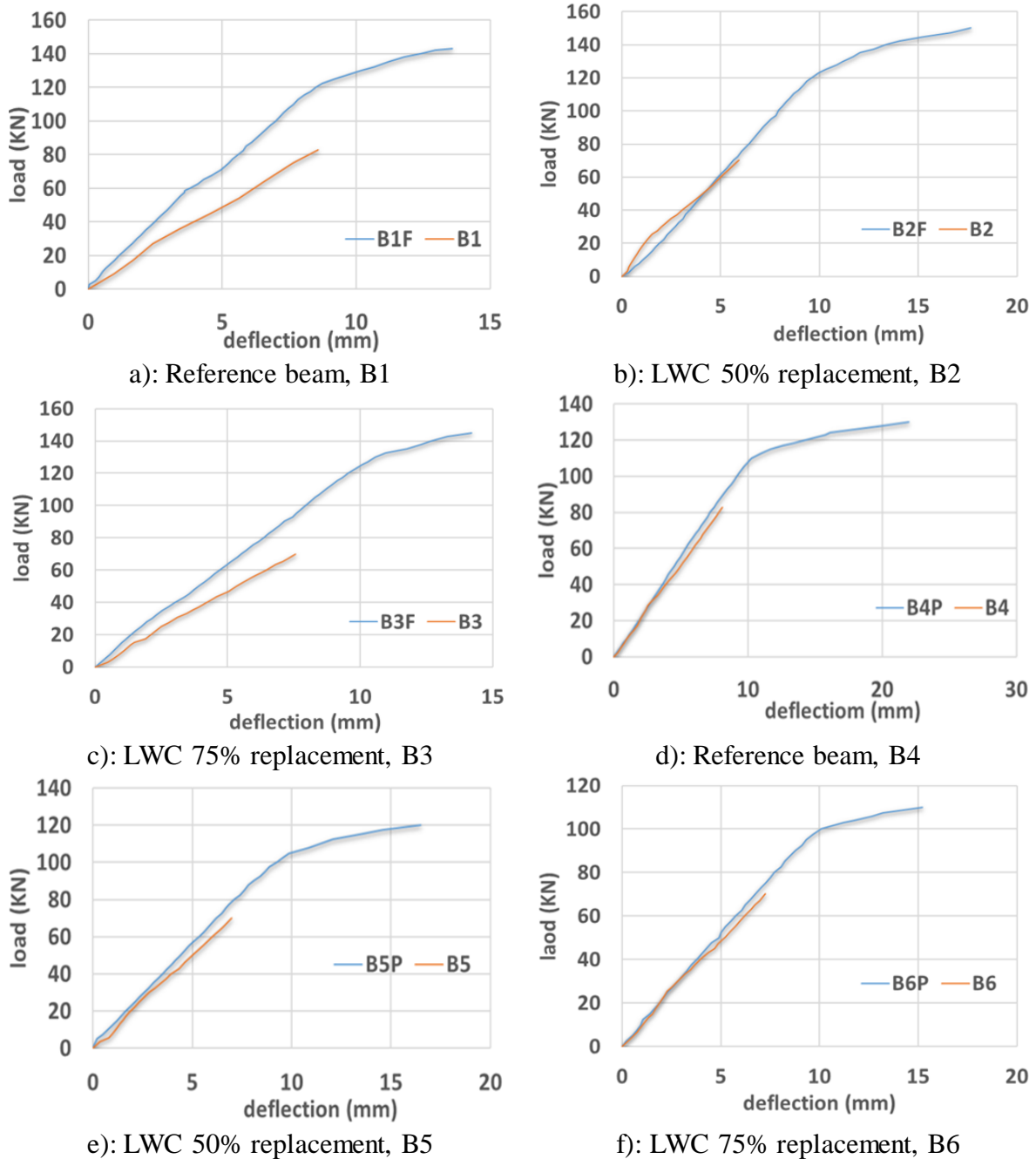
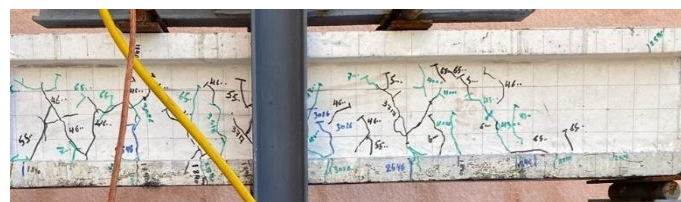


Figure 4 Load-deflection curve for beams.

Table 8 summarizes the failure load and mid-span deflection. P_u and P_{cr} are the ultimate strength of the primary and strengthened beams, respectively, while δ_u and δ_{cr} are the mid-span deflection of the primary and strengthened beams. Figure 4 shows the load-deflection curve for all the specimens in the research.

For the beams strengthened with CFRP along the entire length of the beams (B1F, B2F, and B3F), the maximum load increased by (75%, 113% and 107%). This indicates that

significant improvement in load-carrying capacity can be achieved by using CFRP sheets. Investigation of Table 8 shows that beams B1F and B4P have approximately the same initial load carrying-capacity 83 and 82.8 (Table 8) as they have the same initial design criteria (concrete strength and reinforcement). After the application of sheets, the strength enhancement was 75% and 64% respectively, indicating that the use of full-length strengthening better than the middle-third. The short strips of CFRP lead to concentrated tension-stresses at the region directly after strip, and thus the development of diagonal prolong cracking directly upward to the top flange of beams, therefore, resulting in earlier failure of the elements (Figure 5, b).



(a) Full-length strengthening



(b) Partial strengthening of the beam

Figure 5 Crack pattern of beam partial strengthened with CFRP.

It is worth to mention, the initial strengths of B2F, B3F, B5P, and B6P were the same, although they have different aggregate replacements (Table 1). This indicates that pumice reduces the strength of the beams by the same percentage when it is applied with large amounts in the concrete mix (84% of reference beam, Figure 7).

Another important notice can be referred here, the ultimate strength of the beams (B4P, B5P, and B6P) decreases with using lightweight aggregate comparing with (B1F, B2F and, B3F) and that is a proof that the full-length strengthening method improves the beams more effectively than the partial strengthening method especially in lightweight structures.

Figure 6 presents the load-deflection curve for all the beams, and it is obvious that the concrete beams have ductile behaviors with deferent percents. However, all the specimens undergo a plastic zone at the same value (10mm). This is the point where the steel reinforcement starts to yield and the curvature of the beams increases in a rapidly.

Table 8 Experimental test results of beams

Specimens	Load (KN)		Deflection (mm)		Increase in strength %	Mode of failure
	P_u	P_{cr}	δ_u	δ_{cr}		
B1F	83	145.4	8.6	13.6	75	Flexural+ debond
B2F	70.4	150	5.9	17.7	113	Flexural+ debond
B3F	70.1	145	7.6	14.2	107	Flexural+ debond
B4P	82.8	136	8.1	22	64	Flexural
B5P	70	120	7	16.5	72	Flexural
B6P	70.2	110	7.2	15.2	57	Flexural

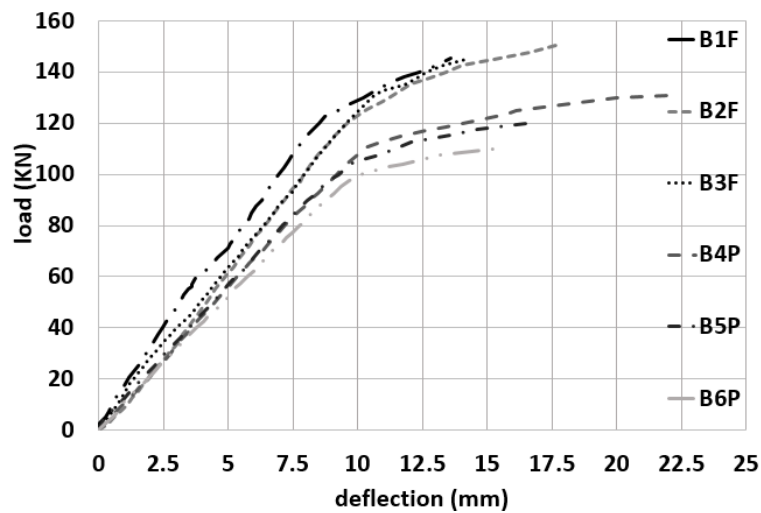


Figure 6 Load-deflection curve for all beams strengthened with CFRP

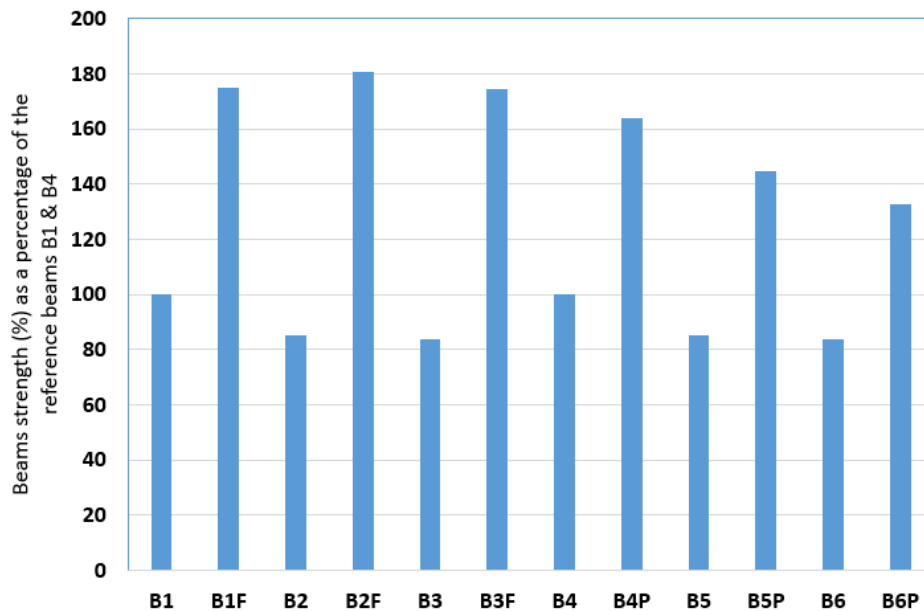


Figure 7 Beams strength as a percent of the reference beams B1 & B4

Figure 7 presents the beams strength ratio as a percent of the reference beams (B1&B4), where any results above 100% represent increasing strength while the results below represent the decrease in strength compared with reference beams. For un retrofitted members (B1~ B6), it is evident that lightweight members have lower strength than Tnormal-weight concrete members. The member with 50% replacement of aggregate with pumice and had full-length strengthening (B2F) gave the most efficient results based on comparison with the reference beam (B1) or itself member before retrofitting (B2).

CONCLUSIONS

This study presented the results of an experimental work that investigates the flexural behavior of the lightweight concrete strengthened with CFRP. The followings may be concluded:

- Strengthening of CFRP significantly improved the efficiency of reinforced lightweight concrete beams (57%-113%).
- Although the debonding of CFRP sheets occurs at a late stage of loading, full ductile behaviors have been achieved for the specimens.

- The load-carrying capacity was increased by 75%, 113%, and 107% for whole length strengthened beams compared with the same beams before strengthening.
- The load-carrying capacity was increased by 64%, 72%, and 57% for middle-third length strengthened beams, compared with the same beams before strengthening.
- Using the full-length sheets improves the behavior of the concrete beams much better than the middle-third strengthening.
- Increasing the percent of pumice in the aggregate (from 50% to 75%) decreases the ultimate strength of the retrofit structure by 3.33% for full-length strengthening (B2F& B3F), while for partial strengthened beams (B5P&B6P), the decrease ratio at the same stage was 8.33%.
- The failure mode for beams with full-length strengthening was sheet debonding while typical flexural failure mode was observed for partial strengthening.
- The strengths of lightweight concrete beams with (50% replacement of aggregate with pumice, and 75% replacement of aggregate with pumice) were 85% and 84% respectively with compare to normal weight aggregate concrete.

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