PORT SAID ENGINEERING RESEARCH JOURNAL
Port Said University - Faculty of Engineering
Volume 17 No. 2 September 2013 pp: 105 - 117

Performance of Lightweight Concrete Beams Strengthened With GFRP

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ABSTRACT

This paper presents an investigation to improve the flexural behavior of reinforced lightweight concrete beams made of light-weight expanded clay aggregate (LECA) as 50% replacement (by volume) to the normal-weight aggregates and addition of foaming agent as percentage of weight of cement. A series of 44 lightweight reinforced concrete (LWRC) beams of 700 mm length and a rectangular cross section of 100x100 mm were cast, strengthened and then tested under three-points bending test to study the effectiveness of using externally applied glass fiber-reinforced polymer (GFRP) composites as a method of increasing the flexural strength of under-reinforced LWRC beams. The variables considered for this study was four concrete mixes and the number of GFRP layers with and without sulfate attack. The behavior of the tested beams was analyzed in terms of mode of failure load, ultimate carrying load, ultimate deflection, and toughness. Despite the experimental results illustrated that the beams strengthened with GFRP laminates exhibited better performance. Also the results show that the use of GFRP as an external reinforcement to strengthen or repair concrete structural members (pre-loaded) is more effective.

KEYWORDS: Lightweight concrete; flexural performance; GFRP layers; preloaded.

1. INTRODUCTION

The use of lightweight aggregate in concrete has many advantages, this include: a) reduction of dead load that may result in reduced footings size, b) lighter and smaller pre-cast elements needing smaller and less expensive handling and transporting equipment, c) reduction in the size of columns and slabs and beams dimensions that result in larger space availability, d) high thermal insulation, and e) enhanced fire resistance [1, 2 and 3]. Strengthening of concrete beams with externally bonded fiber-reinforced plastic (FRP) materials appears to be a feasible way of increasing the load-carrying capacity and stiffness characteristics of existing structures. W, Saadatmanesh [4] showed that, there has been a growing interest in the use of lightweight concrete in the construction industry in the past few decades. Structural lightweight concrete can be designed to achieve similar strength as normal weight concrete. Kaushal Parikh [5] reported that, particularly, ageing or deterioration of existing RC structures is one of the major challenges facing the construction industry today. If the flexural or shear strength of RC members is not sufficient to maintain their service functions, strengthening of these members become necessary.

One of the challengers in the strengthening concrete structures is selection of GFRP laminations, because of its drawbacks of low corrosion resistance and of handling problems involving excessive size and weight, there is a need for the engineering community to look for alternatives. Due to lightweight, high strength and good fatigue and corrosion properties, Fiber Reinforced Plastics (FRP) have been intensively used in the repair and strengthening of aerospace structures. Teng J.G. et al, [6] and N. Pannirselvam et al, [7] showed that, repair with externally bonded FRP reinforcement is a highly practical strengthening system, because of ease and speed of installation, efficiency of structural repair and corrosion resistance of the materials. Several studies on the behavior of reinforced concrete beams strengthened with FRP composite sheets provided valuable information regarding the strength, deformation, ductility and long-term performance of the FRP strengthening systems. Installation of externally bonded up-gradation systems using FRP is faster and less labor-intensive.

2. OBJECTIVE OF THIS STUDY

The main objective of this study is characterize the flexural behavior of lightweight concrete beams with and without GFRP and examine the composite action of the GFRP laminates at all load levels, and loaded to 80% of load levels, unloaded, and then repaired with GFRP, before loading up to failure. Also study the impact of externally bonded of GFRP laminates on strength, deformation and toughness of the test beams after soaked in sulfate sodium at 6 months.

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3. EXPERIMENTAL PROCEDURE

To achieve the main idea of the current study, an experimental program consisted of forty four concrete beams contain lightweight expanded clay aggregate (LECA) as a particle replacement (by weight) to the normal weight coarse and fine aggregates with a percentage equal 50% and strengthened by GFRP.

3.1 Materials and Concrete Mixes

Four concrete mixes were designed in the current research, one mixture normal weight concrete (NWC) while the other three mixes lightweight concrete (LWC). The unit weight of three mixes (LWC) ranged between 1847 kg/m³ to 1955 kg/m³. The material used in this study are ordinary Portland cement CEM I 42.5N. Silica fume was replacement by 10% to cement for mixes (NWC, LWC-35 and LWC-28), and addition by 15% to cement for mixture (LWC-19). Natural sand and crushed stone (Dolomite) normal weight fine and coarse aggregates respectively. While, in three LWC mixes, coarse and fine light-weight expanded clay aggregates (LECA) were used as partial replacements to the normal weight coarse and fine aggregates, respectively, with a percentage equals 50% (by volume). The used coarse LECA possessed a volume weight equals 600 kg/m³ and a specific weight equals 1.0, while the fine LECA possessed a volume weight equals 1100 kg/m³ and a specific weight equals 1.6. Chemical admixtures (Super plasticizer and foaming agent admixtures), a high range water reducing, the used dosage of the admixture was 2% of cementitous materials for NWC, LWC-35 and LWC-28 mixes, and 0.8% of cement content for LWC-19. Foaming agent was addition to reduce unit weight of concrete, the used dosage of foaming was around 3% of cement content for mixture LWC-19. Glass Fiber Reinforced Polymer (GFRP) sheets were used in this investigation with tensile strength equal 1941.2 MPa, with corresponding strain 0.023, modulus of elasticity equal 83.7 GPa, and thickness with 0.55 mm. Techno Epoxy 165 was used as resign between GFRP sheet and surface of concrete, and its properties as the presented in Table 1. Tests to determine the properties of the materials were carried out according to E.S.S [8] and [9]. The properties of aggregates, cement and silica fume are shown in Tables 2, 3.

All concrete mixes were designed using absolute volume method. Three 15x30 cm cylinders were tested for each mix and average compressive strengths are evaluated. Table 4 presents the concrete mixtures proportions and concrete strength.

Table 1. Properties of Techno epoxy 165

Color	Grey
Solid content	100%
Density at 20°C	2.1 g/cc
Processing time at 20°C	60 minutes
Compressive strength (7 days) (BS 6319)	80-85 N/mm²
Tensile strength	13.6 N/mm²
Flexural strength	23.9 N/mm²

Table 2. Basic properties of aggregates

Property	Coarse aggr.	Fine aggr.	Leca aggr.
Specific gravity (S.S.D)	2.61	2.63	1.60
Bulk density (t/m3)	1.56	1.78	0.60
Water absorption (%)	2.05	—	19.1
Clay and and fine dust	2.40	1.4	—
Impact value (%)	12.6	—	—
Flakiness index (%)	36.8	—	—
Elongation index (%)	9.60	—	—
Abrasion resistance (%)	17.8	—	—

3.2 Test Specimens

All concrete specimens were prepared and cured for 28 days in tap water, then strengthening with glass fiber reinforced polymer. A total forty four beams with identical cross section 10 x 10 cm and 70cm length were tested under three points loading. To examine the structural behavior of GFRP lightweight concrete beams, the beams were divided into four groups; the first one consist of four beams represent the control group, the second group consist of twelve beams strengthened with GFRP before loading, the third group consist of twelve beams loaded to 80% of load levels, unloaded, and then repaired with GFRP, before loading up to failure, and the fourth group consist of sixteen beams with and without GFRP and submerged in 10 % sulfate sodium for six months, before loading up to failure. Table 5 shows the specimen's and reinforcement details. The steel reinforcement was normal mild steel with diameter 6 mm (steel 280/420). The primary interest in the instrumentation of the beams was concerned with measuring the deflection at the mid-span, which is in the region of pure flexure without any shear force. Fig. 1 depicts the test setup and the instrumentation. Fig. 2 illustrated details of tested beams.

Table 3. Chemical, physical and mechanical properties of cement and SF

Component/property			Cement	SF
Chemical composition (%)	SIO2		21.0	96.39
	Al2O3		6.10	0.65
	Fe2O3		3.00	0.33
	CaO		61.5	0.62
	MgO		3.80	0.04
	K2O		0.30	0.37
	SO3		2.50	0.05
	Na2O		0.40	0.2
	Loss on ignition		1.60	1.34
	Insoluble residue		0.90	—
Physical and mechanical properties	Specific gravity		3.15	2.15
	Specific surface area (cm2/g)		3,550	264,500
	Setting time (min.)	Initial	135	—
		Final	180	—
	Soundness (mm)		1.00	—
	Compressive strength (MPa)	2-days	21.4	—
		28-days	47.7	—

Table 4. Concrete mixtures proportions, and concrete strength

Ingredient	NWC	LWC-35	LWC-28	LWC-19
Cement (kg/m³)	315	315	315	405
Silica fume (kg/m³)	35	35	35	61
NW fine aggregate (kg/m³)	625	351	313	578
NW coarse aggregate (kg/m³)	1250	527	625	347
LW fine aggregate (kg/m³)	0	211	188	—
LW coarse aggregate (kg/m³)	0	176	208	78
Limestone powder (kg/m³)	—	—	—	158
Super plasticizer (kg/m³)	7	7	7	3.24
Foaming agent (kg/m³)	—	—	—	14
Water (kg/m³)	175	175	175	162
Unit weight at 28 days (kg/m³)	2412	1915	1955	1847
Compressive strength at 28 days (kg/cm²)	590	350	280	190

Table 5. The specimen's and reinforcement details

Mix Id.		Dimensions of beam (mm)	No. of specimen	Reinforcement
G 1	Control	100*100*700	4	2 Ø 6 mm Bottom
G 2	Strengthened	100*100*700	12	2 Ø 6 mm Bottom
G 3	Preloaded	100*100*700	12	2 Ø 6 mm Bottom
G 4	Sulfate	100*100*700	16	2 Ø 6 mm Bottom

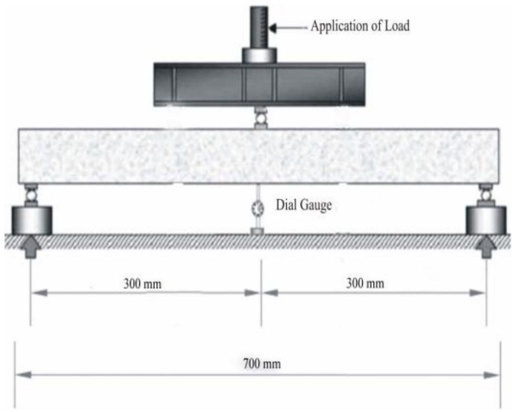


Fig. 1: Arrangement of three points bending.

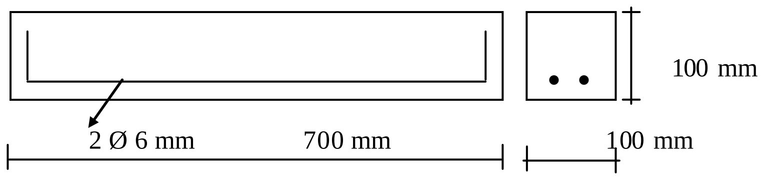


Fig. 2: Details of tested beams

4. RESULTS AND DISCUSSION

4.1 Compressive Strength Test Results

After 28 days, the compressive tests was conducted on cylindrical specimens (15*30 cm) for four mixtures, normal weight concrete (NWC), lightweight concrete 35 MPa (LWC35), lightweight concrete 28 MPa (LWC28) and lightweight concrete with 19 MPa (LWC19). The results of compressive strength were presented in fig. 3. It is observed that the compressive strength of tap water specimens after 28 days was 590, 350, 280 and 190 kg/cm² for NWC, LWC-35, LWC-28 and LWC-19 respectively, and the compressive strength of specimens soaked in 10% sulfate sodium was 364, 231, 150 and 125 kg/cm² for NWC, LWC-35, LWC-28 and LWC-19 respectively after six months. The reduction of compressive strength of specimens soaked in 10% sulfate sodium was 38.3%, 34%, 46.4% and 34.2% for NWC, LWC-35, LWC-28 and LWC-19 respectively. Mixes LWC-35 and LWC-19 were less affected by sulfate attack due to its light weight than mix LWC-28 which gain these mixes more air entrained that exhibited the expanded itrengite which results from the reaction between concrete and sulfates.

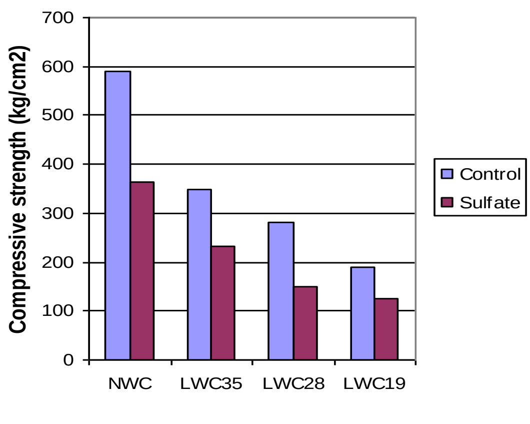


Fig. 3: Compressive strength of concrete mixes

- Results of test beams

4.2 Failure Mode of Tested Beams

The beams L0 and L1 of NWC failed by the yielding of steel reinforcement followed by tension failure of concrete at mid span as shown from figures 4 and 5. It is termed as conventional flexural tensile failure. The beams (LWC35-L0) failed by the yielding of steel reinforcement, followed by tension failure of concrete at mid span as shown from Fig. 6. The beam L2 of LWC-35 was failed due to diagonal shear, followed by concrete crushing failure at compression zone as shown from Fig. 7. The beam (LWC28-L0) failed by, tension failure of concrete followed by the yielding of steel reinforcement at mid span as shown from Fig. 8. Beam LWC-28 of three layers failed by compression failure with diagonal crack as shown from Fig. 9. All preloaded beams were failed due to tension failure of concrete at mid span followed by yielding of steel reinforcement, as shown from Figs. 10, 11, 12 and 13. Beams exposure to 10% sulfate sodium for six months were exhibited a pure bending cracks followed by tension failure of concrete at mid span, as shown from Figs. 14 to17.

Fig. 4: Failure mode of (NWC - L0)

Fig. 5: Failure mode of (NWC - L1)

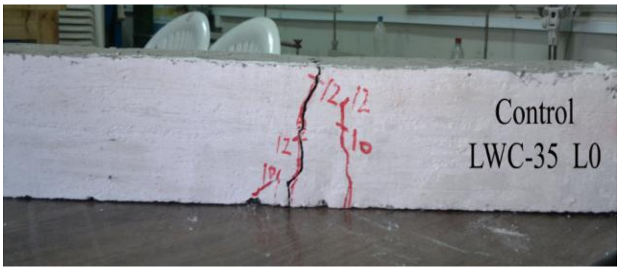


Fig. 6: Failure mode of (LWC35 – L0)

Fig. 7: Failure mode of (LWC35 – L2)

Fig. 8: Failure mode of (LWC28 – L0)

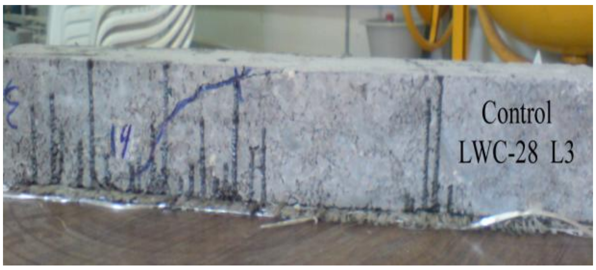


Fig. 9: Failure mode of (LWC28 – L3)

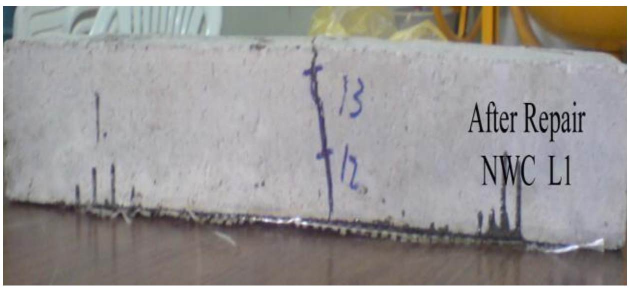


Fig. 10: Failure mode of preload (NWC–L1)

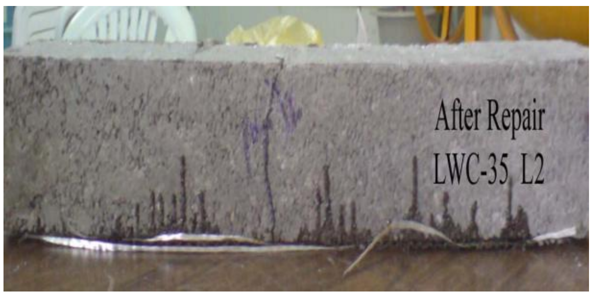


Fig. 11: Failure mode of preload (LWC35–L2)

Fig. 12: Failure mode of preload (LWC28–L3)

Fig. 13: Failure mode of preload (LWC19-L1)

Fig. 14: Failure mode of sulfate (NWC–L0)

Fig. 15: Failure mode of sulfate (LWC35-L1)

Fig. 16: Failure mode of sulfate (LWC28–L2)

Fig. 17: Failure mode of sulfate (LWC19-L3)

4.3 Load - Mid Span Deflection Records

In general, the Load-deflection behavior is slightly nonlinear as a result of the relatively nonlinear stress–strain behavior of the GFRP and the nonlinear characteristics of the lightweight concrete figs 18, 19, 20, 21 and 22. The cracking loads are relatively low compared to ultimate loads. The ultimate load carrying capacity is increased highly and reduced deflection is obtained when compared to the control specimen. However, there is a significant increment in attaining ultimate load at comparatively smaller deflection. This eventually shows the considerable increment in stiffness by increased GFRP layers and the compressive strength of concrete. The results of tested beams are tabulated in table 6.

The ultimate loads of control specimens for beams (NWC, LWC35, LWC28 and LWC19) were (12.5, 12, 11 and 10 KN), whereas the results of ultimate load were (15, 14, 13 and 11 KN), (15.5, 15, 14 and 12 KN) and (16, 15, 14.5 and 12.5 KN) for strengthened beams of one, two and three GFRP layers respectively. There was an increment of 28%, 25%, 32% and 25% in the total load carrying capacity of three layers beams for NWC, LWC35, LWC28 and LWC-19 compared with control beams of each mix as shown from fig. 19. More increment of LWC mixes was LWC-28 which was denser and less voids than LWC-35 and LWC-19.

Beams loaded up to 80% of load levels, unloaded, and then repaired with GFRP behaved in a similar way as those strengthened before loading. The ultimate load of specimens was (12.5, 12, 11 and 10 KN) for control beams of (NWC, LWC35, LWC28 and LWC19), where the results of strengthened beams for one, two and three layers GFRP were (13, 12.5, 12 and 10 KN), (14, 13, 12.5 and 11 KN) and (16.5, 14.5, 13 and 12 KN) respectively. There was an increment of (32%, 21%, 18% and 20%) in the total load carrying capacity of three layers beams for NWC, LWC35, LWC28 and LWC-19 respectively compared with control beam of each mix as shown from fig. 21.

For flexural tests results, the load capacity of the beam strengthened with one laminate was 10 – 20% higher than the control beam, the beam strengthened with two laminates was 20 - 27% greater than the control beam, and the beam strengthened with three laminates was 25 - 32% higher than the control beam.
In comparison to the control beam, as the stiffness of the beams strengthened with GFRP plates increased, the cracking load of the beams increase. Whether, the ultimate load of the beams strengthened with GFRP

remained almost constant it was seen that the failure mode of beams was not de-bonding, but GFRP rupture. However, the cracking and yield loads of the GFRP beams were greater than those of preload GFRP beams. Beams subjected to sulfate attack were decreased with related to control beams in the ultimate load and lower stiffness than control beams. This was due to effect of sulfate sodium attack after six months on steel reinforcement, and concrete mixture as revealed from results of compressive strength and bending tests. The decreases of ultimate load was around 20%, 14%, 29% and 20% of (NWC–L0), (LWC-35 – L1), (LWC-28 – L2) and (LWC-19 – L3) respectively as shown from Fig. 22. More degradation of mix LWC-28 was due to the compression of expanded itrengite because of minor voids of the mix.

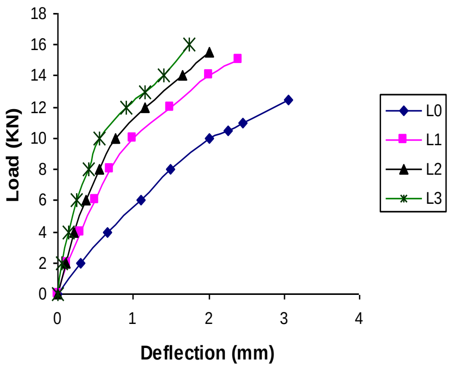
Table 6. The results of tested beams

Beams groups	Beam No.	Cracking Load (KN)	Ultimate Load (KN)	Ultimate deflection (mm)	Toughness (KN.mm)
Control	NWC – L0	11	12.5	3.05	22.70
	LWC-35 – L0	10	12.0	3.80	30.30
	LWC-28 – L0	10	11.0	3.50	24.80
	LWC-19 – L0	5	10.0	2.80	14.73
Strengthened	NWC – L1	14	15.0	2.40	23.84
	LWC-35 – L1	14	14.0	2.15	18.03
	LWC-28 – L1	10	13.0	2.30	17.38
	LWC-19 – L1	2	11.0	2.10	11.69
	NWC – L2	14	15.5	2.00	20.62
	LWC-35 – L2	10	15.0	2.15	21.50
	LWC-28 – L2	10	14.0	2.10	18.92
	LWC-19 – L2	10	12.0	1.80	12.43
	NWC – L3	12	16.0	1.75	18.98
	LWC-35 – L3	10	15.0	1.80	18.52
	LWC-28 – L3	14	14.5	1.90	18.60

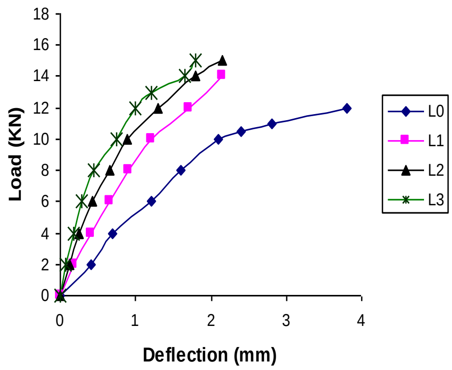
	LW C-19 – L3	12	12.5	1.60	13.15
Preloaded	NW C – L1	12	13.0	2.50	20.93
	LW C-35 – L1	10	12.5	2.70	21.62
	LW C-28 – L1	12	12.0	2.20	12.91
	LW C-19 – L1	8	10.0	2.10	9.95
	NW C – L2	14	14.0	1.80	14.81
	LW C-35 – L2	10	13.0	1.85	15.58
	LW C-28 – L2	10	12.5	1.90	11.52
	LW C-19 – L2	8	11.0	2.00	11.19
	NW C – L3	16	16.5	1.96	20.98
	LW C-35 – L3	14	14.5	1.80	17.06
	LW C-28 – L3	11	13.0	1.80	16.47
	LW C-19 – L3	12	12.0	1.90	13.65
Sulfate	NW C	-	10.0	3.30	20.89
	LW C-35	8	10.0	3.50	21.77
	LW C-28	8	9.0	3.00	14.00
	LW C-19	6	6.0	2.50	7.28
	NW C – L1	-	12.0	2.70	19.20
	LW C-35 – L1	10	12.0	2.80	18.72
	LW C-28 – L1	8	10.0	2.50	11.87
	LW C-19 – L1	8	8.0	2.50	7.88

	NWC – L2	-	12.0	2.20	15.90
	LWC-35 – L2	12	12.0	2.40	16.47
	LWC-28 – L2	10	10.0	2.10	10.79
	LWC-19 – L2	8	8.0	2.20	9.12
	NWC – L3	-	13.0	2.00	16.32
	LWC-35 – L3	13	13.0	2.20	17.29
	LWC-28 – L3	10	12.0	2.15	15.39
	LWC-19 – L3	10	10.0	1.60	7.87

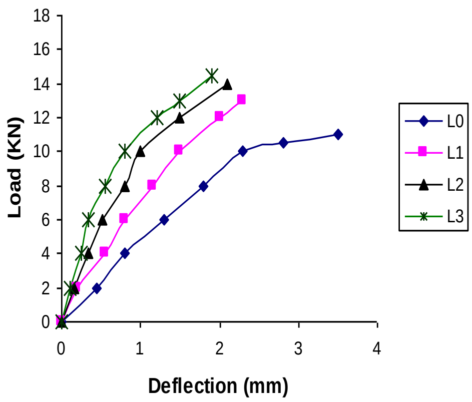
L0 (Control beam) – L1 (One layer GFRP)
L2 (Two layers GFRP) – L3 (Three layers GFRP)



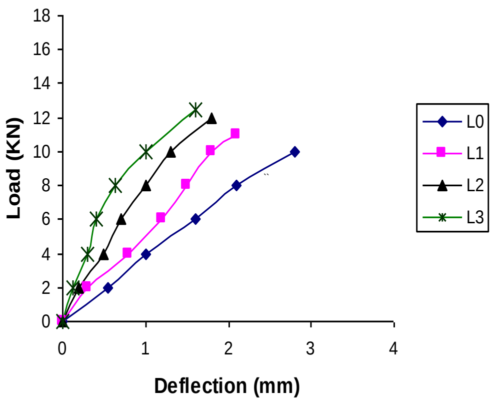
a) Load-Deflection behavior (NWC)



b) Load-Deflection behavior (LWC35)

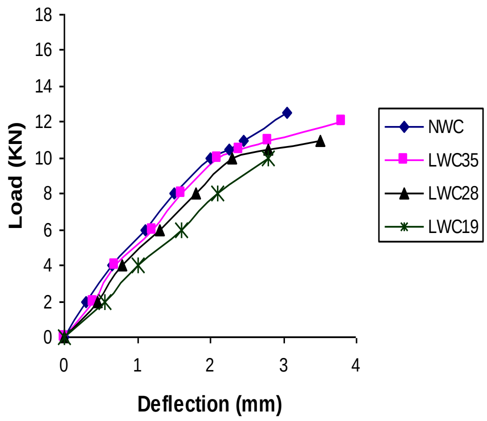


c) Load-Deflection behavior (LWC28)

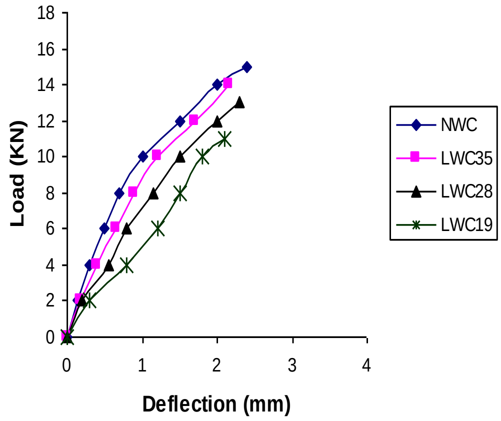


d) Load-Deflection behavior (LWC19)

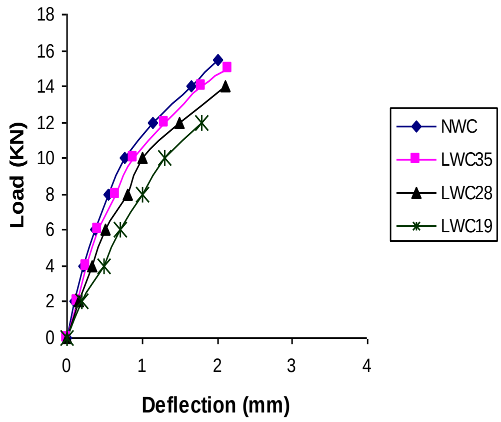
Fig. 18: Effect of GFRP layers number



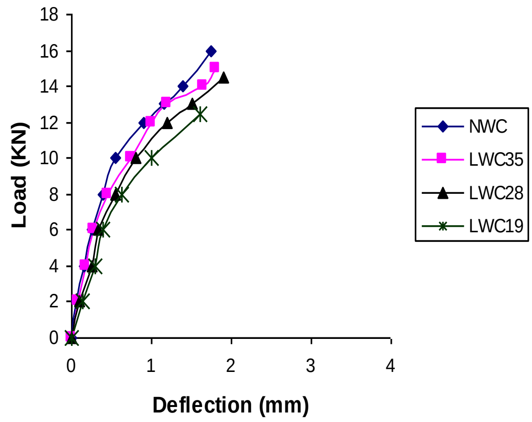
a) Load-Deflection behavior (L0)



b) Load-Deflection behavior (L1)

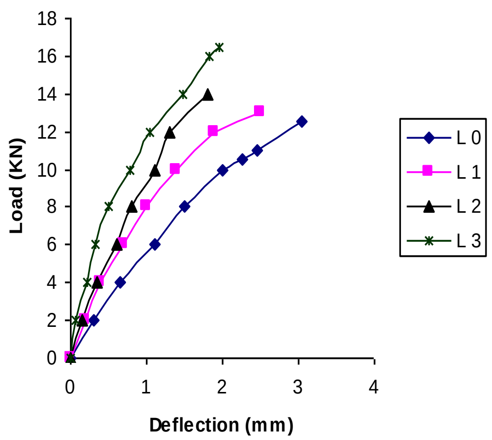


c) Load-Deflection behavior (L2)

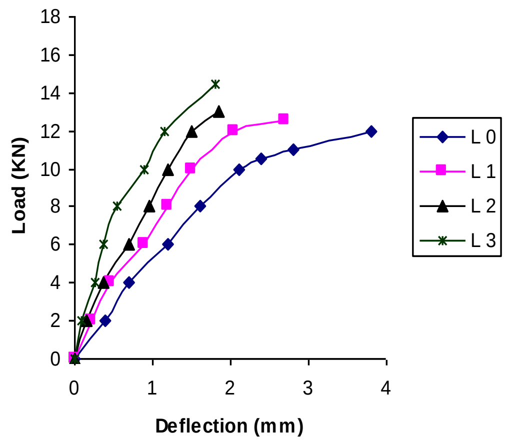


d) Load-Deflection behavior (L3)

Fig. 19: Effect of concrete mixture type.

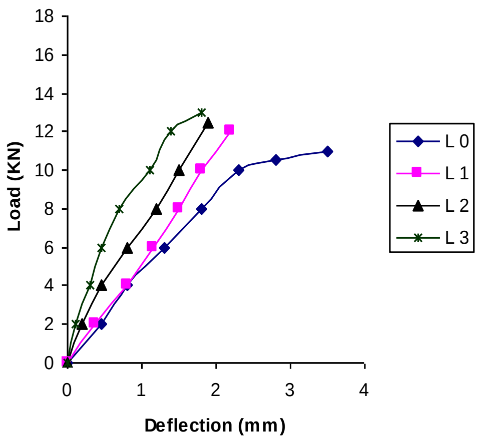


a) Load-Deflection behavior (NWC)

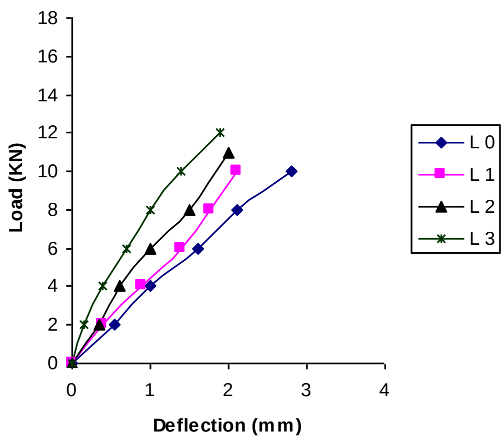


b) Load-Deflection behavior (LWC35)

Fig. 20: Effect of GFRP layers number on preloaded beams (to be continued)

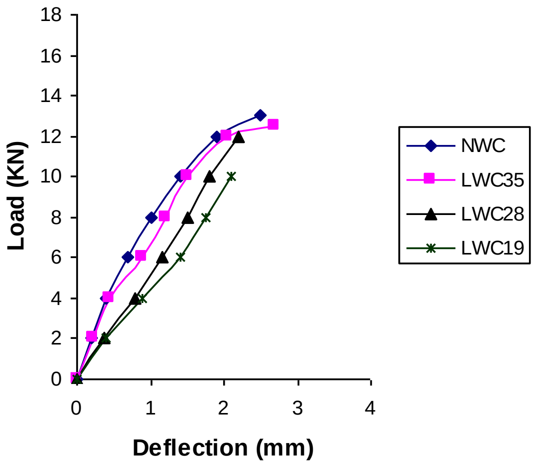


c) Load-Deflection behavior (LWC-28)

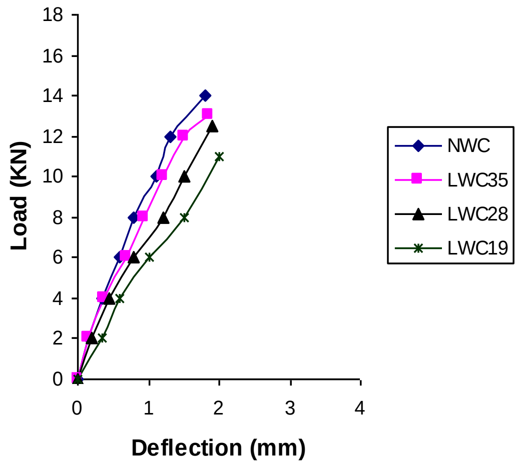


d) Load-Deflection behavior (LWC19)

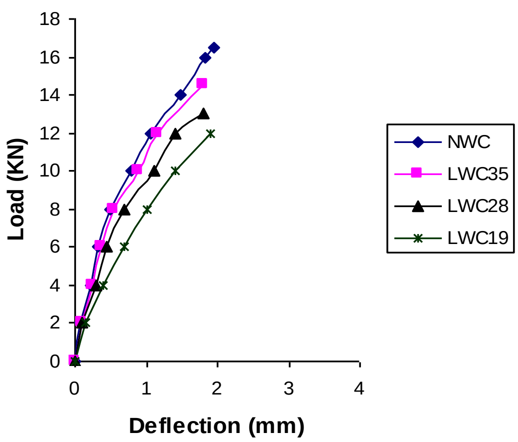
Fig. 20: Effect of GFRP layers number on preloaded beams



a) Load-Deflection behavior (L1)

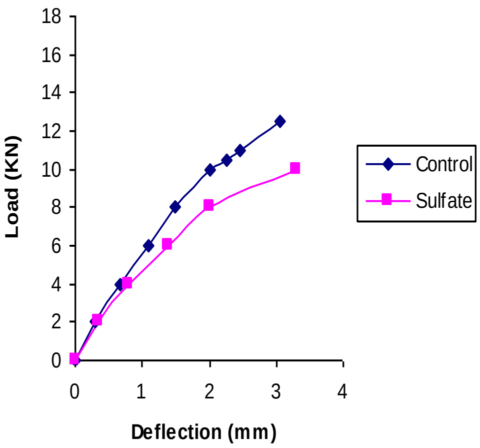


b) Load-Deflection behavior (L2)

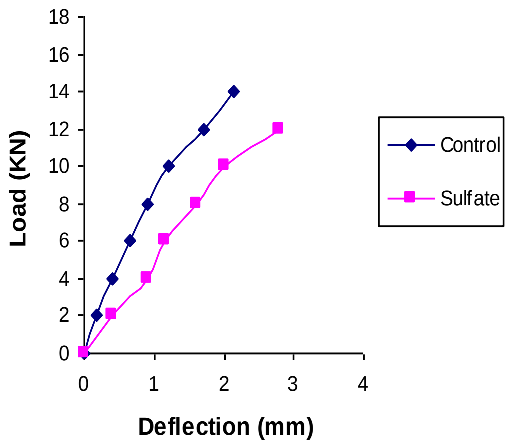


c) Load-Deflection behavior (L3)

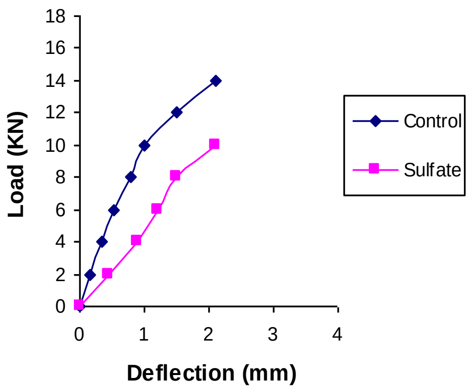
Fig. 21: Effect of mixture type on preloaded beams



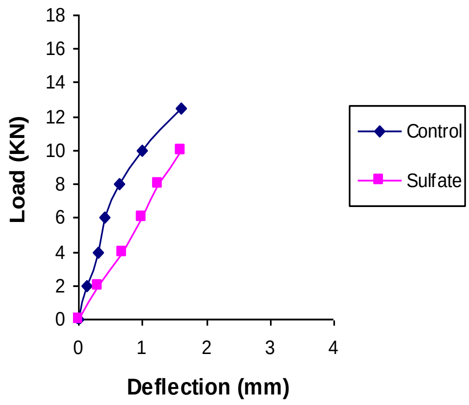
a) Load-Deflection behavior (NWC – L0)



b) Load-Deflection behavior (LWC-35 – L1)



c) Load-Deflection behavior (LWC-28 – L2)

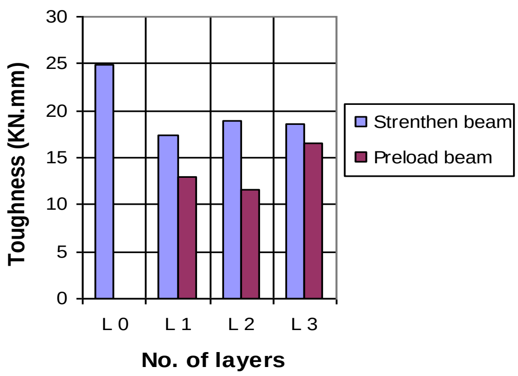


d) Load-Deflection behavior (LWC-19 – L3)

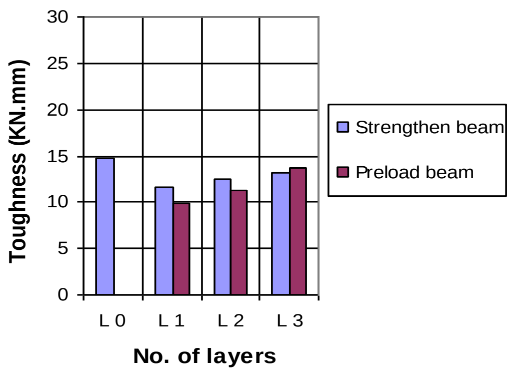
Fig. 22: Effect of sulphate sodium on reinforced beams.

4.3 Toughness

The results of toughness value are shown in fig. 24. The experimental results clarify the enormous influence of the glass fibers on the toughness of LWRC beams. Preload beams showed a lower toughness than the strengthened beams, due to brittle failure caused by de-bonding failure between the concrete and GFRP layers. Disregarding from preload beams (LWC-19-L3), which the toughness is almost less than the strengthened beams; the toughness of the control beam (LWC-19) was less than that of the control beam (LWC-28) by around 41%. However, the ductility of beams (LWC-19) strengthened by GFRP were lightly high than the ductility of preload beams by 17% and 11% for one and two layers respectively. On the other hand, the ductility of the strengthened beams for (LWC-28) was higher than the preload beams by 35%, 64% and 13% for beams strengthened by one, two and three GFRP layers respectively.



a) Toughness of beams (LWC-28)



b) Toughness of beams (LWC-19)

Fig. 24: Toughness of strengthening and preload beams

5. CONCLUSIONS

- In general, the Load-deflection behavior is slightly nonlinear as a result of the relatively nonlinear stress–strain behavior of the GFRP and the nonlinear characteristics of the lightweight concrete.
- The experimental results clarify the enormous influence of the glass fibers on the ultimate load of LWRC beams. It is found that the total load carrying capacities of the light-weight concrete beams were substantially increased by strengthening the beams with GFRP in subsequent layers.
- However, GFRP beams showed a significant increment in attaining ultimate load at comparatively smaller deflection. This eventually shows the considerable increment in stiffness by increased GFRP layers and the compressive strength.
- The test results reveal that; beams loaded up to 80% of load levels, unloaded, and then repaired with GFRP behaved in a similar way as those strengthened before loading.
- GFRP light-weight concrete beams showed a lower ductility than the control beam, due to brittle failure caused by de-bonding failure between the concrete and GFRP.
- Toughness of strengthened beams for weak lightweight concrete beams LWC-19 were almost the same of preload beams where as the toughness of strengthened lightweight concrete beams increased by about (13-64%) for lightweight concrete LWC-28.
- light-weight concrete beams of control , one layer & two layers failed by tension failure of concrete at mid span followed, by the yielding of steel reinforcement, while three layers beams exhibited a diagonal cracks followed by crushing of concrete at compression zone. On the other hand all repaired beams even of three layers showed pure bending failure at mid span of test specimens.

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