

Performance of Carbon Fiber Filament Reinforcing Cement Mortar

Ahmed Hamed El-Sayed Salama^{1, 2*}, Walid Fouad Edris^{1, 3}

¹ Civil Engineering Department, Hijawi Faculty for Engineering Technology, Yarmouk University, Irbid 211-63, Jordan.

² Civil Engineering Department, Al-Azhar University, Nasr City 11884, Cairo, Egypt.

³ Department of Civil Engineering, Giza High Institute of Engineering and Technology, Giza, Egypt.

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Abstract

This paper aims to study the effect of Carbon Fiber Filament (CFF) with different ratios and lengths on the physical and mechanical properties of cement mortar. An experimental program included 3 cm fixed length of CFF with 0, 0.25, 0.5, 0.75, and 1% different ratios by weight of cement addition were used in cement mortar cubes. Another experimental program of 0.5% CFF ratio with 1, 2, 3, 4, and 5 cm different lengths by weight of cement addition was used in cement mortar prisms. The physical and mechanical properties of cement mortar containing CFF were experimentally investigated at 7 and 28 days of curing. Workability, by means of flow table test, were measured. Density is conducted for cubes and prisms at the age of 28 days. At ages of 7 and 28 days, compressive and flexural strengths were studied. The study showed a reduction in workability with the increase of CFF ratios and lengths by 0.0 to 2.7% and by 0.9 to 5.4% respectively. Moreover, an improvement in density, compressive, and flexural strengths was observed. At ages of 7 and 28 days, the results showed that compressive strength increased by 33 and 31% respectively at 0.5% of CFF ratio while the flexural strength increased by 125 and 327% respectively with CFF length of 5 cm.

Keywords: Carbon Fiber Filament; Cement Mortar; Physical and Mechanical Properties.

1. Introduction

Cement is the basic component in mortar manufacturing which is used as binder material. The major cons of cement mortar are resulted from its low tensile resistance, fracture toughness, low cracking resistance, and its brittle failure. Carbon fiber additions are considered as one of the main solutions to increase its toughness and bending resistance of the cement mortar by inhibiting the initiation, and propagation of cracks [1–5]. Polyacrylonitrile, rayon, resins as raw materials or methane and benzene as gases were considered as sources to produce Carbon fiber (CF) [6, 7]. First CF product was used as a byproduct of the coke-making and petro-chemical in the chemical industries [8]. Recently, interest and knowledge of the properties of carbon fiber for use as a modern building material had increased, as it is an environmentally friendly material with a high safety factor, and it also helped to improve the structural composition of cement mortar [9–13].

Under stress conditions, cement mortar with dispersion of CF form a micro- filament network that improved the mechanical properties [14]. Another study showed that the cracking toughness of cement mortar increased with the increasing of high aspect proportion of CF [15].

* Corresponding author: ahmed.salama@yu.edu.jo

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A previous study demonstrated that CF increased both of compressive and flexural strengths of mortars through microscopic and microstructural analyses [16]. Flexural strengths and fracture energies were increased with different types recycled CF reinforcement mortars [17]. Moreover, the volume reduction of cement mortar deformations decreased with the addition of CF [18, 19].

Different carbon fiber lengths, amounts, and distributions are considered as various forms of additions which improve the performance of cement mortar reinforced by carbon fiber [16, 20-23]. According to different carbon fiber lengths, short fiber is defined as fibers with a length less than ½ inch (12.7 mm) [24]. The addition of carbon fiber and polypropylene with 6 and 8 mm length increased the flexural load (i.e., 260%) [25]. The addition volume of carbon fiber by 2% increased its flexural resistance [25]. Another study showed that the compressive strength and impact energy were increased by 14.1% and 145%, respectively with addition of 24 mm length carbon fiber bundles surface silane removal [26]. Due to different carbon fiber amounts (ratios), for mortar containing carbon fibers (0.2-0.4 Vol. %), the linearity between the volume resistivity and the compressive stress was enhanced with the presence of either methylcellulose or latex as dispersants [27]. The characteristics of cement mortars by short carbon fibers addition, with different ratios (2, 3, 4% by weight of cement) were investigated. The study demonstrated that only flexural strength enhanced by increasing the carbon fiber content [28].

The objective of this experimental study is to investigate the effect of CFF ratios and lengths on the behavior of mortar mixtures. First, cube specimens with 0, 0.25, 0.5, 0.75, and 1% CFF ratios with 3cm fixed-length were conducted to evaluate compressive strength. Then, the specimen with optimum compressive strength was selected to examine its flexure strength with 1, 2, 3, 4, and 5 cm CFF lengths.

2. Experimental Procedures

2.1. Materials

In this experimental study, Ordinary Portland cement used was (OPC Type I 42.5N) coming from Northern Cement Company (NCCO) and complying with Jordanian standard specifications (JSS. 30/1979). XRF results for cement percentage of oxide compositions are shown in Table 1.

Table 1. XRF results of cement oxide percentage

Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	K ₂ O	Na ₂ O	MgO
Percentage (%)	64.30	16.10	9.40	7.30	2.47	0.38	0.03	0.02

Locally available natural sand coming from a quarry located at the province Jerash with particles smaller than 2 mm, fineness modulus of 2.25, and specific gravity of 2.60 g/cm³ and complying with Jordanian standard specifications (JSS. 96/1987) was used for mortars. Grading curve of fine aggregate is shown in Figure 1.

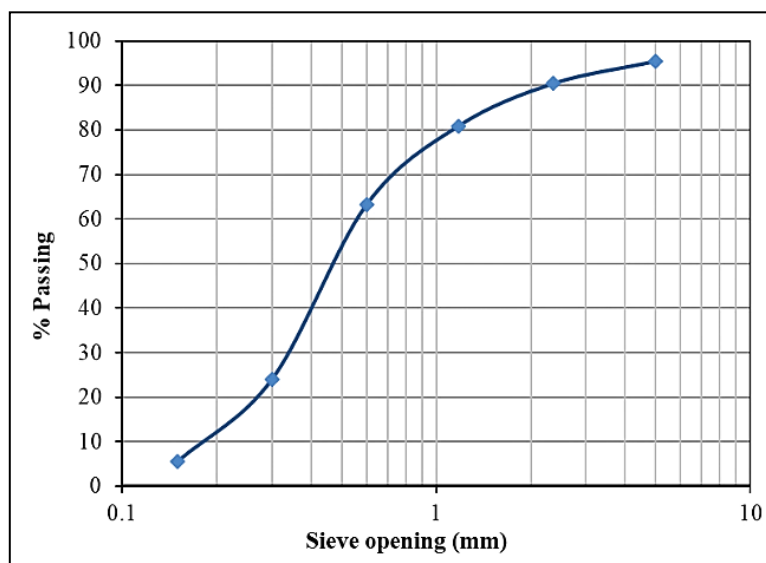


Figure 1. Relation between sieve opening size and passing percentage of fine aggregate

Water used in mixing and curing purposes was clean, fresh, taken from potable water supplies, and complying with Jordanian standard specifications (JSS. 1376/2003). CFF was t700s 24k continuous filament carbon fiber obtained from Torsay Torayca, then shredded to its desired size. CFF data sheets are shown in Table 2 and Figure 2.

Table 2. Carbon fiber filament datasheet

Fiber Properties		Functional Properties	
Tensile Strength	4900 MPa	Specific Heat	0.18 Cal/g·°C
Tensile Modulus	230 GPa	Thermal Conductivity	0.0224 Cal/cm·s·°C
Strain	2.1 %	Electric Resistivity	1.0 x 10 ⁻³ Ω·cm
Density	1.80 g/cm ³	Chemical Composition	Carbon: 93 %
Filament Diameter	7 μm		Na + K: <50 ppm

**Figure 2. T700s 24k continuous filament carbon fiber**

2.2. Preparation of Mortar Specimens

Fresh mortars were prepared with cement to sand ratio of 1:2.75 and water to cement ratio of 1:2 by weight. 3cm length carbon fiber filament (CFF) with 0, 0.25, 0.5, 0.75, and 1% different proportions by weight of cement addition were used for preparing cement mortar cubes. Another 0.5% ratio of CFF with 1, 2, 3, 4, and 5 cm different lengths by weight of cement addition was used for preparing cement mortar prisms as given in Table 3.

Table 3. Mix proportion of mortar specimens

Mortar Designation	Mix proportion						
	Cement (gm)	Sand (gm)	Water (gm)	CFF Designation			
				CFF/C (%)	Weight (gm)	Length (cm)	
Cubes	C	600	1650	300	0.00	0.00	0
	C1	600	1650	300	0.25	1.50	3
	C2	600	1650	300	0.5	3.00	3
	C3	600	1650	300	0.75	4.50	3
	C4	600	1650	300	1.00	6.00	3
Prisms	P	1230	3382.5	615	0.00	0.00	0
	P1	1230	3382.5	615	0.50	6.15	1
	P2	1230	3382.5	615	0.50	6.15	2
	P3	1230	3382.5	615	0.50	6.15	3
	P4	1230	3382.5	615	0.50	6.15	4
	P5	1230	3382.5	615	0.50	6.15	5

For all mortars, an inclined beater rotary mixer was used for mixing. Concerning the mortar specimens, the cement and sand were first mixed dry for 2 minutes. Then, water was added and mixed for another 3 minutes. Finally, CFF was added and mixed for another 1 minute. To study mortar workability, flow table measurements were carried out immediately after mixing according to ASTM C1437-99 [29] as shown in Figure 3(a). After flow table, average diameters were measured. To study the physical and mechanical properties of mortar, 30 mortar cubes, with 0, 0.25, 0.5, 0.75, and 1% CFF ratios and 3 cm fixed length, of size 5×5×5 cm were cast [30, 31].

15 cubes were tested to determine the compressive strength at the age of 7 days. Other 15 cubes were tested for density and compressive strength at the ages of 28 days as shown in Figure 3(b). To measure the flexural strength (modulus of rupture) of mortars, 30 prisms of size 4×4×16 cm with 1, 2, 3, 4, and 5 cm different lengths of CFF and 0.5% fixed ratio were cast [32]. 15 prisms were tested to determine the flexural strength at the age of 7 days and 15

prisms at the age of 28 days as shown in Figure 3(c). Universal hydraulic testing machine (capacity 2000 kN) was used to determine the compressive and flexural strengths of all specimens. All specimens were compacted by using a vibrator table and demolded after 24hrs then cured in fresh water at $23\pm 2^{\circ}\text{C}$ until the testing age. All tests were carried out in triplicate specimens. Figure 4 shows the flow chart of the research methodology.

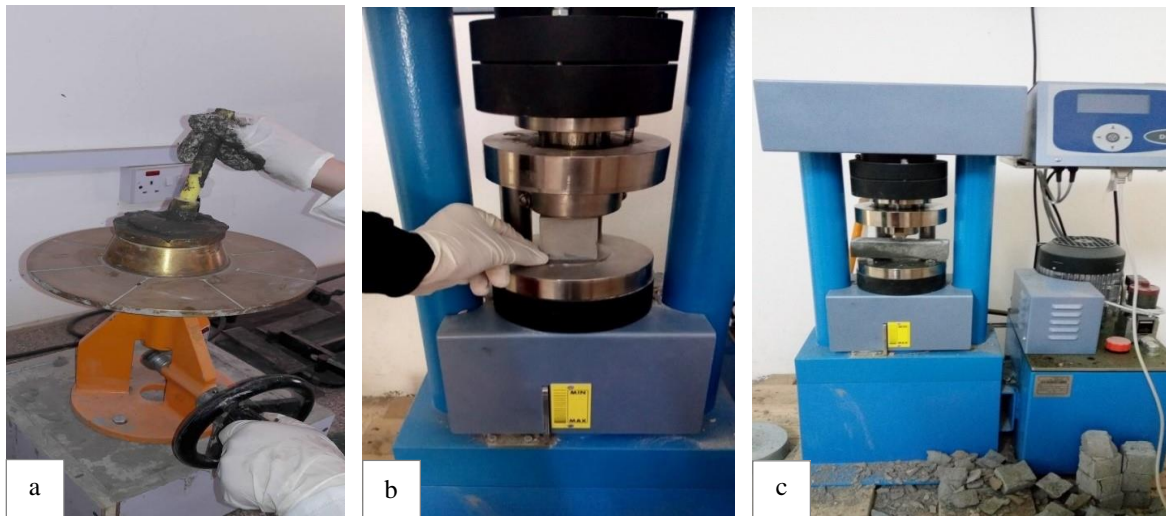


Figure 3. (a): Flow table test, (b): Compression test, (c): Flexural test

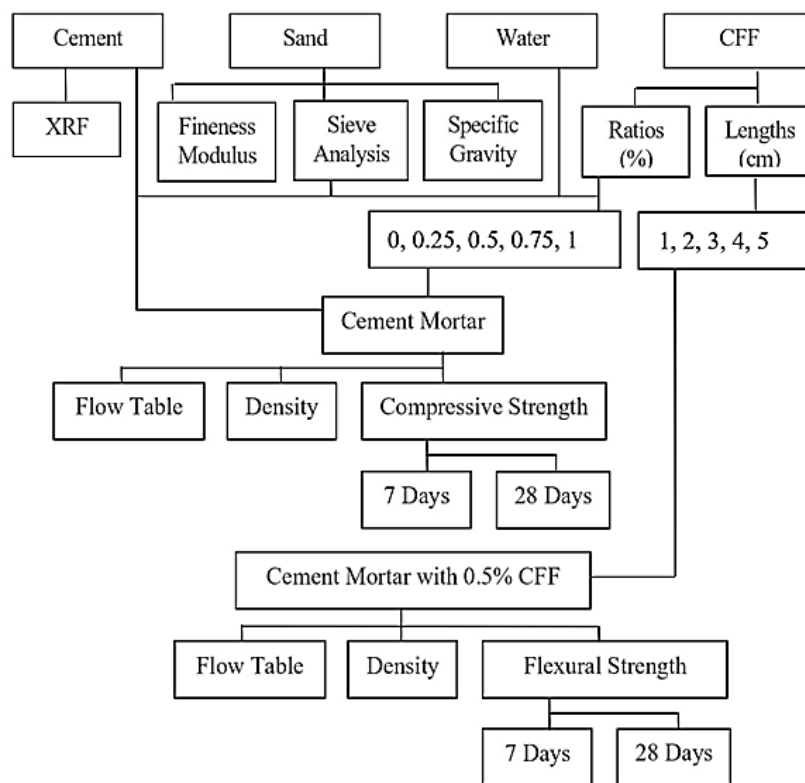


Figure 4. Research methodology flowchart

3. Experimental Results and Discussions

3.1. Workability

Workability of all mortar specimens was measured by Flow table measurements [29]. Table 4 displays the variation of the average measured diameters of the flow table test for mortars that contain CFF. Table 4 shows that the inclusion of CFF reduced the workability for cubes and prisms mortar specimens. For cube mortars with 3 cm fixed length, no reduction in workability was observed at 0.25% (C1) CFF addition, while a reduction in workability was observed from 0.5% (C2) to 1% (C4) CFF addition. For prism mortars with a 0.5% fixed ratio, a reduction in workability was observed from 1cm (P1) to 5 cm (P5) CFF addition. The results showed that the effect of CFF length addition was more effective than CFF ratio.

Table 4. Average diameter for mortar specimens

Average Diameter (mm)	Specimen										
	Cubes					Prisms					
	C	C1	C2	C3	C4	P	P1	P2	P3	P4	P5
	112	112	111	110	109	112	111	111	110	108	106

3.2. Density

Table 5 shows the average bulk density for different ratios of CFF mortar cubes ranged from 0% to 1% and for different lengths of CFF mortar prisms ranged from 0 to 5 cm after 28 days of curing age.

Table 5. Average bulk densities of mortar cubes and prisms at 28 days of curing age

Average Bulk Density (gr/cm ³)	Specimen										
	Cubes					Prisms					
	C	C1	C2	C3	C4	P	P1	P2	P3	P4	P5
	2.09	2.091	2.093	2.094	2.096	2.09	2.091	2.092	2.093	2.097	2.10

Table 5 showed that the average densities slightly increased with the increase of CFF ratios. Average bulk density increased from 0.25% (C1) to 1% (C4) CFF addition. Moreover, prism specimens with CFF lengths from 1cm (P1) to 5cm (P5), increased the average bulk densities. The results showed that the effect of CFF length addition was more effective than CFF ratio.

3.3. Compressive Strength

Table 6, and Figures 5, and 6 designate the average compressive strength test results for different concentrations of 3cm CFF mortar cubes ranged from 0 to 1% as a function of curing time.

Table 6. Average compressive strengths of mortar cubes at 7 and 28 days of curing age

Average Compressive Strength (MPa)	Cubes curing age									
	7 days					28 days				
	C	C1	C2	C3	C4	C	C1	C2	C3	C4
	19.6	24.22	26.09	23.1	22.27	32.15	39.31	42.21	37.50	36.14

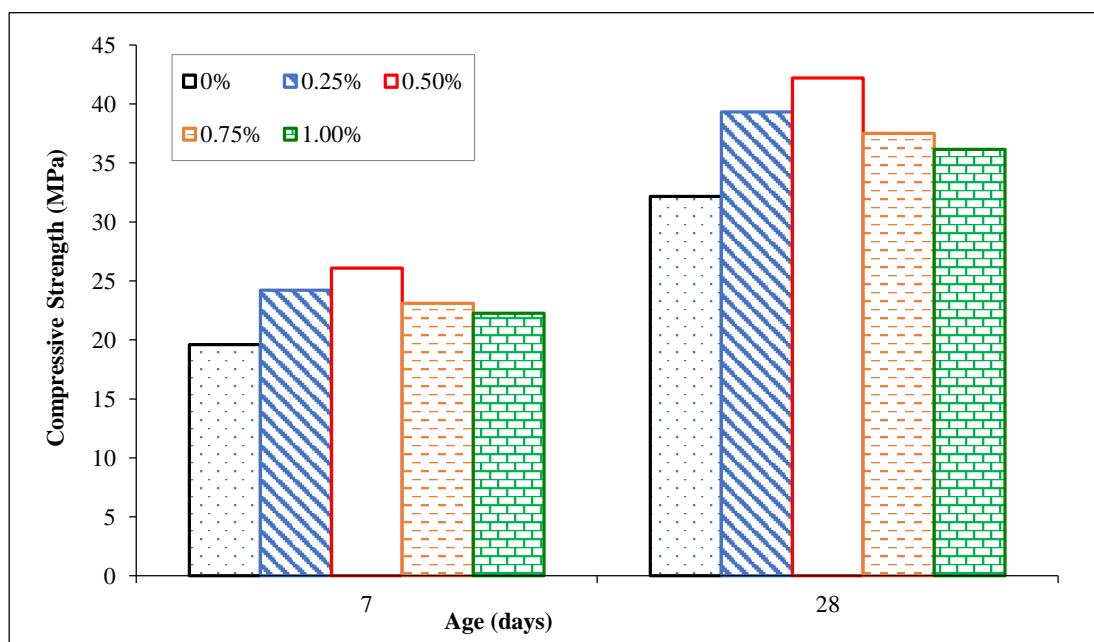


Figure 5. Average compressive strengths of mortar cubes at 7 and 28 days of curing age

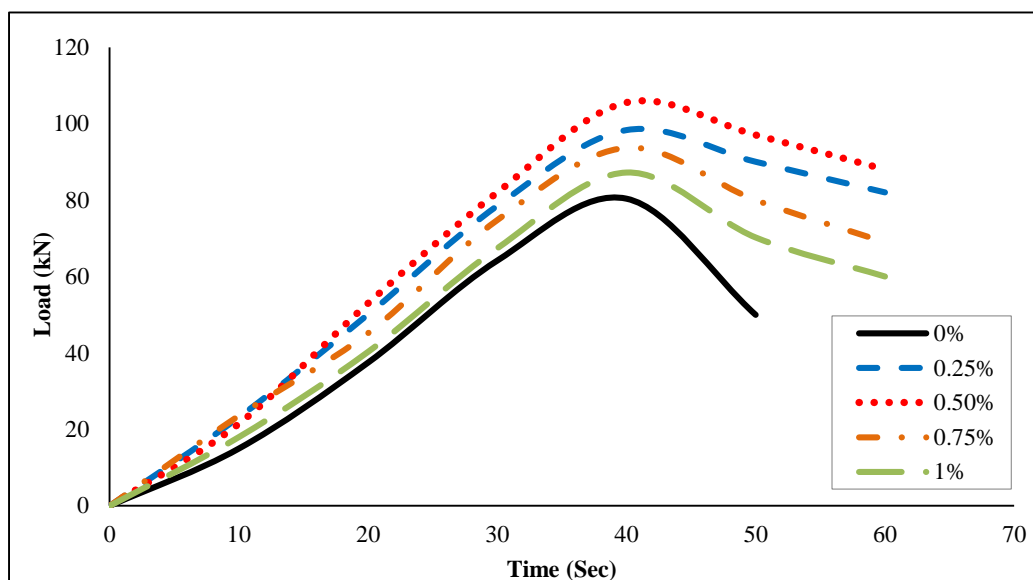


Figure 6. Relation between time and compressive load for mortar cubes at 28 days of curing age

It can be indicated that the optimum peak of compressive strength was at the addition of 0.5% CFF ratio by 33% and 31% at ages of 7 and 28 days, respectively. The addition ratio of 0.25% CFF enhanced the compressive strength by 24% and 22% at ages of 7 and 28 days, respectively. The addition ratio of 0.75% CFF improved the compressive strength by 18 and 17% at ages of 7 and 28 days, respectively. The compressive strength increased by 14% and 12% at ages of 7 and 28 days respectively with a 1% CFF addition ratio. The results showed that the compressive strength increased for all specimens with CFF ratio compared with the control specimen.

At the age of 7 days, compressive strength values were increased, for 0.25 and 0.5% CFF addition, due to the higher bond between fibers and matrix interfaces. While for 0.75% and 1% CFF addition (high carbon volume fraction), the macropores increased due to improper compaction and, thus, decreased the compressive strength [33]. At the age of 28 days, the mechanical bond strength improvement results from the presence of fiber which permits to delay formation of the micro-cracks and arrest the propagation of the micro-cracks which leads to the enhancement of the compressive strength. Moreover, compressive strength mainly based on the mortar workability, degree of the cube compaction, and density [34]. The same results were obtained by [35] for the compressive strength which decreased with more than 3% CFF content. The cube failure behavior during the compression test occurred on the cube edge as shown in Figure 7 due to cracks that initiated at the top and propagated to the bottom and widened till failure with load increasing [36].



Figure 7. Failure pattern of the cube with CFF addition

3.4. Flexural Strength

Table 7, and Figure 8 explain the average flexural strength test results for different lengths of 0.5% CFF mortar prisms ranged from 0 to 5 cm as a function of curing time.

Table 7. Average flexural strengths of mortar prisms at 7 and 28 days of curing age

Average Flexural Strength (MPa)	Prisms curing age											
	7 days						28 days					
	P	P1	P2	P3	P4	P5	P	P1	P2	P3	P4	P5
	1.66	2.07	2.53	2.66	3.72	7.07	2.52	3.14	3.85	4.02	5.66	10.73

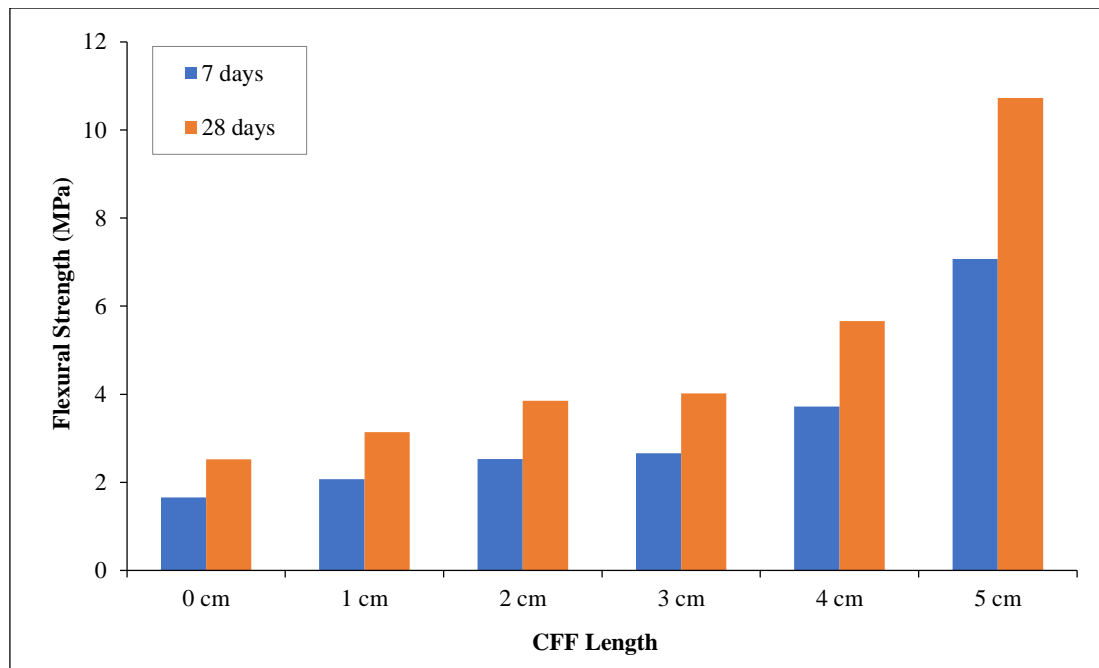


Figure 8. Average flexural strengths of mortar prisms at 7 and 28 days of curing age

It can be noticed that the flexural strength was improved at the addition of 1, 2, 3, 4, and 5 cm CFF length by 25, 53, 61, 125, and 327% respectively at ages of 7 and 28 days with 0.5% fixed ratio. The results showed that the flexural strength was significantly increased with CFF length increasing due to the fibers bridge formation which resists the crack opening, its high strength/modulus, and bonding effects of fibers resulting from the densified microstructure of mortar. In addition, longer carbon fiber enhanced tensile stress, and changed its failure mode from slip failure to fracture failure [37]. As the flexure test starts, the applied load led to CFF elongation and thus energy dissipation. The prism failure behavior during the flexure test was occurred by increasing the applied load which propagate the cracks and led to the plastic behavior of the prism [38]. Results obtained was closed to [37] which improved its flexural strength by using a 24 mm length of the carbon fiber.

4. Conclusion

In this study, the experimental performance of cement mortar containing carbon fiber filament (CFF) with different ratios and lengths was investigated. Workability, density, compressive and flexural strengths were studied. Cement mortar containing carbon fiber filament (CFF) with 0, 0.25, 0.5, 0.75, and 1% of CFF with different ratios and fixed 3 cm length by weight of cement addition were used in cement mortar cubes to specify its compressive strength. For cube mortars with 3 cm fixed length, no reduction in workability was observed at 0.25% CFF addition, while a reduction in workability was observed from 0.5 to 1% CFF addition. Average bulk density increased from 0.25 to 1% CFF addition. The results showed that the optimum peak of compressive strength was at the addition of 0.5% CFF ratio by 33% and 31% at ages of 7 and 28 days, respectively. The selected ratio of CFF (0.5%) with 1, 2, 3, 4, and 5 cm different lengths by weight of cement addition was used in cement mortar prisms to determine its flexural strength. For prism mortars with a 0.5% fixed ratio, a reduction in workability was observed from 1 cm to 5 cm CFF addition. Moreover, prism specimens with CFF lengths from 1 to 5 cm, increased the average bulk densities. The results demonstrated that the flexural strength was improved at the addition of 1, 2, 3, 4, and 5 cm CFF length by 25, 53, 61, 125, and 327% respectively at ages of 7 and 28 days with 0.5% fixed ratio and the optimum peak of flexural strength was at 5 cm of CFF addition.

5. Declarations

5.1. Author Contributions

Conceptualization, A.H.E.S. and W.F.E.; methodology, A.H.E.S. and W.F.E.; formal analysis, A.H.E.S. and W.F.E.; data curation, A.H.E.S. and W.F.E.; writing—original draft preparation, A.H.E.S. and W.F.E.; writing—review and editing, A.H.E.S. and W.F.E.; supervision, A.H.E.S. and W.F.E. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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