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Mechanical Properties of Hybrid Carbon Fibers Reinforced Modified Foamed Concrete

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ABSTRACT

Foamed concrete (FC) is a type of lightweight concrete characterized by a high void space ratio and cementitious binders. In this research, the fresh and mechanical properties of fiber-reinforced modified foamed concrete (made with fly ash, silica fume, and superplasticizer) with a density of 1300 kg/m^3 were studied. Carbon fibers of different lengths (12 mm, 20 mm, and 28 mm) were introduced in two ways: as single fibers (12 mm) and as hybrid fibers combining lengths of 20 mm and 28 mm.
The results showed that the compressive and split tensile strengths increased by approximately 43% compared to the control mix (modified with additives) when using a single fiber of 12 mm at a volume proportion of 0.4%. In contrast, using hybrid fibers resulted in increases of about 65% and 66% in compressive and split tensile strengths, respectively. When compared to the single fiber method, the hybrid approach improved compressive and split tensile strengths by about 15% and 16%, respectively.

1. Introduction

Foamed concrete (FC) is a type of lightweight concrete that can be made with or without the use of fine aggregates. It has a high void space ratio and cement binders (Huiskes, Keulen, & Brouwers, 2016). The density of foamed concrete is 400 to 1850 Kg/m^3. The lightweight concrete for structural applications has a density of 1350–1900 kg/m^3, whereas for non-structural uses like thermal insulation, a density of 300–800 kg/m^3 can be used (Neville, 2011). Comparing to regular weight concrete, there are several benefits to using structural lightweight foamed concrete since it has suitable strength and durability. Since its production process is straightforward and dependable, FC is acknowledged as a cost-effective and environmentally friendly substitute for a range of lightweight building materials and components Ramamurthy, Nambiar, & Ranjani, 2009). In the recent years, the need for lightweight building materials that function well in semi-structure and structure applications has increased. The concrete in general is classified as a brittle material. Also, modified foamed concrete with adding additives (fly ash, silica fume, and super plasticizer) can be classified as brittle material. In order for that, reinforcing modified foamed concrete with a hybrid fiber could be an effective way to enhance its mechanical properties. The goal of adding fibers to lightweight concrete is to reducing at their cracking at an early age (Ayyanar, Vishnuram, Muthupriya, & Anbarasan, 2023). Adding a variety type of fibers could improve the properties of concrete (Darole, Kulkarni, Shaikh, & Gite, 2013). The type and amount of fibers utilized affect concrete performance. Consequently, using right type and volume of fiber in concrete can improve its mechanical properties (Moghimi, 2014). The addition of fibers to concrete improves several of its mechanical properties, including toughness, impact resistance, fracture energy, ductility, tensile and flexural strengths, and toughness (Dawood & Ramli, 2011). Fibers were added to

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concrete to improve its strength, early strength, and support. A variety of tests, including flexural strength, split tensile strength, compressive strength, and workability, were performed. Fiber-containing flexural specimens showed a significantly increased strength above those without fibers. Concrete samples that follow the initial crack from splitting due to fibers that were visible during the split tensile test were investigated (Hachim & Fawzi, 2012). Adding carbon fibers gave a 1 % highest compressive strength estimated at 9.77 % but the flow rate decreased by about 8.55 % compared to the reference mix after 28 days (Al–Hail & Fawzi, 2024). A stronger concrete can be made with adding high modulus, high strength fibers like carbon, glass, and steel (Kim et al., 2010). The previous studies had focused on adding fiber to conventional foamed concrete. However, this work focused as single and hybrid ways in terms of fiber length to the foamed concrete modified with additives (fly ash, silica fume, and superplasticizer). Thus, this work aims to use carbon fibers with modified foamed concrete to enhance its mechanical properties.

2. Experimental work

2.1. Materials

In this study, ordinary Portland cement (C) (Type I) with a specific gravity of 3.15, in accordance with ASTM C150-07 (Advancing Standards Transforming Market, 2007) was used to produce the investigated foamed concrete mixes. Table 1 shows the chemical compositions of cement. Natural river sand (S) with maximum size of 2.36 mm and a specific gravity of 2.65 was used (Obaid & Hilal, 2021). Fly ash (FA) (class F) with a specific gravity of 2.09 was used and Table (1) shows its chemical compositions. Furthermore, superplasticizer (SP) with the trade name Sika-ViscoCrete – 180GS and silica fume (SF) with a specific gravity of 2.2 were used. FOAMIX foam agent for lightweight concrete with a density of 16 kg/m^3 and the specific gravity 1.02 kg/m^3 which was generated by mixing foaming agent with water (1 gr foam agent: 40 gr water) was used. In this study carbon fiber, shown in (Figure 1) with lengths of (12 mm, 20 mm, and 28 mm) were used in single and hybrid ways. Table 2 shows the properties of carbon fibers.

Table 1 – Chemical composition of cement and fly ash.

Oxides	SiO_2	Fe_2O_3	Al_2O_3	CaO	SO_3	MgO
Cement	21.01	3.4	6.18	64.1	2.33	2.2
Fly ash	54.9	6.9	25.8	8.7	0.6	1.8

Table 2 – Properties of carbon fiber (from manufacturer).

Length, (mm)	12, 20,28
Specific gravity	1.8
diameter, (micron)	7
Tensile strength, (MPa)	4000
Tensile elastic modulus, (MPa)	230000
Elongation, (%)	1.5
Shape	chopped strand
Carbon content, (%)	98

(a) (b) (c)

Fig. 1 Carbon fiber used in this investigation, (a) length of 12 mm, (b) length of 20 mm, (c) length of 28 mm.

2.2. Mix proportions

The absolute volumes method was used to design all of the investigated foamed concrete mixes with a targeted 1300 kg/m^3 density. The proportions of the mixes of foamed concrete are shown in Table 3. In this study, a hybrid way by combination of two lengths of carbon fibers (20 mm and 28 mm) was adopted in addition to the single way (12 mm). The proportions of fibers in mixes ($FC3mf_h$ and $FC3f_h$) were 0.133% of mix volume for each length, which were chosen from a previous work. The previous work, a statistical program (MINITAP) is used to find the optimal proportions of the lengths of fibers, begins with the selection of study variables. After determining the variables (fiber lengths) and their levels (0-0.133%) for each length 12mm,20mm, and 28mm, they were fed to the statistical software, which is based on the design of experiment method such as response surface method (RSM). After analysis of these variables. Composite design (CCD) was selected to apply the experiment design central, which is based on the response surface methodology, the number of experiments was 20 mixes. After optimization of 20 mixes. The optimal mix ($FC3mf_{h)}$ proposed from Minitab program containing f12=0%, f20=0.133%, and f28=0.133%. In this study, the optimal mix was adopted and compared with four mixes with and without fiber and additives to investigated the mechanical properties of hybrid carbon fiber reinforce modified foamed concrete. The control mixes were FC3 and FC3m. The ($FC3mf_s$) mix contains a single length of 12mm.

Table 3 – Proportions of the investigated foamed concrete mixes.

Materials	FC3	FC3m	$FC3f_h$	$FC3mf_s$	$FC3mf_h$
C (kg/m^3)	450	450	450	450	450
S (kg/m^3)	575	514	575	514	514
FA (kg/m^3)	-	128.5	-	128.5	128.5
SF (kg/m^3)	-	50	-	50	50
SP (kg/m^3)	-	6.7	-	13.4	13.4
Water (kg/m^3)	275	193.5	275	193.5	193.5
f20 (%)	-	-	0.133	-	0.133
f28 (%)	-	-	0.133	-	0.133
f12 (%)	-	-	-	0.4	-
Foam (l/m^3)	370	370	370	370	370

Where,
FC3: foamed concrete mix (without additives and fibers) with a density 1300 kg/m3.
FC3m: modified foamed concrete mix (without fibers) with a density 1300 kg/m3.
FC3fh: hybrid fiber-reinforced foamed concrete mix (without additives) with a density 1300 kg/m3.
$FC3mf_s$: single fiber reinforced modified foamed concrete mix with a density 1300 kg/m^3.
$FC3mf_h$: hybrid fiber reinforced modified foamed concrete mix (optimal mix) with a density 1300 kg/m^3.

2.3. Production and curing

In this study, according to the ASTM-C192M (Advancing Standards Transforming Market, 2007) a rotary mixer was used. Half of the sand was added to the mixer pan, then adding cement, fly ash, silica fume, and fiber. The pan mixer was then filled with the remaining sand and everything was well combined. They were mixed for three minutes to form a homogeneous dry mix. After that, the dry ingredients are gradually mixed with water. In the case of using a SP the combined water and SP were gradually introduced. After mixing was completed, the mix was placed in sample molds in two layers and the sides are lightly tapped using a rubber hammer to prevent bubbles from breaking. A day after casting, the molds are opened and the samples are cured using plastic wrap to prevent evaporation (Figure 2) shows Production and curing stage.

(a) (b) (c)

Fig. 2 Production and curing processes (a) Pan mixer used to production foamed concrete, (b) casting, (c) curing

3. Experimental work

3.1. Tests

To test the spreadability, a 150 mm-high, 75 mm-diameter cylinder with open ends was used This test was carried out according to method suggested by Brewer (1996), to measure the spread diameter of foamed concrete in all directions. Once it was filled, the cylinder was raised vertically to let the fresh foamed concrete pour down. For porosity test, the vacuum saturation device was used (Kearsley & Wainwright, 2002). Prismatic specimens (90 mm x 40 mm x 40 mm) cut out from the center of a 100 mm^3 cube were used to measure the porosity. The samples were put in the oven and allowed to dry at 100 ± 5°C until their weight remained consistent. After that, the samples were put in the vacuum saturation and submerge the samples fully in water and let the mix remain under pressure for an additional three hour. The compressive strength of the foamed concrete mixtures was tested using 100 mm cubes in accordance with ASTM C513-11 (Advancing Standards Transforming Market, 2011). In addition, splitting tensile strength was measured using 100 x 200 mm cylindrical molds in accordance with ASTM C496-C496M (Advancing Standards Transforming Market, 2011). For each of the tests, an average of three specimens was used. To test the flexural strength, prismatic specimens of (160 × 40× 40) mm, as specified in ASTM C348-14 was used. These used devices are shown in (Figure 3).

(a) (b) (c) (d)

Fig. 3 Devices used for measuring (a) compressive strength, (b) splitting tensile strength, (c) flexural strength, (d) vacuum saturation.

4. Result and discussions

4.1. Effect of fibers on spreadability

From the results shown in Table 4, these mixes show how additives have a beneficial impact on spread diameter. As can be seen for FCm3 and FC3, the spread increases when additives are presented. Additionally, with comparing FCm3f_h and FC3f_h mixes it can be seen that the spread diameter increased by about 46% when additives are presented. While, when added carbon fiber on mixes without additives the spread diameter decreased by about 6.6% as can be observed in FC3f_h and FC3. With comparing FC3m and FC3mf_h mixes, the spread diameter of this mix was more effected by content of fiber and it was dropped from 28 to 22 cm. Adding carbon fibers might significantly decrease foamed concrete workability and spreadability (Dawood & Ramli, 2012). The spread diameter of lightweight foamed concrete significantly reduced with the increasing of carbon fibers percentages. It was reported that, as the percentage of fibers increases, the workability (flow) decreases (Neville & Brooks, 2019). The introduction of fiber somewhat reduces workability. The fibers large specific surface absorbs more of the cementitious mortar around the fibers and, consequently, increases the viscosity of concrete, which contributes to a slight reduction in the values of the spreadability (Amran, Fediuk, Vatin, Huei Lee, Murali, Ozbakkaloglu, Klyuev, & Alabduljabber, 2020).

Table 4 – Spread diameter of investigated mixes.

Mixes	Spread diameter (cm)
FC3	16
FC3m	28
FC3mf_s	19
FC3f_h	15
FC3mf_h	22

4.2. Porosity

Table 5 shows the result of porosity for investigated foamed concrete mixes. Compared FC3 with FC3m it can be seen that the additives led to decrease the porosity by about 2.6 %. It was reported that the use of fly ash as an additive led to a decrease the porosity by about 4% (AAbbas & Hilal, 2021). From the results the porosity decreased with adding carbon fiber as observed in FC3 comparing with FC3fh reduction (about 7.7%). the use of carbon fibers may significantly reduce the porosity of foamed concrete (Abbas, Dawood, & Mohammad, 2018).

Table 5 – Porosity values of all investigated mixes.

Mixes	Porosity (%)
FC3	29.22
FC3m	28.05
FC3mf_s	26.41
FC3f_h	27.13
FC3mf_h	26.5

4.3. Compressive strength

The results of compressive strength test for all mixes are shown in (Figure 4). The results show that the compressive strength increased with adding carbon fiber can noticed in mixes FC3fh, FC3mfh, and FC3mfs. In addition, the compressive strength was enhanced when a hybrid way (different lengths) was adopting. The FC3mfh mix was increased by about 65% when compared with control mix (FC3m). With adopting the single length (12mm) the compressive strength increased by about 43%. When compared the (FC3 and FC3m) the additives enhanced the compressive strength by about 99%. The fibers formed a bridge structure between the hardened products, which increased the adsorption force between the hardened products of foamed concrete, thus increasing its compressive strength (Zhao, Liu, & Wang, 2022). the use of carbon fibers increases the compressive strength of foamed concrete due to an improvement in mechanical bond strength and reduction of porosity (Abbas et al., 2018).

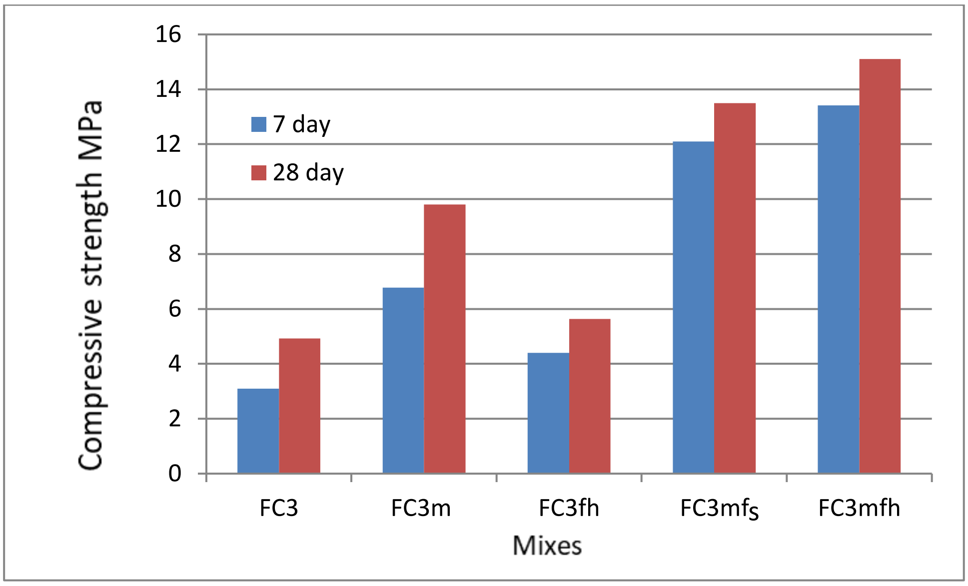

Fig. 4 Compressive strength of investigated mixes.

4.4. Splitting tensile strength

(Figure 5) shows the results of splitting tensile strength of investigated mixes. From the result, it was observed that the splitting tensile strength was increased with added carbon fiber. The splitting tensile strengths of control mixes (FC3 and FC3m) was 0.76 MPa and 1.365 MPa, respectively. The effect of fiber on splitting tensile strength for FC3mf$_h$ comparing with FC3m , Fc3mf$_s$ with FC3m, and FC3f$_h$ with FC3 was increased by about 66%, 43%, and 62%, respectively. Adopting a hybrid way was increased the splitting tensile strength by about 16% compared with the single way. This has been associated with the carbon fibers high tensile strength, which could increase the foamed concrete tensile strength, and its ability to prevent cracks (Dawood & Ramli, 2012).

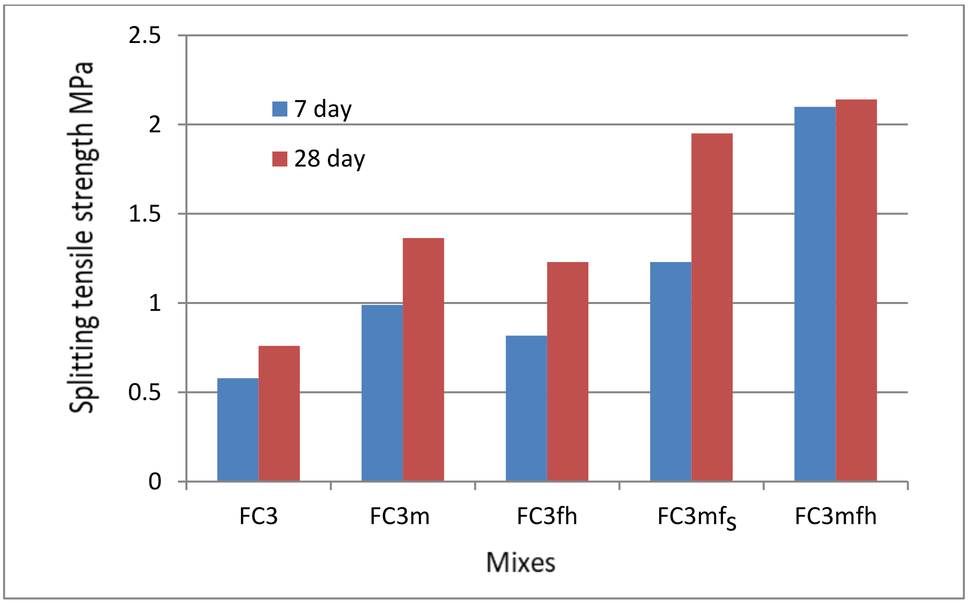

Fig. 5 Splitting tensile strength of investigated mixes.

4.5. Flexural strength

The results of flexural strengths are shown in (Figure 6), it was noticed that the addition of fiber with modified foamed concrete increased the flexural strength**.** The carbon fiber with additives improved the flexural strength by about 162% as noted in FC3mf$_h$ mix comparing with FC3m mix. With the addition of carbon fiber, (FC3f$_h$) the flexural strength was increased by about 99% of that of mixes without additives (FC3). Adopting a hybrid way was increased the splitting tensile strength by about 25.4% compared with the single way. This increase in flexural strength may be resulted from better compaction and homogenous distribution of fibers in mortar mixes and the ability of different types of fibers to restrain and bridge the cracks (Sahmaran & Yaman, 2007).

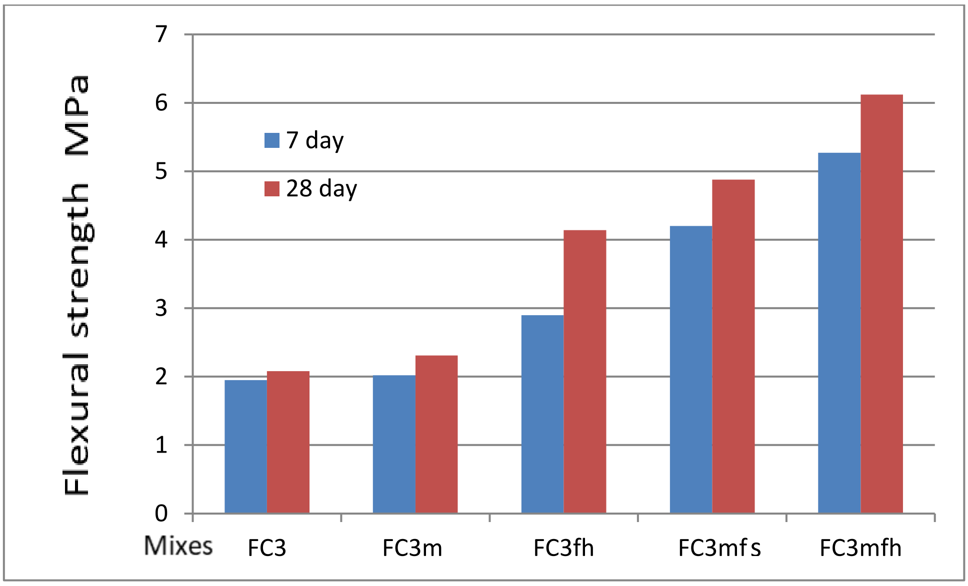

Fig. 6 Flexural strength of investigated mixes

5. Conclusions

From the obtained results, the following conclusions can be drawn:

1. Using the additives (fly ash, silica fume, and superplasticizer) helped in enhancing not only the spreadability but also the mechanical properties.
2. Added carbon fibers to foamed concrete led to decrease its spread diameter.
3. The porosity of foamed concrete was slightly reduced with adding carbon fibers.
4. The mechanical properties of foamed concrete (compressive strength, splitting tensile strength, and flexural strength) were improved with the addition of fibers in both single and hybrid ways.
5. Improvement in compressive strength and splitting tensile strength by about 15% and 16%, respectively, were recorded when carbon fibers (20 mm and 28 mm) were added in hybrid way at 0.133% for each length compared to those of the mix made with adding a single fiber (12 mm, 0.4% of mix volume.

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