Proportioning of Foamed Concrete Reinforced with Carbon Fibers

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ABSTRACT

This paper shows the production of foamed concrete reinforced with carbon fibers. Firstly, different mortar mixes were prepared by varying ratio of sand/cement. Continuously, the selected mortar mix was used for the foamed concrete produced due to the results of density, compressive strength, splitting tensile strength and flexural strength test. Secondly, different foam agent amounts (0.8, 1, 1.2 and 1.4 kg/m^3) with 10% of silica fume were included in the selected mortar mix to produce the optimum foamed concrete mix depending on the same set of tests mentioned above. Lastly, various volumetric fractions of carbon fibers (0.5, 1 and 1.5%) were incorporated with the optimum foamed concrete mix and the same set of tests was done to examine such foamed concrete reinforced with carbon fibers.

The results give acceptable ranges of strength for mortar mix using 1.9 sand/cement ratios. Besides, the foamed concrete produced by the inclusions of foaming agent 1 kg/m^3 shows acceptable ranges of density and strength to be suitable for the reinforcing by carbon fibers. The carbon fiber included in the foamed concrete exhibit significant increases for the strengths. Such increases are varied from about 35% using 1% carbon fibers to 44% and 116% using 1.5% carbon fibers for compressive, splitting tensile and flexural strength, respectively
Keywords: Sand/cement ratio; Foam agent; Foamed concrete**;** Carbon fibers

INTRODUCTION

Lightweight Foamed Concrete (LFC) is one of the recent advancement of concrete technology in civil engineering that can be used in a wide range of construction projects [1]. Significant improvements over the past 20 years in production equipment and better quality surfactants (foaming agents) has enabled the use of foamed concrete on a larger scale [2].

The foamed concrete is manufactured by blending slurry (cement paste or mortar) with pre-formed stable foam (prepared separately by aerating a foaming agent solution). The characteristics of the foamed concrete are linked to its fluidity, low self-weight, and excellent thermal and sound insulation properties [3].

Few detailed studies have been reported on the use of mineral admixtures as cement replacement material in the production of foamed concrete [4]. The suitable use of silica fume in foamed concrete can result in a higher ratio of strength to density and can reduce the peak temperature due to its lower specific heat capacity. The traditional usage of silica fume for cement replacement in normal concrete was found to improve the fresh and strength properties of concrete [5].

Structural lightweight concrete (SLWC) have a compressive strength more than 17 Mpa with a bulk density less than 1950 kg/m^3. Nowadays, SLWC can be 25% lighter than normal weight

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concrete but with normal to high compressive strength levels [6]. The cellular concrete is considered more durable compared to traditional insulating materials, especially when considering potential chemical / fire exposure such as in process facilities [7].

As it's known the concrete is classified as a brittle material and have poor fracture toughness resistance, and low impact strength. The purpose of using fibers in concrete is to improve the mechanical properties of concrete. The most frequently used reinforcement synthetic fibers in the last decades included organic fibers (acrylic, polyvinyl alcohol, polyolefin, polyethylene and polypropylene) and inorganic fibers (alkali resistant glass and carbon). These different types of fibers have been approved to be effective to improve the properties of concrete. Thus, most properties such as the tensile and flexural strengths, toughness, impact resistance, fracture energy and ductility may have been improved [8].

Therefore, this research was conducted to produce foamed concrete using different mortar mixes and select the suitable mix for inducing variable amounts of foam agent. Furthermore, the appropriate foamed concrete is reinforced with different percentages of carbon fiber and studies the properties of these mixes.

Materials used and mixes selection

Materials

The materials used in this study include cement, sand, water, silica fume foam agent or and carbon fibers.

Ordinary Portland cement (OPC) type (I) commercially known as AL-Mass cement factory (Sulaimaniyah governorate of Iraq) was used in this study. The physical, mechanical and chemical characteristics of ordinary Portland cement are shown in Table 1, Table 2 and Table 3. Such characteristics are conformed to IQS: 5/1984[9] and ASTM C150 [10], respectively. Silica fume (Sika Fume HR) was used as a partial replacement of cement, the material properties are shown in Table 4, the properties of (Sika Fume HR) were corresponded to ASTM C 1240 [11].

Table (1) Physical Properties of Cements*

Physical properties	Results	Limits of IQS: 5/1984
Initial setting time (minute)	100	≥ 45 minute
Final setting time (minute)	320	≤ 600 minute
Fineness (Blaine m^2/ kg)	300	≥ 230 (m^2/ kg)
Soundness by Autoclave Method (%)	0.02	Not more than 0.8
Compressive strength (MPa)		
3 days	21	≥ 15
7 days	27	≥ 23

* The tests were done in National Center for Construction Laboratories and Research.

Table (2) Chemical Composition of Cement*

Composition	Abbreviation	Percentage by weight	Limits of IQS: 5/1984
Lime	CaO	61	-
Silica	SiO_2	19.84	-
Alumina	Al_2O_3	5.08	-
Iron Oxide	Fe_2O_3	4.8	-
Sulphate	SO_3	2.49	≤ 2.8
Potash	K_2O	0.1	
Soda	Na_2O	0.3	
Equivalent Na_2O	$Na_2O+0.658K_2O$	0.36	≤ 0.6%
Magnesia	MgO	2.48	≤ 5.0 %
Loss on ignition	L.O.I.	3.8	≤ 4.0 %
Insoluble residue	I.R.	0.40	≤ 1.5 %

* The tests were done in National Center for Construction Laboratories and Research.

Table (3) Main Compounds (Bogue′s equations) of Cement.

Composition	Abbreviation	Percentage by weight
Tri calcium Silicate	C_3S	49.45

Di calcium Silicate	C_2S	19.57
Tri calcium Aluminate	C_3A	5.34
Tetra calcium Aluminate –Ferrite	C_4AF	14.61

Table (4) Properties of Silica Fume*.

Form	Agglomerated
Particles Color/ Appearance	Grey
Specific Gravity	2.20**
Size of particles	0.1 μ**
Dosage	2 - 10 % by weight of cement
Chloride content	Nil

*The data are from manufacture production report.
** Checked in laboratories of Building and Construction Eng. Dept., University of Technology.

The natural sand used as fine aggregate was supplied from AL- Ukhaider region. The specific gravity and fineness modulus of sand are 2.65 and 3, respectively. The grading limits are according to ASTM C 33-02 [12] given in Table 5.

Table (5) Grading of Fine Aggregate

Sieve No. (mm)	Passing (%)	Limits of ASTM C 33-02
# No.4 (4.75)	95	95-100
# No.8 (2.36)	80	80-100
# No.16 (1.18)	59	50-85
# No.30 (0.6)	44	25-60
# No.50 (0.3)	18	5-30
# No.100 (0.15)	4	0-10

* The test was done in laboratories of Building and Const. Eng. Dept., University of Technology.

Sika Lightcrete 02 was used as a foaming agent to obtain lightweight foamed concrete by entraining a controlled amount of air bubbles to concrete mix. The foaming agent was diluted in 30 parts of water before using it. Whereas, Cutted carbon fibers (80mm) were used in the lightweight foamed concrete, the properties of the carbon fibers are listed in Table 6 and Plate 1.

Table (6) Properties of Carbon Fibers*

Fiber properties	Value
Fiber length**	8 mm
Diameter**	7 ± 2 micron
Aspect ratio	1140
Tensile strength	3.5 GPa
Young's Modulus	230 GPa
density***	1.7 g/cm^3
Chemical Resistance	High
Absorption	Nil
Melt Point**	3500°C
Shape	chopped strand

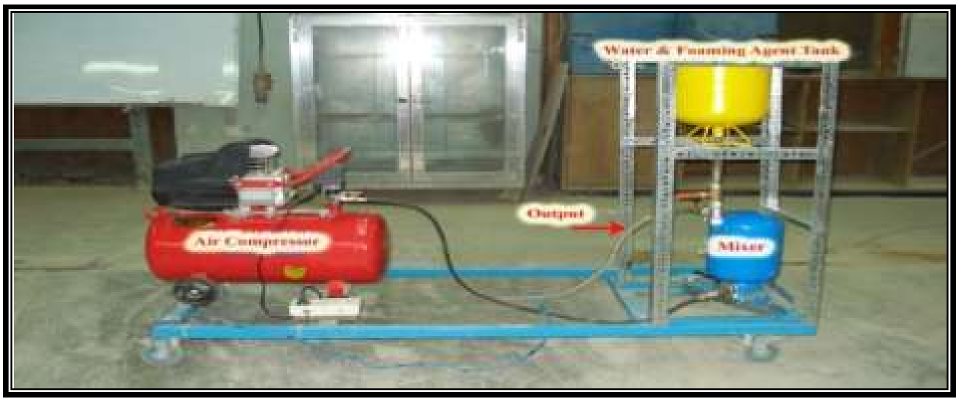
*The data are from manufacture production report.
** Checked in laboratories of Building and Construction Eng. Dept., University of Technology.
***The density measurement was based on ISO 10119:2002 Carbon fiber–Determination of density.

Plate (1): Shape of Carbon Fibers Used in The Study.

Mixes selection

The proportions of the mortar mixtures were varied using different sand to cement ratio. Thus, five mortar mixes (M1-M5) were prepared using 1.8, 1.9, 2, 2.1 and 2.2 sand/cement ratio. However, the w/c ratio was adjusted for each mortar mix, to be suitable for getting flowable mortar (flow = 110% ± 5%). The selected mortar mix was chosen to be applied for preparing foamed concrete mixes with 10% of silica fume as partial replacement of cement. Therefore, the foamed concrete mixes (S1-S5) were prepared using 0, 0.8, 1, 1.2 and 1.4 kg/m^3 of foam agent. Continuously, the selected foamed concrete mix was used for the carbon fibers incorporation. Such foamed concrete mixes reinforced with carbon fibers were presented in mixes C1-C3. The mix proportions for all mixes shown in Table 7.

The mixing procedure was done by mixing cement and sand according to the mix proportion. And then, the required water was added to prepare mortar. For foamed concrete mixes, foam agent was diluted in 30 parts of water according to ASTM C796 [13]. Foam was produced in a laboratory using locally manufactured machine as shown in Plate 2 [14]. Water cement ratio (w/c) was determined depending on flow of the mix (flow range 110 ± 5%). The foam was added to the mortar as shown in Plate 3 and the flow of the batch was measured by using flow table as shown in Plate 4 according to ASTM C 1437 [15]. The fresh density for foamed concrete mixes were measured and recorded as shown in Table 7.



Plate(2): Foaming Machine

Plate (3): Addition of Foam to the Mix.

Plate (4): Flow Table Test.

Table (7) Mix Proportions of Mortar and Foamed Concrete Mixes

Mix	Mix proportion						Flow %	Fresh density kg/m3
	Cement (kg)	Sand (kg)	w/c (%)	Silica fume (kg)	Foam kg/m3	Carbon fiber %*		
M1	1	1. 8	0.42	---	---	---	110	2300
M2	1	1. 9	0.42	---	---	---	110	2290
M3	1	2	0.44	---	---	---	110	2270
M4	1	2.1	0.45	---	---	---	110	2260
M5	1	2.2	0.47	---	---	---	110	2260
S1	0.9	1.9	0.42	0.1	---	---	110	2280
S2	0.9	1.9	0.38	0.1	0.8	---	110	1930
S3	0.9	1.9	0.38	0.1	1	---	110	1820
S4	0.9	1.9	0.38	0.1	1.2	---	110	1800
S5	0.9	1.9	0.38	0.1	1.4	---	110	1760
C1	0.9	1.9	0.35	0.1	1	0.5	80**	1800
C2	0.9	1.9	0.37	0.1	1	1	75	1810
C3	0.9	1.9	0.41	0.1	1	1.5	60	1820

*The amount of carbon fibers has been calculated as a percentage of total mix volume.
** The carbon fibers reduce the sufficient flow value for the foamed concrete mixes.

Experimental work

The average of three cubes of 50 mm was used for testing the compressive strength of mortar mixes according to ASTM C 109 [16]. Continuously, the average of three prisms of 40 × 40 × 160 mm was used to determine the flexural strength of mortar mixes according to ASTM C 348 [17]. On the other hand, for the foamed concrete mixes, the cubes of 100 mm were used to determine the compressive strength according to BS 1881:1992 [18]. The density for all mixes also was examined using 100 mm cubes according to ASTM C 642 [19]. The flexural strength of foamed concrete mixes was done using prismatic molds of 100 × 100 × 400 mm according to ASTM C78 [20]. Whereas, the cylindrical moulds 100 × 200 mm were used for splitting tensile strength according to ASTM C567 [21].

Results and discussion

Fresh and oven dry density

The tests result of fresh and oven dry density for different mixes are shown in Tables 7 and 8. The fresh density of the foamed concrete depends on the amount of the foam agent. Thus the density of such concrete is decreased by the foam agent increase. Thus, the fresh density of foamed concrete was decreased from 1930 kg/m^3 to 1760 kg/m^3 by the increment of the foam agent from 0.8 kg/m^3 to 1.4 kg/m^3, respectively. This behavior is clearly related to the ability of the foam agent to induce the bubbles inside the concrete [22].

Table (8) Properties of Different Mortar and Foamed Concrete Mixes

Mixes		Compressive strength (MPa)		Splitting tensile strength (MPa)		Flexural strength (MPa)		Absorption (%)	Oven dry density kg/m3
		7 Days	28 Days	7 Days	28 Days	7 Days	28 Days	28 Days	28 Days
Group 1	M1	16.3	33.1	2.40	2.73	4.03	5.06	5.23	2170
	M2	19.2	33.5	2.47	3.03	4.37	5.52	6.09	2160
	M3	18.3	30.6	2.58	2.71	4.27	4.79	6.99	2110
	M4	16.5	28.4	1.82	2.05	3.44	4.12	7.13	2100
	M5	15.1	21.1	1.95	2.21	4.13	4.30	8.53	2090
Group 2	S1	25.4	37.1	2.45	2.68	4.44	4.84	5.92	2120
	S2	13.2	18.9	1.89	2.25	1.81	2.37	8.7	1800
	S3	11.2	17.1	1.72	1.95	1.7	2.08	12.22	1670
	S4	7.4	9.6	1.23	1.50	1.63	1.90	12.07	1620
	S5	5.2	6.8	0.9	1.16	1.26	1.44	12.89	1520
Group 3	C1	11.5	17.3	1.8	2	2.6	3.8	9.94	1745
	C2	13.8	23.1	2.0	2.6	3.1	4.3	7.42	1805
	C3	12	21.4	2.1	2.8	3.4	4.5	7.52	1820

On the other hand, the carbon fibers incorporated with the foamed concrete may slightly increase the fresh density of such concrete due to their specific gravity [23].
The oven dry density for mortar mixes was found to be affected by the increment of sand/cement ratio. As the sand increases in the mortar mix, the oven dry density of mortar would be decreased [24].

Figure 1 shows the relationship between the sand/cement ratio and the oven dry density of mortar mixes.

For the foamed concrete mixes, it was noticed that the use of 0.8 kg/m^3 of foam agent would decrease the oven dry density to 1800 kg/m3. Whereas, the density would be reduced significantly to be 1520 kg/m3 due to the use of 1.4 kg/m^3 of foam agent. Figure 2 illustrates the relationship between the foam agent amount and the oven dry density of foamed concrete.

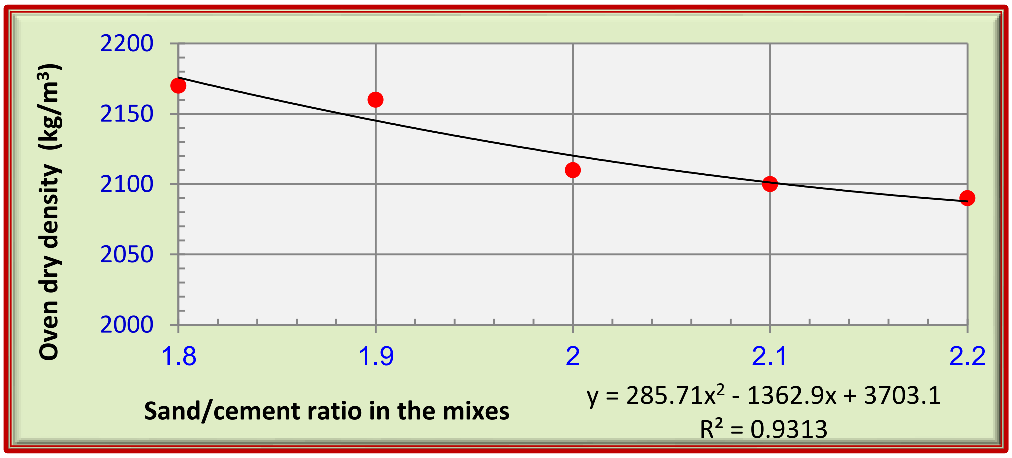


Figure (1): Relationship between the Sand/Cement Ratio and the Oven Dry Density

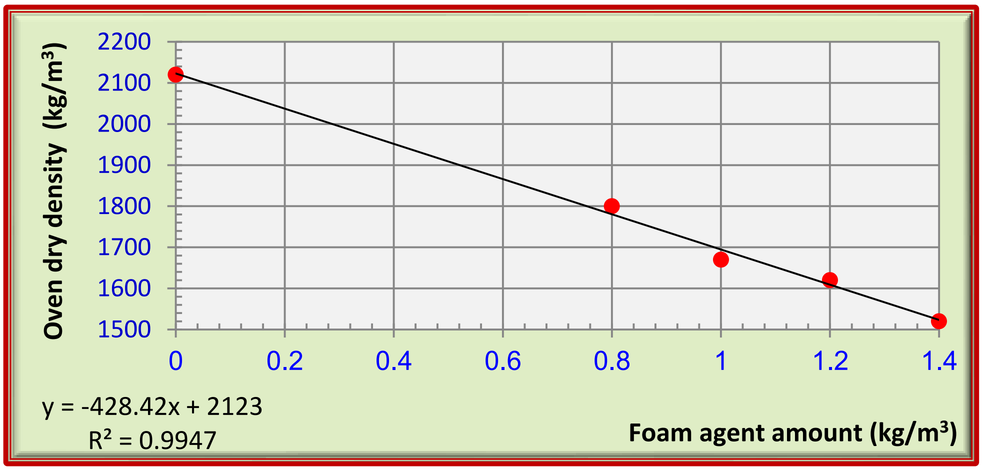


Figure (2): Relationship between the Amount of Foam Agent and the Oven Dry Density.

The reinforcement of foamed concrete by carbon fiber increased the oven dry density of such foamed concrete. This is also can be attributed to the specific gravity of carbon fiber which increases the overall density of foamed concrete mixes [25].

Compressive strength

Table 8 shows the results of compressive strength for specimens at ages of 7 and 28 days after water curing. It can be noticed that the sand/cement ratio has significantly affected on the compressive strength of the mortar mixes. This effect is related to the cement content and the w/c ratio that would vary by the variation of sand/cement ratio in the mortar mixes [22]. Therefore, the highest ratio of sand/cement used in this study in the mortar mixes exhibits more water demand and least compressive strength. However, the use of 1:1.9 (cement: sand) mortar mix gives highest compressive strength and thus has been chosen as the appropriate mix for the production of foamed concrete.

Figure 3 shows the relationship between sand/cement ratio and the compressive strength of mortar mixes at 28 days.

For the foamed concrete mixes, the results reveal that the foam agent may significantly reduce the compressive strength of the foamed concrete mix. Therefore, the comparison between S1 and S5 shows that the use of 1.4 kg/m^3 of foam agent decrease the compressive strength of foamed concrete by about 82% compared with the mix of zero foam agents. This is obviously related to the ability of foam agent by inducing the bubbles inside the mix that may decrease the strength of the cement paste and lastly reduce the overall strength of the mix [23].

However, the balance between the reduced density and the criteria of getting structural compressive strength of the foamed concrete mix enables the researchers to select the mix S3 (foam agent = 1 kg/m^3) for the inclusion of carbon fibers with foamed concrete mix.

Figure 4 shows the relationship between the amount of foam agent in the mix and the compressive strength of foamed concrete at 28 days.

For the foamed concrete reinforced with carbon fibers mix, the results of compressive strength give higher values by the inclusion of such fibers in the foamed concrete mix compared with plain foamed concrete. The highest value has obtained due to the use of 1% carbon fiber in the foamed concrete mix and the percentage of increase is about 35% higher than that of plain foamed concrete. This is can be attributed to the stiffness of the carbon fibers that may enhance the compressive strength of the foamed concrete [25].

However, the use of 1.5% carbon fiber decrease that percentage of increase to be about 25% compared with plain foamed concrete. This is due to the property of fibers which make the concrete mix needs more water to be suitable for casting [23].

Figure 5 illustrates the percentages increase of compressive strength of foamed concrete by the inclusion of carbon fibers.

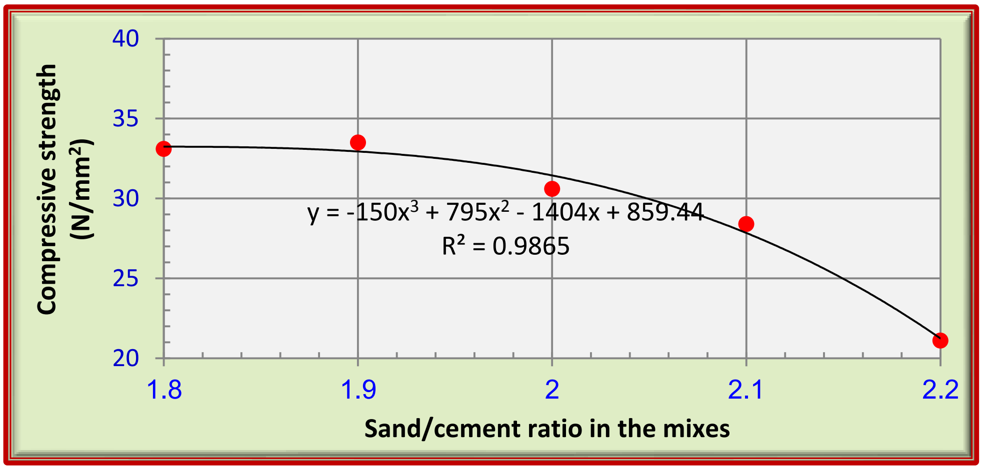


Figure (3): Relationship between the Sand/Cement Ratio and the Compressive Strength.

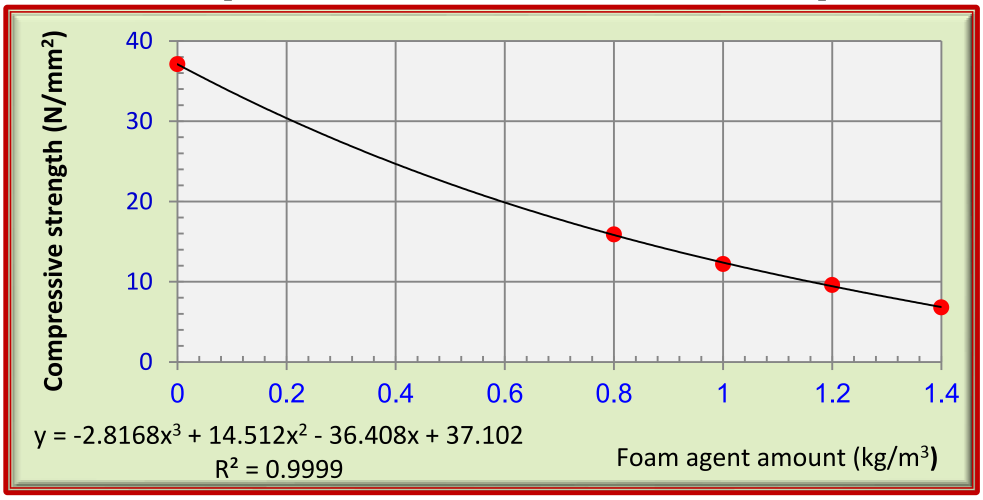


Figure (4): Relationship between the Amount of Foam Agent and the Compressive Strength.

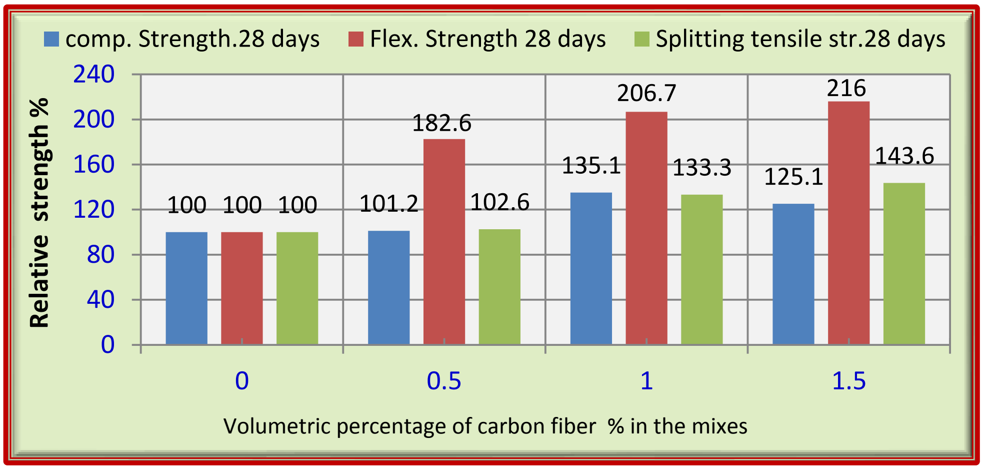


Figure (5): Relationship between the Volumetric Percentage of Carbon Fiber and the Relative Strength.

Splitting Tensile strength

The results of splitting tensile strength for specimens at ages of 7 and 28 days after water curing are shown in Table 8. It can be seen that the sand/cement ratio has affected significantly on splitting strength with similar trend on that effect of compressive strength of the mortar mixes. This effect is also related to the cement content that may increase the splitting tensile strength of mortar by the reducing the sand/cement ratio in the mortar mixes [22]. However, the highest value of splitting tensile strength has been obtained by mixing 1:1.9 (cement: sand) of mortar mix.

Figure 6 presents the relationship between sand/cement ratio and the splitting tensile strength of mortar mixes at 28 days. The results of foamed concrete mixes show that the foam agent may significantly reduce the splitting tensile strength of the foamed concrete mix. Thus, the comparison between S1 and S5 shows that the use of 1.4 kg/m^3 of foam agent decrease the splitting tensile strength of foamed concrete by about 43% compared with the mix of zero foam agents due to same purposes listed in compressive strength.

Figure 7 shows the relationship between the amount of foam agent in the mix and the splitting tensile strength of foamed concrete at 28 days.

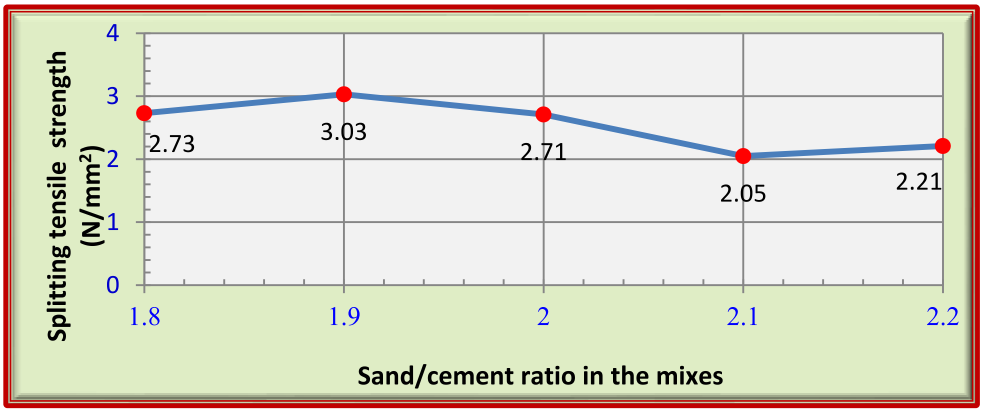


Figure (6): Relationship between the Sand/Cement Ratio and the Splitting Tensile Strength.

For the carbon fibers incorporated in foamed concrete, the results show that the inclusion of such fibers in the foamed concrete mix increase the splitting tensile strength of foamed concrete. As the volumetric fraction of carbon fiber increases, The splitting tensile strength of foamed concrete increases too. Thus, highest value has been obtained due to the use of 1.5% carbon fiber in the foamed concrete mix and the percentage of increase is about 44% higher than that of plain foamed concrete. This is related to the high tensile strength of carbon fibers that may promote the tensile strength of the foamed concrete and the ability of the fibers to bridge the cracks enhancing the homogeneity of the foamed concrete [25].

Figure 5 illustrates the percentages increase of splitting tensile strength of foamed concrete by the inclusion of carbon fibers.

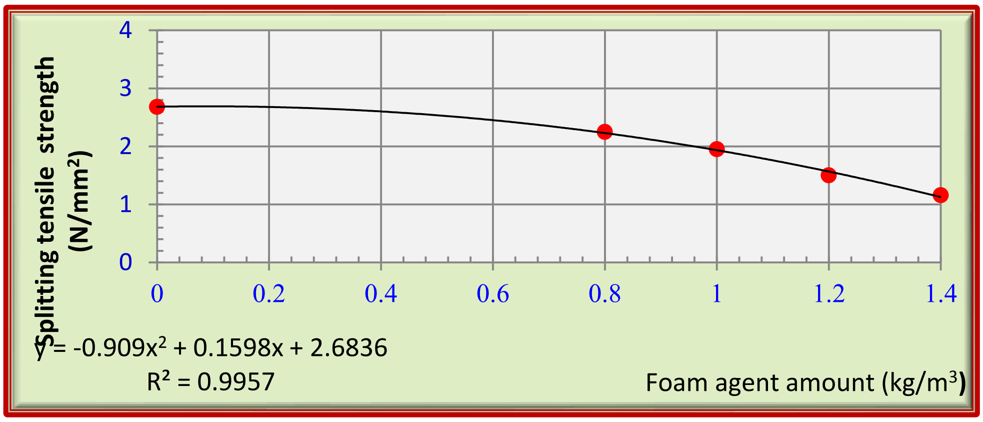


Figure (7): Relationship between the Amount of Foam Agent and the Splitting Tensile Strength.

Flexural strength

The results of flexural strength for specimens at ages of 7 and 28 days after water curing are shown in Table 8. It can be observed that the sand/cement ratio has affected significantly on flexural strength as similar effect as that of compressive and splitting tensile strength of the mortar mixes. Again, the highest value of flexural strength has been got by mixing 1:1.9 (cement: sand) of mortar mix. Figure 8 presents the relationship between sand/cement ratio and the flexural strength of mortar mixes at 28 days.

For foamed concrete mixes, the results illustrate that the foam agent may drastically decrease the flexural strength of the foamed concrete mix. Thus, the comparison between S1 and S5 shows that the use of 1.4 kg/m^3 of foam agent reduces the flexural strength of foamed concrete by about 70% compared with the mix with no foam agent. Figure 9 shows the relationship between the amount of foam agent in the mix and the flexural strength of foamed concrete at 28 days.

On the other hand, the results of flexural strength of foamed concrete reinforced with carbon fibers show that the inclusion of fibers increases the flexural strength of foamed concrete. The highest value has been recorded due to the use of 1.5% carbon fiber in the foamed concrete mix and the percentage of increase is about 116% higher than that of plain foamed concrete. This is also mentioned before, as the micro-mechanical feature of crack bridging operates from the stage of damage evolution to ultimate loading and beyond [26]. Figure 5 illustrates the percentages increase of flexural strength of foamed concrete by the inclusion of carbon fibers.

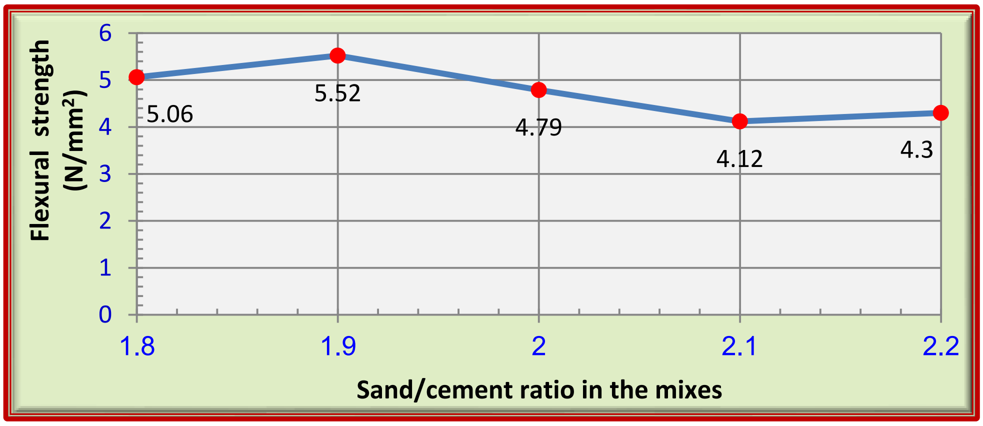


Figure (8): Relationship between the Sand/Cement Ratio and the Flexural Strength.

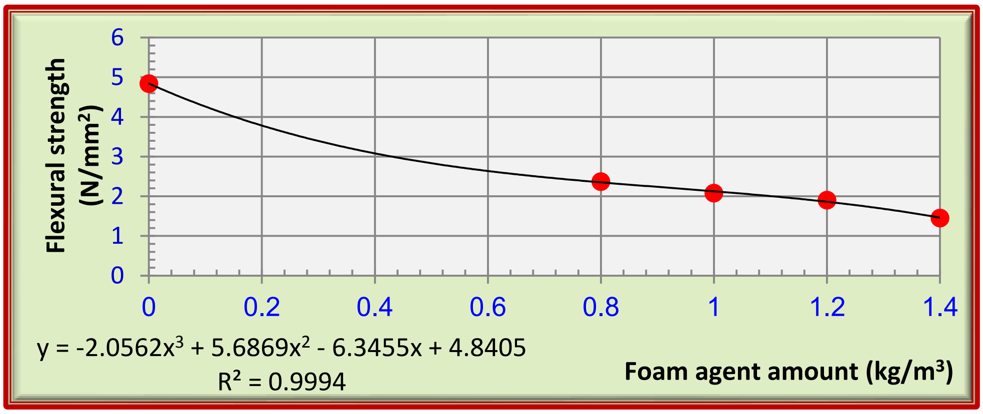


Figure (9): Relationship between the Amount of Foam Agent and the Flexural Strength.

Absorption

Table 8 shows the results of absorption for specimens at ages of 28 days after water curing. It can be seen that the mortar mixes give least values of absorption due to the reduced voids or pores in mortar mixes. However, the increase in absorption is noticed in mortar mixes with highest sand/cement ratio. For the foamed concrete mixes, it is obviously observed that the increase in the absorption is related to the highest foam agent amount in the mix. Thus, the comparison between S1 and S5 show that the use of 1.4 kg/m^3 of foam agent may increase the absorption from 5.92 % (no foam agent in the mix) to 12.89%.

Lastly, the results of foamed concrete mixes reinforced with carbon fibers reveal that these fibers reduce the absorption from 12.22% (1kg/m^3 foam agent with no fiber) to 7.42% (1 kg/m3 foam agent + 1% carbon fibers) due to the ability of these fibers to make the cement paste of the foamed concrete more dense and seal some pores in the mix.

CONCLUSIONS

This paper illustrates the production of foamed concrete reinforced with carbon fibers by mixing varied ratios of sand/cement to obtain an optimum mortar mix that would be suitable for such production. Some conclusions can be drawn as follows:

1. The use of 1:1.9 (cement: sand) ratio for mortar mixes gives the best performance of compressive, splitting tensile and flexural strengths. The increment of such ratio would increase the water demand for the mortar mix to maintain the same consistency. Thus, this proportion was chosen for the production of foamed concrete.
2. For the foamed concrete, the use of 1 kg/m^3 of foam agent is found to reduce the oven dry density to 1670 kg/m^3. On the other hand, the mechanical properties of such foamed concrete produced by this amount of foam agent would be suitable for structural application.

3. The use of carbon fibers for reinforcing the foamed concrete shows significant increase for compressive strength. Thus, the use of 1% of carbon fiber as volumetric fraction increases the compressive strength from 17.1MPa to 23.1 MPa.

4. The incorporation of carbon fibers boosts the best performance regarding to splitting and flexural strengths. Therefore, as the volume fraction of carbon fibers increase in the mix, such strengths are increased too. The use of 1.5% of carbon fibers increases dramatically the splitting tensile and flexural strengths by about 44% and 116% respectively, compared with plain foamed concrete.

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