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Nano Silica Impacts the Microstructure and Mechanical Properties of Carbon Fiber-Reinforced Foam Concrete

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ABSTRACT

Foamed Concrete is a popular choice in the construction industry due to its excellent thermal and acoustic insulation properties and ability to support structures. This study investigated the effects of incorporating nanomaterials into carbon fiber-reinforced foam concrete to enhance its mechanical properties. The experimental work was conducted in two phases. First, a lightweight foam concrete mixture with varying amounts of foam agent was produced, with the optimal balance being 11 Kg/m3 to achieve the target density of 1343 Kg/m3 within the range of 1300-1350 Kg/m3 at 28 days, and the appropriate compressive strength of 17.4 MPa. Adding carbon fibers reduced the flow test by approximately 6.63% compared to the control foam concrete mix. When 1% of Nano-silica was added, the high consistency of the mixture decreased by 7.27% compared to the control foam concrete mix reinforcing with three percentage of carbon fibers increased its compressive strength by approximately 19.8%, with the best percentage being 1%. However, the dry density increased by 8.33% compared to foam concrete mixture. When Nano silica was used,the compressive strength increased by 14.39%, and the dry density increased by about 14.64% at 28 days compared to the foam concrete-reinforced carbon fibers mix. The results demonstrated that carbon fiber and Nano Silica had a synergistic effect on enhancing the mechanical properties of the foam concrete, exerting positive impacts on reducing the porosity and improving the pore distribution at 1%. Adding Nano silica with carbon fibers further transformed large voids into small ones and introduced closed pores, leading to an enhanced microstructure for foamed Concrete.

1. Introduction

1.1 Light Wight foamed Concrete

Civil engineering has seen a noteworthy innovation in concrete technology with the advent of Cellular Lightweight Concrete (CLWC). This material offers remarkable versatility and can be used in various construction projects. [1]. Thanks to advancements in production equipment and top-quality surfactants (foaming agents) over the last twenty years, foamed Concrete can now be effectively utilized on a larger scale [2]. Foamed Concrete, which mixes cement paste with pre-made foam, is lightweight and exceptionally insulating [3].

Creating cellular Concrete involves two commonly used techniques: pre-made foam or combining foaming agents with the cement and water mixture. The latter technique incorporates cement, lime, sand, water, and an expansion agent to form a porous microstructure within the Concrete. This method reduces the weight of the Concrete, making it more cost-effective and easier to handle. Air bubbles are formed through a premade foam or chemical surfactant, which maintains their size and shape throughout the setting process. Foamed Concrete is significantly lighter than regular Concrete by 10% to 80%, reducing the need for reinforcing steel and transportation costs. It is a versatile and lightweight material ideal for construction projects as it results in structures that experience less settling. Additionally, it is an eco-friendly option, as spent plastic from expired lead-acid batteries can create lightweight Concrete.

1.2 Fiber Reinforced Concrete (F.R.C.)

The use of fibers in brittle materials dates back around 3500 years ago when the hill of Aqar Quf near Baghdad was constructed with sun-baked bricks reinforced with straw. Nowadays, steel, polypropylene, and glass fibers are commonly used for the same purpose, with cellulose fibers being utilized at least 50 years before them [9]. Adding fibers to Concrete has several benefits for engineers, including improving elasticity or plastic cracking characteristics within six hours after casting, increasing flexural or tensile strength, enhancing hardness and impact resistance by utilizing post-cracking ductility to regulate cracking and the mode of failure, and increasing toughness. However, it is essential to note that introducing short fibers to a three-dimensional random fiber distribution with realistic fiber volumes will not significantly change the stress at which solidified concrete cracks.

1-3 Nanomaterials in concrete

Enhance its durability and sustainability by increasing surface reactivity, thereby improving strength and service life while reducing weight and size. Nanoparticles offer numerous benefits to the microstructure and properties of cement-based materials. Nanotechnology has improved concrete's mechanical properties and insulation, revolutionizing existing materials with new functionalities. It enhances structural integrity while reducing environmental impact, improves building monitoring, and develops anti-corrosion coatings [11,12].Researchers have studied using foamed concrete with cement and low-lime fly ash as a filler. They found it was easily achievable, had a nearly 1200 kg/m3 density, and compressive strengths of 25 MPa. Two cement-sand and cement-pulverized fuel ash (P.F.A.) combinations were analyzed for foamed concrete's structural and mechanical characteristics. L.W.C., a low-density material ranging from 250 Kg/m3 to 1800 kg/m3, can be improved by adding fly ash, blast furnace slag, or silica fume with P.C. Additionally, fiber reinforcement can prevent early-age cracking and make cellular concrete less brittle and more ductile. A study evaluated the strength of foamed concrete with carbon fiber reinforcement and found that adding carbon fiber significantly increased the strength, with 1% carbon fibers resulting in a 35% increase and 1.5% resulting in even more improvement. The study used various mortar mixtures, adjusted the sand/cement ratio, and supplemented with foaming agents, including silica fume, to achieve acceptable density and strength levels. The orientation and distribution of fibers are the primary parameters influencing the performance of fiber-reinforced concrete.[14].In his 2021 study, Badai delved into the possibilities of incorporating sustainable local energy networks into existing infrastructures to create environmentally-friendly designs. He aimed to demonstrate the feasibility of utilizing current resources and technology to decrease thermal energy consumption and ultimately transition conventional cities into smart cities. Additionally, adding fibers and recycled car tires to self-compacted, stretched concrete beams significantly reduced crack width and enhanced flexural behavior compared to unreinforced beams. The numerical analysis findings aligned with the physical results, highlighting the matrix and fibers' mechanical properties [16].

2. Experimental Work and Materials

The study utilized Ordinary Portland cement (O.P.C.) CEM I sourced from the AL-Mass cement factory in Iraq, by the Iraqi specification No. 5/2019 [17], as evidenced in Tables 1 and 2. Fine aggregate that met the sand grading requirements of Iraqi Standard I.Q.S. No. 45/1984 [18] was obtained from the AL-Ukhaider region and is detailed in Table 3. All concrete mixing and curing procedures adhered to Iraqi specifications (1703\ 1992) [19], and tap water was used. The water-reducer from Sika Company is recommended in a dosage of (0.5-2) liters per 100kg of cement, in compliance with ASTM C 494/C 494M-17. Type G [20] was the standard concrete Superplasticizer used. Carbon fiber reinforcement from Sika Wrap was chosen due to its lightweight, flexible, durable properties and high strength. The study used the foaming agent Lightcrete-400 from Sika Chemistry Factory to generate the required foam for lightweight cellular Concrete, following ASTM C796-97 [21] and introducing entraining air bubbles in the mix. Finally, Nano Silica and metal nanoparticles from the U.S. Research Nanomaterials Inc. were used as additives in cement.

Table 1. Chemical Composition And Main Compounds Of Cement

Oxide composition and chemical properties	Test result	[20] requirements
Lime (CaO)	61.75	-
Silica (SiO_2)	20. 62	-
Alumina (Al_2O_3)	4.77	-
Iron oxide (Fe_2O_3)	3.42	-
Magnesia (MgO)	4.82	≤ 5%
Sulfate (SO3)	2. 05	≤ 2.8% for C3A >3.5%
Loss on Ignition (L.O.I.)	1.37	≤ 4%
Insoluble residue (I.R.)	0.73	≤ 1.5%
Main Compounds (Bogue's equation)		
Tri calcium silicate (C_3S)	51.82	-
Di calcium silicate (C_2S)	20.105	-
Tri calcium aluminate (C_3A)	6.86	-
Tetra calcium aluminate - ferrite (C_4AF)	10.39	-

Table 2. Physical properties of Ordinary Portland Cement

Physical properties	The test result of the cement	Limits of I.Q.S. No. 5/2019
Specific surface area, Blaine Method (Kg/ m^2).	375	≥ 2500
Setting time Initial setting (min) -Final setting (min	 83 3:90	 ≥ 45 ≤ 10
Soundness using the autoclave method	0.11	≤ 0.8
Compressive Strength (MPa)		
2-days	25	≥ 20
28-days	47	≥42.5

Table 3. Grading of fine aggregate

Sieve size (mm)	Passing%	[21] requirements
10	100	100
4.75	100	90– 100
2.36	100	85 – 100
1.18	100	75 – 100
0.6	22.58	60– 79
0.3	61.5	12– 40
0.15	96.73	0 – 10
Fineness modulus = 1. 81		

3-1 Methodology

At the beginning, experimental attempts included prepare normal mortar without foam agent. After made the experimental mixes and achieve to optimal ratio of materials included cement content 300 Kg/m^3 with different variables percentage of material such as cement to sand ratios (C:S) 1:1.5,water to cement ratios (W/C) 0.35, superplasticizer (SP) 1.8% by weight of cement.

3-2 Mix Procedure For Foamed Concrete

The optimal ratio of C: S was 1: 1.5 and W/C 0.35 and SP 1.8%,. These ratio produced uniform mixing and excellent workability with After making the mortar mixes, we set a best compressive strength within 43 MPa at28 days . The experimental work conformed by mixed for a minute the ideal ratio of materials, C:S (1:1.5), W/C (0.35), and (1.8%)Superplasticizer(SP) and a foaming agent are added to separate portions of water. Using an electric mixer set to high speed for two minutes, the remaining water and foaming agent are combined until a stable bubble foam forms. The mixture is mixed with foam, then added to the mortar after a homogenous mixture has been developed, it ceases. Two layers of casting are carried out after lubricating the sides and base of the mold with a modest amount of oil. After that Compressive strength was evaluated for(7and 28) days and different percentages (0.5% ,0.75% ,1%) of Fibers are carefully blended to ensure that they are evenly distributed throughout the mixture in order . As Table 5. [18,25,26]..Then adding the Nano materials (Nano Sio2) in different proportions (0.2%,0.5%,1%) by the weight of cement content to foamed concrete reinforced with carbon fibers (CFRFC) .As Table 4 , by carried testing the compressive strength for 28 days ,after achieving on optimal of Nano Sio2(NS) was 1% , We investigate the mechanical properties of formed concrete reinforced by Nano silica and carbon fiber , the workability and the compressive strength with the dry density at(7and 28)days shown in(Figure.1) .

Figure 1. Casting details to cast and curing ,test the compressive strength and flexural strength for different volume carbon fiber and Pour the optimal mixture by 1% Nano slice and carbon fibers and curing in water at 7 and 28 days

Table 4. Mixing details for components by optima CFRFC

Mix symbol	C/S	w/c	SP %	Foam agent (Kg/m^3)	Carbon fiber %	NS %
MF0	1:1.5	0.35	1.8	0	0	0
MF9	1:1.5	0.35	1.8	11	0	0
MC1	1:1.5	0.35	1.8	11	0.50	0
MC2	1:1.5	0.35	1.8	11	0.75	0
MC3	1:1.5	0.35	1.8	11	1	0

Table 5 .Mixing Details for Components by Optima CFRC& NS

Mix symbol	C/S	w/c	SP %	Carbon fiber %	NS %
MC3	1:1.5	0.35	1.8	1	0
MNS1	1:1.5	0.35	1.8	1	0.2
MNS2	1:1.5	0.35	1.8	1	0.5
MNS3	1:1.5	0.35	1.8	1	1

3.3 Concrete Testing

3.3.1 Flow Test

The consistency of mortar is determined using a flow table device as per ASTM C 230-14[24]. The mix dose for various concrete types is determined by adjusting the (w/c) ratio and foam agent dosage. The flow of LWFC is expressed as the percentage increase in the original concrete source diameter, which is calculated using the following equation:

D Flow = [(brackets0] × 100

Here, D represents the spread rate in the base diameter for concrete from four directions measured in mm.

3.3.2 Dry Density Test

The dry density of hardened concrete is determined using ASTM C567 [25] standards based on dried samples' weight and volume measurements. Samples are analyzed at 7 and 28 days, and the density is calculated by dividing the sample weight by volume.

3.3.3 The Compressive Strength Test

The compressive strength test is an important mechanical property for predicting the durability and effectiveness of LWFC. The test uses a cubic specimen measuring 50x50x50mm in line with ASTM C-513/513 M -11[26]. This test involves applying constant compression forces perpendicular to the direction of concrete pouring with a fixed load on an electrical testing instrument to a cube with a 2000 K.N. capacity. The compressive strength of each cube is determined by dividing the failure load by the applied cube area, as described in section.

$F_{cu} = P/A$

Where:

F cu: compression strength (MPa).

A: Face area of the cube (mm2).

P: Compressive load at failure. (N)

4. Result and Discussion

4.1 workability

Incorporating foaming agents into mortar mixtures can improve the flow characteristics, resulting in more excellent workability. The introduction of increased foam levels has been shown to correspond with a broader spread of fresh foam concrete. In a flow test aimed at achieving a density of 1343 Kg/m^3, the flow was measured at 117mm [27]. However, adding carbon fibers in ratios of 0.5%, 0.75%, and 1% has decreased the flow rate of foam concrete. For a 1% addition, the ideal percentage was discovered to be 6.63% lower than that of foamed Concrete [19]. Including Nanoparticles (N.S.) has been shown to increase the stability and viscosity of a fresh mix. However, high levels of cementation materials and fibers can negatively impact consistency. Consequently, the high consistency of lightweight foamed Concrete reinforced with carbon fibers decreases by 7.27% with a 1% addition of nanosilica [28]. More detailed information can be found in Tables 6 and 7 and Figures 2 & 3.

Table 6. Different Percentage Of Nano Silica Addition To Foam Concrete Reinforced By Carbon Fiber With Flow (mm)

Mix Symbol	Carbon Fiber %	Flow (mm)
MF9	MF9+ CF 0%	117
MC1	MF9 + CF 0.50%	113
MC2	MF9 + CF 0.75%	112
MC3	MF9 + CF 1%	110

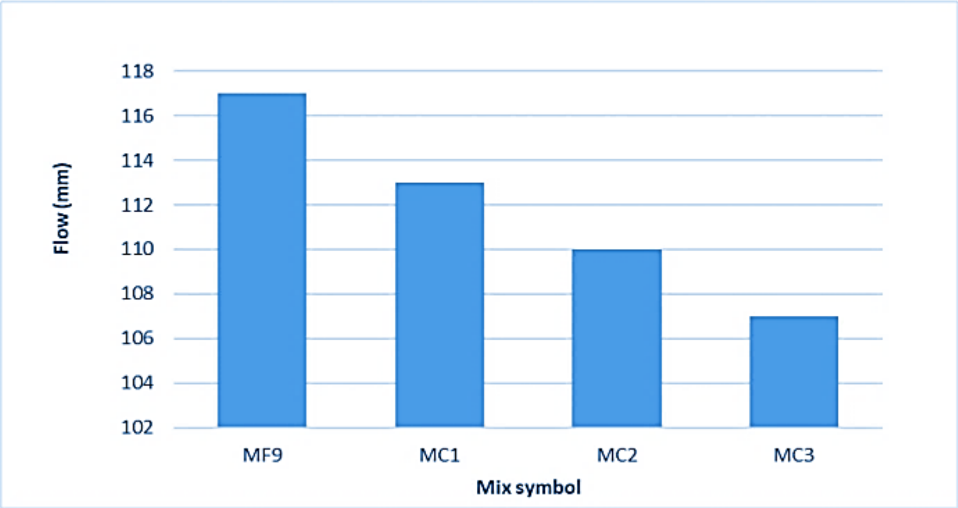

Figure 2. Different percentage of carbon fibers addition to foam concrete with flow (mm)

Table 7. Addition Different Percentage Of Carbon Fiber With Flow (mm) To Foam Concrete

Mix symbol	NS%	Flow (mm)
MC3	MF9 + CF 1%	110
MNS1	MF9+ MC3+ NS 0%	110
MNS2	MF9 + MC3+ NS 0.2%	105
MNS3	MF9 + + MC3+ NS 0.5%	102

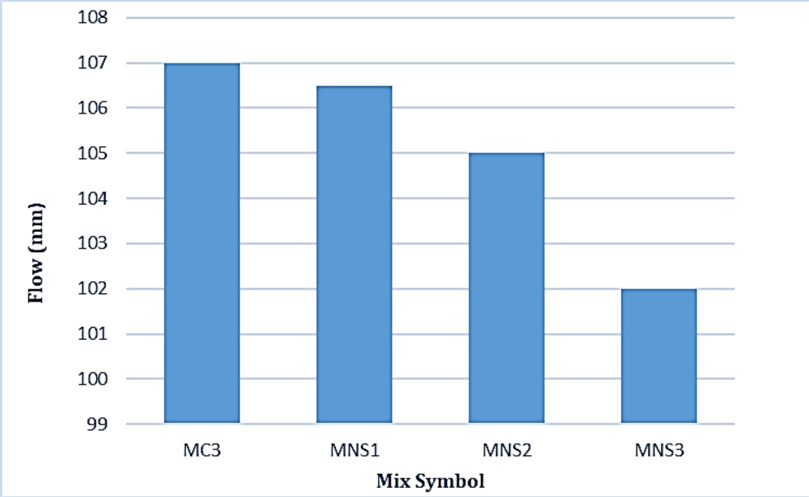

Figure 3. Different percentage of Nano silica addition to foam concrete reinforced by carbon fibers with flow(mm)

4-2 The effect of carbon fibers and Nano silica on foam concrete's Compressive strength and dry density.

Foamed Concrete is a unique type of concrete that features a distinct structure with empty spaces or cells created using foaming agents or gas-forming chemicals. However, the use of excess foam agents can result in air gaps, leading to a decrease in compressive strength based on dry density. A recent study found that at a target density of 1343 kg/m3, the compressive strength decreased by 65% compared to the control density of 2253 kg/m3, with the dry density decreasing by 40% after 28 days.

To address this issue, the study introduced carbon fibers into the foamed concrete mix at 0.5%, 0.75%, and 1% of the concrete volume. The results were impressive, with compressive strength increasing by 6.9%, 9.77%, and 19.8%, respectively, compared to the control foamed concrete mix after 28 days. Furthermore, the study incorporated Nano silica in three different percentages of 0.2%, 0.5%, and 1% of the weight of cement added to the foamed concrete. The optimal ratio was found to be 1%, which further enhanced the compressive strength. The study also showed that using low-density fibers like carbon fibers was more effective in achieving the maximum percentage of compressive strength and helped with insulation. For more information on this, Table 8 and Figure 4 provide more details.

The study results showed that the addition of carbon fibers and Nano silica to concrete significantly increased its compressive strength and dry density. The study found that using 1% carbon fiber and 1% Nano SiO2 produced the specimens with the highest compressive strength, with a 14.39% increase when compared to foamed concrete reinforced with 1% carbon fiber alone. Furthermore, increasing the Nano SiO2 content resulted in a 14.64% increase in dry density after 28 days, as indicated in Table 9. The study also revealed that adding 1% Nano SiO2 significantly improved the strength and abrasion resistance of the concrete due to its large surface area and ability to speed up hydration reactions. The study also found that Nano-SiO2 was more effective in increasing strength than silica fume. However, the study noted that the production method and conditions for synthesizing Nano-SiO2 and its dispersion in the paste can affect the outcomes. Additionally, the study discovered that using nanomaterials led to a more optimized pore distribution and reinforced pore structure, further enhancing mechanical strength. Finally, the addition of fibers improved the bonding between the foamed concrete, as seen in Table 9 and Figure 5.

Table 8. Effect of Different percentage of Carbon Fibers on The Compressive Strength (MPa) for Foamed Concrete at 7 and 28 Days

Mix symbol	`Compressive Strength (MPa)	
	7 days	**28 days**
MF0	34	43
MF9	11.6	17.4
MC1	12.4	18.6
MC2	13.6	19.1
MC3	15.9	20.85

Table 9. Effect of addition of different percentages of Nano silica on foam concrete reinforced by carbon fibers 1% on the dry density (Kg/m^3) and Compressive Strength (MPa) at 7,28 days

Mix symbol	Dry density(Kg/m3)		`Compressive Strength (MPa)	
	7 days	**28 days**	**7 days**	**28 days**
MC3	1320	1455	15.9	20.85
MNS1	1342	1476	16.74	20.98
MNS2	1395	1535	17.8	21.71
MNS3	1451	1668	18.3	23.85

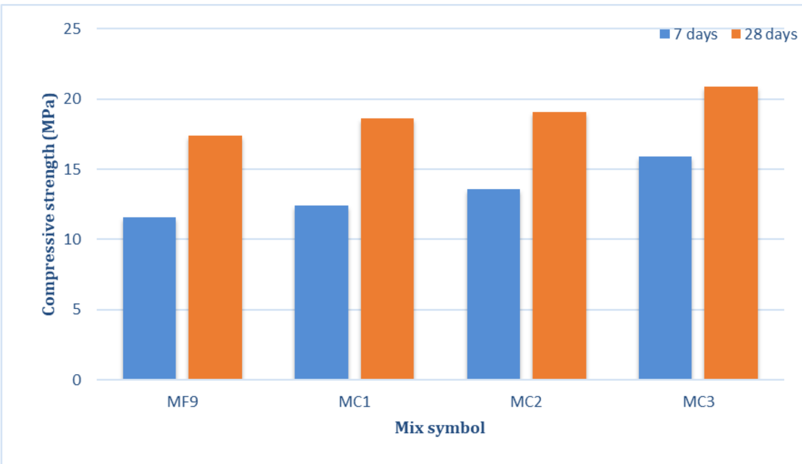

Figure 4. Effect of different percentage carbon fibers on the Compressive Strength (MPa) for foamed Concrete at 28 and 7 days

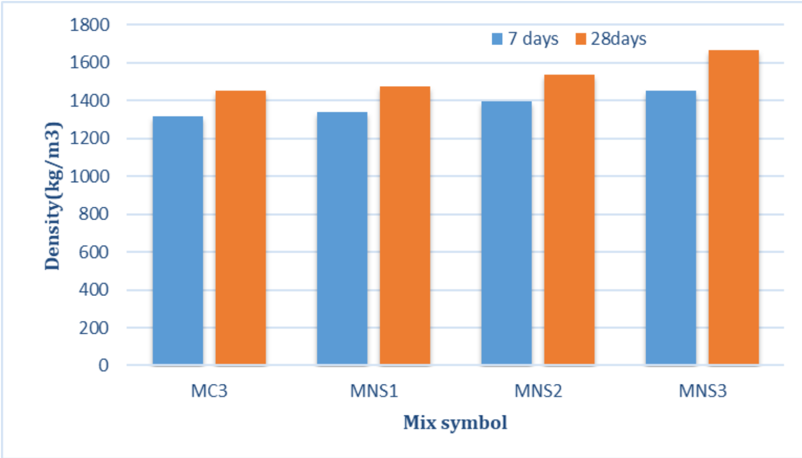

Figure 5. Effect of addition of different percentages of Nano silica on foam concrete reinforced by carbon fibers 1% on the dry density (Kg/m^3) at 7, 28 days

5. Conclusions

In a study exploring the mechanical properties of foam concrete reinforced with carbon fibers and nanomaterials, researchers observed an enhanced concrete microstructure that resulted in more robust and superior-quality concrete. Carbon fibers were randomly dispersed throughout the lightweight concrete to promote uniform distribution. Furthermore, the nanomaterials were meticulously mixed with the cement to prevent clumping before blending with other materials. Here are some key findings from the study:

1. Increasing the amount of foam in the mixture led to a notable increase in flow rate. For instance, a W/C ratio of 0.35 resulted in a flow rate increase of 117 mm compared to the control mix. However, adding 1% carbon fibers caused the flow rate to decrease by roughly 6.63%. Moreover, a high-consistency mixture with 1% carbon fiber and 1% Nano silica decreased the flow rate by 7.27% compared to the control foam concrete reinforced with a 1% carbon fiber mix.

2. Once the target density of 1300-1350 Kg/m3 was reached, the concrete's compressive strength and dry density experienced a decrease of 65% and 40%, respectively, compared to the control mix without foam.

3. The concrete's compressive strength increased by 6.9%, 9.77%, and 19.82% after 28 days when 0.5%, 0.75%, and 1% carbon fiber were added to the volume of the concrete, respectively. The optimal percentage of fiber added was found to be 1%, as compared to the control foam mix.

4. The compressive strength of the concrete increased by 14.39% when 1% Nano SiO2 was added, and the dry density increased by 14.64% when 0.2%, 0.5%, and 1% Nano silica were added by weight of cement to foamed concrete reinforced with carbon fibers after 28 days. This was all compared to control foam concrete reinforced with a 1% carbon fiber mix

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