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Behavior of Hybrid Composite System for Fibrous Ferro-Foam Cement

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ABSTRACT

The structural behavior of Nine Fibrous Ferro-Foam cement (FFFC) panels with (400×600×40) mm has been investigated in this study. Ferro-Foam cement is an alternative light weight composite material combine two technologies: ferrocement and foam concrete, to exploit the beneficial advantages of both technologies in line with sustainability. The mechanical properties of foamed concrete were optimized by increasing density and steel fiber addition. The first group includes four panels with different densities made of plain foamed concrete with silica fume and superplastizer without fibers to evaluate density effect. Mixes with 1800 Kg/m^3 were selected to analyze steel fiber role on panels structural behavior (fiber content 0.5% and 0.6%) in the second group. Three FFFC panels in third group with density 1800 Kg/m^3 and 0.6% steel fiber (optimum) reinforced with (2, 4 and 6) layers of steel wire mesh to study the effect of reinforcement. The results indicated that increasing the density of foamed concrete improves compressive and flexural strength. The addition of steel fibers significantly increases load capacity and ductility, while increasing number of steel wire mesh layers further improves structural performance and crack control. These findings suggest that FFFC panels are a promising sustainable alternative for a variety of construction applications.

1. INTRODUCTION

In ferro-cement, layers of mesh or metal reinforcement are incorporated into the cement mortar. In terms of ACI 549R-97, Ferrocement is a thin wall reinforced concrete containing layers of closely spaced wire mesh embedded within the cementitious matrix. Due to its high strength-to-weight ratio, durability, and crack-resistant characteristics, it has a good reputation. The use of ferro-cement in construction has been widespread for building walls, roofing, and water tanks. Engineers have explored the potential of ferro-cement in the construction field for many years. The availability of ferrocement components in many countries, the lack of skilled labor required, and the possibility of using prefabrication or do-it-yourself techniques all contribute to making ferrocement a cost-effective and attractive option for strengthening concrete structures. Water tanks, roofs, boats, pipes, silos constructions, and affordable housing are some conventional ferrocement applications. Moreover, ferrocement can be utilized in a range of applications such as precast components, retaining walls, sculptures, bus shelters, bridge decks, repairs, and different roofing systems. Moreover, the fine wire mesh functions are to enhance the ductility of the ferrocement composite by a crack-arresting mechanism. ferrocement technology has been utilized for of repair, rehabilitate and strengthening of traditional RC beams in numerous research works, in an innovative approach to boost beam strength. Ferro cement has also found application in cost-effective small-scale housing designs, slender structural components for buildings, and roofing solutions. The effect of inclusion various fiber types into the mortar of Ferro-cement has been investigated [1].

The number of wire mesh layers embedded during construction considered one of main factors affecting the behavior of ferro-cement elements, as it has a direct impact on the overall strength, rigidity, and longevity of the structure. Increased number of reinforcement layers leads to a substantial enhancement in the behavior of the concrete element. These added layers offer greater tensile strength and cooperate in the uniform distribution of loads across the structure, which leads to increased load carrying capacity with improved cracking resistance and deformation [2]. Yet, exceeding layers number beyond specified limits leads to negative results like spalling of the matrix and separation of extreme fibers, resulting in premature failure. whereas, using fewer layers of reinforcement can lead to lowering strength and stiffness hence, increasing cracks, deformation, and failure of the member under load. In general, the number of mesh reinforcement layers plays a significant role in overall behavior of ferro-cement members. Engineers and designers can enhance the efficiency of ferro-cement structures and guarantee their reliability and long-term stability by understanding this role.

2. LIGHT WEIGHT FOAMED CONCRETE

A major benefit of lightweight foamed concrete owing to its superior strength-to-weight ratio, enabling more versatility in both design and construction. This implies that constructions made from lightweight foamed concrete are more effective, economical, and eco-friendly than conventional building materials.

Lightweight foamed concrete, (also called cellular concrete), is a cementitious material comprise air voids with high volume, typically induced by incorporating foam. Foam is simply formed through blending foaming agent with water and compressed air. The produced lightweight foamed concrete demonstrate density ranging 300-1800 Kg/m^3, making it a desirable material for different applications in construction like, insulation, filling, and structural members. Foamed cement is evaluated for its low dead weight, seismic resistance, insulation characteristics for sound and thermal conductivity. In addition, benefits include ease of production and construction along with a range of variable strength at low manufacturing costs. In view of these, it is suitable for many applications such as: improvement of consolidation soft soil foundation; thermal insulation for buildings; reinforcement in gas and oil wells [3, 4]. In contrast, as crisis of global energy has increased, energy saving has become a crucial goal worldwide. Moreover, the volume of gas introduced within foam cement is higher than standard cement induce reduction in density and cement content promoting foamed cement as green building materials with energy-saving properties [5].

Moreover, its ability to bear bending loads though sustaining lightweight and insulating characteristics makes it appropriate for structural and non-structural components in building and could be exceptional choice for regions prone to earthquake or areas having conditions with unstable soil [6].

Flexural strength is pivotal to the structural performance and durability of concrete members, especially in applications such as slabs, beams, and panels. Foamed concrete reveals intrinsically brittle behavior attributed to its lower density and porous microstructure. Fibers such as steel, polypropylene, and glass, added to concrete to enhance its tensile properties, ductility, and resistance to crack. The inclusion of steel fibers to foamed concrete mixes boost its mechanical properties, supports controlling spread of cracks, improves energy absorption capacity under flexural loads. The result is more ductile response, permitting the material to undertake more deformations and bears higher loads before failure. Furthermore, steel fibers perform as reinforcement into foamed concrete medium, efficiently bridging cracks and improving the composite's overall tensile strength. The reinforcement mechanism participates to the formation of a pseudo-ductile behavior in the material; however, the load is redistributed and localized stress concentrations are relieved along the crack path. Hence, steel fibers can delay the onset of cracking and raise ultimate flexural capacity for foamed concrete. Higher aspect ratios and volume fractions tend to enhance crack bridging efficiency and improve the load-carrying capacity of the composite [7-12].

The potential applications of foamed concrete for structural purposes have been taken by many researchers. Hulimka et al. [13] stated that employing bi-directional composite reinforcing mesh made of carbon fibers in foam concrete slabs, leads to a considerable capacity improved and reduced mode of brittle failure. According to Lee et al. [14] lightweight reinforced foamed mortar beams with reinforcement configuration same as conventional weight concrete beams exhibited lower ultimate loads. Whereas lightweight foamed mortar slabs sustained higher ultimate loads. With inadequate resisting to shear forces, flexural failure for slabs and for beams was an issue. More deflection and width of cracks demonstrated by lightweight foamed concrete beams reinforced with GFRP compared with steel reinforced beams due to reduced elasticity modulus for GFRP bars [10].

A study by Prabha et al. [15] investigates the flexural behavior of composite panels with steel sheets and foam concrete core for building floor/roof panels, showed improved strength with fiber reinforcement and suitability for residential buildings up to 5 meters in span. In 2019, Falliano et al. [16] concluded that in all conditions, the additional glass-fiber-reinforced-polymer mesh showed significant effect on compressive strength with considerable enhanced capacity in flexural, especially specimens with reduced density and more fiber content. The reinforced foamed concrete hollow square beam exhibited superior performance in flexural behavior compared to conventional solid and unreinforced hollow square beams, showing more strength, less deflection, and fewer cracks, as derived by Othman et al. [17]. In 2022, Qatawna et al. [18] investigated 4-point flexural test for one-way fiber reinforced foamed concrete slabs with and without reinforcement of glass fiber grid. The study concluded that lightweight foamed concrete (LWFC) can be a suitable substitute material for structural concrete applications in the construction industry today [18]. Kaushar [19], in 2022, concluded that the flexural strength of foamed concrete specimen reinforced with basalt fiber was ten times more than plain foam mix with higher load carrying capacity.

3. FERRO-FOAM CEMENT

Lightweight foamed concrete is gradually become increasingly attractive in construction owing to its low density and good thermal and sound insulation properties, but it also has lower strength. Merging both, light weight concept represented by foamed concrete, with Ferro-cement technology combines their benefits, enables expanding the applications for each in building and construction industry.

Memon et al. [20] found that ferrocement box with lightweight non-autoclaved aerated concrete as an encasement could be used in earthquake prone areas due to high performance, good compressive and flexural strengths with enhanced ductility. The performance of ferro foam concrete girder beam exposed to static load was studied by Afifuddin and Abdullah [21] to investigate the possibility of using the girder beam as an alternative material for bridge girder. The results revealed the possibility of using ferro foam concrete material in short span bridges as a girder. In 2023, Lim et al. [22], evaluate the effects utilization of hexagonal wire mesh and square wire mesh by ferrocement application on compressive and flexural strengths of 1000 Kg/m^3 LWFC block and beam correspondingly. It was concluded that each wire meshes are sufficient to be integrated in production of foamed concrete block and beam. Much better results were provided by square wire mesh. The flexural behavior of ferrocement slabs was evaluated studying different factors such as number of reinforcement layers of foam content [23]. Ferrocement slab panels exhibit enhanced ductility due to the addition of foaming agent.

Most studies have either focused on the mechanical properties of foamed concrete with or without fibers or ferrocement applications independently, without exploring both together. This study aims to fill this gap by providing a detailed investigation on the behavior of Fiber reinforced ferro-foam cement.

The research question in the study focuses on understanding the behavior and performance of Fibrous Ferro-Foam Cement as a composite material. Specifically, investigating how the inclusion of fiber and the optimization of foamed concrete properties (such as density) affect the mechanical and structural performance of ferrocement elements. This includes examining aspects like strength, ductility, and overall load-bearing capacity in construction applications.

The hypotheses of the research may include the following:

1. **Density and Mechanical Properties**: This hypothesis posits that denser foamed concrete will exhibit better structural performance. Different densities range 1200, 1400, 1600 and 1800 Kg/m^3 were taken in first group.
2. **Effect of Steel Fiber Addition**: The addition of steel fibers to the foamed concrete will enhance the overall mechanical properties of the Fibrous Ferro-Foam Cement panels, resulting in improved load-carrying capacity, ductility, and crack resistance compared to panels without steel fibers. Steel fiber added to 1800 Kg/m^3 with different % fiber dose (0.5% and 0.6%) in second group.
3. **Reinforcement Layer Impact**: This hypothesis suggests that more reinforcement layers will lead to better distribution of applied loads and reduced crack propagation.
4. **Crack Control Mechanism**: The incorporation of steel fibers and wire mesh will provide a more effective crack control mechanism in the Ferro-Foam Cement panels, leading to a delay in the initiation and propagation of cracks under flexural loading.
5. **Ductility and Deflection Response**: Panels with a higher number of reinforcement layers and steel fibers will exhibit greater ductility and higher ultimate deflection values before failure, indicating a more resilient structural behavior compared to those with fewer layers or without fibers. Layers were investigated in third group using (2, 4 and 6) layers of steel wire mesh.
6. **Sustainability and Cost-Effectiveness**: The use of Fibrous Ferro-Foam Cement as a construction material will prove to be a sustainable and cost-effective alternative to traditional materials, offering comparable or superior performance while reducing environmental impact.

These hypotheses guide the research by providing specific statements that can be tested and validated through experimental investigation, ultimately contributing to a deeper understanding of the behavior and applications of Fibrous Ferro-Foam Cement.

4. RESEARCH SIGNIFICANCE

This research on Fibrous Ferro-Foam Cement marks a significant advancement in construction materials by merging ferrocement and lightweight foamed concrete. It addresses key industry challenges, including the need for sustainable, cost-effective, and high-performance materials. By enhancing mechanical properties such as load-bearing capacity and crack resistance, it aims to improve the structural integrity of buildings, especially in disaster-prone areas.

Additionally, it contributes to sustainability goals by promoting green building practices through optimized resource use and waste reduction. The economic benefits of this innovation can also support more viable construction projects, particularly in developing regions. Ultimately, the findings may inspire further research, fostering continuous improvement and innovation within the construction field. The motivation for this research on fibrous foamed cement (FFC) stems from the need for an innovative and sustainable construction material that addresses the limitations of conventional concrete, such as weight and environmental impact. Increasing urbanization demands materials that provide structural integrity while being cost-effective and environmentally friendly.

Ferrocement is recognized for its high strength-to-weight ratio and durability, making it suitable for a variety of applications. Combined with lightweight foamed concrete, which offers advantages such as reduced density and improved insulation, FFFC aims to create a robust composite material.

Overall, this research aims to contribute to the advancement of sustainable construction practices in the construction industry.

5. METHODOLOGY

Flow chart is added to visually summarize the experimental process as shown in Figure 1. The work was conducted entirely in structural lab belong to Engineering College in Diyala University.

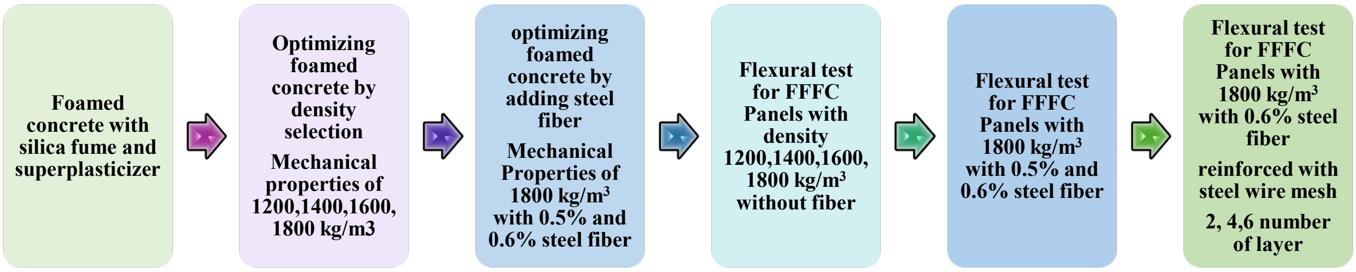

Figure 1. Experimental work stages

5.1 Materials

5.1.1 Cement

Type I Portland cement (OPC) comply with ASTM C150 [24] with physical and chemical analysis in Tables 1 and 2 has been used with foamed concrete mixes through this work.

5.1.2 Sand

Fine silica sand with 600 μm particle size was used, with sieving results according to ASTM C778 [25] laid in Table 3.

5.1.3 Superplasticizers

Aqueous solution of modified Polycarboxylate basis, Sika Visco Crete®-5930 conforming to ASTM C494M-04 [26]. technical properties are shown in Table 4.

5.1.4 Silica fume

Silica fume comply to ASTM C1240 [27] added to cement by 10% of cement weight with characteristics seen in Table 5.

5.1.5 Foaming agent

Table 6 contains properties of foaming agent used according to ASTM C796 [28], while Figure 2 (a)-(b) for foam generator machine and stable foam produced.

5.1.6 Steel fibers

Steel fiber with hooked shaped end, low carbon conforming ASTM A820 [29] was used. It was (60mm) length and (L/d=80) aspect ratio shown in Figure 2(c).

5.1.7 Reinforcement

Square wire mesh with average wire diameter 0.6 mm and opening of (15×15) mm used for reinforcing Ferro-foam cement panels. The yield strength was determined to be 405 MPa. Ultimate strength with average of 600 MPa and modulus of elasticity 95 Gpa.

Table 1. Oxide analysis for cement

Oxide Composition	Content	ASTM C150
SiO_2	20.4	-
CaO	61.7	-
Al_2O_3	5.45	-
Fe_2O_3	4.79	-
MgO	1.5	5.0 (max)
SO_3	1.9	2.8 (max)
C_3A	6.35	-
C_3S	47.23	-
C_2S	23.06	-
C_4AF	14.6	-
Insoluble Residual (I.R)	0.42	1.5 (max)
Loss of Ignition (L.O.I)	2.08	4.0 (max)

Table 2. Cement Physical analysis results

Physical Properties Test	Results	ASTM C39
Fineness (Blaine) (m^2/kg)	405	230 (min)
Soundness (autoclave)		0.8% (max)
Setting time Initial(min.) Final(hr.)	135 3:25	00:45 (min) 10:00 (max)
3-day compressive strength	24.2 MPa	15 (min)
7-day compressive strength	32.5 MPa	23 (min)

Table 3. Sieve results of fine sand

Sieve Size	Passing%	ASTM C778
1.18 mm	100	100
600 μm	94.5	96-100
300 μm	22.6	20-30
150 μm	4.65	0-4
pan	0.0	0

Table 4. Material characteristics of superplasticizers

Form / Color	Liquid, Amber
Density (at 25°C)	Approximately 1.11 kg/lt
Specific Gravity	1.07 ± 0.01 kg/L
pH	Approximately 5.5
Chloride Content	Nil (EN 934-2)

Table 5. Characteristics of silica fume

Form / Color	Grey Powder	ASTM C1240
Fineness, m^2/g	27.3	Min 15
Density (bulk), kg/m^3	660	-------
Content of moisture	0.6%	Max 3%
Loss on ignition	3.4%	Max 6%
Sulfuric anhydride	0.3%	------
Total SiO_2 content	94.7%	Min 85%
Available alkali	0.01%	-------
Chloride ion	0.055%	------
Relative strength	116%	Min 105%

Table 6. Characteristics of foaming material

Form / Color	Transparent Liquid / Yellow
Basic material	Synthetic air entraining liquid
Density	at 20°C, 1.0075 – 1.0175 kg/L
Value of pH	9-11
Content of total Chloride Ion	Max. 0.1%, Chloride-free

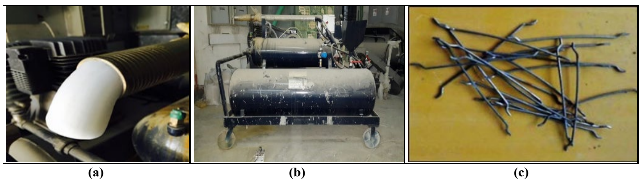

Figure 2. a) Stable foam, b) Foam generator, c) Steel fibers

5.2 Molding

Cubes (150×150×150) mm^3 were used for compressive strength testing, while cylinders (100×300) mm^3 were used for strength of splitting and modulus of elasticity. For flexural strength testing, Prisms with (100×100×500) mm^3 were used. Three specimens for each property to be tested at 28 days, part of molds used during experimental work shown in Figure 3.

Figure 3. Molds with lightweight foamed concrete

5.3 Mix proportions

The mix proportion of the lightweight foamed concrete was determined based on the required densities and specifying the ratio of sand to cementitious materials ratio (S/C=1), w/c ratio is (0.32). Light weight Foamed Concrete with different densities produced, range of densities were 1200, 1400, 1600 and 1800 kg/m^3. Mix proportions details shown in Table 7.

5.4 Mixing procedure

The dry materials were first mixed, i.e., cement and sand in a concrete mixer, (vertical inclined mixer to provide homogeneous mixing for the materials). Then, water added, mixing until homogeneity. To control density of foamed concrete, stable air bubbles added to the fresh mixture through incorporating preformed foam produced by mixing foaming agent with water (1:30 by volume) and air using foam generator. Pre-formed foam was weighted and added into the wet mix gradually until the desired density was achieved. The fresh density test for each mix was then carried out before fresh foamed concrete mix was poured into the molds. After molding and finishing, specimens of foamed concrete were covered with plastic sheet to prevent evaporation of water and kept in the lab.

5.5 Curing

Specimens were demolded after 24±2 hrs. from casting, then moved to curing tanks under controlled temperature of 23±2 hrs. for 28 days until testing age.

5.6 Fresh concrete testing method

5.6.1 Fresh density test

Fresh density of foamed concrete was measures using 1liter capacity container and the following equation was used:

$$D_{frersh}=M/V \tag{1}$$

where, M=Weight of fresh concrete (Kg); V=Capacity of the container (m^3); D_{fresh}=Unit weight of fresh concrete (Kg/m^3).

Table 7. Mix proportion for lightweight foamed concrete

Mix	Target Density (Kg/m^3)	Fresh Density (Kg/m^3)	Cement (Kg)	Sand (Kg)	Water (L)	SF (Kg)	Steel Fiber %	SP (L)	Foam (L)
FC1200	1200	1190	465	516	165	51	-	2.6	466
FC1400	1400	1425	542	602	193	60	-	3.1	377
FC1600	1600	1610	619	688	220	69	-	3.5	288
FC1800	1800	1795	697	774	248	77	-	4	199
FC1800-0.5%	1800	1835	684	760	243	76	0.5	3.9	208
FC1800-0.6%	1800	1850	682	758	243	76	0.6	3.9	210

FC: Foamed concrete with silica fume and superplasticizer, SF: Silica fume, FC-0.5% and FC-0.6%: Foamed concrete with 1800Kg/m^3 density with steel fiber.

5.7 Hardened concrete testing

5.7.1 Compression test

An axial compressive load with a specified rate of loading was applied to 150 mm cube until failure occurred. The test conducted according to BS 1881-116 [30].

5.7.2 Splitting tensile strength

The compression load is applied diametrically on a cylinder of concrete (150×300) mm placed horizontally in testing machine, with two bearing strips, above and below the specimen complying to ASTM C496 [31].

5.7.3 Flexural strength

The flexural test was performed according to ASTM C78 [32], using third point loading method on prismatic specimen with dimensions (100 mm width, 100 mm height and length of 500 mm). Figure 4(a) shows flexural strength test.

5.7.4 Modulus of elasticity

Concrete Elasticity Modulus is a key factor impacting the flexural behavior as it is directly associated to the stiffness. The results represent average of three cylindrical specimens, test was carried out following the ASTM C469/02 [33].

5.8 Casting for panels and test setup

The reinforcement was steel wire mesh fixed to the mold then the foamed concrete was poured, and the surface was finished. The dimensions of the specimens were 750 mm×500 mm×40 mm reinforced with square wire mesh has an average wire diameter 0.6 mm and opening of 15mm×15mm. Figure 4 (b)-(c) shows specimen fixed with wire mesh, while Figure 4 (d)-(f) final ferro-foam specimens prepare casted for flexural test. Nine specimens were tested, in first group, four specimen of density 1200, 1400, 1600, 1800 Kg/m^3 to explore the effect of density on flexural behavior. Two specimens with different steel fiber content (0.5% and 0.6%) having same 1800 Km^3 density were tested to investigate the effect of fiber dosage on flexural behavior. The last three specimen were for fiber reinforced Ferro- foamed cement with 1800 Kg/m^3 and different number of wire mesh layers. To measure the deflection at the middle span of the specimen, dial gauge was fixed at the middle center under the specimen. Moreover, strain gauges were used to calculate the strain ferro-foamed panels. Test setup shown in Figure 5 with details in Table 8.

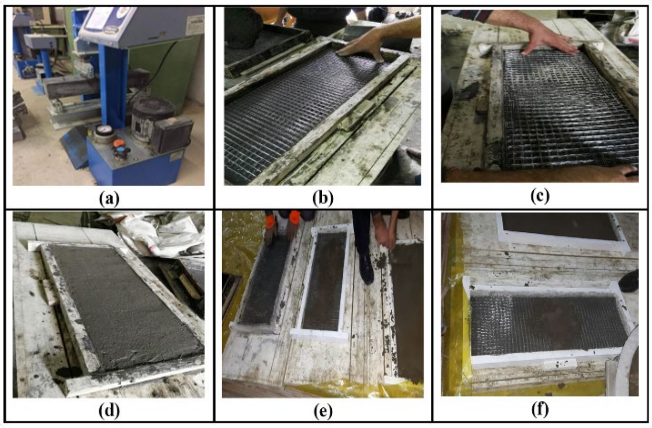

Figure 4. (a) Flexural test; (b), (c) and (d) Steel wire mesh setup; (e) and (f) Ferro-foam specimens

Figure 5. Test setup for flexural test specimen

Table 8. Details of specimen for flexural test

No.	Specimen	S.F	SP	Steel Fibers	No. of Layers
1	FC1200	10%	0.5%	-	-
2	FC1400	10%	0.5%	-	-
3	FC1600	10%	0.5%	-	-
4	FC1800	10%	0.5%	-	-
5	FC1800-0.5	10%	0.5%	0.5 %	-
6	FC1800-0.6	10%	0.5%	0.6 %	-
7	FC1800-0.5-2L	10%	0.5%	0.5 %	2
8	FC1800-0.5-4L	10%	0.5%	0.5 %	4
9	FC1800-0.5-6L	10%	0.5%	0.5 %	6

6. RESULTS AND DISCUSSIONS

6.1 Mechanical properties

Mechanical behavior of LWFC is affected by its material choice and composition (type and amount of cement, sand, w/c ratio, content of foam and any other admixtures or additives). Compressive and tensile strength, elasticity modulus and ductility, also play important role in the overall behavior of LWFC under flexural loading. It is essential to understand the interaction between these properties to design structural elements with lightweight foamed concrete.

Development of lightweight foamed concrete with enhanced properties can be achieved via silica fume and super plasticizers. Silica fume, a silicon metal production byproduct with pozzolanic properties, can enhance the compressive and flexural strength as well as durability of the concrete owning to filling the voids between cement particles, lead to denser and more compact concrete matrix. Moreover, extra calcium silicate hydrate (C-S-H) gel would be produced, promoting strengthens and reducing permeability, due to reaction with calcium hydroxide within cement paste. On the other hand, workability, flowability, early and ultimate compressive strengths and durability of concrete mixes are enhanced when using Super plasticizers which is chemical admixtures, the results obtained in this study conform these resulted by Saeed et al. [1] and Ahmed and Abed [7]. Results of mechanical properties for the LWFC mixes with silica fume and superplasticizer are shown in Table 9.

Foamed concrete involves cement matrix with foam (air bubble) with further complicated structure characteristics than ordinary concrete. Compressive strength increases with increasing density, i.e., reducing porosity and air voids caused by the foam added to the mix. It is concluded that compressive strength inversely proportioned with foam dosage which confirmed by Abd et al. [9]. Hence, other strength indicators like splitting and flexural strength, which are deeply related to compressive strength, are also affected by density of foamed concrete mixes. The modulus of elasticity for foam concrete measures its stiffness and is crucial for determining its properties, such as its ability to hold compression and tension as well as its opposition to creep and fatigue. Higher compressive strength led to higher modulus of elasticity same results found by Abd and Jassam [11]. Figure 6 demonstrate that, due to the presence of pores, the mechanical properties are highly affected by density in foamed concrete.

At low density level, considerable amounts of foam are consumed; hence its strength value is declined, i.e., reducing the density means reducing the strength. At low density, pores will coalesce jointly and when some bubbles merged and unified, they will initiate larger pores. Forming pores with larger size and more voids weakening the bond between pores and the surrounding medium, hence, poor mechanical properties, with easily cracks formation under applied loads. The splitting and flexural strength possess comparable manner of strength progress with compressive strength. However, the increasing rate due to development in compressive strength is considerably higher than that for splitting and flexural strength. The percentages increase in mechanical properties of foamed concrete due to increasing density is demonstrated in Table 10.

Optimization of 1800 Kg/m^3 mix by inclusion of steel fiber aimed to enhance the mechanical properties for this mix for structural application owing to its optimum strength properties in term of compressive, splitting, flexural and elasticity modulus among other mixes with higher density.

Steel fiber addition clearly improved mechanical properties for 1800 Kg/m^3 mix for both fiber dosage (0.5% and 0.6%). The percentages increase in mechanical properties of 1800 Kg/m^3 is demonstrated in Table 11, whereas Figure 7 shed light on properties of 1800 with and without fibers. These results were in line with findings obtained from other researchers as stated by Gencel et al. [3] in 2022 confirming the positive effect of steel fiber on mechanical properties of light weight foamed concrete mixes. Hence, the optimum fiber content would be 0.6% according to the obtained results.

Table 9. Mechanical properties of LWFC mixes

No.	Target Density Kg/m^3	f_c` (Mpa)	f_t (MPa)	f_r (MPa)	*E* (Gpa)
1	1200	10.7	0.76	1.9	4.65
2	1400	15.3	1.56	2.62	5.8
3	1600	19.8	1.8	3.44	8.31
4	1800	25.8	2.17	3.48	10.8
5	1800- 0.5%steel	44.8	3.1	3.14	16.4
6	1800-0.6%steel	46.19	3.44	5.42	17.85

f_c`: compressive strength, f_r: splitting tensile strength, f_t: flexural strength and *E* is modulus of elasticity

Table 10. Density effect on mechanical properties of LWFC

No.	Target Kg/m^3	f_c` (%)	f_t (%)	*fr* (%)	*E* (%)
1	1200	-	-	-	-
2	1400	43	105	38	25
3	1600	85	137	81	79
4	1800	141	186	83	132

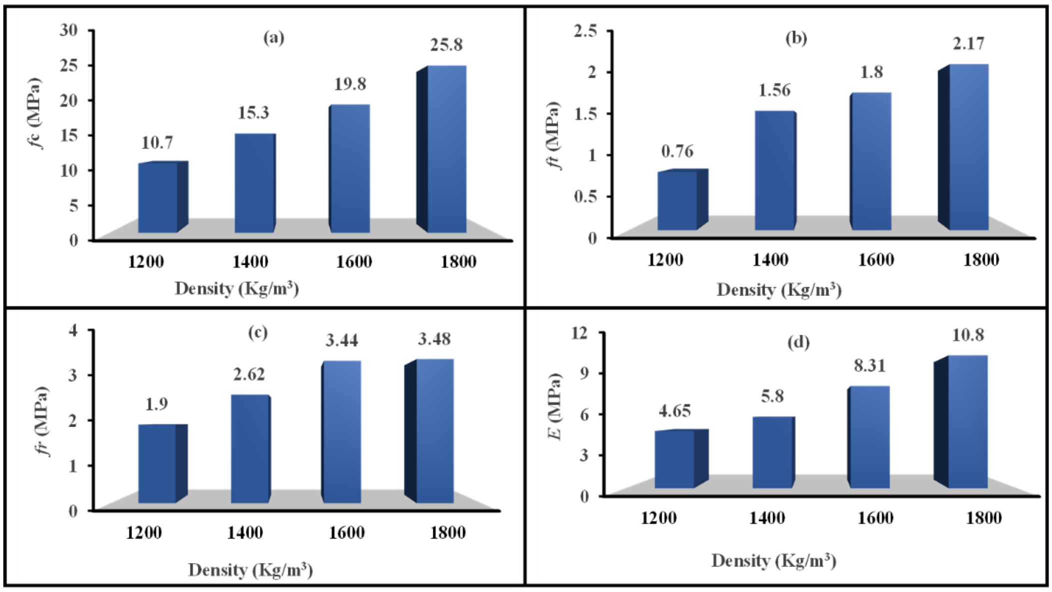

Figure 6. Mechanical properties for LWFC; (a) compressive strength at 28 days, (b) splitting strength, (c) modulus of rupture, (d) modulus of elasticity

Table 11. Steel fibers effect on 1800 Kg/m^3 LWFC

No.	Target Density Kg/m^3	f_c` (%)	f_t (%)	f_r (%)	E (%)
1	1800	-	-	-	-
2	1800-0.5% steel	74	43	18	52
3	1800-0.6% steel	79	49	56	65

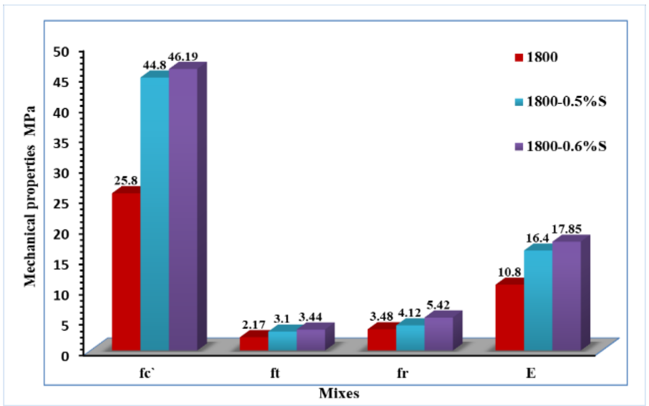

Figure 7. Effect of fibers on mechanical properties of LWFC

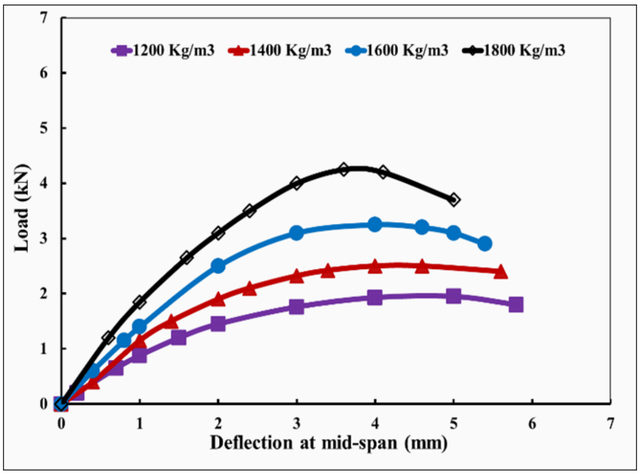

Figure 8. Deflection of LWFC with different densities

6.2 Load-deflection response

6.2.1 Effect of density

Typical load-deflection profiles for LWFC specimens with different densities 1200, 1400, 1600 and 1800 Kg/m^3 is drawn in Figure 8. For all specimens, the measured deflection was at the mid-span. Brittleness is generally recognized as the susceptibility of a material to split suddenly before substantial irretrievable (plastic) deformation has initiated. Foamed concrete exhibits noticeable brittle failure due to its internal microstructures.

Foamed concrete clearly exhibits different behavior compared to normal concrete, one of the main reasons is, the compressive strength of concrete largely attributes to the presence of coarse aggregate which does not likely exist in foamed concrete. The hypothetical alternative for coarse aggregate in foamed concrete is the presence of (air voids) or pores distributed randomly, induced by addition of foam which is totally different and weaker with no doubt. High amount of foam added lead to merging voids in a high degree, result in larger voids with irregular vast distribution void sizes and reduction in strength, thus, suffer large amount of deformation. Therefore, a more ductile behavior was observed, i.e., reduced density result in higher ductility as found by Hilal et al. [34]. Since no fiber has been added, the specimens exhibit a brittle behavior as expected with no ability to prevent crack initiation due to flexural loading as shown in Figure 9.

Specimens with higher density have higher load capacity, hence, 1800 Kg/m^3 had the highest peak load, while the 1200 Kg/m^3 specimen earn the lower load capacity. However, higher densities specimen undergoes more brittle failure as those with lower density continue in carrying load at lower rate but with more deflection, increasing load led to failure. It is likely to conclude brittleness from the curve of load-deflection. Materials with more brittleness tendency have inclined section of the curve with more decline. This might belong to reduced porosity at higher density with low volume of foam added, and better interface between cement matrix and sand particles due to silica fume presence with SP, voids will be smaller in size prohibited from joining together, thus, resulting in distribution a tighten void size attained higher strength consequently brittle behavior [35].

6.2.2 Effect of steel fibers

The improvement in load carrying capacity of specimens with steel fiber compared to these without fiber addition is very clear for both percentages of fiber addition to 1800 Kg/m^3 is clarified in Figure 10.

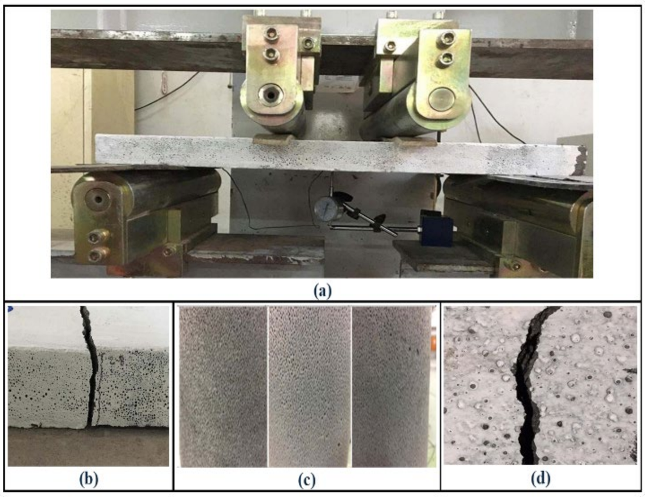

Figure 9. (a) LWFC specimen without fiber; (b) and (d) brittle behavior of LWFC under flexural load with wide crack in mid-span; (c) porous surface for different densities LWFC

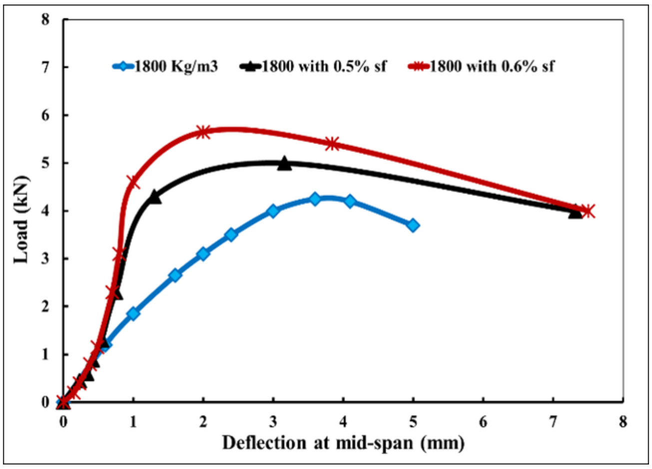

Figure 10. Deflection of LWFC with and without steel fibers

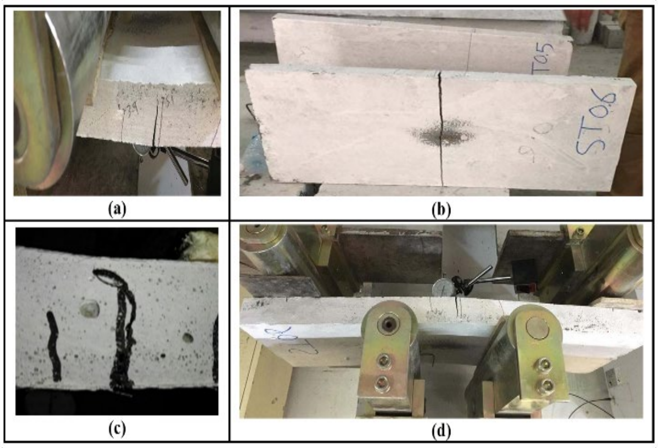

Figure 11. Steel fiber effect on deflection behavior of LWFC

Flexural strength was also increased with steel fibers; owing to its role in bridging cracks through specimens and, at the final phase a fractured or pulled-out steel fiber may appear due to allocation of tensile stress across the cracks. The tensile region of steel fiber LWFC specimens still undertake a load at the preliminary stage of initiation of cracks. This could belong to the ability of steel fibers to restrict cracks at both micro- and macro-stages. At micro-stage, fibers prevent the initiation of cracks, whereas at macro-stage, fibers offer efficient bridging improving toughness and ductility [1].

The random alignment of steel fibers in the mortar matrix support controlling the crack propagation by improving the overall resistance to cracking of the matrix and restrict formation of micro-cracks directly after the load is applied on the member. Thus, arrested smaller cracks from growing to main cracks lead to higher ultimate load carrying capacity as shown in Figure 11.

6.2.3 Combined effect of fibers and wire mesh layers

The combined effect of steel fibers and different steel wire mesh layers on deflection behavior of fiber reinforced ferro foamed panels has been plotted in Figure 12. All specimens were failed in flexure in a tensile manner; the cracks were initiated in the tensile stress region, prior to yielding of wire mesh layers occurred. Generally, as the load was raised cracks begins to appear, wider cracks at the middle area of the panels developed after that. Occurrence of complete failure was caused by increasing the applied load.

These figures indicate that, for all specimens tested, load-deflection curves were nearly same, having linear behavior at the initial stage then, a nonlinear behavior till failure. The behavior can be categorized to three phases. In the initial phase, the panels exhibit elastic behavior, outstanding no visible cracks; the deflections are proportioned linearly to the applied load. A drift from linearity of this relationship is clear when the first stage ended. This phase is followed by, occurring of cracks in the tensile zone of specimens and spread with rising width of crack, representing the second phase of the load with deflection at mid-span. Through this phase, a progressive yielding of steel within layers of wire mesh took place, the mesh layers yield at variable loading stages because, they were placed with different number of multiple layers. The failure stage, which is last phase, indicated as the plastic stage as well, is started by inelastic reinforcement straining the at tension zone and is depicted by a rapid grow in deflection until occurrence of failure.

When increasing the number of wire mesh layers, the capacity of ferrocement panels for load carrying, it is also clear from Figure 12 that the ductility of the fiber reinforced Ferro foamed panels became higher with increasing the amount of reinforcement which confirmed by Saeed et al. [1] in 2022 as they concluded same results. This is attributed to the increased specific surface area for the mesh reinforcement, progressive strength of uniformly distributed steel meshes through the traverse section, and higher ductility was detected in specimens with steel fibers, where the cracks initiated consistently and with reduced width on the bottom exterior of the specimens under test attributed to steel fiber bridging effect. The enhanced ductility of ferro foamed panels can be drawn from the outcomes of this study and might belong to the following three reasons: (a) Cement matrix (b) Higher bonding between steel fiber and cement paste due to hooked ends of the fiber type used, result in higher pull-out capacity. This could enhance the crack arresting behavior. The tensile stress allocation occurs through the cracked regions, leading to higher load capacity and (c) Delay of failure occurrence caused by increasing reinforcement, i.e., number of wire mesh across the thickness of specimens, leads to acting as a barrier during the crack propagation.

The flexural failure was the failure mode; steel wires yielding took place, and no observed crushing for mortar observed on the compression face of transverse section. All cracks were formed at the lower face of the slabs. It may be concluded that the presence of steel fiber with wire meshes plays a principal role in controlling the crack patterns with preferable manner, recognized by multiple cracks with lower crack width through test as shown in Figure 13.

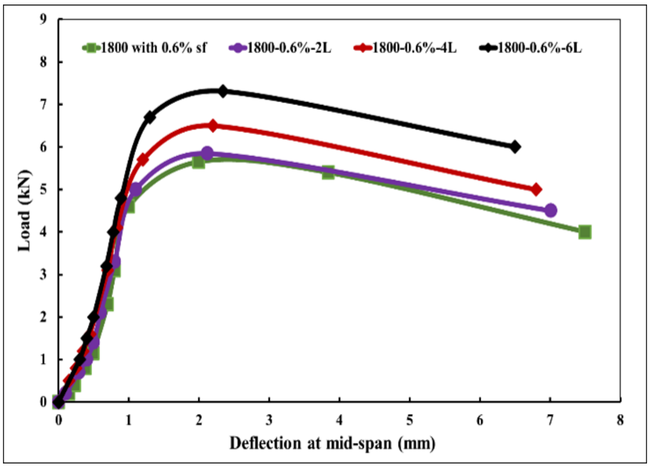

Figure 12. Effect of steel fiber and steel wire mesh deflection behavior of LWFC

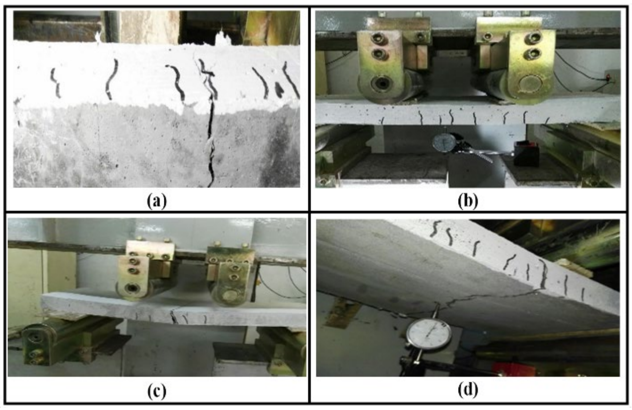

Figure 13. Deflection of FFFC panels

6.3 Load-strain response

The load-strain behavior in Figure 14 for steel fiber ferro-foamed cement panels resembles their load-deflection behavior. Specimens with steel fiber retain higher load capacity and hold higher stain rate. By adding fibers to light weight foam concrete, the material ductility can be significantly improved. The fibers act as a reinforcement network, which helps to absorb energy and prevent the propagation of cracks. This results in a material that is more resistant to failure and can withstand higher deformation prior attaining its ultimate capacity. This unusual behavior belongs to the reduced rate for strain increase with higher load for the matrix of mortar owing to the existing of steel fibers that acts to discontinue the cracks in micro and macro level.

The effect of steel wire mesh number of layers depicted in Figure 13. The constant growth in load with each strain increase is due to the mutual effect of mobilization of the flexural capacity of the ferrocement panels and the role of steel fibers in crack discontinuity. The increase is due to the existing of steel fibers, which create a network structure, resulting in reduction of stress concentricity at the tip of the cracks in addition to the role of wire mesh reinforcement. All the cracks initiated from tension zone toward compression region. The first crack observed under the load application point. At higher levels, when the load increased, additional cracks occurred on each side of the first crack. In the tension region, the crack in the mortar matrix appears as steel fibers begins acting. The fiber transfers the load through the crack, and, as the fiber is randomly dispersed, the cracks route will be shortened, thus, improving load carrying capacity for the whole mortar matrix. The wire mesh reinforcing technique for ferro-cement provided adequate restriction and terminated the brittleness problem. As the steel wire mesh start yielding, the linear load-deflection behavior disappeared, and the stiffness is lowered when flexural cracks initiated. Values of deflection indicate that fiber reinforced ferro-foamed panels exhibit enhanced ductility.

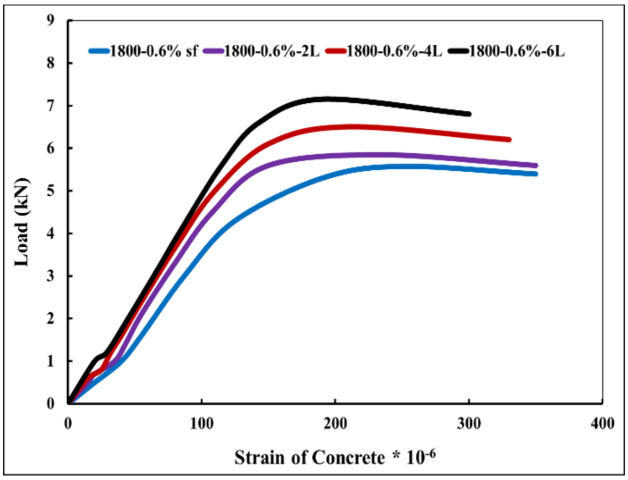

Figure 14. Strain of fiber reinforced ferro-foamed concrete

Increase in number of layers of mesh exhibited good ductility by showing a considerable increase in ultimate deflection values before failure. This increase is attributed to the increase in the specific surface area of the mesh, also due to the resistance provided by the mesh under flexure, these results agreed with finding from Saeed et al. [1]. As the number of layers of mesh is increased, there is a good control over the initiation and spreading of cracks that leads to the prolong in the initiation of first crack and the following flexural cracks. In general, specimens with three layers of mesh presented good crack control mechanism by via formation of uniformly dispersed narrow cracks providing sufficient elongation for wire meshes which leads to an improved ultimate load capacity and ductility.

7. CONCLUSION

This study investigates the structural behavior of Fibrous Ferro-Foam Cement (FFFC), Nine FFFC panels were fabricated. These panels were with different fiber volume ratio, different densities and various number of wire mesh layers were fabricated and tested for their flexural behavior. Based on the laboratory results, the following outcomes has been drawn:

1. The density of foamed concrete is the major parameter affecting mechanical properties and overall behavior.
2. Increasing density of light weight foamed concrete increases its strength in term of compressive, splitting tensile flexural as well as modulus of elasticity.
3. The increase in density from 1200 to 1800 kg/m^3 increases compressive strength, splitting strength, flexural strength and modulus of elasticity by 141%, 186%, 83%, 132% respectively.
4. Addition of steel fiber enhance all properties of light weight foamed concrete remarkably. The rate of increase in mechanical properties due to steel fibers addition was 79%, 49%, 56%, 65% for compressive, splitting, flexural strength and modulus of elasticity, respectively.
5. For FFFC panels, increasing number of reinforcement layers of steel wire mesh has significant effect, increases its load carrying capacity, reducing crack width improving ductility. Moreover, combining steel fibers along with steel wire mesh in different layers enhances whole behavior of panels in term of deflection response, crack pattern, load carrying capacity, mode of failure.

The merging of lightweight foamed concrete with ferro-cement, along with the incorporation of steel fiber, offers a promising perspective to boost the structural behavior of panels. By leveraging the unique properties of each material, researchers and engineers can develop innovative construction solutions that are lightweight, durable, and cost-effective. The high tensile strength of the steel mesh helps to distribute applied loads more evenly throughout the concrete matrix, reducing the likelihood of cracking or prevent crack propagation improving the overall structural safety of the material. Additionally, the lightweight nature of foamed concrete combined with the high strength of ferro-cement can result in a lightweight yet robust construction material that is well-suited for a wide range of applications.

8. RECOMMENDATION

While FRFFC panels offer promising benefits, challenges remain in optimizing their mix design, understanding long-term durability, and addressing cost considerations. Future research directions include exploring sustainable fiber options, investigating the impact of different foam types, and developing design guidelines for FRFFC panel applications. The research work with lightweight foamed concrete is still limited, but it promises a wide domain for future studies. As the construction industry continues to evolve, the development of advanced materials and technologies will play a crucial and important role in defining the future of civil engineering and infrastructure development.

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NOMENCLATURE

ACI	American Concrete Institute
ASTM	American society for testing and materials
C-S-H	Calcium silicate hydrate
D_{fresh}	Fresh density for foamed concrete
E	Modulus of elasticity
FC	Foam Concrete
FFC	Ferro-foamed cement
FFFC	Steel fiberous Ferro-foam cement
L/D	Aspect ratio for steel fiber, length/diameter
LWFC	Light weight foamed concrete
M	Mass
OPC	Ordinary Portland Cement
RC	Reinforced Concrete
SF	Silica fume
SP	Super plasticizer
V	Volume
f_c`	Compressive strength
f_r	Splitting tensile strength
f_t	Flexural strength
μ	Micrometers