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Influence of Silica Fume Incorporation on the Fresh, Thermal and Mechanical Properties of Expanded Polystyrene (EPS) Foamed Concrete

Magdy A. Abd-ElAziz, Ahmed Serag Faried*, Mahmoud M. A. Kamel

Department of Civil Engineering, Faculty of Engineering, Fayoum University, Fayoum, Egypt

Email address:

asg00@fayoum.edu.eg (A. S. Faried)

*Corresponding author

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Abstract: This paper aims to study the fresh, thermal and mechanical properties of lightweight concrete (LWC) incorporating expanded polystyrene foam (EPS) beads as a lightweight aggregate (LWA). Various mixtures of EPS foamed concrete are produced by partial replacing normal aggregates by 0%, 15%, 25%, 35% and 50% of EPS foam beads by volume. In EPS foamed concrete, the ordinary Portland cement (OPC) was replaced by silica fume (SF) with different ratios 0%, 5%, 10 and 15% by weight. Sixteen mixtures are prepared to investigate the fresh, thermal and mechanical properties of EPS foamed concrete. The test program includes determination of fresh density, slump, compacting factor, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity and thermal conductivity. Generally, using of EPS beads in concrete decreases its mechanical properties and thermal conductivity, although the workability improvement. Replacing the OPC with SF improves the mechanical properties of EPS foamed concrete, this improvement continues to the percentage of 10% and ultimate improvement in the ratio of 5%. Modulus of elasticity improves in EPS foamed concrete with SF content till 25% EPS foam. The workability of EPS foamed concrete decreases with the increasing of SF ratios.

Keywords: Fresh Properties, Mechanical Properties, Thermal Conductivity, Lightweight Concrete, Foam, Expanded Polystyrene (EPS), Silica Fume

1. Introduction

Using alternative affordable and sustainable products is a trend already well-established among the worldwide research community [1]. According to Bouvard *et al.* [2], the interest in LWC to decrease the volume of load-bearing elements and get better properties comparing with conventional concrete. Broadly, the lightweight aggregates are classified into two different types, the first, natural (e.g., pumice, volcanic cinder, diatomite) and, the second, artificial (e.g., perlite, sintered fly ash, clay, expanded shale). To produce lightweight concrete with a wide range of densities it can use the Polystyrene beads as an aggregate, which can be easily, incorporate into concrete or mortar [3].

EPS foams have a cellular microstructure with closed cell membranes made of expandable polystyrene (EPS) and its density was less than 50 kg/m^3 [4]. Recent applications of EPS lightweight concrete include cladding panels, curtain walls, composite flooring systems, load-bearing concrete blocks, sub-base material for pavements, and floating marine structures. Because it had a good energy-absorbing characteristic of LWC, so it is used as impact-resistant structural protection layers, [5].

The EPS particles can be derived from recycling, and that do not absorb water as vermiculite does [6], so it is suitable for developing concretes for both structural and non-structural applications by varying its volume percentage in mortar or concrete [7]. On the other hand, most of researchers found during this study show that an increase in EPS foam content will lead to a decrease in the compressive strength and other mechanical properties of concrete [9-11]. The improvement in the workability of fresh concrete increases with increasing foam content [5, 12]. Rahim J. A.,et al, [13] determine the modulus elasticity and poison ratio of expanded Polystyrene (EPS) lightweight concrete containing steel fiber by stress-strain in lateral and longitudinal direction. Steel fiber enhanced the values of modulus elasticity and poison ratio of expanded Polystyrene (EPS) lightweight concrete.

ACI 116R [14] define that the silica fume (SF) is a very fine non-crystalline silica produced in electric furnaces. SF is well known to improve the mechanical characteristics of concrete, the principal physical of its effect on concrete is being a filler, which efficiently reduces permeability and adversely reduces the PH value [15, 16]. Fresh concrete containing SF is more cohesive and less prone to segregation than concrete without it and the water demand for concrete containing SF increases with increasing amounts of silica, due to the high surface area of S.F [17].

The main objective of this paper is providing the effect of silica fume on the mechanical and fresh properties of EPS lightweight concrete containing it.

2. Experimental Study

2.1. Materials

The materials used in this work were ordinary Portland cement (OPC), fine aggregate, coarse aggregate, EPS foam beads and silica fume powder (SF). The physical properties of cement are confirming with ASTM C150 [18] Type I. The normal weight fine aggregate used was river sand with a fineness modulus and specific gravity of 2.2 and 2.6 respectively; while the used coarse aggregate was crushed stone with a maximum particle size of 19 mm and 2.62 specific gravity. The EPS foam properties are defined as shown in Table 1. The mean particle size of SF was 0.1 µm and its bulk density was defined as 300 Kg/m^3. The mineralogical composition of OPC and SF are listed in Table 2.

Table 1. *Chemical and physical properties of EPS foam.*

Molecular weight	Density (kg/m^3)	Beads Diameter (mm)	Thermal conductivity W/(m.K)	Compressive strength (N/mm^2)
300,000	17	0.6 – 1.4	0.04	0.10

Table 2. *Chemical composition of used OPC and SF.*

Compositions	Percentage of Weight (% Wt.)	
	OPC	SF
Silicon dioxide (SiO_2)	21.36	93.4
Aluminum oxide (Al_2O_3)	5.50	0.42
Iron oxide (Fe_2O_3)	3.21	0.52
Calcium oxide (CaO)	63.60	1.91
Magnesium oxide (MgO)	0.69	--
Sulfur trioxide (SO_3)	2.44	0.34
K_2O	0.15	0.76
Na_2O	0.55	0.25
Chloride (Cl-)	--	0.2
Loss of Ignition (LOI)	2.30	2.2

2.2. Mix Proportions

Table 3. presents the mix composition of the investigated mixes, for the anticipated testing exactly, sixteen different mixtures of component materials were produced according to ECP 203 [19] (they are labeled as E for EPS foam and S for SF; then followed by the percentage). The EPS foam aggregate was used as 0%, 15%, 25%, 35% and 50% of natural aggregate by volume. The OPC replaced by weight by 0%, 5%, 10% and 15% SF percentages. Water to binder ratio was constant in all mixtures (0.45). Mixing was performed in a horizontal pan mixer in the laboratory. The mixing of materials was done in a specific sequence, by placing a part of the water in the mixer and adding the dry EPS aggregates, which was thoroughly mixed for about 5 min to get the aggregates wetted with water. Then, the remaining materials were added to the mixer and the remaining water was gradually added while the mixing was in progress. The mixing was continued until a mix of uniform consistency was achieved. They were removed from the molds 24 h after casting. Once removed from the molds, all of the specimens were moved to moist curing tank in the lab that meet the ASTM C511 [20] standards, where they remained undisturbed for the remainder of the curing process under constant temperature 24°C.

2.3. Experimental Procedure

The fresh concrete densities, slump and compacting factor values were measured immediately after mixing for all the concretes according to ECP 203, ASTM C138 and ASTM C143 respectively [19, 21, 22]. The concrete specimens were cast in steel molds, followed immediately by curing at room temperature for 24 h before being demolded. After demolding, the specimens were stored in a control room maintained at 24 ± 1°C and 95% RH, and stored in water for curing until testing. The test specimens were cast with hand compaction only. The density of hardened EPS concrete test was conducted in accordance with ASTM C567 [23] at the age of 7 and 28 days. The compressive strength of hardened EPS lightweight concretes was measured on cube specimens (150 mm x 150 mm x150 mm) at the age of 7 and 28 days, at a loading rate of 2.5 kN/s according to ASTM C39 [24]. In addition, modulus of elasticity was calculated on the same cube specimens at the age of 28 days, as per ASTM C469 [25]. Cylindrical samples of 150 mm diameter and 300 mm height were cast to study the splitting tensile strength behavior, which carried out in accordance with ASTM C496 [26] at the 7 and 28 days age. The two point load flexural strength test was conducted according to ASTM C78 [27] at the age of 28 days using 150 mm x 150mm x 750mm prisms.

Table 3. *Mixing design of EPS foamed concrete with SF.*

Mix Name	OPC (Kg/m³)	Fine Agg. (Kg/m³)	Coarse Agg. (Kg/m³)	S.F. (Kg/m³)	EPS Foam (Lit./m³)
E0S0	400	612	1224	0	0
E0S5	380	612	1224	20	0
E0S10	360	612	1224	40	0
E0S15	340	612	1224	60	0
E15S0	400	525	1035	0	171
E15S5	380	525	1035	20	171
E15S10	360	525	1035	40	171
E15S15	340	525	1035	60	171
E25S0	400	467	910	0	286
E25S5	380	467	910	20	286
E25S10	360	467	910	40	286
E25S15	340	467	910	60	286
E35S0	400	409	784	0	400
E35S5	380	409	784	20	400
E35S10	360	409	784	40	400
E35S15	340	409	784	60	400
E50S0	400	321	595	0	572
E50S5	380	321	595	20	572
E50S10	360	321	595	40	572
E50S15	340	321	595	60	572

E= EPS Foam, S= Silica Fume.

3. Results and Discussion

3.1. Fresh Concrete Properties

3.1.1. Density

The fresh EPS foamed concrete density varies from 2262 kg/m³ to 1509 kg/m³. The increasing of the EPS ratio decreases the fresh density. Density of fresh EPS concrete decreases by 10%, 18%, 25% and 36% by increasing the percentage of EPS foam in LWC 15%, 25%, 35% and 50% respectively as shown in Table 4. In the same way, replacing SF by 10% and 15% percentages reduce the density of fresh EPS concrete.

3.1.2. Workability

The consistency of fresh concrete was evaluated in terms of the slump test. The values of the test ranged between 20 mm to 59 mm. The increasing of EPS ratio increases the slump of the fresh LWC as plotted in Figure 1. This result is in agreement with [11, 28, and 29]. The increasing of the workability was occurring due to the decreasing of the bulk density of the EPS concrete while the volume of the cement paste increasing. In addition, small spherical bubbles in the foam act like ball bearings, thereby “lubricating” the paste and improving the workability; the results are in agreement with Chen and Liu [5]. As the EPS ratio increases, the slump of the fresh EPS concrete increases. The slump improvement ranges from 40% to 195% at EPS foam content from 15% to 50% respectively. Using large quantities of SF in EPS foam concrete in (10% and 15%) decreases the slump value. Slump results show that, the increasing of SF percentages decreases the slump value in normal density concrete (NDC). The 5% SF percentage improves the slump in EPS foamed concrete. While, the slump value of 10% and 15% SF decreases, but the values still higher than reference mix at replacing the aggregates with 25% EPS foam or more. The increasing EPS foam in LWC with SF increases the slump value in most percentages, except 15% EPS foam with 10% SF and 50% EPS foam with 15% SF, as shown in Figure 1. On the other hand, the increase of the percentage of SF in EPS concrete reduces the compacting factor for most mixtures, except which contains 10% SF and 25% EPS foam.

Table 4. *Fresh properties results.*

Mix Name	Fresh Concrete Density		Slump		Compacting Factor	
	Values (Kg/m³)	% decrease	Values (mm)	% decrease	Values	% decrease
CM	2503	0	20	0	0.79	0
E0S5	2512	0.36	18	-10	0.89	12.66
E0S10	2503	0	16	-20	0.76	-3.8
E0S15	2481	-0.88	12	-40	0.68	-13.92
E15S0	2262	-9.63	28	40	0.84	6.33
E15S5	2278	-8.99	28	40	0.86	8.86
E15S10	2219	-11.35	14	-30	0.78	-1.27
E15S15	2210	-11.71	15	-25	0.72	-8.86
E25S0	2050	-18.1	38	90	0.85	7.59
E25S5	2073	-17.18	53	165	0.94	18.99
E25S10	2034	-18.74	34	70	0.95	20.25
E25S15	2007	-19.82	22	10	0.88	11.39

Mix Name	Fresh Concrete Density		Slump		Compacting Factor	
	Values (Kg/m^3)	% decrease	Values (mm)	% decrease	Values	% decrease
E35S0	1884	-24.73	40	100	0.88	11.39
E35S5	1863	-25.57	54	170	0.96	21.52
E35S10	1898	-24.17	40	100	0.94	18.99
E35S15	1825	-27.09	23	15	0.88	11.39
E50S0	1608	-35.76	42	110	0.90	13.92
E50S5	1538	-38.55	59	195	0.98	24.05
E50S10	1553	-37.95	42	110	0.95	20.25
E50S15	1509	-39.71	22	10	0.77	-2.53

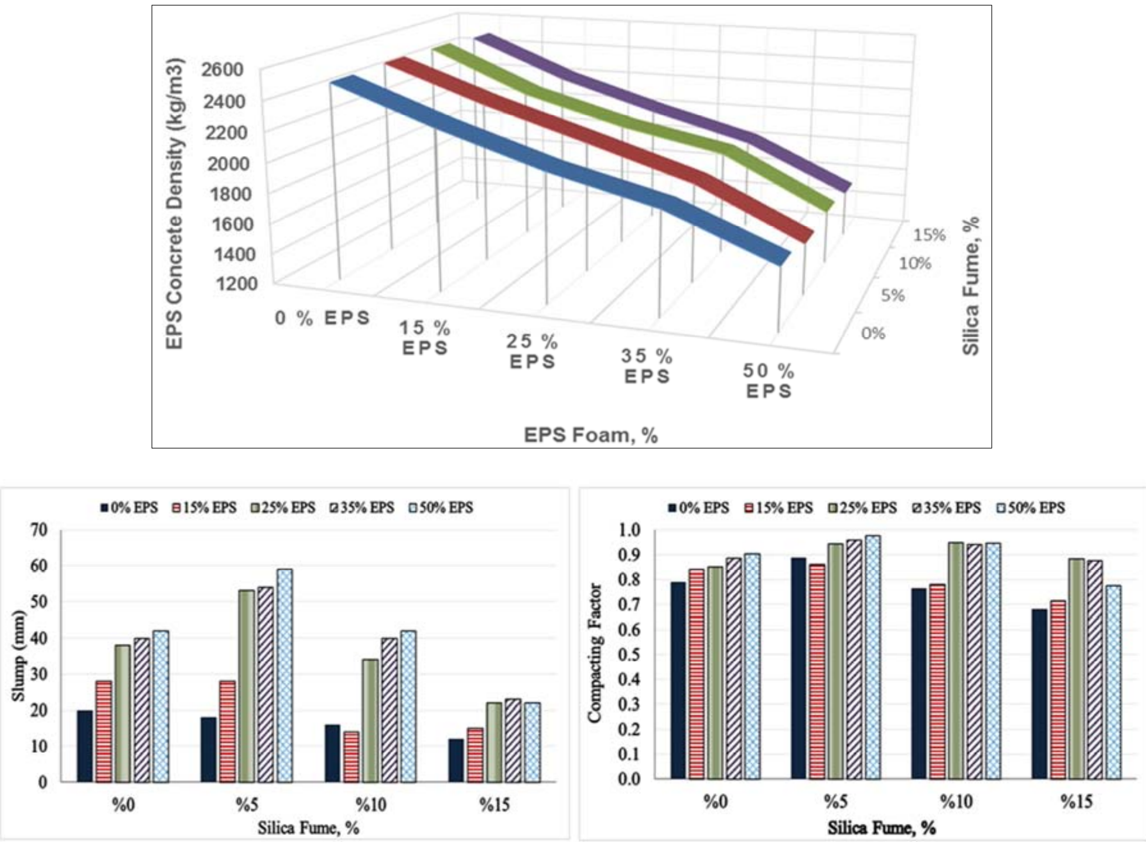

Figure 1. *Effect of SF of Density, slump and compacting factor of EPS foamed concrete.*

3.2. Mechanical Properties

3.2.1. Hardened Density

Density is one of the important parameters, which can control many properties in lightweight concrete and it is mainly controlled by the amount and density of lightweight aggregate [9]. It can be observed from Table 5 that, for most of the specimens, the early age hardened densities of EPS concrete (7 days) are higher than later age densities (28 days); this result in agreement with the relation utilized by Holm [30].

Table 5. *Thermal and mechanical properties results.*

Mix Name	Hardened Density kg/m^3				Average Compressive Strength (N/mm^2)				Average Splitting Tensile Strength (N/mm^2)			
	7 Days		28 Days		7 Days		28 Days		7 Days		28 Days	
	Value	%	Value	%	Value	%	Value	%	Value	%	Value	%
CM	2484	0	2449	0	26.01	0	34.04	0	1.98	0	2.45	0
E0S5	2581	3.9	2559	4.49	28.74	10.5	40.03	17.6	2.22	12.12	2.92	19.18
E0S10	2532	1.93	2496	1.92	34.47	32.53	47.19	38.63	2.58	30.3	3.49	42.45
E0S15	2449	-1.41	2412	-1.51	21.92	-15.72	31.2	-8.34	2.04	3.03	2.64	7.76
E15S0	2202	-11.35	2148	-12.29	19.27	-25.91	23.73	-30.29	1.51	-23.74	2.1	-14.29
E15S5	2339	-5.84	2315	-5.47	21.01	-19.22	27.36	-19.62	1.83	-7.58	2.76	12.65
E15S10	2341	-5.76	2287	-6.61	20.86	-19.8	27.71	-18.6	1.83	-7.58	2.7	10.2
E15S15	2248	-9.5	2190	-10.58	16.69	-35.83	22.62	-33.55	1.67	-15.66	2.41	-1.63
E25S0	2034	-18.12	1965	-19.76	12.58	-51.63	13.94	-59.05	1.16	-41.41	1.66	-32.24
E25S5	2041	-17.83	1978	-19.23	16.83	-35.29	20.87	-38.69	1.19	-39.9	1.85	-24.49

Mix Name	Hardened Density kg/m^3				Average Compressive Strength (N/mm^2)				Average Splitting Tensile Strength (N/mm^2)			
	7 Days		28 Days		7 Days		28 Days		7 Days		28 Days	
	Value	%	Value	%	Value	%	Value	%	Value	%	Value	%
E25S10	2090	-15.86	2031	-17.07	13.57	-47.83	15.91	-53.26	1.04	-47.47	1.58	-35.51
E25S15	2029	-18.32	2026	-17.27	13.44	-48.33	17.36	-49	1.15	-41.92	1.76	-28.16
E35S0	1861	-25.08	1795	-26.7	8.46	-67.47	10.4	-69.45	1.07	-45.96	1.36	-44.49
E35S5	1872	-24.64	1816	-25.85	9.45	-63.67	11.16	-67.22	0.92	-53.54	1.27	-48.16
E35S10	1791	-27.9	1802	-26.42	8.17	-68.59	9.84	-71.09	0.91	-54.04	1.22	-50.2
E35S15	1737	-30.07	1728	-29.44	6.96	-73.24	8.56	-74.85	0.77	-61.11	1.02	-58.37
E50S0	1549	-37.64	1486	-39.32	5.53	-78.74	6.67	-80.41	0.84	-57.58	1.11	-54.69
E50S5	1566	-36.96	1559	-36.34	5.06	-80.55	5.89	-82.7	0.62	-68.69	0.89	-63.67
E50S10	1485	-40.22	1488	-39.24	3.74	-85.62	5.29	-84.46	0.7	-64.65	0.98	-60
E50S15	1482	-40.34	1475	-39.77	3.64	-86.01	4.87	-85.69	0.6	-69.7	0.82	-66.53

Table 5. *Contine.*

Mix Name	Modulus of Rupture (N/mm^2) at 28 Days		Modulus of Elasticity (N/mm^2) at 28 Days		Thermal Conductivity (W/m.K) at 28 Days	
	Value	%	Value	%	Value	%
CM	4.18	0	24699.5	0	1.1	0
E0S5	3.88	-7.18	28532.7	15.52	1.09	-0.91
E0S10	4.25	1.67	28481.6	15.31	1.07	-2.73
E0S15	2.81	-32.78	22216.7	-10.05	1.06	-3.64
E15S0	3.13	-25.12	12239.1	-50.45	0.95	-13.64
E15S5	2.93	-29.9	14352.6	-41.89	0.95	-13.64
E15S10	2.97	-28.95	14019.4	-43.24	0.94	-14.55
E15S15	2.47	-40.91	10681.1	-56.76	0.92	-16.36
E25S0	2.71	-35.17	11125.7	-54.96	0.81	-26.36
E25S5	2.23	-46.65	12016.2	-51.35	0.79	-28.18
E25S10	2.29	-45.22	9642	-60.96	0.76	-30.91
E25S15	2.03	-51.44	9568.6	-61.26	0.75	-31.82
E35S0	2.35	-43.78	8678.1	-64.87	0.71	-35.45
E35S5	2.07	-50.48	8900.7	-63.96	0.70	-36.36
E35S10	1.67	-60.05	8233.2	-66.67	0.68	-38.18
E35S15	1.59	-61.96	6898.5	-72.07	0.65	-40.91
E50S0	1.61	-61.48	6453	-73.87	0.52	-52.73
E50S5	1.51	-63.88	5563	-77.48	0.50	-54.55
E50S10	1.52	-63.64	6230.5	-74.77	0.47	-57.27
E50S15	1.48	-64.59	5340.4	-78.38	0.44	-60

3.2.2. Compressive Strength

The compressive strength of 7 and 28 days results is presented in Table 5 and Figure 2. The data show that there is a systematic nonlinear decrease in the compressive strength as the EPS foam content is increased. The highest decrement is (78.8%) for E50S0 mixture at 7 days, while at the age of 28 days the highest decrement ratio in average compressive strength (80.4%) for the same mixture. The compressive strength increases with using SF in NDC as per ACI 234R-06 [17]. Figure 2 indicates that, the 10% percentage of SF gives the maximum compressive strength in NDC. On the other hand, the maximum improvement in EPS concrete occurred at the ratio of 5% SF. The good effect of SF on the EPS foamed concrete compressive strength continuous till 25% EPS foam. While, the higher percentage of SF (15%) decreases the compressive strength in EPS foam concrete for most specimens. This may be due to that, the mixing water increases with the increase of the silica fume and the free water as well as the total porosity is increased.

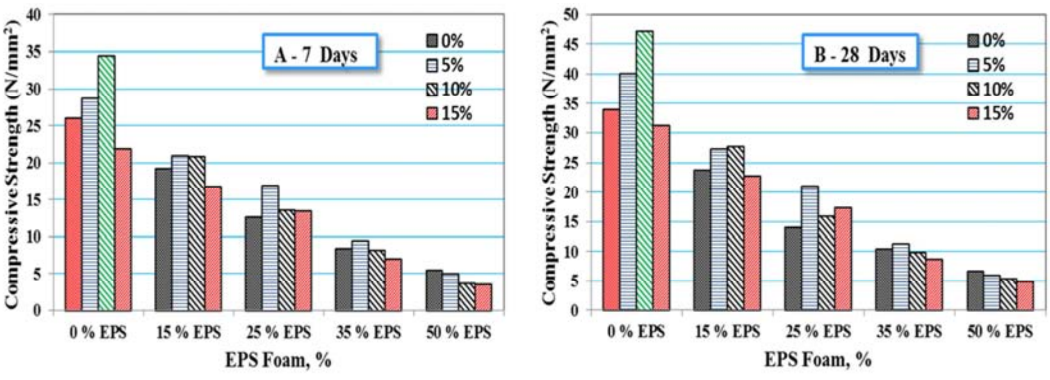

Figure 2. *Effect of SF of compressive strength of EPS foamed concrete.*

3.2.3. Splitting Tensile Strength

The tensile strength increases with the increase of SF in NDC; while the EPS foamed concrete tensile strength decreased with the increase of the EPS foam ratio. Table 5 presents the results for early and late ages splitting tensile strength. The percentage of decrement in splitting tensile strength is less than the decrement in compressive strength at the same ages. The decrement of EPS concrete splitting tensile strength in early ages (7 days) is more than the late ages (28 days) that for the all test specimens. The difference of tensile strength decrement between early and late ages is significantly high in LWC with lower amount of EPS foam (15% and 25%), while the difference is low with high EPS foam percentage (50%). It is clear from Figure 3 that, the optimum improvement in splitting tensile strength occurs at mixture E0S10 in NDC. On the other hand, the optimum improvement is developed with mixtures E15S5 and E25S5 and E50S5 for EPS foamed concrete. The improvement of tensile strength with SF in EPS foamed concrete is continued till 25% EPS foam content, after that no more improvement appears with SF percentages.

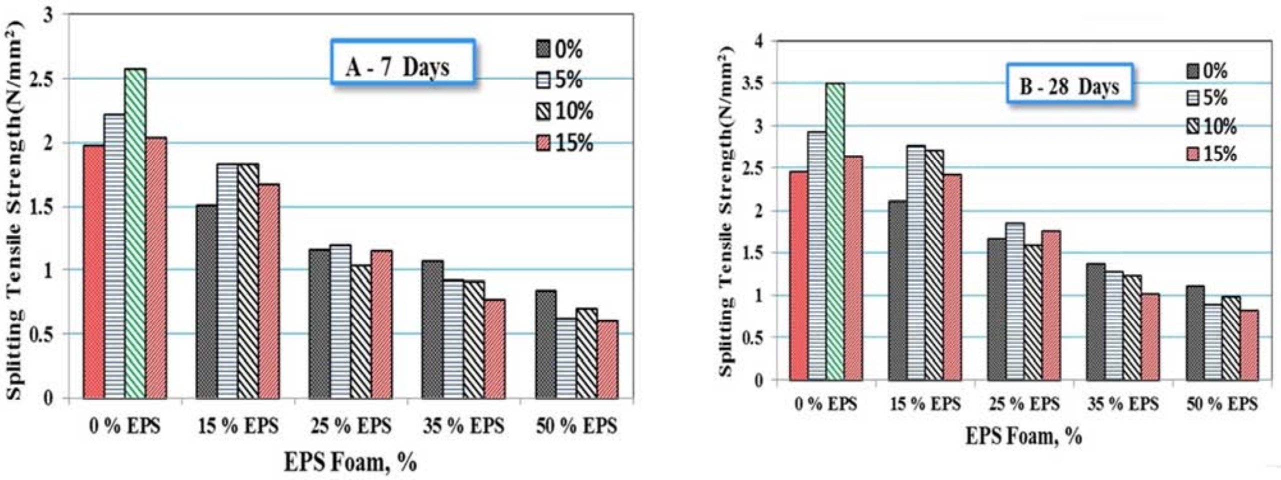

Figure 3. *Effect of SF on the splitting tensile strength of EPS foamed concrete.*

3.2.4. Flexural Strength

The modulus of rupture was found to share a similar relationship with EPS foam content as other mechanical properties as presented in table 5. The value of modulus of rupture systematically decreased nonlinearly as the EPS foam content increased from 0% to 50%. At higher levels by replacing EPS foam (25% and 50%) the decrement in flexural strength is higher than tensile strength but lower than compressive strength Table 5. Flexural strength increased by adding SF in NDC such as other mechanical properties. Figure 4 indicates that, the flexural strength improves with the ratio of 10% SF only in NDC. Otherwise, the SF doesn't improve the flexural strength in EPS foamed concrete.

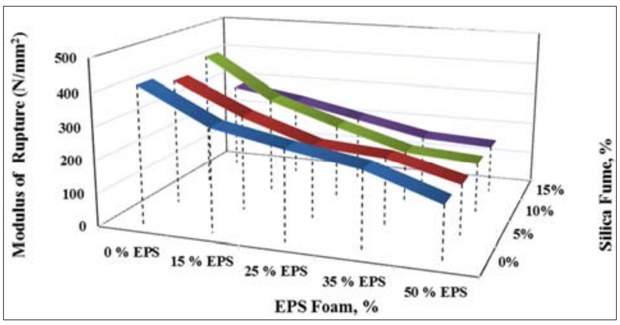

Figure 4. *Effect of SF on modulus of rupture of EPS foamed concrete.*

For the control specimens and the specimens of lower EPS foam contents, the cracks and splitting occurred at a rate that was too fast to observe. For specimens with EPS foam content of 50% the crack propagation could be observed as it extended from the bottom face of the beam until the test ended due to the failure criteria without splitting Figure 5.

Figure 5. *Failure modes of EPS foam concrete beams with SF percentages under flexural strength.*

3.2.5. Modulus of Elasticity

From Table 5 the value of Elasticity is decreasing with the EPS foam percentage increasing. The highest decrement is obtained at EPS 50% mixture with a ratio of 74% for specimen E50S0. It is clear from Figure 6 that, SF with ratios 5% and 10% enhances the EPS foamed concrete modulus of elasticity until the ratios of 25% and 15% EPS foam respectively. The optimum percentage of SF that improves EPS concrete is 5%. On the other hand, the ratio 15% SF doesn't improve the EPS foamed concrete modulus of elasticity.

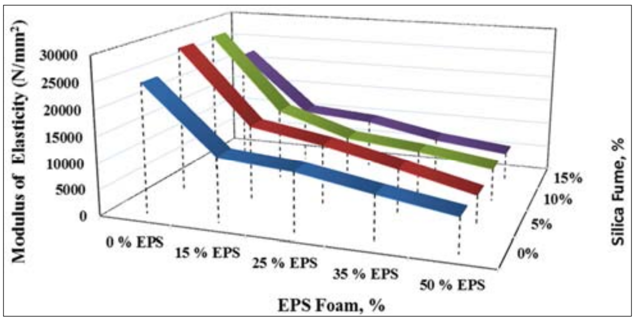

Figure 6. *Effect of SF on modulus of elasticity of EPS foamed concrete.*

It is observed that, in contrast to NDC, the failure modes of all EPS foamed concrete percentages are gradual in different levels (Figure 7), and the specimens are capable of retaining the load after failure without full fragmentation. The gradual failure in EPS foamed concrete is mainly attributed to the good energy-absorbing quality of the EPS beads. It could be said that, the EPS foam concrete is highly efficient at energy absorption capacity under compressive load. Similar results were obtained by [5, 31].

Figure 7. *Failure modes under compression test.*

3.3. Thermal Properties

From Table 5 the value of Thermal conductivity is decreasing with the EPS foam percentage increasing. The highest decrement is obtained at EPS 50% and silica fume 15% mixture with a ratio of 60% for specimen E50S15. It refer that the EPS foam had a good insulation behaviour, which improve the isolation system of foamed concrete.

4. Conclusions

In this study, the effect of foam and SF content on the properties of EPS foamed concrete was investigated, and the results can be summarized as follows:

a) Fresh EPS concrete density decreases with increasing ratio of EPS. The high amount of SF in EPS concrete reduces the fresh concrete density in all mixtures slightly.
b) All EPS foam concretes without any special bonding agents show good consistency and could be easily compacted. The 5% SF percentage improves the slump of EPS foamed concrete. The SF with ratios 10% and 15% enhances the EPS foamed concrete slump until the ratio of 25% EPS foam.
c) There are no remarkable changes in hardened density at age of 7 days or 28 days while using SF in EPS foamed concrete, except the 15% SF content it reduces the hardened density slightly.
d) All mechanical properties studied have the same trend. It decreases with the increasing of EPS foam percentages in the LWC.
e) Compressive strength decrement of EPS foamed concrete at the age of 7 days is less than that at the age of 28 days.
f) The difference of tensile strength decrement between early and late ages is significantly high in LWC with lower amount of EPS foam (15% and 25%), while the difference is low with high EPS foam percentages (50%).
g) EPS foamed concrete with SF has ultimate percentage 5% that gives maximum compressive strength and splitting tensile strength values. The 10% percentage of SF has a good effect on compressive strength in EPS foamed concrete till 25% EPS foam.
h) The loss of flexural strength is noticeable at low levels by replacing EPS foam. At higher levels by replacing the EPS foam the decrement in flexural strength is higher than tensile strength but lower than compressive strength. Flexural strength in EPS foamed concrete doesn't improve with the addition of SF.
i) Modulus of elasticity of EPS foamed concrete is directly proportional to the density of concrete. SF with ratios 5% and 10% enhances the EPS foamed concrete modulus of elasticity until the ratios of 25% and 15% EPS foam respectively. The optimum percentage of SF that improves EPS concrete is 5%.
j) It can be noticed from stress strain curves that, the EPS foam concrete is high efficient at energy absorption capacity under compressive load. It is observed that, the failure modes of all EPS foamed concrete percentages are gradual in different levels and the specimens are capable of retaining the load after failure without full fragmentation.
k) Thermal conductivity is decreasing with the EPS foam percentage increasing.

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