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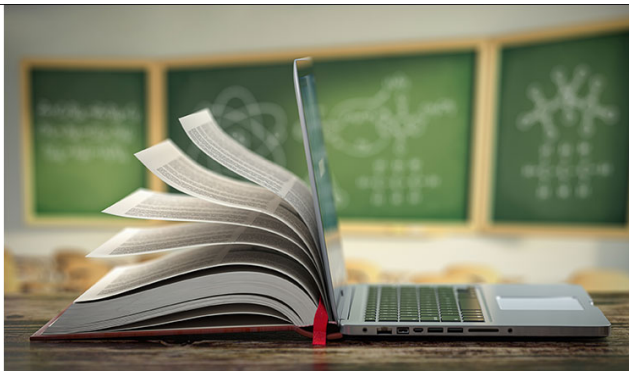
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Foamed concrete containing various amounts of organic-mineral additives

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Abstract. The present study evaluated the combined effects of organic-mineral additive based on a superplasticizer SR 5000F and the active mineral additive Fly Ash, Blast Furnace Slag and Silica Fume SF-90 on properties of foam concrete (FC). The calculation of mixture proportions of FC is applied in accordance with the absolute volume method. Besides, the compressive strength and flexural strength of foam concrete are determined by Russian standard GOST 10180-2012. The results from experiments show that flexural and compressive strength of the FC obtained respectively, from 3.25 to 5.08 MPa and from 13.91 to 26.87 MPa. The use of an organic-mineral additive in the mixture was led to increasing the compressive and flexural strength of foam concrete at the age of 28 days, respectively, from 8% to 93% and from 6% to 56%. The relationship between compressive strength and curing age, compressive and flexural strengths of the FC were also determined in this investigation. The results of this study demonstrated that the use of appropriate amounts of fly ash and blast furnace slag to partially replace natural sand could produce eco-friendly foam concrete, which has many positive environmental impacts.

1. Introduction

Lightweight concrete is of utmost importance to the construction industry. Most of the current concrete research focuses on high-performance concrete, by which is meant a cost-effective material that satisfies demanding performance requirements, including durability [1, 2]. The advantages of lightweight concrete are using the local industrial waste if found suitable for lightweight concrete, can be economically utilized. The use of lightweight concrete results in the reduction of costs to the extent of about 30÷40% [3, 4]. Nowadays, with the incorporation of a considerable amount of entrained air from 20% to 50% in the mixture, foamed concrete (FC) is produced which is a workable, low-density, pumpable, self-leveling, and self-compacting for construction building, as well as to improve the thermal insulation performance of the enclosing structures of buildings.

As also reported from the previous studies [5 - 7], FC is typically made by mixing water, cement, and foam. By adding materials such as stable foam, small cell or the air bubble will form inside the concrete which is one of the factors makes it lighter than normal concrete. In recent years, FC is used more as a nonstructural concrete for filling voids in infrastructures, and good thermal insulation and sound insulation in high-rise buildings with less increase in the dead load [8, 9].



According to Russian standard GOST 25820-2014, the structural concretes from light-weight concrete must satisfy the following basic requirements:

- (i). average density not higher than D2000 (2000 kg/m³);
- (ii). compressive strength of at least 12.5 MPa

According to [10 - 12], light-weight concrete has a density lower 1800 kg/m³. Recently there are a few authors [13-16] reported their research results on the compressive strength, porosity, permeability, density, ash content and the effect on the properties of foamed concrete. However, studies only stop at density lower 1600kg/m³.

Because the objective of the current investigation was to determine the properties of foam concrete with a wet density of 1700 kg/m³ and compressive strength from 10 to 30 MPa containing fly ash and blast furnace slag in Vietnam as a partial replacement of quartz sand.

The aim of the present investigation included three specific objectives to:

- Apply in accordance with the absolute volume method and combined with standard ACI-523.3R-93 to calculate the concrete mixture compositions.
- Effect of organic-mineral additives on the strength and pore structure of foam concrete samples tested.
- Quantitatively simulation of the relationships between the compressive strength and curing period; the compressive strength and flexural strength at age of 28 days of foam containing various amounts of organic-mineral additives.

2. Research programs

2.1. Materials used

a). Quartz sand (QS) of the "Lo River" (Vietnam) was used as fine aggregate in concrete mixtures with a specific weight of 2.65 g/cm³ and particle size from 0.14 mm to 1.25 mm.

b). The 40-Grade ordinary Portland cement (C) produced by the factory "But Son" (Vietnam) with the specific gravity of 3.10 g/cm³, which was used as a major binder material in this study. In Tables 1 and 2 are presented the physical-mechanical properties and the mineralogical composition of the "But Son" Portland cement, respectively.

Table 1. The physical properties of "But Son" Portland cement

Retained content on sieve 0.09 mm (%)	Soundness - Lechatelier (mm)	Surface area (cm ² /g)	Setting time (min)		Compressive strength (MPa)			Standard consistency (%)
			Initial	Final	3-day	7-day	28-day	
5.5	2.5	3660	120	360	27.4	35.3	45.8	29.5

Table 2. The mineralogical composition of "But Son" Portland cement

Mineral composition (% mass)				
C ₃ S	C ₂ S	C ₃ A	C ₄ AF	Other
56.15	22.47	5.14	11.25	4.99

c). Fly Ash (FA) and Blast furnace slag (BFS) used in this work were obtained from TPP "Hai Phong" (Vietnam) and the factory "Hoa Phat" (Vietnam), respectively. Besides, Silica fume SF 90 Silica Fume SF-90 (SF90) (Vina Pacific) was used as an additive in the concrete mixes. The basic characteristics of Fly Ash " Hai Phong ", Blast furnace slag and Silica Fume SF-90 are given in Tables 3.

Table 3. The physical properties of Fly Ash " Hai Phong ", Blast furnace slag and Silica Fume SF-90

Material type	Specific weight (g/cm ³)	Unit weight of natural porous state (kg/cm ³)	Surface area (cm ² /g)	Water demand	Passing sieve 10 μm (%)
Fly Ash	2.34	850	3980	28.5	6.7
Blast furnace slag	2.29	830	4550	32.5	5.2
Silica Fume SF-90	2.15	760	10150	31.8	-

The analysis results of chemical compositions of Portland cement, Fly Ash " Hai Phong ", Blast furnace slag and Silica Fume SF-90 are presented in Table 4.

Table 4. Chemical composition of cement, fly ash, blast furnace slag and Silica Fume SF-90

Materials	The average chemical composition, % mass.									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	TiO ₂	MgO	K ₂ O	Na ₂ O	LOI ^(a)
Portland cement	22.56	5.29	3.47	63.37	-	-	2.01	0.61	0.14	2.55
Fly ash	59.91	23.29	5.67	1.68	0.49	-	1.45	-	-	7.51
Blast furnace slag	35.45	13.52	-	40.88	0.14	0.5	7.89	0.28	-	1.34
Silica Fume SF-90	91.63	2.24	2.48	0.52	-	-	-	-	0.56	2.57

Note: ^(a)LOI - Loss on ignition.

In addition, the particle size distributions details of all binder materials are shown in Figure 1.

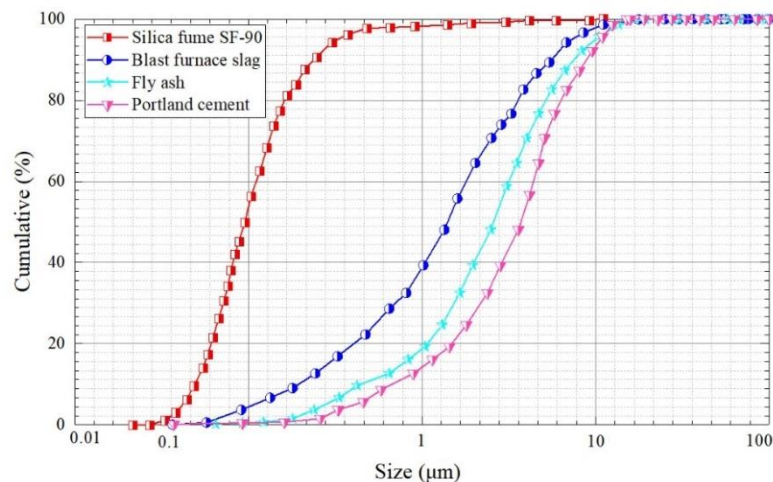


Figure 1. Sieving analysis of Silica Fume, Blast Furnace Slag, Fly Ash and Portland cement as measured by laser diffraction analysis

e). SR 5000F SilkRoad superplasticizer (SR5000) (Hanoi-Korea Co., Ltd., Vietnam) was used as a water-reducing plasticizing additive with a specific gravity of 1.1 g/m^3 at a temperature of $25 \pm 5^\circ\text{C}$, an optimum dosage of 1.5% by mass of Portland cement, which reduces the water demand of equal-moving concrete mixtures by 30%.

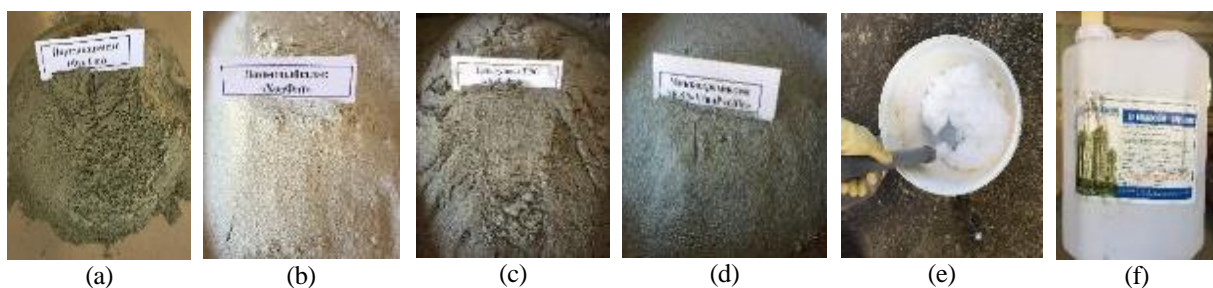


Figure 2. (a) - Portland cement "But Son", (b) - Blast furnace slag "Hoa Phat", (c) - Fly ash TPP "Hai Phong", (d) - Silica fume SF-90, (e) – Foam EABASSOC, (f) - Superplasticizer SR 5000F "SilkRoad"

g). The foaming agent of EABASSOC was used, which made in the United Kingdom with a specific weight of 1.02 g/cm^3 . For the current research, the EABASSOC foaming agent was diluted with water at the proportion of 2.5%.

All types of raw materials for foamed concrete in this study are shown in Figure 2.

Foam stability. Foaming properties such as foam stability were evaluated by a high-speed agitating method. Of the EABASSOC foaming agent solution (2.5%) with a volume of 100 ml was placed in a 300 ml stainless steel cup and agitated at 10,000 r/min for 10 min with a blade type mixer [17, 18]. The foam was transferred into a graduated flask (200 ml), and the whole volume was measured immediately. The foaming stability was calculated by the formula (1):

$$\text{Foaming stability} = \frac{\text{Volume of foam after 10 min(ml)}}{100 \text{ (ml)}} \times 100\% \quad (1)$$

The results test of properties and foam stability of the EABASSOC foams are presented in Table 5, while the scheme test setup, in which the foam was obtained, are shown in Figure 3.

Table 5. Evaluation Test for Foam Agent

Volumetric mass density (g/l)	45		
Time test (hours)	1	2	3
Foaming stability (%)	92	76	65

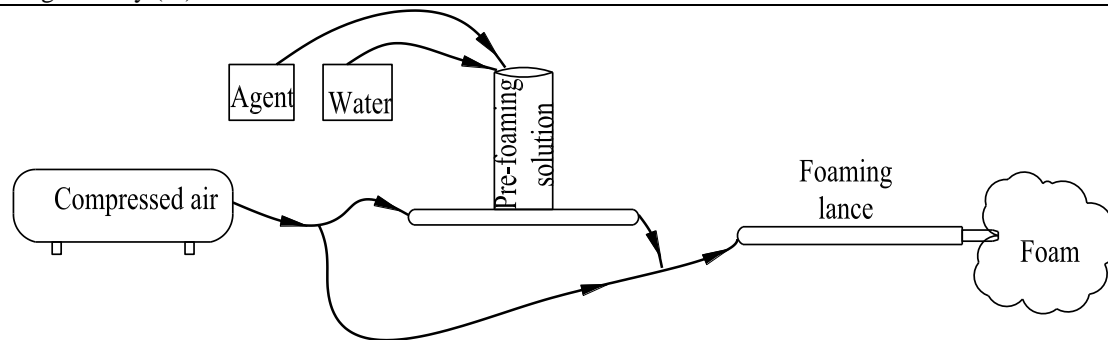


Figure 3. The layout of experimental equipment to obtain foaming from foaming agents, compressed air and water

h). Local tap water (W) was used for both mixing concrete and curing of the test samples in this study.

2.2. Mixture proportions and samples preparation

(a) Mixture proportions

As it is known, density and strength are very important properties of foam concrete. For foamed concrete, the design method of mixture proportion is to determine its density to achieve effective control of concrete strength in the hardened state.

In the present study, the mix proportions of foam concrete tests were arrived at as per the procedure in accordance with ACI-523.3R-93 standard, applied in accordance with the absolute volume method and combined with formulas (2) and (3) of published researches [19 - 21].

$$D_{FC} = C + QS + FA + BFS + SF90 + SR5000 + W \quad (2)$$

$$V_F = K_d * \left(1000 - \frac{C}{\rho_C} - \frac{QS}{\rho_{QS}} - \frac{FA}{\rho_{FA}} - \frac{BFS}{\rho_{BFS}} - \frac{SF90}{\rho_{SF90}} - \frac{SR5000}{\rho_{SR5000}} - \frac{W}{\rho_W} \right) \quad (3)$$

where: D_{FC} - the design wet density of foam concrete samples (kg/m^3);

C, QS, FA, BFS, SF90, SR5000, W - respectively, the Portland cement, Quartz sand, Fly Ash, Blast Furnace Slag, Silica Fume, Superplasticizer SR 5000F and water dosages of 1 m^3 foam concrete (kg);

ρ_C , ρ_{QS} , ρ_{FA} , ρ_{BFS} , ρ_{SF90} , ρ_{SR5000} and ρ_w - respectively, the specific gravity of Portland cement Quartz sand, Fly Ash, Blast Furnace Slag, Silica Fume, Superplasticizer SR 5000F and water (kg/m^3);

V_F - foam addition (m^3);

K_d - Redundancy factor, in this work $K_d = 1.1$ for the foaming agent of EABASSOC (United Kingdom) with good stability [22].

The target wet density (unit weight) of all concrete samples tested was 1700 kg/m^3 , and the target compressive strength of foam concrete in the hardened state was controlled within the range of 10-30 MPa. According to [20], mass Portland cement is fixed as $PC = 450 \text{ kg/m}^3$ for all foam concrete mixtures.

When designing the composition of concrete mixtures based on the following provisions:

- + For the mixes of foam concrete without superplasticizer water-to-cement ratio (W/C) of 0.5 [23].
- + Based on the results test of this investigation showed that with mixes foam concrete using superplasticizer SR 5000F, the water-cement ratio was 0.25.
- + The control mix (FC-1) of foam concrete test doesn't contain mineral additives (Fly ash, Blast furnace slag, and Silica fume) and superplasticizer. The test mixed number 02 (FC-2) and 03 (FC-3) of foam concrete with W/C of 0.5, the BFS and FA were used to replace 30% by mass of QS, respectively [8, 18, 24]. Besides, the superplasticizer SR 5000F was used in the mixes foam concrete number 04 (FC-04) and 05 (FC-05) with a water-cement ratio was 0.22, the Silica fume SF-90 was used to replace 10% of PC (by weight), used the BFS and FA to replace 30% by weight of QS, respectively.

Further details about all mixtures of foamed concrete, containing Blast Furnace Slag, Fly Ash and Silica Fume, are listed in Table 6.

Table 6. Compositions of foam concrete mixtures

No.	W/C	SR5000/C	SF90/C	BFS/QS	FA/QS	C	QS	SR5000	FA	BFS	SF90	W	W ^(*)	F(L)
FC-1 (control)	0.5	-	-	-	-	450	1025	-	-	-	-	225	225	267
FC-2	0.5	-	-	0.3	-	450	718	-	-	308	-	225	287	247
FC-3	0.5	-	0	-	0.3	450	718	-	308	-	-	225	256	250
FC-4	0.25	0.015	0.1	0.3	-	450	778	6.8	-	308	45	113	174	316
FC-5	0.25	0.015	0.1	-	0.3	450	778	6.8	308	-	45	113	143	319

When: W^(*) - the real water consumption of 1m³ foam concrete (kg), which can be calculated by the formulas (4):

$$W^{(*)} = W + \alpha * FA + \beta * BFS \quad (4)$$

In the form: α and β - respectively, the coefficient of Fly Ash and Blast Furnace Slag, which was determined by the total amount of water wetting of mineral admixture surfaces. Based on the experimental results of this work, for the Fly Ash, α is 10% by mass, while for the Blast Furnace Slag, β is 20% by mass.

(b) Samples preparation

From data in Table 6, Portland cement, sand, fly ash, blast furnace slag and silica fume in the dry state were poured into a mixer "MasterMix" at the laboratory and mixed at a rate of 50 rpm from 1 to 3 minutes at a temperature of 20⁰C to generate a dry mixture. Next, water and superplasticizer are added to mix for 2 minutes during the mixing process to obtain a wet binder mixture. Meanwhile, the foam of EABASSOC produced by a foam generator was injected into a foam concrete mixer and stirred for 1 minute. Right after mixing, the foam concrete was poured into a mold tested and maintained in static for 24 hours. After demolding (24 hours), the foam concrete specimens were put into the standard curing box for curing to the prescribed age, and the relevant performance indexes of the sample were tested (refer Figure 4).



(a) Concrete mixture without foam



(b) Foam + concrete mixture



(c) Foam concrete mixture

Figure 4. Foam concrete mixing process

2.3. Methods

Dry density (D , kg/m^3) and compressive strength tests (f_{cs} , MPa) of the foam concrete was performed at 1, 3, 7, 14 and 28 days using cubic specimens of $150 \times 150 \times 150$ mm (Figure 6), while flexural strength of the concrete was performed at 28 days using beam specimens of $100 \times 100 \times 400$ mm (Figure 5) as stipulated by Russian standard GOST 10180-2012.



Figure 5. Testing flexural strength



Figure 6. Testing of the specimen under compression

3. Test Results and Discussion

3.1. Mechanical properties of foam concrete tested

The mechanical properties of all-foam concrete samples at different curing times are listed in Table 7.

Table 7. Properties of foam concrete

No.	Dry density (kg/m^3)	Compressive strength at different ages (MPa)					Flexural strength at the age of 28 days (MPa)
		1-day	3-day	7-day	14-day	28-day	
FC-1 (control)	1656	2.25	5.62	8.46	12.36	13.91	3.25
FC -2	1662	2.43	6.43	10.95	13.61	15.02	3.46
FC -3	1665	2.64	6.69	13.2	14.44	16.36	3.87
FC -4	1649	4.01	12.08	17.18	22.73	24.72	4.86
FC -5	1653	4.34	15.77	19.07	24.67	26.87	5.08

The flexural and compressive strength values of the concrete samples were in the range of $3.25 \div 5.08$ MPa and $13.91 \div 26.87$ MPa at 28 days curing time, respectively. In particular, the dry density of all samples of foam concrete is smaller than the design of a wet density of 1700 kg/m^3 .

In Figure 7, the experimental results from compressive and flexural strength measurements on the foam concrete samples control mix (FC-1) without mineral additives and foam concrete tested, containing FA and BFS replacing 30% by mass of fine aggregate in mixes FC-2, 3, 4 and 5 are presented.

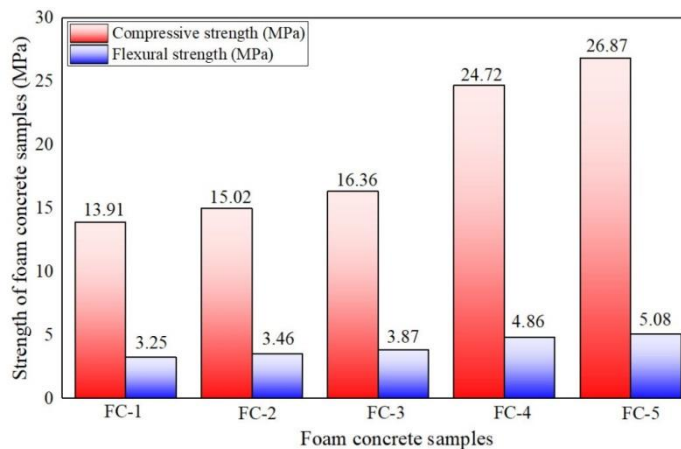


Figure 7. The average values of compressive and flexural strength of the foam concrete samples at 28 days
Data presented in this Figure indicates that:

(1). The compressive strength of foam concrete specimens with mixes FC-2, 3, 4 and 5 at the age of 28 days is observed to increase, respectively, to 8%, 18%, 78% and 93% in comparison with the strength of the foam concrete samples control mix (FC-1).

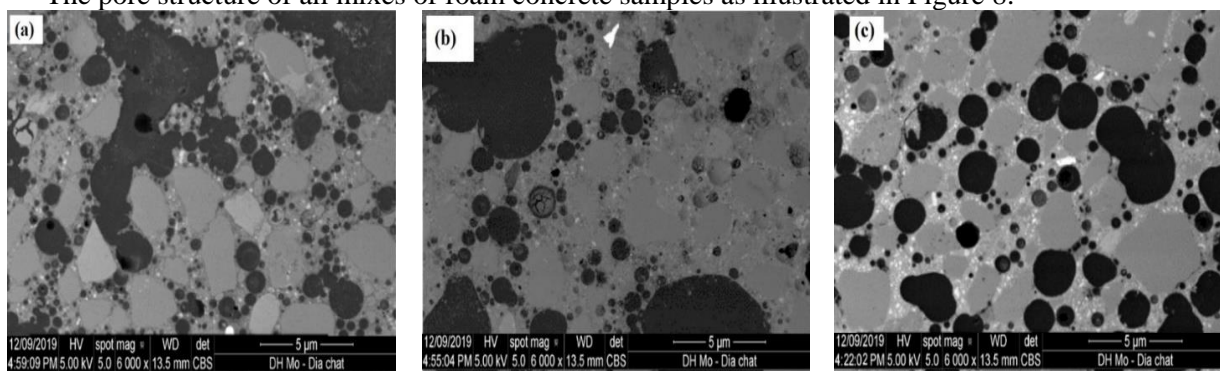
(2). For the flexural strength of foam concrete specimens, FC-2, 3, 4 and 5 at the age of 28 days is higher, respectively, 6%, 19%, 50% and 56% in comparison with the strength of the foam concrete samples control FC-1.

The strength increase is due to the higher content of hydrated products (calcium silicate hydrate – CSH), which are the main carrier of strength in the hardened state of foam concrete specimens, including active mineral additives due to the reaction of $\text{Ca}(\text{OH})_2$, which produced from cement hydration with the active silica of the mix FA, BFS and SF90 [15, 18, 19]. Additionally, this increase is also explained as due to the significantly small size of the mineral additive, which results filled the pores in the cement stone, thus mechanical properties of foam concrete samples were increased [23].

(3). Both the compressive and flexural strength of FC-5 foam concrete is the highest. This is explained that fine silica fume, containing 91.63% of active silica, while Fly Ash and Blast Furnace Slag only containing 59.91% and 35.45% of SiO_2 .

3.2. Effect of organic-mineral additives on the pore structure of foam concrete samples

The pore structure of all mixes of foam concrete samples as illustrated in Figure 8.



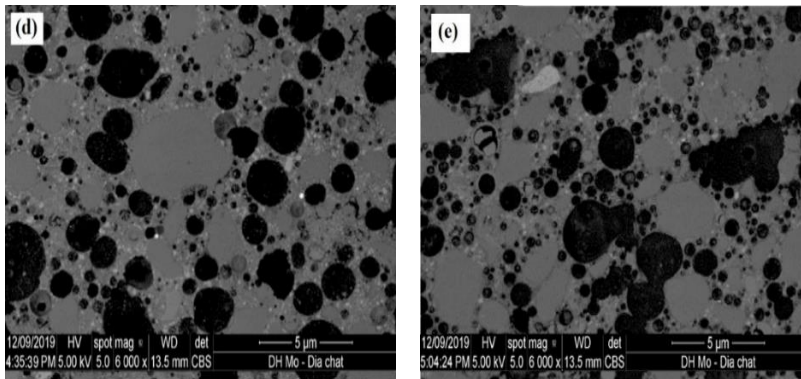


Figure 8. The SEM images of all mixes of foam concrete samples: (a) - FC-1; (b) - FC-2; (c) - FC-3; (d) - FC-4; (e) - FC-5

Based on SEM images in Figure 8 given that with the replacement sand by 30% mass of FA and BFS, incorporating with 10% by mass SF90 in the mixtures foam concrete, the pores of the foam concrete are more evenly distributed and the pores became more rounded. The small bubbles from foaming EABASSOC in the mixes were easily moved and evenly in the structure of samples during the stirring process [22].

3.3. Correlations

For clear observation, the speed of development in compressive strength of the foam concrete specimens and the relationship between compressive strength and curing age for examined samples were displayed in Figure 9.

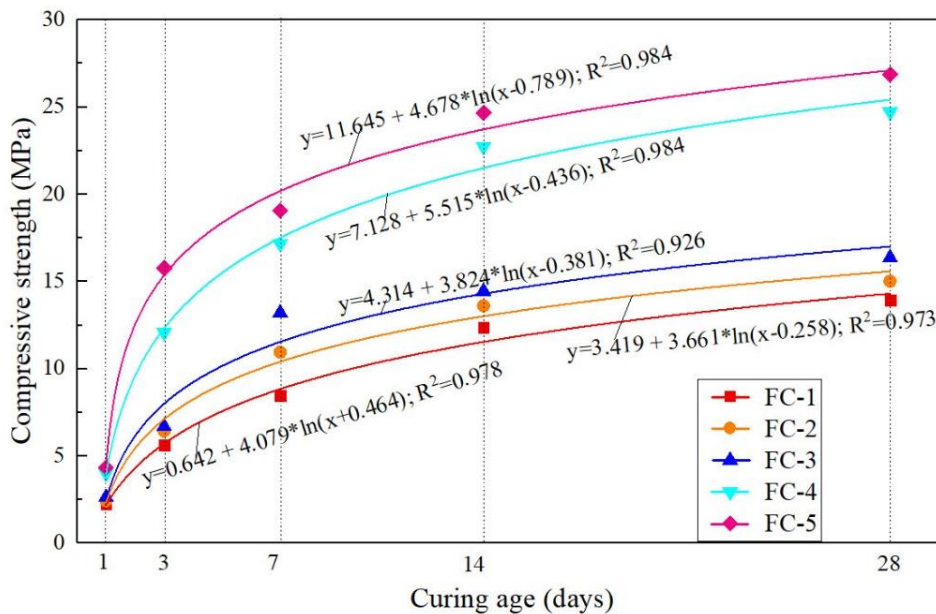


Figure 9. Compressive strength development of foam concrete at different curing periods

As also reported from the previous studies [25 - 28] indicates that for light-weight concrete, the relationship between compressive strength and curing age may have the following shape:

$$y = k_1 + k_2 \cdot \ln(x + k_3) \tag{5}$$

In Equation (5), y is the compressive strength of concrete (MPa) at age (x) days and (k_1), (k_2) and (k_3) are coefficients. According to the data test results, the relationships between compressive strength and curing age for foam concrete are given by the following formulas:

$$+ \text{ For FC-1: } \quad y = 0.642 + 4.079 \cdot \ln(x + 0.464) \text{ with } R^2 = 0.973 \quad (6)$$

$$+ \text{ For FC-2: } \quad y = 3.419 + 3.661 \cdot \ln(x - 0.258) \text{ with } R^2 = 0.973 \quad (7)$$

$$+ \text{ For FC-3: } \quad y = 4.314 + 3.824 \cdot \ln(x - 0.381) \text{ with } R^2 = 0.926 \quad (8)$$

$$+ \text{ For FC-4: } \quad y = 7.128 + 5.515 \cdot \ln(x - 0.436) \text{ with } R^2 = 0.984 \quad (9)$$

$$+ \text{ For FC-5: } \quad y = 11.645 + 4.678 \cdot \ln(x - 0.789) \text{ with } R^2 = 0.9984 \quad (10)$$

It could be noticed that, all mixes foam concrete, containing various amounts of organo-mineral additives follows the proposed formula (5) with the correlation coefficient of more than 0.9 ($R^2 > 0.92$). The values of coefficients (k_1 , k_2 and k_3) for five mixes foam concrete seem to be different.

On the other hand, the relation between compressive (f_{cs} , MPa) and flexural strength (f_{fs} , MPa) of five mixes of foam concrete is given in Figure 10 and given in formula (11).

$$f_{cs} = 2.076 \cdot (f_{fs})^{1.568} \quad (11)$$

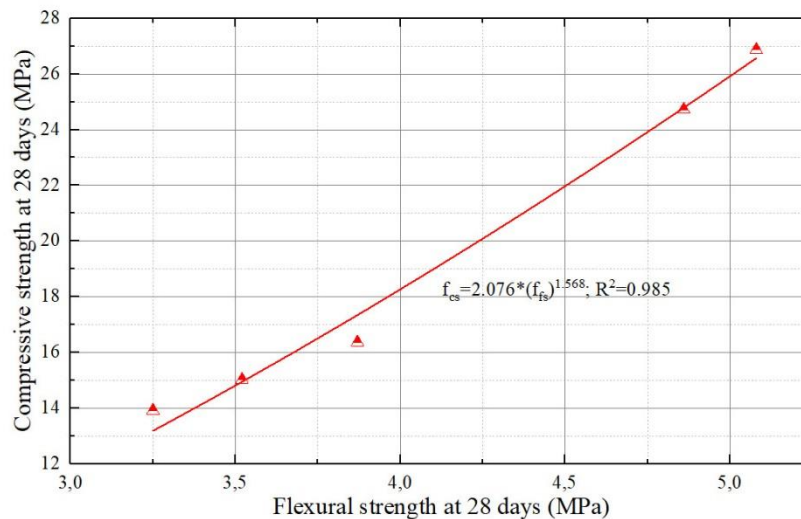


Figure 10. Correlation between compressive and flexural strength of foam concrete

Correlation between compressive and flexural strengths having a positive linear relationship, as evident from Fig. 10. This relationship was found for the compressive strength varying from 13.91 MPa to 26.87 MPa and for the flexural strength varying from 3.25 MPa to 5.08 MPa. The coefficient of correlation was $R^2 = 0.985$, which indicated an excellent relationship.

The results of this study suggest that it might be possible for the foamed concrete to be used in the case of not only lightweight but also structural purpose, besides the conventional cases such as filling, insulation or lightweight purposes only. Besides, it is found that the use of industrial wastes such as fly ash, Blast Furnace Slag, slag, etc. in foam and lightweight concrete is not only environmental protection and economical but also modifies the concrete properties in both fresh and hardened states to produce green concrete or environmentally-friendly materials.

4. Conclusion

Based on the experimental results, the following conclusions can be drawn:

- The use of an organic-mineral additive based on a superplasticizer SR 5000F and the active mineral additive Fly Ash, Blast Furnace Slag and Silica Fume SF-90 was led to increase the compressive and flexural strength of foam concrete at the age of 28 days, respectively, from 8% to 93% and from 6% to 56%. Therefore, foam concrete with a modified structure from an organic-

mineral additive is a very promising building material and strongly effective for the construction of enclosing structures with enhanced thermal insulation properties and environmentally-friendly materials.

- The compressive strength of lightweight concrete in the range from 13.91 MPa to 24.72 MPa shown that it can be used in load-bearing structures. Meanwhile, it can also reduce the load acting on the foundation thanks to its dry density smaller than 1700 kg/m³.

- The correlations between compressive strength and flexural strength of foam concrete samples could be expressed by $f_{cs} = 2.076 \cdot (f_{fs})^{1.568}$ ($R^2 = 0.985$). Whereas, the correlations between compressive strength and curing period for examined samples were determined with the correlation coefficient of more than 0.9.

- Substantially replacing natural sand in the foam concrete mixture will not only reuse industrial waste, may environmental protection but also reduce concrete costs as well as improve technical properties foam concrete such as green concrete in the future.

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