IOP Conference Series: Materials Science and Engineering

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Abstract. The paper presents mathematical modeling of additives and water's effect on foam concrete's compressive and flexural strength at 28 days of normal hardening. The requirements of GOST 10180-2012 determined the compressive and flexural strength of foam concrete. The initial composition of the foam concrete mix was calculated using the absolute volume method.

Results received first-order regression equations. The compressive strength and flexural strength of foam concrete depended on the relations from x_1 ($\frac{W}{OPC+BFS}$) to x_3 ($\frac{SF90}{OPC}$) and the image surface expression and objective function for the regression equations. The optimal value obtained: compressive strength = 8.075 MPa and flexural strength 1.087 MPa.

1. Introduction

Foam concrete is a lightweight concrete with a porous structure obtained by curing solutions, including binders, fine aggregates of various origins, water, additives and a foaming agent. Besides, foam concrete is an economical, environmentally friendly, lightweight construction material that provides heat and sound insulation, as well as fire resistance [1-5].

Foam concrete has the following advantages [1, 4, 16]:

+ Thermal and moisture resistance.

+ Soundproofing.

+ Possibility of producing bricks or blocks of different geometrical shapes with high accuracy of adherence to dimensions and accuracy of edges, and, consequently, during construction, optimally smooth walls are obtained, which leads to a decrease in the cost of finishing work.

+ Elements made of foam concrete are convenient for transportation.

+ Significantly simplify the construction of buildings and their commissioning.

+ Save money, time and effort.

In addition, in scientific research, numerical simulation methods are often used to predict special properties' effects on the research object. In addition, in concrete technology, experimental planning methods are often used to find the optimal components for technological processes. According to studies [7, 8], it is necessary to collect information about previous studies' input variables when planning an experiment.

When using the experimental planning method, the following should be taken into account.

- Study some major factors affecting the properties of the materials to plan the experiment.
- Assume that some factors do not change.
- Note to minimize the number of experiments.

On the other hand, according to Vietnamese standard TCVN 1451: 1998 [9], clay bricks have a density =1600 kg/m³ and compressive strength = 7.5MPa. Therefore, foam concrete density with a density lower than 1000 kg/m³ instead of clay bricks can reduce the load to the building [1, 5, 10].

According to the research [3, 4], foam concrete with a density < 1000 kg/m^3 has a compressive strength of 4÷6 MPa. Besides, according to studies [11, 12], the water content in foam concrete has a significant effect on concrete's compressive strength. The addition of silica fume to the concrete mixture increases the strength of concrete.

Therefore, this study aims to use mathematical modeling about the influence of input factors on the concrete strength foam at 28 age days with a density of 900 kg/m^3.

2. Research programs

2.1. Materials used

The properties of Ordinary Portland Cement (OPC), Blast furnace slag (BFS) and silica fume (SF90) were shown in Table 1. Ordinary Portland Cement (OPC) with a specific gravity of 3.12 (g/cm^3) and Blaine fineness of 3650 cm^2/g was used in all foam concrete mixtures. Blast furnace slag from the metallurgical factory "Hoa Phat" (Northern Vietnam), with ρ = 2.29 (g/cm^3), Blaine fineness =4540 cm^2/g. Silica Fume SF-90 (Viet Nam) with ρ = 2.15 (g/cm^3), Blaine fineness =10160 (cm^2/g).

In this study, superplasticizers (SR5000) were used to improve the performance of concrete mixtures with ρ = 1.1 g/m^3 at a temperature of 25 ± 5°C.

The physical and chemical properties of cement (OPC), silica fume (SF90) and blast furnace slag (BFS) are shown in Table 1.

Table 1. Properties of OPC, BFS and SF90.

Property		SF90	BFS	OPC
Chemical	SiO_2	90.78	36.01	21.98
	Al_2O_3	2.23	13.77	5.31
	Fe_2O_3	2.51	-	3.46
	CaO	0.52	41.05	62.33
	MgO	-	7.36	2.01
	SO_3	-	0.14	-
	Na_2O	0.57	-	0.14
	K_2O	-	0.28	0.62
	Loss on ignition	3.39	1.39	4.15
Physical	Specific gravity (g/cm^3)	2.15	2.29	3.12
	Fineness (cm^2/g)	10160	4540	3650

EABASSOC Foaming Agent (United Kingdom) is a highly concentrated, highly efficient liquid used in Foamed Concrete production. Dosage Rate: 0.3 - 0.6 l/m³ with ρ = 1.02 g/cm^3. For this study, the EABASSOC foaming agent is mixed with water at a rate of 2.5%.

Mixing water to obtain a concrete mixture meets the requirements of GOST 23732-2011, pH = 7.5. [13].

2.2. Procedure for the preparation of foam concrete

The fresh foam concrete comes from a process of continuously mixing foam and paste until an even mixture is obtained. The foam concrete preparation process is illustrated in Figure. 1. Cement, silica fume and blast furnace slag are first mixed at a lower speed of about 40÷50 rpm for a short while, followed by the addition of water and superplasticizer to mix for 2 minutes during the mixing process to obtain a wet binder mixture. Then, the foaming agent is added to the mixture and continue to mix. The mixture is then put into a mold and put it in a static state for 24 hours. These foam concrete samples were then tested after 28 days of age [14, 15].

Figure 1. The process of preparing samples (from left to right, top to bottom)

2.3. Research Methods

The absolute volume method was used to determine the composition of the foam concrete mixture [16, 17].

The mechanical properties of foam concrete at the age of 28 days are determined according to Russian standard GOST 10180-2012 [18] (Figures 2 and 3).

Figure 2. Flexural strength test samples

Figure 3. Compression test samples

Using the method of Box-Wilson central composite designs to find the optimal amount of additive silica fume (SF90), superplasticizer (SR5000) and the water-cement ratio [8, 19].

3. Test results and Discussion

In this study, the cement amount was fixed OPC = 350 kg/m^3 [2, 20]. Based on the analysis of scientific literature [2, 3, 5, 6, 11] and experimental research results. The ratio of selected material components is as follows:

- x_1 – the ratio of $\frac{W}{OPC+BFS}$ from 0.2 to 0.22
- x_2 – the ratio of $\frac{SR5000}{OPC}$ from 0.01 to 0.02
- x_3 – the ratio of $\frac{SF90}{OPC}$ from 0.05 to 0.15

The number of necessary experiments N when planning the first order is determined by the formula (1):

$$N = 2^k = 2^3 = 8 \quad (1)$$

Table 2. Orthogonal experiment design

№ Experience	Variable factors			Reals variable		
	x_1	x_2	x_3	$\frac{W}{OPC+BFS}$	$\frac{SR5000}{OPC}$	$\frac{SF90}{OPC}$
1	+1	+1	+1	0.22	0.02	0.15
2	-1	+1	+1	0.20	0.02	0.15
3	+1	-1	+1	0.22	0.01	0.15
4	-1	-1	+1	0.20	0.01	0.15
5	+1	+1	-1	0.22	0.02	0.05
6	-1	+1	-1	0.20	0.02	0.05
7	+1	-1	-1	0.22	0.01	0.05
8	-1	-1	-1	0.20	0.01	0.05

Table 3. Code and real values of variable experiment factors

Codes	Variable factors		
	x_1	x_2	x_3
-1	0.20	0.01	0.05
0	0.21	0.15	0.10
+1	0.22	0.02	0.15

Compositions of foam concrete and the values of the compressive and flexural strength of foam concrete at the age 28 days of normal hardening are in tables 4, 5.

Table 4. Compositions and flexural strength of foam concrete samples at the age of 28 days

№	Foam concrete components						Flexural strength R_{fs}^{28}, MPa						S_{1i}^2
	OPC	BFS	SR5000	SF90	W	Foam (L)	R_{fs1}	R_{fs2}	R_{fs3}	$Y_{1i}^{cp}=R_{fsi}^{cp}$	$\overline{R}_i$	$\left(Y_{1i}^{cp}-\overline{Y}_{1i}\right)^2$	
1	350	356	7.0	53	155.3	547.80	1.01	1.02	1.02	1.02	1.021	0.00002	0.00004
2	350	356	7.0	53	141.2	561.92	1.09	1.10	1.12	1.10	1.086	0.00033	0.00016
3	350	356	3.5	53	155.3	550.98	1.00	1.00	1.01	1.00	1.021	0.00027	0.00003
4	350	356	3.5	53	141.2	565.10	1.08	1.11	1.07	1.09	1.086	0.00000	0.00039
5	350	356	7.0	18	155.3	564.08	0.97	0.97	0.98	0.97	0.957	0.00029	0.00009
6	350	356	7.0	18	141.2	578.20	1.05	1.04	1.02	1.03	1.022	0.00013	0.00020
7	350	356	3.5	18	155.3	567.26	0.96	0.95	0.97	0.96	0.957	0.00001	0.00005
8	350	356	3.5	18	141.2	581.38	0.98	0.98	1.02	0.99	1.022	0.00101	0.00050
	$MaxS_1^2=0.00050$						$\sum\left(Y_{1i}^{cp}-\overline{Y}_{1i}\right)^2=0.00206$					$\sum S_{1i}^2=0.00146$	

Table 5. Compositions and compressive strength of foam concrete samples at the age of 28 days

№	Foam concrete components						Compressive strength R_{cs}^{28}, MPa						S_{2i}^2
	OPC	BFS	SR5000	SF90	W	Foam (L)	R_{cs1}	R_{cs2}	R_{cs3}	$Y_{2i}^{cp}=R_{csi}^{cp}$	$\overline{R}_i$	$\left(Y_{2i}^{cp}-\overline{Y}_{2i}\right)^2$	
1	350	356	7.0	53	155.3	547.80	7.51	7.6	7.55	7.55	7.58	0.00065	0.00203
2	350	356	7.0	53	141.2	561.92	8.11	8.2	8.3	8.20	8.07	0.01745	0.00903
3	350	356	3.5	53	155.3	550.98	7.42	7.46	7.5	7.46	7.58	0.01410	0.00160
4	350	356	3.5	53	141.2	565.10	8.02	8.25	7.98	8.08	8.07	0.00015	0.02123
5	350	356	7.0	18	155.3	564.08	7.17	7.22	7.31	7.23	7.13	0.01147	0.00503
6	350	356	7.0	18	141.2	578.20	7.78	7.69	7.57	7.68	7.62	0.00375	0.01110
7	350	356	3.5	18	155.3	567.26	7.12	7.09	7.28	7.16	7.13	0.00138	0.01043
8	350	356	3.5	18	141.2	581.38	7.28	7.41	7.55	7.41	7.62	0.04220	0.01823
	$MaxS_2^2=0.02123$						$\sum\left(Y_{2i}^{cp}-\overline{Y}_{2i}\right)^2=0.09113$					$\sum S_{1i}^2=0.07870$	

(a) Testing the reproducibility of experiments

Repeatability testing method by Cochran's criteria. The formula calculated the calculated value by Cochran's criteria.

$$G_{pacc}=\frac{\max S^2}{\sum S_i^2} \quad (2)$$

Based on the values of the flexural strength of foam concrete samples at the age of 28 days. We obtain:

$$S_{ll}^2=\sum S_{1i}^2=0.00146 \text{ and } MaxS_1^2=0.00050 \rightarrow G_{1pacc}=\frac{MaxS_1^2}{\sum S_{1i}^2}=\frac{0.00050}{0.00146}=0.3429$$

Besides that, based on the values of foam concrete samples' compressive strength at the age of 28 days. We have also obtained:

$$S_{ll}^2 = \sum S_{2i}^2 = 0,07870 \text{ and } MaxS_2^2 = 0.02123 \rightarrow G_{2pacc} = \frac{MaxS_2^2}{\sum S_{2i}^2} = \frac{0.02123}{0.07870} = 0.2698$$

Critical values for Cochran's test $G_{cr} = G(f_1, f_2)$ was found from Table 4.36 of the Cochran distribution [21] depending on the values f_1, f_2 and α:

- level of significance $\alpha = 0.05$.
- degrees of freedom of the numerator $f_1 = k - 1 = 3 - 1 = 2$.
- denominator $f_2 = N = 8$.

$\Rightarrow G_{cr} = 0.5157$. So, $G_{1pacc} = 0.3429 < G_{cr} = 0.5157$ and $G_{2pacc} = 0.2698 < G_{cr} = 0.5157$

Therefore, the hypothesis of homogeneity satisfies the condition $F_{pacc} < F_{tab}$.

(b) Check the coefficients of the regression equation.

The formula determines estimated coefficients of the regression equation:

$$b_j = \frac{\sum_{i=1}^{N} x_{ji} y_j}{\sum_{i=1}^{N} x_{ji}^2} \forall j = \overline{1...n}; b_{ju} = \frac{\sum_{i=1}^{N} x_{ji}^2 x_{ui} y_j}{\sum_{i=1}^{N} x_{ji}^2 x_{ui}^2} \forall j.u = \overline{1...n}; j \neq u \quad (3)$$

The results are shown in Table 6.

Table 6. Coefficients of regression equations

b_i / Y_j		b_0	b_1	b_2	b_3	b_{12}	b_{23}	b_{31}	b_{123}
Y_1	R^{28}_{fs}. MPa	1.0214	-0.0328	0.0107	0.0320	-0.0042	-0.0036	-0.0102	0.0032
Y_2	R^{28}_{cs}. MPa	7.5988	-0.2463	0.0687	0.2263	-0.0279	-0.0154	-0.0721	0.0213

Based on the calculation results. the following regression equations were obtained:

$$Y_1 = 1.0214 - 0.0328x_1 + 0.0107x_2 + 0.0320x_3 – 0.0042x_1x_2 - 0.0036x_2x_3 – 0.0102x_3x_1 + 0.0032x_1x_2x_3 \quad (4)$$

$$Y_2 = 7.5988 - 0.2463x_1 + 0.0687x_2 + 0.2263x_3 - 0.0279x_1x_2 - 0.0154x_2x_3 – 0.0721x_3x_1 - 0.0213x_1x_2x_3 \quad (5)$$

The significance of the coefficients of the regression equations was checked by the Student criterion ($t_\alpha (f)$).

The coefficient b_j is considered significant if: $t_{bj} \geq t_\alpha (f)$.

in which:

$t_\alpha (f)$ - critical value for student's t distribution at a significance level $\alpha = 0.025$ and degrees of freedom $f = (k - 1) \times N = (3 - 1) \times 8 = 16$.

According to [21] on the table 3.2 $\Rightarrow t_\alpha (f) = 2.1199$.

The formula determined regression equations:

$$t_{bj} = \frac{|b_j|}{S_{ve}} \quad (6)$$

The formula determined the variance estimates of the regression coefficients of the S_{ve} equation:

$$S_{ve} = \sqrt{\frac{S_{ll}^{2}}{N}} \quad (7)$$

For the regression equation (4) $S^2_{ll} = \sum S_i^2$ = 0.00146 and N = 8 we have also obtained:

$$S_{ve} = \sqrt{\frac{S_{ll}^{2}}{N}} = \sqrt{\frac{0.00146}{8}} = 0.01351 \quad (8)$$

The values Student criterion for checking the significance of the regression equation (4) are given in table 7.

Table 7. Checking the coefficients of the equation (4)

j	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
b_j	b_0 1.0214	b_1 -0.0328	b_2 0.0107	b_3 0.0320	b_{12} -0.0042	b_{23} -0.0036	b_{31} -0.0102	b_{123} 0.0032
$\lvert b_j \rvert$	1.0214	0.0328	0.0107	0.0320	0.0042	0.0036	0.0102	0.0032
t_{bj}	75.6259	-2.4248	0.7898	2.3693	-0.3085	-0.2653	-0.7527	0.2406

After checking the coefficients, the authors obtained the equations:

$$Y_1 = 1.0214 - 0.0328x_1 + 0.0320x_3 \quad (9)$$

For the regression equation (5) $S^2_{ll} = \sum S_i^2$ = 0.07870 and N = 8 we have also obtained:

$$S_{ve} = \sqrt{\frac{S_{ll}^{2}}{N}} = \sqrt{\frac{0.07870}{8}} = 0.09918 \quad (10)$$

Similar to the equation (4) the values of the Student criterion of the regression equation (5) are given in Table 8.

Table 8. Checking the coefficients of the equation (5)

j	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
b_j	b_0 7.5988	b_1 -0.2463	b_2 0.0687	b_3 0.2263	b_{12} -0.0279	b_{23} -0.0154	b_{31} -0.0721	b_{123} 0.0213
$\lvert b_j \rvert$	7.5988	-0.2463	0.0687	0.2263	-0.0279	-0.0154	-0.0721	0.0213
t_{bj}	76.6125	-2.4828	0.6932	2.2811	-0.2815	-0.1554	-0.7268	0.2142

From table 7, we obtained the equation:

$$Y_2 = 7.5988 - 0.2463x_1 + 0.2263x_3 \quad (11)$$

(c) Verification of equations (9) and (11)

The testing of the model's full hypothesis is based on calculations of the full variance S^2_{av} (12) and the Fisher F_{fc} (13) criterion:

$$S_{av}^2 = \frac{\sum (Y_i^{cp} - \bar{Y}_i)^2}{N - m} \quad (12)$$

$$F_{fc} = \frac{S_{av}^2}{S_{ll}^2} \quad (13)$$

In which:

Y_j – the regression equation response value.

N - number of all possible tests. N = 8.

m - number of estimated regression coefficients. m = 3.

The values F_{pacc} was compared with the value F_{tab} (f_1. f_2) from the table 3.5[21]. determined by the number of degrees of freedom f_1 = N = 8 and f_2 = N – m = 8 – 3 = 5. Therefore F_{tab} (8. 5) = 3.69.

With regression equation (8). $S_{av}^2 = \frac{0.00206}{8-3} = 0.00041$ and $S_{ll}^2 = \sum S_i^2 = 0.00146$.

$$\Rightarrow F_{fc} = \frac{S_{av}^2}{S_{ll}^2} = 0.28276 \Rightarrow F_{fc} = 0.28276 < F_{tab} = 3.69$$

With regression equation (10). $S_{av}^2 = \frac{0.09113}{8-3} = 0.01823$ and $S_{ll}^2 = \sum S_i^2 = 0.07870$.

$$\Rightarrow F_{fc} = \frac{S_{av}^2}{S_{ll}^2} = 0.23159 \Rightarrow F_{fc} = 0.23159 < F_{tab} = 3.69$$

Therefore. equations 9 and 11 satisfy the condition $F_{fc} < F_{tab}$

Using the Matlab computer program. We can obtain the response surfaces for the regression equations (9) and (11) are presented in Figs 4 and 5.

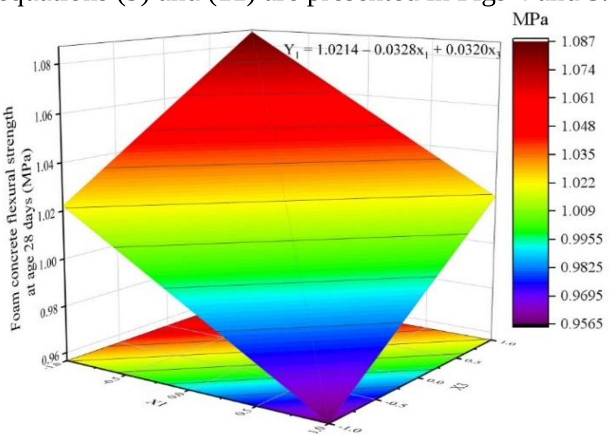

Figure 4. First-order surface equation (9)

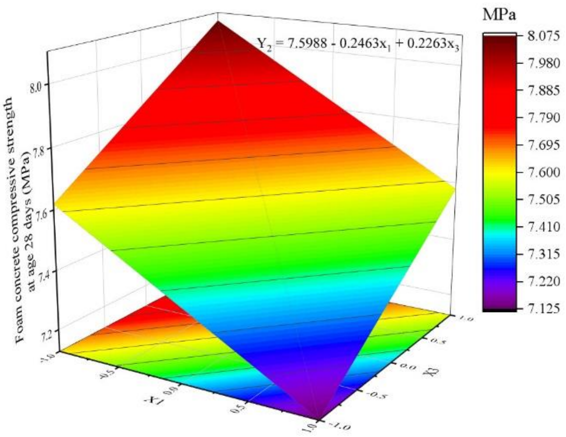

Figure 5. First-order surface equation (11)

Figures 4 and 5 show that when $x_1 \frac{W}{OPC+BFS}$ decreases and $x_3 \frac{SF90}{OPC}$ increases: the compressive strength and flexural strength of foam concrete increase. The increase in foam concrete's power can be explained by the fact that SF90 contained 90.78% of amorphous silica. It is shown that silica fume densifies compressed products' structure due to the binding of free calcium hydroxide with calcium hydro-silicate. Besides, according to research [4][3] also shows that the concrete strength increases when the water-cement ratio increases.

4. Conclusions

Based on the test results, the following conclusions are drawn on tested foam concrete samples:

Foam concrete containing a modifier of organic minerals, including blast furnace slag, silica fume, superplastic additive SR5000, the purpose of which is to plan a first-order experiment: compressive strength and flexural strength of a foam concrete sample after 28 days of normal curing (MPa) depending on the variables x_1 ($\frac{W}{OPC+BFS}$) and x_3 ($\frac{SF90}{OPC}$) according to the regression equations (9) and (11).

From the regression equations (9), (11), we see that a decrease in the ratio (x_1) simultaneously an increase in the rate (x_3) leads to an increase in the compressive strength and flexural strength of the concrete sample under test. The influence of the ratio (x_2) in the range of the considered value is insignificant, and therefore it can be neglected.

Compressive strength of foam concrete = 8.075 MPa and density <1000kg/m^3 can replace clay bricks to help reduce building load.

Soon the authors continue to study the effects of rates x_1 ($\frac{W}{OPC+BFS}$) and x_3 ($\frac{SF90}{OPC}$) to the mechanical properties of foam concrete by the method of central composite design for two input factors.

Acknowledgments
The authors would like to thank for the help of the Faculty of Civil Engineering's laboratory of Hanoi University of Mining and Geology. laboratory of College of industrial and constructional (Vietnam) and the Department "Technology of Binders and Concretes" at the National Research Moscow State University of Civil Engineering (Russian Federation).

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