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Modeling the influence of input factors on foam concrete properties

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Abstract. The paper presents the use of blast furnace slag as a fine aggregate in foam concrete. Besides, the paper also presents the research results of the effect of the water-cement ratio and Silica fume on the mechanical properties of foam concrete. The absolute volume method was used to calculate the ratio of foam concrete mixture. Besides, the mechanical properties of foam concrete were determined at the age of 28 days. The method of Box-Wilson central composite design for two factors was used to predict the effect of the water-cement ratio and Silica fume on foam concrete properties. The results showed that the proposed regression equations of this mathematical model achieved an adequate prediction accuracy. Using computer programs obtained surface images of equations (10) and (12). Besides, the maximum value of the objective function was determined with compressive strength = 8.52 MPa and flexural strength = 1.21 MPa. This research result is a premise for studying foam concrete bricks to replace clay bricks in construction works.

1. Introduction

In scientific research, numerical methods and computer models used to predict specific properties are of particular importance [1–3]. Besides that, in concrete technology often uses mathematical methods to find the optimal concrete components for technological processes [4, 5].

Experiment planning is a procedure for selecting the number and conditions of the experiments necessary and sufficient to obtain a mathematical model of the process [5–7].

The following should be kept in mind when planning experiments:

– Note to minimize the number of experiments.
– Assume that some factors remain unchanged.
– Research a few important factors affecting the properties of materials to plan experiments.

The studies [5, 8–10] shown that when planning an experiment. It is necessary to gather additional information about the input variables and object under study, employing the skills and knowledge obtained in previous studies. It is needed to collect additional information about the input variables and object under investigation, employing the skills and knowledge obtained in previous studies.

As known, foamed concrete is a highly aerated mortar, typically containing 30 to 80 % air bubbles by volume. It comprises Portland cement, water, fine aggregate, additives and mechanically produced foam. It has high workability, which allows it to flow and compact under its weight [11, 14].

When using foam concrete in construction, there are advantages [3, 11, 13].

– Low thermal conductivity.
– Little weight.
– Easy to transport.
– Ease of use.

- Ease of processing. (Due to the low density, aerated concrete products are easily sawn with a conventional hacksaw if necessary, to shorten their size.)
- Long service life.
- Compressive strength and flexural strength decrease with increasing density.

Besides that, silica fume is the most popular material used in concrete to increase its strength. For this study, silica fume is replaced in the range of 0.05÷0.15 % the weight of cement [15].

According to the research results [14–18], the use of clay bricks as a fine aggregate in foam concrete improves the mechanical properties of foam concrete and protects the environment.

Besides, according to the previous research results, the author has studied foam concrete with a density of 900 kg/m^3 using a silica-fume additive, superplasticizer. The result is compressive strength at the age of 28 days, from 7 MPa to 8 MPa. Besides, according to the Vietnamese standard of clay bricks used for construction works, compressive strength is > 7.5 MPa and density = 1600 kg/m^3 [19].

Therefore, the overarching purpose of this study is to use the method of central composite design for two input factors to predict the effect of superplasticizer and silica-fume on compressive and flexural strength of foam concrete at 28 days of age with a density of 900 kg/m^3.

2. Materials and Methods

2.1. Materials

Portland cement (OPC) CEM I 42.5 N produced by the factory “But Son” (Vietnam) with ρ = 3.10 g/cm^3. Its chemical properties are presented in Table 1.

Quartz sand (QS) of the "Lo River" (Vietnam) was used as fine aggregate in concrete mixtures with ρ = 2.65 g/cm^3 and particle size from 0.14 mm to 1.25 mm.

Blast furnace slag (BFS) from the factory "Hoa Phat" (Vietnam) with ρ = 2.297 g/cm^3.

Table 1. Chemical composition of OPC, BFS and SF90.

Chemical components (wt. %)	Cement (OPC)	Blast furnace slag (BFS)	Silica fume (SF90)
SiO_2	22.42	36.02	90.78
Al_2O_3	5.31	13.44	2.22
Fe_2O_3	3.45	-	2.46
SO_3	-	0.15	-
K_2O	0.64	0.29	-
Na_2O	0.15	-	0.57
MgO	2.03	7.66	-
CaO	62.56	40.47	0.54
TiO_2	-	0.5	-
Loss on ignition (%)	3.44	1.47	3.43
Blaine fineness (cm^2/g)	3665	4560	10120

Silica fume SF-90 (SF90) (Vietnam) was used as a binder. The analysis results of the chemical compositions of both SF90 and BFS are presented in Table 1. Besides, the particle size distribution details of raw materials used are shown in Figure 1.

Superplasticizer SR 5000F SilkRoad (SR5000) (Korea), which reduces water consumption, was used as a plasticizing additive. Its density at a temperature of 25±5°C was 1.1 g/cm^3. The optimal dosage of the superplasticizer is 1.5 % of the mass of Portland cement, which makes it possible to reduce water consumption in concrete mixtures by 30 %.

EABASSOC foaming agent manufactured at the factory EABSSOC in the United Kingdom. The foaming additives have the following specifications:

+ Specific weight 1.02 g/cm^3.

+ Dosage rate 0.3-0.6 lit/m^3.

- Mixing water (W) conforming to standard requirements GOST 23732-2011 and TCVN 4506:2012 [20, 21].

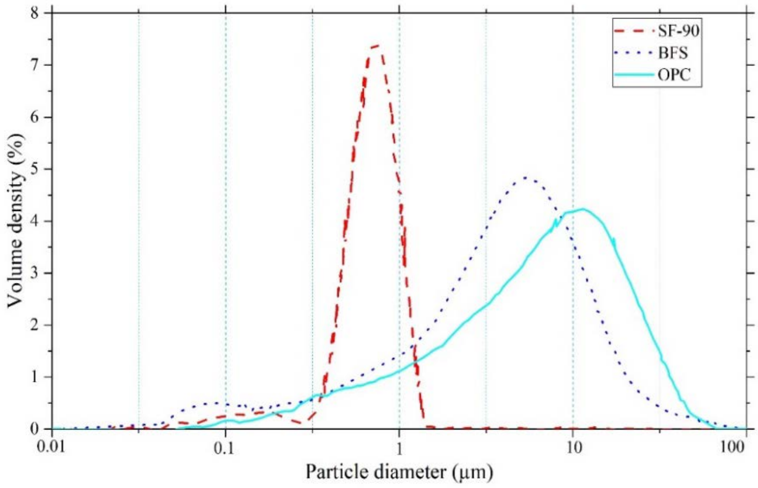

Figure 1. The particle size distribution of OPC, BFS and SF90.

The process of preparing test foam concrete samples is shown in Fig. 2.

Figure 2. The process of preparing foam concrete samples (from left to right, top to bottom).

2.2. Methods

The compressive strength and flexural strength of foam concrete at 28 days of age have been determined according to the Russian state standard GOST 10180-2012 [22].

On the one hand, this paper will analyze the chemical composition and the grain composition of BA and OPC by laser granulometry method on the device BT-9300Z (China). On the other hand, the calculation method of concrete mixture composition is applied by the absolute volume method of the Australian Standard [23].

The effect of Silica fume SF90, water-cement ratio to compressive strength and flexural strength of foam concrete have been identified by using the rotationally variable central compositional planning method for two factors.

3. Results and Discussion

3.1. Preliminary Determination components

In the present study, the mix proportions of foam concrete are given in Table 2. From the data of the study [15], the content of Portland cement is constant OPC of 350 kg/m3. Besides, SR5000 and SF90 have been used to increase strength and reduce water with ratio SR5000/OPC = 0.015, SF90/OPC = 0.1 [14, 24–25].

***Table 2. Compositions of foam concrete mixtures*.**

Mix number	OPC (kg)	QS (kg)	BFS (kg)	SR5000 (kg)	SF90 (kg)	W (kg)	Foam (L)
FC-1	350	356	-	5.25	35	154	579.8
FC-2	350	-	356	5.25	35	154	558.5

Fig. 3 shows that the compressive and flexural strength of FC-2 is higher than the FC-1. In addition, the compressive strength at 28 days of FC-2 = 8.11 MPa > 7.5 MPa. Therefore, the author has used FC-2 to optimize the components by the experimental planning method.

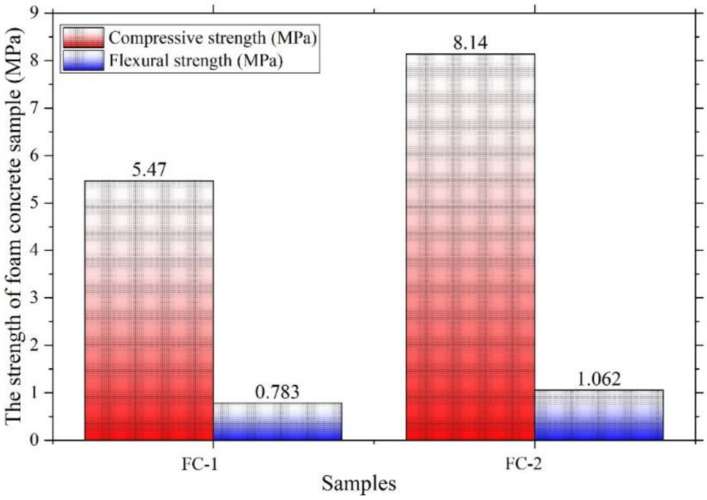

Figure 3. The compressive and flexural strength of foam concrete samples at 28 days.

3.2. Determine the optimal components

The factors that significantly affect the compressive and flexural strength are the W/OPC ratio, the amount of silica fume additive. According to research [15, 24, 26], the amount of silica fume additive in the range of 0.05÷0.15 is optimal. Additionally, based on the test results of this study, it is shown that the ratio of water-cement is in the range of 0.38÷0.42. The factors affecting the intensity of foam concrete were selected as below.

– x_1 – the rate of $\frac{W}{OPC}$ from 0.372 to 0.428;

– x_2 – the ratio of $\frac{SF90}{OPC}$ from 0.029 to 0.171.

***Table 3. Values and ranges of influencing factors*.**

Factors		Levels of variation				
Variable coding	Real variable	-1.414	-1	0	+1	+1.414
x_1	$\frac{W}{OPC}$	0.372	0.38	0.40	0.42	0.428
x_2	$\frac{SF90}{OPC}$	0.029	0.05	0.10	0.15	0.171

Number of experiments needed N when second-order planning determined by the formula;

$$N = 2^k + 2*k + m \tag{1}$$

in which: k = 2 is number of input factors.

- m is the number of repeated experiments in the center, m = 5.
- $\Rightarrow N = 2^2 + 2\times2 + 5 = 13$.

The author used a second-order orthogonal central compositional plan to obtain a mathematical model. The results obtained during the experiment and the procedure for calculating the regression coefficients are given in Tables 4, 5, 6.

Table 4. Compositions of foam concrete according to the method of quadratic orthogonal experiments.

Nº	Real variable		Variable coding		Compositions of foam concrete mixture, kg/m^3					
	$\frac{W}{OPC}$	$\frac{SF90}{OPC}$	x_1	x_2	OPC	BFS	SR5000	SF90	W	Foam (L)
1	0.42	0.15	+1	+1	350	354	3.5	47	144.90	564.56
2	0.38	0.15	-1	+1	350	364	3.5	47	135.10	570.10
3	0.42	0.05	+1	-1	350	379	3.5	23	144.90	565.29
4	0.38	0.05	-1	-1	350	389	3.5	23	135.10	570.83
5	0.428	0.1	+1.414	0	350	365	3.5	35	147.00	563.74
6	0.372	0.1	-1.414	0	350	379	3.5	35	133.00	571.65
7	0.4	0.171	0	+1.414	350	354	3.5	53	140.00	567.17
8	0.4	0.029	0	-1.414	350	389	3.5	18	140.00	568.22
9	0.4	0.1	0	0	350	372	3.5	35	140.00	567.70
10	0.4	0.1	0	0	350	372	3.5	35	140.00	567.70
11	0.4	0.1	0	0	350	372	3.5	35	140.00	567.70
12	0.4	0.1	0	0	350	372	3.5	35	140.00	567.70
13	0.4	0.1	0	0	350	372	3.5	35	140.00	567.70

Table 5. Calculation of regression equations for flexural strength at 28 days.

Nº	Variable coding					$\frac{W}{OPC}$	$\frac{SF90}{OPC}$	R_{fs}^{28}, MPa		$(Y_{1j}-\widehat{Y}_{1j})^2$	$(Y_{01j}-\widehat{Y}_{01j})^2$
	x_1	x_2	x_1^2	x_1x_2	x_2^2			Y_{1j}	$\widehat{Y}_{1j}$		
1	+1	+1	1	1	1	0.414	0.135	0.95	1.05	0.00938	-
2	-1	+1	1	-1	1	0.386	0.135	0.92	0.97	0.00228	-
3	+1	-1	1	-1	1	0.414	0.065	0.99	0.98	0.00007	-
4	-1	-1	1	1	1	0.386	0.065	0.93	0.9	0.00075	-
5	+1.414	0	2	0	0	0.42	0.1	1.1	1.05	0.00296	-
6	-1.414	0	2	0	0	0.38	0.1	0.94	0.93	0.00004	-
7	0	+1.414	0	0	2	0.4	0.15	1.1	1.01	0.00887	-
8	0	-1.414	0	0	2	0.4	0.05	0.88	0.91	0.00113	-
9	0	0	0	0	0	0.4	0.1	1.09	1.12	0.00078	0.0008
10	0	0	0	0	0	0.4	0.1	1.14	1.12	0.00048	0.0005
11	0	0	0	0	0	0.4	0.1	1.09	1.12	0.00078	0.0008
12	0	0	0	0	0	0.4	0.1	1.14	1.12	0.00048	0.0005
13	0	0	0	0	0	0.4	0.1	1.13	1.12	0.00014	0.0001
	$\sum(Y_{1j}-\widehat{Y}_{1j})^2=0.02816$									$\sum(Y_{01j}-\widehat{Y}_{01j})^2=0.0027$	

Table 6. Calculation of regression equations for compressive strength at 28 days.

Nº	Variable coding					$\frac{W}{OPC}$	$\frac{SF90}{OPC}$	R_{cs}^{28}, MPa		$(Y_{2j}-\widehat{Y}_{2j})^2$	$(Y_{02j}-\widehat{Y}_{02j})^2$
	x_1	x_2	x_1^2	x_1x_2	x_2^2			Y_{2j}	$\widehat{Y}_{2j}$		
1	+1	+1	1	1	1	0.414	0.135	7.15	7.86	0.50803	-
2	-1	+1	1	-1	1	0.386	0.135	7.36	7.62	0.07007	-
3	+1	-1	1	-1	1	0.414	0.065	7.6	7.31	0.08622	-
4	-1	-1	1	1	1	0.386	0.065	7.47	7.07	0.16135	-
5	+1.414	0	2	0	0	0.42	0.1	7.98	7.69	0.08477	-
6	-1.414	0	2	0	0	0.38	0.1	7.25	7.35	0.01045	-
7	0	+1.414	0	0	2	0.4	0.15	8.49	7.8	0.47072	-

Nº	Variable coding					$\frac{W}{OPC}$	$\frac{SF90}{OPC}$	R_{cs}^{28}, MPa		$(Y_{2j}-\widehat{Y}_{2j})^2$	$(Y_{02j}-\widehat{Y}_{02j})^2$
	x_1	x_2	x_1^2	x_1x_2	x_2^2			Y_{2j}	$\widehat{Y}_{2j}$		
8	0	-1.414	0	0	2	0.4	0.05	6.52	7.02	0.24717	-
9	0	0	0	0	0	0.4	0.1	8.37	8.48	0.01254	0.0125
10	0	0	0	0	0	0.4	0.1	8.76	8.48	0.07728	0.0773
11	0	0	0	0	0	0.4	0.1	8.21	8.48	0.07398	0.074
12	0	0	0	0	0	0.4	0.1	8.49	8.48	0.00006	0.0001
13	0	0	0	0	0	0.4	0.1	8.58	8.48	0.0096	0.0096
$\sum(Y_{2j}-\widehat{Y}_{2j})^2=1.8127$								$\sum(Y_{02j}-\widehat{Y}_{02j})^2=0.173$			

3.2.1. The calculation of the estimates of the coefficients

Base on the research [27], The coefficients of the regression equation, calculated by the formulas (2): The results are shown in Table 7.

$$b_j=\frac{\sum_{i=1}^{N}x_{ij}y_j}{\sum_{i=1}^{N}x_{ij}^2}\forall_j=\overline{1...n};\;\; b_{ju}=\frac{\sum_{i=1}^{N}x_{ij}^2x_{ui}y_j}{\sum_{i=1}^{N}x_{ij}^2x_{ui}^2}\forall_{j,u}=\overline{1...n};j\neq u \tag{2}$$

Table 7. Coefficient of the quadratic regression equation.

b_j / Y_j		b_0	b_1	b_2	b_{12}	b_{11}	b_{22}
Y_1	R_{fs}^{28}, MPa	1.118	0.040	0.033	-0.008	-0.064	-0.079
Y_2	R_{cs}^{28}, MPa	8.482	0.119	0.278	-0.085	-0.481	-0.536

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

$$Y_1=1.118+0.040x_1+0.033x_2-0.008x_1^2-0.064x_2^2-0.079x_1x_2 \tag{3}$$

$$Y_2=8.482+0.119x_1+0.278x_2-0.481x_1^2-0.536x_2^2-0.085x_1x_2 \tag{4}$$

3.2.2. Check the coefficients of the regression equation (3) and (4)

Critical values for Cochran's test $G_c = G_Q(t_Q, n_1)$ was found from Table 3.2 of the Cochran distribution [28] depending on the values:

– Level of significance Q = 0.05.
– Degrees of freedom of the numerator $n_1 = m - 1 = 5 - 1 = 4$;
– $\Rightarrow t_{0,025}(4) = 2.7764$

Regression equations were determined by the formula:

$$t_{bj}=\frac{|b_j|}{s_{bj}} \tag{5}$$

The variance estimate of the regression coefficients of the equation S_{bj} was determined by the formula:

$$S_{bj}=\sqrt{\frac{s_{ll}^2}{\sum_{i=1}^{N}x_{ij}^2}} \tag{6}$$

in which: S^2_{ll} is the estimating observation-error variance, determined by the formula:

$$S_{ll}^2 = \frac{\sum_{j=1}^{m}(Y_{oj} - \widehat{Y}_o)^2}{m-1} \quad (7)$$

$$\widehat{Y_o} = \frac{1}{m}\sum_{j=1}^{m} Y_{oi} \quad (8)$$

in which:

m is the number of repeated experiments in the center, m = 5;

$\widehat{Y}_o$ is the average value of m experiments in the center;

Y_{oj} is the obtained value of the i-th experiment in the center.

For the regression equation (3):

$$\sum_{j=1}^{5}(Y_{01j} - \widehat{Y}_{01})^2 = 0.0027 \Rightarrow S_{1ll}^2 = \frac{0.0027}{5-1} = 0.00067 \quad (9)$$

The values of the student criterion for the test are given in Table 8.

Table 8. Student coefficients for checking the regression equation (3).

j	0	1	3	4	5	6
b_j	b_0 1.118	b_1 0.040	b_2 0.033	b_{12} -0.008	b_{11} -0.064	b_{22} -0.079
$\lvert b_j \rvert$	1.118	0.040	0.033	0.008	0.064	0.079
S_{bj}	0.012	0.009	0.009	0.013	0.010	0.010
t_{bj}	96.580	4.320	3.566	-0.580	-6.532	-8.059

After checking the coefficients, discarding negligible coefficients. We obtained the equation:

$$Y_1 = 1.118 + 0.040x_1 + 0.033x_2 - 0.064x_1{}^2 - 0.079x_2{}^2 \quad (10)$$

For the regression equation (4):

$$\sum_{j=1}^{5}(Y_{02j} - \widehat{Y}_{02j})^2 = 0.173 \Rightarrow S_{2ll}^2 = \frac{0.173}{5-1} = 0.043 \quad (11)$$

The values of the student criterion for the test are given in Table 9.

Table 9. Student coefficients for checking the regression equation (4).

j	0	1	3	4	5	6
b_j	b_0 8.482	b_1 0.119	b_2 0.278	b_{12} -0.085	b_{11} -0.481	b_{22} -0.536
$\lvert b_j \rvert$	8.482	0.119	0.278	0.085	0.481	0.536
S_{bj}	0.093	0.074	0.074	0.104	0.079	0.079
t_{bj}	91.073	1.617	3.778	-0.816	-6.083	-6.779

After checking the coefficients, discarding negligible coefficients. We obtained the equation:

$$Y_2 = 8.482 + 0.278x_2 - 0.481x_1{}^2 - 0.536x_2{}^2 \quad (12)$$

3.2.3. Check the adequacy of the experimental model

- Testing the Hypothesis of the Adequacy of the model is based on the calculations of the adequacy variance $S^2{}_d$ (14) and Fisher's Criterion F_{pacc} (13):

$$F_{pacc} = \frac{S_d^2}{S_{ll}^2} \tag{13}$$

$$S_d^2 = \frac{\sum_{j=1}^{N} (Y_j - \widehat{Y}_j)^2}{N - m} \tag{14}$$

where $S^2{}_{ll}$ is the estimating observation-error variance;

$S^2{}_d$ is variance;

m is the number of repeated experiments in the center; m = 5.

Y_j is the observed value of the i-th experiment;

$\widehat{Y}_j$ is the values of a function obtained from an experiment following the i-th experiment;

F_Q, (v_1, v_2) from the Table 3.5 [28], at a significance level Q = 0.05; determined by the number of degrees of freedom $v_2 = N = m - 1 = 4$ and $v_1 = N - m = 13 - 5 = 8$. So, the value: $F_Q(8, 4) = 6.0410$.

For the regression equation (10):

$$\sum_{j=1}^{13} (Y_{ij} - \widehat{Y}_{1j})^2 = 0.02816 \Rightarrow S_{1d}^2 = \frac{0.02816}{13-5} = 0.00352 \text{ and } S_{1ll}^2 = 0.00067.$$

$$\Rightarrow F_{1pacc} = \frac{S_{1d}^2}{S_{1ll}^2} = \frac{0.0352}{0.00067} = 5.254 < F_{0.05}(8,4) = 6.0410.$$

For the regression equation (12):

$$\sum_{j=1}^{13} (Y_{2j} - \widehat{Y}_{2j})^2 = 1.8127 \Rightarrow S_{2d}^2 = \frac{1.8127}{13-5} = 0.226 \text{ and } S_{2ll}^2 = 0.043.$$

$$\Rightarrow F_{2pacc} = \frac{S_{2d}^2}{S_{2ll}^2} = \frac{0.2266}{0.043} = 5.286 < F_{0.05}(8,4) = 6.0410$$

Therefore, equation (10) and (12) satisfy the condition $F_{pacc} < F_{tab}$.

Response surfaces for the regression equations (10) and (12) are presented in Fig. 4 and 5.

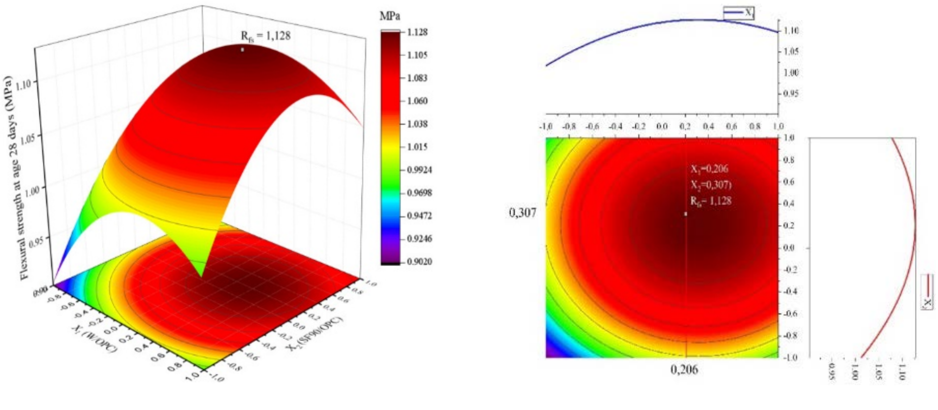

Figure 4. Second-order surface equation (10).

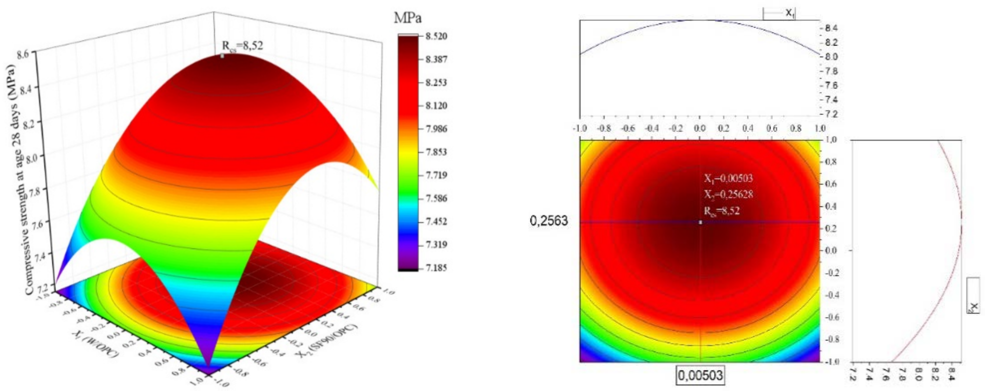

Figure 5. Second-order surface equation (12).

3.2.4. Search for the maximum value of the second-order regression equation and selection of the optimal composition

The first case:

When $x_1 = 0.206$, $x_2 = 0.307$ and flexural strength $R_{fs} = 1.128$ MPa.

Replacement: $x_1 = 0.206$, $x_2 = 0.307$ into the equation (10) $\Rightarrow R_{cs} = 8.495$ MPa.

The second case:

When $x_1 = 0.00503$, $x_2 = 0.25628$ and compressive strength $R_{cs} = 8.52$ MPa.

Replacement: $x_1 = 0.00503$, $x_2 = 0.25628$ into the equation (12) $\Rightarrow R_{fs} = 1.21$ MPa.

Thus, the most optimal value: $x_1 = 0.00503$ and $x_2 = 0.25628$.

- $$\Rightarrow \frac{W}{OPC} = (\frac{W}{OPC})_0 + 0.02 * x_1^{opt} = 0.40 + 0.02 * 0.00503 = 0.4001;$$

$$\Rightarrow \frac{SF90}{OPC} = (\frac{SF90}{OPC})_0 + 0.05 * x_2^{opt} = 0.1 + 0.05 * 0.25628 = 0.1128.$$

Thus, the optimal composition of the foam concrete is presented in Table 10.

Table 10. The optimal composition of the foam concrete mixture to obtain maximum compressive strength and flexural strength.

Nº	The ratio of raw materials		Foamed concrete mix compositions, kg/m^3					
	$\frac{W}{OPC}$	$\frac{SF90}{OPC}$	OPC	BFS	SR5000	SF90	W	Foam (L)
1	0.4001	0.1128	350	367	3.5	39	140.0	567.4

4. Conclusions and future work

Based on the analysis of the data obtained from the experiment, the following conclusions can be drawn:

1. Based on test results, preliminary components have been identified to optimize components.

2. Static processing of the results, performed by mathematical methods for planning experiments to optimize the composition of the designed foam concrete, with a certain probability and the number of retests. The foam concrete samples are then compared with the results obtained by various methods.

3. The obtained second-order regression equations (10) and 12) describe the dependence of compressive strength and flexural strength of foam concrete at 28 days of standard hardness $x_1 = 0.00503$ and $x_2 = 0.25628$.

4. Using computer programs obtained surface images of equations (10) and (12), as shown in Fig. 4, 5. Besides, the maximum value of the objective function was determined.

5. The optimal composition of the foam concrete mix with the highest compressive strength and flexural strength are presented in Table 10.

6. The paper's result is the basis for designing foam concrete bricks to replace clay bricks in Vietnam.

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