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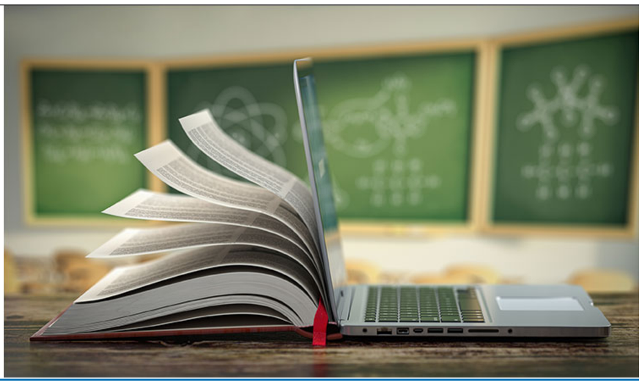

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Modelling of the effect of the water-cement ratios on properties foam concrete

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Abstract. Foam concrete has been widely used in the High-Rise buildings for both structural, non-structural purposes and other applications. This paper discusses the development of foam concrete containing various the water-cement ratios from 0.4 to 0.8 was prepared from ordinary Portland cement SEM I 42.5 N and foaming agent of EABASSOC. Effects of the water-cement ratio on the porosity structure of foam concrete, as well as dry density and strength of the tested foam concrete, were discussed. Moreover, quantitatively simulation of the relationship between compressive strength at age 28 days and dry density of foam concrete is determined through experimental results for predicting the properties of foam concrete from the knowledge of its mixture proportions. Results of this study showed that the water-cement ratio can influence the porosity in the microstructure of foam concrete, while the optimal water-cement ratios of the foam concrete prepared with design density of 400, 500, 600, 700, and 800 kg/m^3 are also obtained of 0.58, 0.54, 0.56, 0.55, and 0.53, respectively.

1. Introduction

Foam concrete (FC) and many other types light-weight concrete have been widely used in the productions of the wall cover, which is located at the cover of the High-Rise buildings and direct contact with the sun because of the material's characteristic lightweight, conducting low heat, and low noise and pollution [1, 2]. Nowadays, in the construction industry, the foam concrete is spurred by increased regulations to reduce carbon footprint, limit greenhouse gas emission and limited landfill spaces.

In recent times, several of the studies mainly focus on the effect of aluminium powder, mineral and chemical additives on the properties of FC mixtures [3–6]. Besides, the correlations of the pore, porosity structure and dry density of foam concrete with the material's strength, thermal conductivity, and sound absorption were also reported. The water to cement ($\frac{W}{C}$) ratio is an important parameter that influences characteristics of foam concrete [7–12].

Data presented in the published researches [13–15] were examined the effect of water-cement ratio on the pore structure and properties of foam concrete mainly emphasize high-porosity of this concrete. By contrast, some other few works have discussed the influences of water-cement ratio on the pore structure and performance of ordinary foam concrete [16, 17].

Furthermore, in previous investigations [18-20] used circulating fluidized bed fly ash in the proportion of FC-mixes and studied the physical and chemical properties of pore shells in the paste from a water-cement mix. There found that air bubbles in cement paste of high consistency are easily broken during stirring and the density of the corresponding concrete increases during such process.

Although many investigations are analyzed the effect of $\frac{W}{C}$ ratio on the pore structure of ordinary foam concrete, none modeled relating of the relationship between the compressive strength and dry density of foam concrete with various $\frac{W}{C}$ ratio. One of the objectives of this study is to fulfill this need.

The purpose of this investigation is the effects of water-cement ratio on porosity, dry density and compressive strength of foam concrete. Moreover, the simulation of the relation between compressive strength and dry density of tested concrete is determined.

The aim of the present study included four specific objectives to:

- Apply in accordance with the absolute volume method and combined with formulas of the previously published studies to calculate the concrete mixture compositions.
- Effect of water-cement ratio on the porosity structure, dry density and strength of foam concrete tested.
- Quantitatively simulation of the relationships between the compressive strength and dry density of foam concrete with various water-cement ratio.

2. Experimental details

2.1. Materials

a). The cement used was SEM I 42.5 N ordinary Portland cement produced by the Tam Diep Cement Co., Ltd (Vietnam). The physical properties and chemical composition of OPC "Tam Diep" are presented in Tables 1 and 2, respectively.

Table 1. The physical properties of ordinary Portland cement "Tam Diep"

Specific weight (g/cm^3)	Blaine fineness (cm^2/g)	Soundness - Lechatelier (mm)	Standard consistency (%)	Initial setting time (min)	Final setting time (min)	3-day compressive strength (MPa)	28-day compressive strength (MPa)
3.15	3850	2.4	29.5	125	245	29.4	50.9

Table 2. The main chemical composition of ordinary Portland cement "Tam Diep" (wt%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Loss of ignition
21.76	4.59	3.15	63.24	1.38	2.14	0.24	0.45	3.05

b). The foaming agent of EABASSOC conforming to ASTM C869M-11 was used, which made in the United Kingdom with a specific weight of 1.02 g/cm^3. For the current study, the EABASSOC foaming agent was diluted with water at the proportion of 2%. Next, the foam was produced by aerating to a density of 50 kg/m^3 by using a foam generator (FoamMaster-I, THT International Co., Ltd., Vietnam).

c). Local clean water is used throughout this work for both making concrete mixes and curing of specimen's foam concrete tested.

2.2. Mix proportion calculation of foam concrete

Dry density and compressive strength are two very important properties of lightweight concrete. For foamed concrete, the design method of mixture proportion is to determine its dry density to achieve effective control of strength at different curing period. In this case of the investigation, the mixture proportions of foam concrete were arrived at as per the procedure is given in ASTM C796-2004, apply in accordance with the absolute volume method and combined with formulas (1), (2), (3), and (4) of published studies [21, 22].

$$\rho_{FC} = K_m * C \quad (1)$$

$$W = \frac{W}{C} * C \quad (2)$$

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

K_m - the coefficient of mass, which was determined by the total amount of dry materials and the total amount of non-evaporative materials in the finished specimens. For the ordinary Portland cement, K_m is 1.2.

C - the cement dosage of 1m^3 foam concrete (kg);

W - the water consumption of 1m^3 foam concrete (kg);

$\frac{W}{C}$ - the water-cement ratio can be selected according to from 0.4 to 0.6.

Finally, the paste volume from cement and water mix and foam volume in 1m^3 foamed concrete can be calculated by the formulas (3) and (4):

$$V_1 = \frac{C}{\rho_c} + \frac{W}{\rho_w} \quad (3)$$

$$V_2 = K_d * (1 - V_1) \quad (4)$$

where: V_1 - the total volume of paste is composed of water and cement (m^3);

ρ_c and ρ_w - respectively, the specific gravity of Portland cement and water (kg/m^3);

V_2 - foam addition (m^3);

K_d - Redundancy factor.

In addition, for foam concrete, it is necessary to mention the redundancy factor - K_d, which depends on the quality of foaming agent, foaming time and foam added to the slurry when the loss of re-mixing raw materials. As also reported from the research [21] achieved the value of redundancy factor (K_d) in the range of 1.1 ÷ 1.3 and for the foaming agent of EABASSOC (United Kingdom) with good stability and K_d = 1.1 in this work. Further details about all mixtures of foamed concrete with the water-cement ratio from 0.4 to 0.6 are listed in Table 3.

Table 3. Foam concrete mixing proportioning

Mixes No.	Design density of FC-specimens (kg/m^3)	$\frac{W}{C}$	FC-mix proportions 1 m^3		
			Cement (kg)	Water (kg)	Foam (l)
Mix-1	400	0.4	333	133	836
Mix-2	400	0.45	333	150	817
Mix-3	400	0.5	333	167	799
Mix-4	400	0.55	333	183	781
Mix-5	400	0.6	333	200	762
Mix-6	500	0.4	417	167	770
Mix-7	500	0.45	417	188	747
Mix-8	500	0.5	417	208	724
Mix-9	500	0.55	417	229	701
Mix-10	500	0.6	417	250	678
Mix-11	600	0.4	500	200	704
Mix-12	600	0.45	500	225	676
Mix-13	600	0.5	500	250	649
Mix-14	600	0.55	500	275	621
Mix-15	600	0.6	500	300	594
Mix-16	700	0.4	583	233	638
Mix-17	700	0.45	583	263	606
Mix-18	700	0.5	583	292	574
Mix-19	700	0.55	583	321	541
Mix-20	700	0.6	583	350	509
Mix-21	800	0.4	667	267	572
Mix-22	800	0.45	667	300	535
Mix-23	800	0.5	667	333	498

Mix-24	800	0.55	667	367	462
Mix-25	800	0.6	667	400	425

According to data in Table 3, cement and water were poured into a mixer "MasterMix 0.5" at the laboratory and mixed at a rate of 50 rpm from 3 to 5 minutes at a temperature of 25^{o}C to generate a cement paste. Meanwhile, the foam of EABASSOC produced by a foam generator "FoamMaster-I" was injected into a foam concrete mixer and stirred for 2 minutes. Right after mixing, the foam concrete was poured into a mold tested and maintained in static for 24 hours. After demolding (1-day curing), the foam concrete specimens were placed in a standard concrete curing cabinet (HBY- 40C, China) until the curing age tested.

2.3. Test Method

2.3.1. The porosity of foam Concrete

As it is known, the pore structure of lightweight concrete and the distribution of pores are the very important characteristic that influences the properties of the materials such as strength and durability. In this case the study, the porosity of the foam concrete pore structure has investigated.

The true density (ρ_1) of the specimens was tested in accordance with standard GOST 30744-2001 (Russia). Whereas, the absolute dry volume density of the specimens was denoted by ρ_2 and identified by a 150x150x150 mm cube sample by GOST 10180-2012 (Russia). Then, the porosity (P) of foam concrete pattern was determined using the formula (5):

$$P = \frac{\rho_1 - \rho_2}{\rho_1} \times 100\% \tag{5}$$

where: P - the porosity of the specimens (%);

ρ_1 - the true density of the specimens (kg/m^3);

ρ_2 - the volume density of the specimens (kg/m^3).

2.3.2. Foam concrete properties

Dry density (D, kg/m^3) and compressive strength tests (f_{cs}, MPa) of the foam concrete were performed at 28 days using cubic specimens of 150×150×150 mm (Figure 1) as stipulated by Russian standard GOST 10180-2012. The compressive strength of the specimens was measured by a fully automatic, constant stress testing machine (Controls Advantest 9, Italia) under a loading rate of 200 N/s.

Figure 1. (a) - Foam concrete samples and (b) - Compression test sample

3. Results and Discussion

The experimental results of all concrete specimens used in this study are listed in Table 4.

Table 4. Characteristics of foam concrete samples tested

Mixes No.	$\frac{W}{C}$	Average porosity (%)	Dry density (kg/m^3)	Compressive strength at age 28 days (MPa)
Mix-1	0.4	80.9	425	0.35
Mix-2	0.45	81.5	422	0.56
Mix-3	0.5	81.7	418	0.82
Mix-4	0.55	82.1	410	0.95
Mix-5	0.6	82.7	403	0.9
Mix-6	0.4	77.0	522	0.57
Mix-7	0.45	77.3	518	0.85
Mix-8	0.5	77.5	510	1.36
Mix-9	0.55	77.9	508	1.55
Mix-10	0.6	78.0	501	1.24
Mix-11	0.4	72.8	619	1.15
Mix-12	0.45	73.2	610	1.48
Mix-13	0.5	73.1	610	2.67
Mix-14	0.55	73.5	608	2.6
Mix-15	0.6	73.6	600	2.54
Mix-16	0.4	67.2	740	2.16
Mix-17	0.45	68.0	726	2.48
Mix-18	0.5	68.6	720	3.45
Mix-19	0.55	69.0	702	3.12
Mix-20	0.6	69.6	700	3.15
Mix-21	0.4	62.6	846	3.4
Mix-22	0.45	63.7	832	4.51
Mix-23	0.5	63.4	830	5.68
Mix-24	0.55	64.1	824	5.52
Mix-25	0.6	64.5	817	4.74

3.1.1. Effect of $\frac{W}{C}$ ratio on the porosity structure of foam concrete test

The effect of the water-cement ratios on the porosity of FC-samples with design density in the range of 400÷800 kg/m^3 is shown in Figure 2.

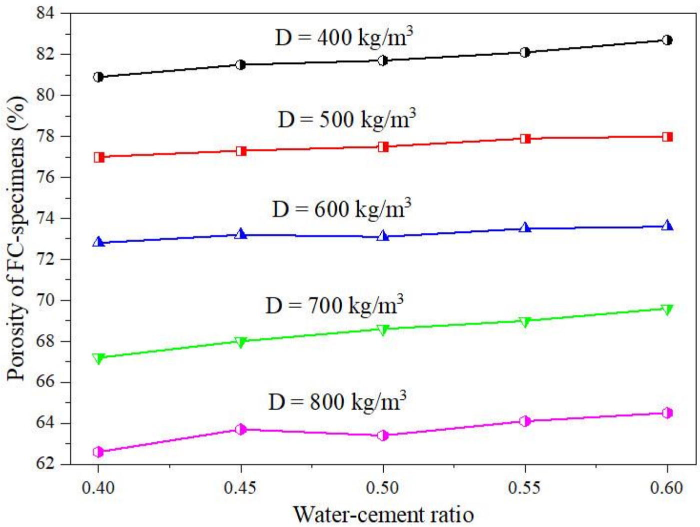

Figure 2. Effect of the water to cement ratio on the porosity of the FC-specimens

Data presented in this Figure indicates that:

- The foam concrete with smaller $\frac{W}{C}$ ratio was exhibited a smaller porosity in the microstructure of FC-samples. This could be explained by a greater number of connected pores in the distribution of concrete porosity, similar to the results presented in previously published study [23].
- The FC mixtures with smaller dry density displayed more content of air bubbles because of the higher volume of foaming, which would involve a smaller proportion of the paste based on a mix of cement-water used [24] and would bring its porosity higher.
- With the increase in both $\frac{W}{C}$ ratio and dry density, the average porosity of the foam concrete increased gradually (Table 4). This resulting may be due to the gradual decrease in both content paste and relative viscosity of the cement-water mix, thus decreasing the foam volume and the bubble-maintaining capacity of the paste [15].

3.1.2. Effect of water-cement ratio on the compressive strength at age 28 days of FC samples

According to the experimental results of this investigation, the effect of $\frac{W}{C}$ ratio on the compressive strength of FC-samples is given in Figure 4.

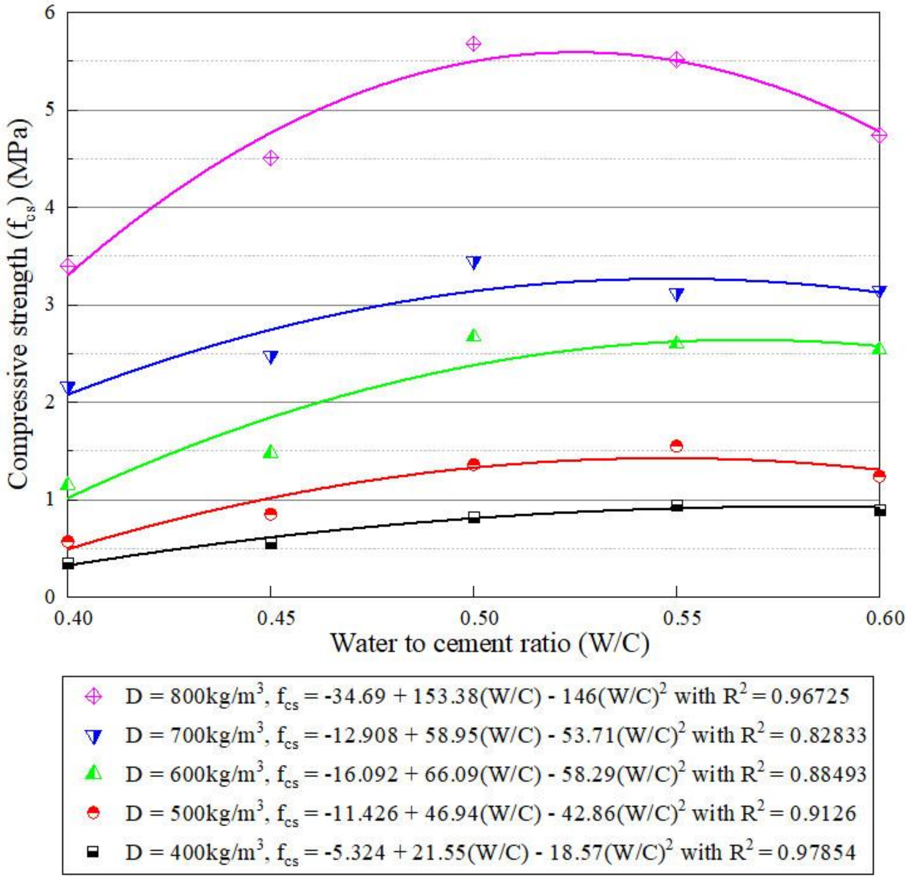

Figure 3. Effect of $\frac{W}{C}$ ratio on the compressive strength of foam concrete

From the results of this study shown that with the increase in water to cement ratio, the compressive strength of FC-samples increased first and then decreased gradually (Table 4 and Figure

3). This result was achieved because, on the one hand, when the $\frac{W}{C}$ ratio was smaller than the optimal value, a smaller $\frac{W}{C}$ ratio generated higher proportions of small thin-walled, connected pores in the porosity distribution of FC structure. On the other hand, the $\frac{W}{C}$ ratio that exceeded the optimal value resulted in the smaller foam volume in the cement-water mix tested. Moreover, the air bubbles in the paste easily were broken during stirring and uneven porosity distribution of FC structure.

Additionally, with an excessive increase in water-cement ratios would cause stress concentration, and redundant free water content would form capillary channels after the hydration reaction of cement with mix water or its evaporation, finally resulting in consequently reducing the strength and other mechanical properties of the foam concrete.

The relations between compressive strength (f_{cs}, MPa) at age 28 days and $\frac{W}{C}$ ratio of FC-samples are illustrated in Figure 3 and given by formulas (6), (7), (8), (9), and (10) (in Table 5).

Table 5. The regression equations of Figure 3

Design density (kg/m^3)	Regression equation	Optimal $\frac{W}{C}$ ratio	Coefficient of correlation (R^2)	Equation No
400	$f_{cs} = -5.324 + 21.55 * \frac{W}{C} - 18.57 * (\frac{W}{C})^2$	0.58	0.97854	(6)
500	$f_{cs} = -11.426 + 46.94 * \frac{W}{C} - 42.86 * (\frac{W}{C})^2$	0,54	0.9126	(7)
600	$f_{cs} = -16.092 + 66.09 * \frac{W}{C} - 58.29 * (\frac{W}{C})^2$	0,56	0.88493	(8)
700	$f_{cs} = -12.908 + 58.95 * \frac{W}{C} - 53.71 * (\frac{W}{C})^2$	0,55	0.82833	(9)
800	$f_{cs} = -34.69 + 153.38 * \frac{W}{C} - 146 * (\frac{W}{C})^2$	0,53	0.96725	(10)

Next, from the regression equations (6), (7), (8), (9), and (10) were obtained the optimal water-cement ratios of the foam concrete mixtures prepared with design density of 400, 500, 600, 700, and 800 kg/m^3, respectively, of 0.58, 0.54, 0.56, 0.55, and 0.53, which also displayed in Table 5.

3.1.3. The simulation relation between compressive strength and dry density of FC-samples

It is well known that the smaller the porosity of foam concrete and larger its dry density, the higher its mechanical properties. From the review of published researches [25, 26], the fitting relationships between the tested 28 days compressive strength and dry density of foam concrete were to follow an exponential relationship and are represented as the following formula (11):

$$y = A * e^{Bx} \tag{11}$$

In the form: y is the compressive strength of concrete (MPa) at age 28-day and x is the dry density (kg/m^3), while (A) and (B) are constants of this regression equation.

According to experimental results in this study, for all proportions of foam concrete, the relations between compressive strength at 28-day and dry density containing various $\frac{W}{C}$ ratios were simulated and illustrated details in Figure 4.

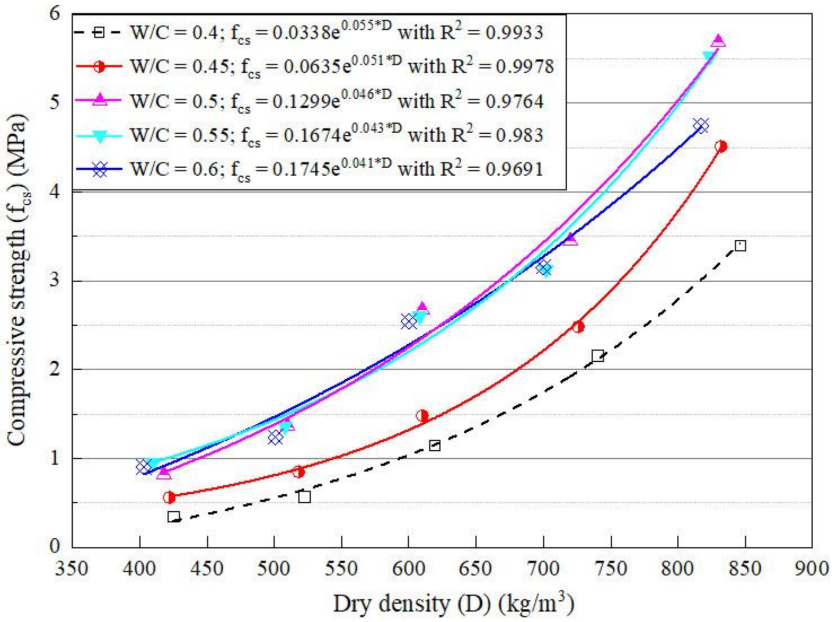

Figure 4. Correlation between compressive strength at 28-day and dry density of foam concrete tested

It could be noticed that, for mixes of foam concrete containing $\frac{W}{C}$ ratios of 0.4, 0.45, 0.5, 0.55, and 0.6, respectively, follow the proposed formula (11) (as above) with a correlation coefficient more than 96% ($R^2 > 0.96$), while the values of coefficients (A and B) for each proportion of foam concrete tested seem to be different. These simulation relations have shown that the suggested equations in Figure 4 would predict the development of compressive strength of FC-samples for a given dry density and $\frac{W}{C}$ ratios with the negligible error.

4. Conclusions

Based on the test results, the following conclusions are drawn on tested foam concrete samples containing various water-cement ratio used in the experimental investigation:

- The foam concrete with smaller $\frac{W}{C}$ ratio was exhibited a smaller porosity in the microstructure of FC-samples. This could be explained by a greater number of connected pores in the distribution of concrete porosity.
- The foam concrete with smaller dry density displayed more content air bubbles because of the higher volume of foaming, which would involve a smaller content of the paste of cement-water mix and would bring its porosity higher.
- The relationships between compressive strength at age 28 days and various $\frac{W}{C}$ ratio of FC-samples are reported, while the optimal water-cement ratios of the foam concrete prepared with design density of 400, 500, 600, 700, and 800 kg/m^3 are also obtained of 0.58, 0.54, 0.56, 0.55, and 0.53, respectively.
- The relations between compressive strength at 28-day and dry density of foam concrete were simulated with a correlation coefficient $R^2 > 0.96$. Moreover, from these simulation relations would predict the development of compressive strength of FC-samples for a given dry density and water-cement ratios.

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