PROPERTIES OF FOAM CONCRETE USING TERNARY BINDERS OF FLY ASH, SLAG AND CEMENT

CÁC ĐẶC TÍNH KỸ THUẬT CỦA BÊ TÔNG BỌT SỬ DỤNG XI MĂNG, TRO BAY VÀ XỈ LÒ CAO NGHIỀN MỊN LÀM CHẤT KẾT DÍNH

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Abstract: *Recently, amount of industrial by-products such as fly ash and blast furnace slag is increasing due to the human demand and industry development of country. The recycle of these materials in the production of foam concrete is an objective of this study. Six concrete mixtures were designed with ternary binders of cement, fly ash, and ground granulated blast furnace slag and water-to-binder ratio of 0.20. The foam content was used as 22.4% to 60.8% of total sample volume. The effect of foam content on the properties of foam concrete is also investigated. Test results indicate that the unit weight, compressive strength, ultrasonic pulse velocity, and thermal conductivity of concrete decrease, but water absorption of concrete increases with increasing foam content. The compressive strength of concrete with foam content of 22.4% and 34.7% are 32.5 and 20.3 MPa, respectively, which can be used in bearing structure. With the use of higher foam content, the compressive strength of corresponding foam concrete significantly reduces and which can be just used as thermal insulation bricks or roof tiles. Under observation by using scanning electron microscopy, the foam concrete with high foam content shows a lot of air bubbles. The presence of these bubbles is a cause to the reduction in density and quality of foam concrete.*

Keywords: *Foam concrete, foam content, fly ash, ground granulated blast furnace slag, thermal conductivity, compressive strength, dry unit weight.*

Tóm tắt: *Những năm gần đây, khối lượng các sản phẩm phụ trong quá trình sản xuất công nghiệp như tro bay, xỉ lò cao ngày càng tăng để đáp ứng nhu cầu tiêu thụ của con người và phát triển nền công nghiệp của đất nước. Mục tiêu của nghiên cứu này là tái sử dụng các sản phẩm phụ trên trong sản xuất bê tông bọt. Sáu hỗn hợp bê tông bọt được thiết kế với tỷ lệ nước-chất kết dính là 0.2 và sử dụng hỗn hợp xi măng, tro bay, xỉ lò cao nghiền mịn làm chất kết dính. Hàm lượng bọt so với tổng thể tích mẫu được thiết kế thay đổi từ 22.4% đến 60.8%. Ảnh hưởng của hàm lượng bọt lên các đặc tính kỹ thuật của bê tông bọt được trình bày trong nghiên cứu này. Kết quả thí nghiệm cho thấy, khối lượng thể tích khô, cường độ chịu nén, vận tốc truyền xung siêu âm và hệ số dẫn nhiệt của bê tông bọt giảm, trong khi độ hút nước của bê tông bọt tăng khi tăng hàm lượng bọt. Các mẫu có hàm lượng bọt 22.4% và 34.7% có cường độ chịu nén tương ứng là 32.5 Mpa và 20.3 MPa, chúng có thể được sử dụng trong các kết cấu chịu lực. Khi tăng hàm lượng bọt, cường độ chịu nén của bê tông bọt giảm đáng kể và chúng có thể được sử dụng làm gạch và ngói cách nhiệt. Quan sát dưới kính hiển vi điện tử quét cho thấy, các mẫu bê tông bọt sử dụng hàm lượng bọt cao có nhiều bọt khí bên trong. Các bọt khí này chính là nguyên nhân làm giảm độ đặc chắc cũng như chất lượng của bê tông bọt.*

Từ khóa: *Bê tông bọt, hàm lượng bọt, tro bay, xỉ lò cao nghiền mịn, hệ số dẫn nhiệt, cường độ chịu nén, khối lượng thể tích khô.*

1. Introduction

As stated in previous studies, foam lightweight concrete is currently concerned by many researchers over the world due to its low density, low material consumption, and superb thermal insulation [1-3]. The use of lightweight concrete helps to reduce the dead loads acting on the structure components, and also reduce the production cost and transportation [4]. However, its properties strongly depend on many factors such as dry density, foam agents, curing condition, quality of raw materials, and forming specimen technology [5]. Jones and McCarthy [2] have stated that it is difficult to achieve compressive strength of above 25 MPa, therefore the use of foam concrete is still limited in retaining wall and sound insulation roof tiles. It is also used as replacement of traditional fired clay bricks in Abbas and Dunya's study [6]. It is noticed that the compressive strength and density of foam lightweight concrete has a close relationship [3, 5, 6]. Previous studies [3, 5, 6] have pointed out that the reduction in density resulted in reduction in its compressive strength. Therefore, the compressive strength of foam lightweight concrete has a large varying values from 1.07 MPa to 45 MPa corresponding to its density from 600kg/m^3 to 2000 kg/m^3 [5-6]. The foam lightweight concrete achieved compressive strength of higher than 25 MPa has density around 1800 ÷ 2000 kg/m^3, this density is similar to that of normal concrete. It means that the production of foam lightweight concrete with low density but high compressive strength is still a big attractive concern to researchers.

Recent years, together with rapid development of Vietnam's industry, the demand for electricity and steel is also increasing, leading to the extension and construction of many coal power plants and steel production companies through the country. As results, a large quantity of bottom ash and fly ash were released from thermal power plants in Vietnam, and it is still increasing day by day [7]. On the other hand, the production of foam lightweight concrete can consume a large number of industrial wastes such as fly ash and ground granulated blast furnace slag (GGBFS) [8-10]. With the use of fly ash to replace 10 ÷ 50% amount of cement, Richard and Ramli [9] have produced foam concrete with target density of 1600 kg/m^3, its corresponding compressive strength was around 10.5 MPa. The use of GGBFS in the production of foam concrete was also studied by Wee et al. [10]. In which, GGBFS was used to replace 50% amount of cement. Test results showed that the foam concrete produced in this study had a density from 600 to 1900 kg/m^3, and its respective compressive strength were from 2.0 to 58 MPa. However, the use of both fly ash and GBFS is still limited in the literature. In the present study, the use of ternary binders of cement, fly ash, and GGBFS in the production of foam concrete is investigated. The effect of foam content on the properties of foam concrete is also investigated.

2. Experimental program

2.1 Material properties

Cement, fly ash, and GGBFS are used as binder materials in this study. In which, cement is Nghi Son Type - PCB40, fly ash is sourced from Nghi Son coal power plant, and GGBFS is Hoa Phat Type - S95. Physical and chemical properties of all these binders are shown in Table 1. Specific gravity of fly ash is the lowest among these binders, followed by GGBFS and cement. The particle shape of them, which are observed by using scanning electron microscopy (SEM), are shown in Fig. 1. The shape of fly ash particles is spherical with different sizes, while the shape of cement and GGBFS are irregular. As seen in Fig. 1b, there are some unburnt impurities in SEM image of fly ash, this explains for a higher loss on ignition of fly ash (6.91%) compared with other binder materials in Table 1. This may affect the properties of foam concrete as presented later.

Natural river sand with particle size from 0.15 mm to 0.63 mm and density of 2.68 T/m^3 is used as fine aggregate. As aforementioned, properties of foam lightweight concrete strongly depend on quality of raw materials. In the beginning, natural sand with the size from 0.15 mm to 5.0 mm was used, however the volume of foam concrete is significant change during the forming process and it is difficult to fabricate the samples. The use of small sand makes the volume of foam concrete is more stable, therefore the sand with the size of 0.15 ÷ 0.63 mm is used in this study. Foam EABASSOC with density of 1.02 T/m^3, which is original from England and is supplied by Thang Tien Company, is used in this study. The ratio of foam to water is 1/30 as suggested from producer. The superplasticizer (SP) with density of 1.05 T/m^3 is utilized to reduce the water content in all concrete mixture.

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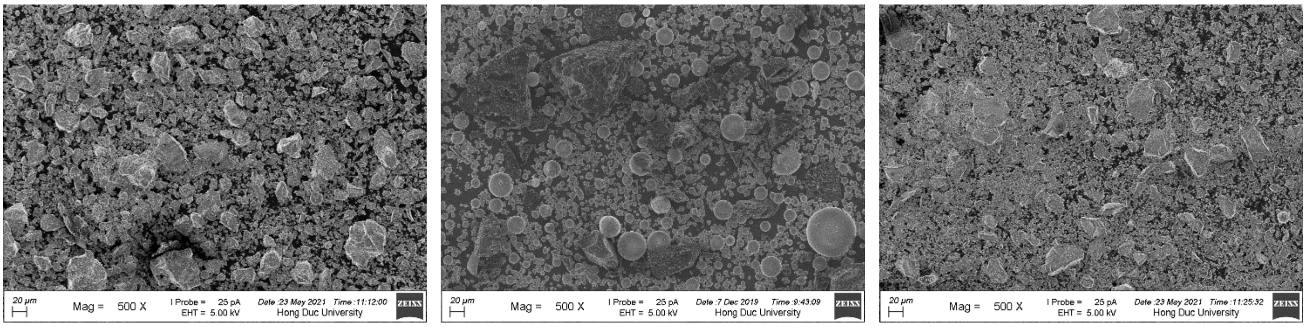
Table 1. *Physical and chemical analysis of binder materials*

Items		Cement	Fly ash	GGBFS
Physical properties	Specific gravity	3.12	2.16	2.82
Chemical compositions (%)	SiO_2	22.30	55.73	36.87
	Al_2O_3	6.68	21.67	12.38
	Fe_2O_3	4.73	6.58	-
	CaO	55.45	1.06	30.73
	MgO	2.40	2.17	14.8
	Loss on ignition	0.45	6.91	0.38



(a) (b) (c)

Figure 1. *SEM images of (a) cement, (b) fly ash, and (c) GGBFS*

2.2 Mixture proportions

Six foam concrete mixtures were designed with a constant water-to-binder ratio (W/B) of 0.20. Proportions of each raw material are showed in Table 2. In which, GGBFS is used as 30% amount of total binder materials by weight for all mixtures, while fly ash is used as 10 and 20% amount of total binder materials in mixtures M3, M5, M6, and mixtures M1, M2, and M4, respectively. In order to make foam concrete samples with various density, the foam content is used as from 22.4% to 60.8% total volume of samples. It is noticed that an electronic device was attached to the foam generator machine to control the amount of foam produced over the time. However, it is hard to control the exact the amount of foam produced, hence these values presented in Table 2 are assumed to equal the total amount of void in the samples. In the practice, the exact amount of foam used is higher than these values presented in Table 2 due to the foam bubbles broken in the air during the experiment. The effect of foam content on the properties of foam concrete such as compressive strength, water absorption, ultrasonic pulse velocity, and thermal conductivity is investigated in this study.

It is noticed that the water-to-binder ratio and superplasticizer were selected by trials from experiment, so that the mortar paste from cement-fly ash-GGBFS and sand has a sufficient workability. The plasticity of mortar paste is an important factor affecting the success of sample formation.

Table 2. *Mixture proportions*

Mixture ID.	W/B	Proportion ingredients (kg/m^3)						Foam (m^3)
		Cement	Fly ash	GGBFS	Sand	Water	SP	
M1	0.20	594.4	237.8	356.7	292.7	237.8	1.7	0.224
M2		499.9	199.9	299.9	249.9	199.9	1.4	0.347
M3		568.4	94.7	284.2	236.8	189.5	1.3	0.395
M4		375.8	150.3	225.5	187.9	150.3	1.1	0.509
M5		394.8	65.8	197.4	164.5	131.6	0.9	0.580
M6		368.3	61.4	184.2	153.5	122.8	0.9	0.608

2.3 Specimen preparation and test programs

Based on Table 2, all materials were prepared with their corresponding proportion for mixture. The superplasticizer and water were mixed together. Dry materials (Fig. 2a) including cement, fly ash, GGBFS, and sand were mixed first in three minutes. After that the mixture of water and SP were added and mixed until achieving homogeneous paste with sufficient workability. The foam was created using the Foam Master I machine provided by Thang Tien Company. Foam was slowly poured into the mortar paste with the proportion increase from mixture M1 to mixture M6 in order to produce concrete samples with different density. The mixer was continuously run until a uniform mixture was obtained. The steel mold with dimension of 100 × 100 × 100 mm was used to fabricate the samples. After 24 hours, the specimens were demolded and stored at room condition until the testing days. The specimens after demolding in the laboratory are illustrated in Fig. 2c.

The wet unit weight of foam concrete was immediately tested after the uniform mixture of mortar paste and foam was obtained. Compressive strength, ultrasonic pulse velocity, and thermal conductivity tests were conducted at 7, 14, and 28 days, while the water absorption, dry unit weight, and microstructure of concrete were tested at 28 days. Each measurement was conducted in three samples and the average values are reported herein. The microstructure of foam concrete is examined using the scanning electron microscopy of Hong Duc University.

(a) (b) (c)

Figure 2. *Specimen preparation (a) drying materials, (b) foam, and (c) concrete samples*

3. Results and Discussion

3.1 Unit weight and water absorption

Table 3 shows the wet and dry unit weight of all foam concrete mixtures corresponding to the foam content. It is clearly seen that as increasing foam content results in decreasing both wet and dry unit weight of foam concrete. This finding is related to the amount of air bubbles existed inside the foam concrete, leading to the reduction in concrete density. The dry unit weight of foam concrete produced in this study reduces from 1553 kg/m^3 to

849 kg/m^3 corresponding to foam content change from 22.4% to 60.8% by volume of samples. This range is similar to density of foam concrete from previous studies [2, 7]. This finding also means that with the use of at least 40% foam by volume of samples, the density of samples is lower than 1000 kg/m^3. Fig. 3 shows the relationship between dry unit weight and foam content, which can be described by linear equation as follows (Eq. 1).

$$y = -18.78x + 1990 \quad (1)$$

Opposite trend is observed for water absorption. According to Table 3, the water absorption of foam concrete increases with increasing foam content. The water absorption value changes from 4.0% to 28.1%, similar to experimental result from Abbas and Dunya's study (from 1% to 26%) [6]. The effect of foam content on the water absorption of foam concrete is shown in Fig. 4, and Eq. (2) is used to describe their relationship.

$$y = 0.98e^{0.05x} \quad (2)$$

Table 3. *Unit weight of concrete*

Mixture ID.	Foam (% by volume)	Wet unit weight (kg/m^3)	Dry unit weight (kg/m^3)	Water absorption (%)
M1	22.4	1726	1553	4.0
M2	34.7	1451	1337	4.6
M3	39.5	1375	1301	5.7
M4	50.9	1091	986	9.8
M5	58.0	955	914	17.5
M6	60.8	891	849	28.1

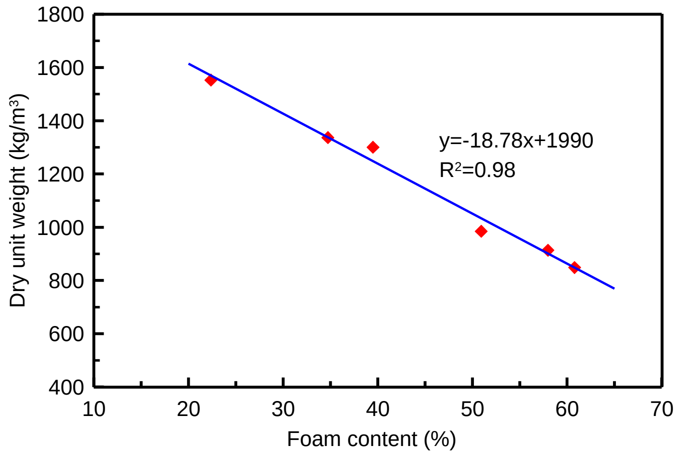


Figure 3. *Relationship between dry unit weight and foam content*

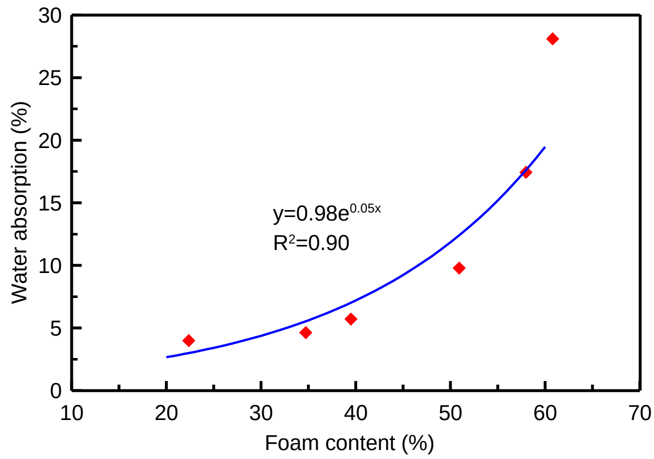


Figure 4. *Relationship between water absorption and foam content*

3.2 Compressive strength

Compressive strength is an important property of foam concrete, deciding where it can be used for. The compressive strength of all foam concrete in this study are presented in Table 4. When the foam content changes from 22.4% to 60.8%, the 28-days compressive strength of foam concrete decreases from 32.5 MPa to 1.9 MPa. It is noticed that the compressive strength of foam concrete is associated with its dry unit weight [3, 5, 6]. Based on previous studies, the compressive strength of foam concrete was ranged from 1.07 MPa to 29 MPa corresponding to its density from 850 kg/m^3 to 1600 kg/^{3} [2, 5]. In the present study, the concrete with density of 849 kg/m^3 (Mixture M6) and 1600 kg/m^3 (Mixture M1) has 28-days compressive strength of 1.9 MPa and 32.5 MPa, respectively, similar to those results from previous studies [2, 5]. The reduction in compressive strength is related to the air bubbles in foam concrete, which also causes the decrease in density of foam concrete as aforementioned, this will be clarified later by using scanning electron microscopy. Mixtures M1 and M2 with compressive strength of above 20 MPa, which can be used in bearing structure. On the other hand, remain mixtures (M3 to M6) with low compressive strength can be used as bricks, retaining walls, and roof tiles. A linear relationship between the compressive strength and foam content (Eq. 3) is obtained by linear regression as shown in Fig. 5.

$$y = -0.80x + 48.78 \quad (3)$$

Table 4. *Compressive strength*

Days	Compressive strength (MPa)					
	M1	M2	M3	M4	M5	M6
7	18.8	11.0	9.6	3.4	3.0	1.1
14	22.2	11.7	11.0	3.7	3.2	1.5
28	32.5	20.3	16.1	3.9	3.8	1.9

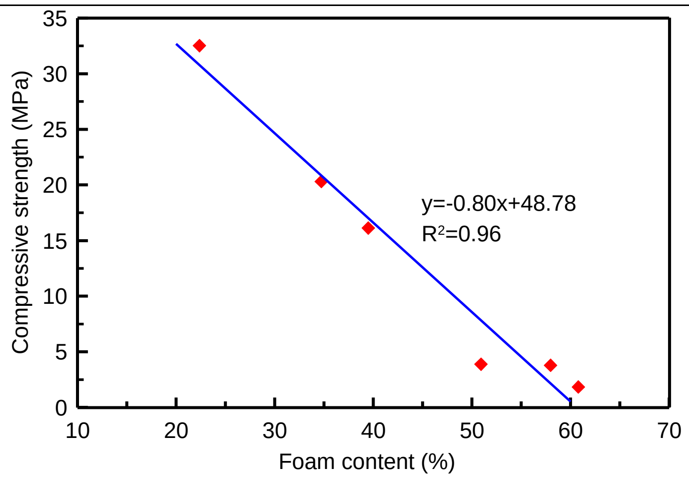


Figure 5. *Relationship between compressive strength and foam content*

3.3 Ultrasonic pulse velocity

The ultrasonic pulse velocity test is non-destructive method, which is used to assess the relative quality of concrete. Concrete with high value of ultrasonic pulse velocity often shows the high quality with high strength and high density. The value of ultrasonic pulse velocity is also used to classify the concrete as mentioned in previous study [11]. Table 5 shows the ultrasonic pulse velocity values of all foam concrete samples in this study. It is clear to see that the concrete with high density (low foam content) shows a higher ultrasonic pulse velocity value than the concrete with low density (high foam content), except Mixtures M4 and M5 at 7-days age (this could be an error during the measurement). It is also noticed that the compressive strength and density of foam concrete has a close relationship. The higher density, the higher compressive strength is. Therefore, the ultrasonic pulse velocity value of foam concrete has an association with its compressive strength. For mixtures M1 to M3 with compressive strength of above 15 MPa, their ultrasonic pulse velocity values are higher than 3100 m/s. On the contrary, ultrasonic pulse velocity values of mixtures M4 to M6 with compressive strength of lower than 4 MPa are lower than 2500 m/s. Equation (4) shows the linear relationship between 28-days ultrasonic pulse velocity value of concrete and foam content.

$$y = -49.45x + 5088.3 \quad (4)$$

Table 5. *Ultrasonic pulse velocity*

Days	Ultrasonic pulse velocity (m/s)					
	M1	M2	M3	M4	M5	M6
7	3507	2879	2946	2137	2295	1842
14	3745	3117	3089	2416	2382	1895
28	4130	3175	3129	2476	2433	2024

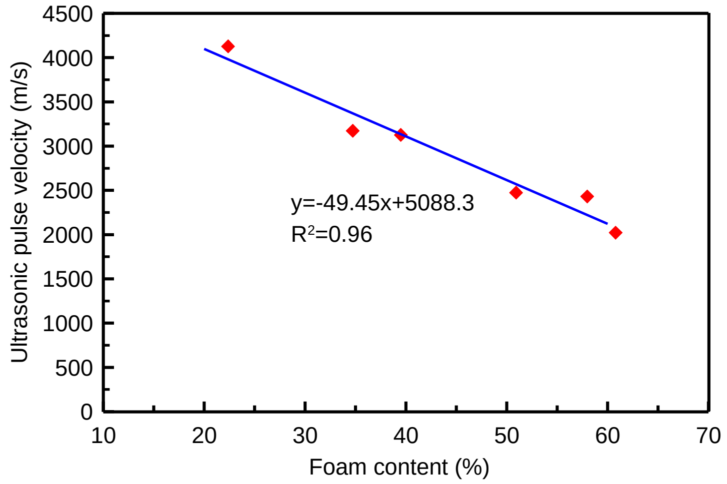


Figure 6. *Relationship between ultrasonic pulse velocity and foam content*

3.4 Thermal conductivity

Thermal conductivity test is used to assess the heat insulation capacity of concrete. The concrete with low thermal conductivity value is often utilized in the thermal isolated structure. Table 6 shows the thermal conductivity values of all foam concrete investigated in this study. As well as compressive strength, the thermal conductivity of foam concrete increases with the time. At 28 days, these values fall in the range from 0.263 to 1.410 W/m.K. In general, the thermal conductivity value of foam concrete decreases with increasing foam content, except mixtures M2 and M3. It is noticed that mixture M2 was designed with 20% fly ash as total binder weight, while mixture M3 was designed with only 10% fly ash. The proportion of mixture may affect to the thermal conductivity value of foam concrete, which needs to clarify in the future research. Similar to dry unit weight, compressive strength, and ultrasonic pulse velocity, a negative linear equation as shown in Eq. (5) is used to illustrate the correlation between thermal conductivity value and foam content. The thermal conductivity test was also used in previous studies for foam concrete [6, 12]. Test results exhibited that the general range of thermal conductivity value was from 0.1 to 0.48 W/m.K. It is noticed that most foam concrete in the present study has a thermal conductivity value of from 0.263 to 0.679 W/m.K, except mixture M1, which has high compressive strength like normal concrete. With a low thermal conductivity value, these foam concrete in this study can be applied in thermal isolated structure such as roof tiles and thermal insulation walls.

$$y = -0.027x + 1.799 \tag{5}$$

Table 6. *Thermal conductivity*

Days	Thermal conductivity (W/m.K)					
	M1	M2	M3	M4	M5	M6
7	1.334	0.591	0.653	0.365	0.265	0.256
14	1.347	0.598	0.674	0.370	0.277	0.257
28	1.410	0.611	0.679	0.388	0.282	0.263

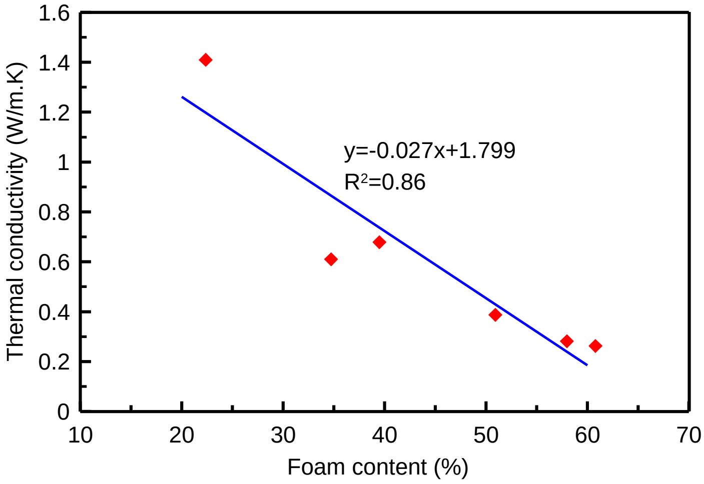


Figure 7. *Relationship between thermal conductivity and foam content*

3.5 Scanning electron microscopy observation

Figure 8 shows the SEM images of all foam concrete with magnification of 500 times. For three first mixtures (M1 to M3) with compressive strength of above 15 MPa, some air bubbles are observed in the microstructure of concrete. The number of air bubbles increases in the last three mixtures (M4 to M6), these mixtures has a low compressive strength as presented above (lower than 4.0 MPa). It is noticed that the former mixtures were designed with low foam content, therefore the air volume in these mixture is less than the later mixtures. For mixture M6, many bubbles connect to each other to create the large air bubble. This explains why this mixture has really low dry unit weight (849 kg/m^3), low compressive strength (1.9 MPa) and high water absorption (28.1%). The air bubbles inside concrete is contributable to the reduction in density, compressive strength, ultrasonic pulse velocity, and thermal conductivity, but increases water absorption of foam concrete. These SEM images are related to those findings about the effect of foam content on the properties of foam concrete as aforementioned.

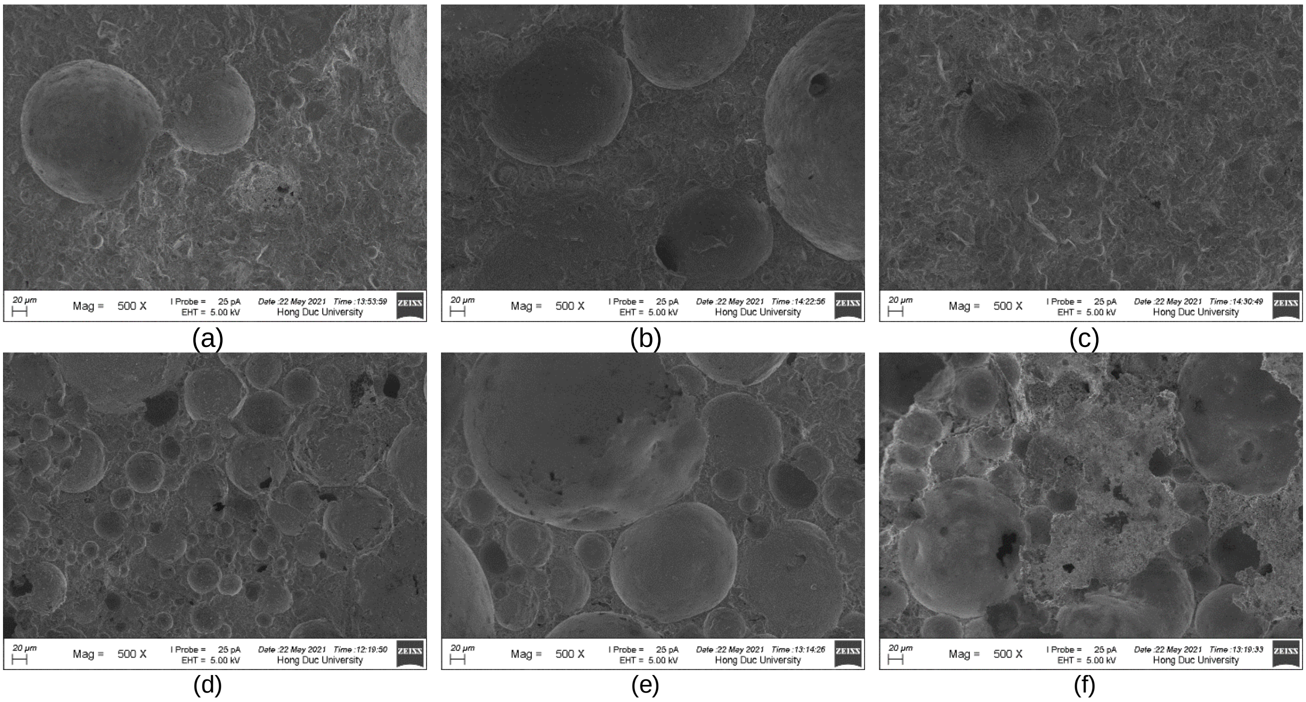


Figure 8. *SEM micrographs of (a) M1, (b) M2, (c) M3, (d) M4, (e) M5, and (f) M6*

4. Conclusions

This study uses the ternary binders of cement, fly ash, and GGBFS in the production of foam concrete. The effect of foam content on the properties of foam concrete is also investigated in this study. Based on the experimental program, some brief conclusions may be drawn as follows.

1) The properties of foam concrete are strongly depended on the foam content. As increase in foam content, unit weigh, compressive strength, ultrasonic pulse velocity, and thermal conductivity of concrete reduce, but water absorption of concrete increases.

2) The concrete with low foam content of 22.4% and 34.7% by total sample volume has a compressive strength of above 20 MPa, which can be used in bearing structure. If increasing the foam content to over 35%, its compressive strength significantly reduces and it can be just used as thermal isolated bricks and roof tiles.

3) The number of air bubbles inside concrete increases with increasing foam content, significantly affecting the properties of foam concrete.

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