INFLUENCE OF COAL GANGUE ON RHEOLOGICAL PROPERTIES AND STRENGTH OF FOAM MORTAR

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This study aimed to investigate the preparation of cement foamed mortar mixed with coal gangue power. Moreover, the following rheological parameters and compressive strength were determined. Additionally, a scanning electron microscope (SEM) was used to reveal its compressive strength's inner mechanism. Results indicated that slump flow of fresh coal gangue power foamed mortar increased first and then kept stable with water-reducing agent. The increasing content of coal gangue power could descend the compressive strength of foamed cement mortar. Compressive strength of foamed cement mortar decreased linearly with foam content and ascended in the exponential or linear functions with volume density. The scanning electron microscope (SEM) images showed that many shapes of hydration products existed in the specimens. Moreover, the microstructure of specimens became denser with decreasing cement-sand ratios.

Keywords: *Foamed mortar; Coal gangue powder; Rheological parameters; Compressive strength; Scanning electron microscope*

1. Introduction

China, as one of the largest coal consumers, produces a large amount of coal gangue (About 15 % by mass of coal) [1-3]. By now, more than 4.5 billion tons of gangue has been accumulated in China, and about 150 million tons of gangue is continuing to be produced every year. However, only about 30% of gangue can be comprehensively reused, leading to massive gangue remaining disposed of. If gangue cannot be treated appropriately, it may cause severe environmental pollution [4-7]. As pointed out in Zhou's study [8], the existing potentially toxic elements in coal gangue can pollute water sources. On the other hand, coal gangue containing active SiO_2 and Al_2O_3 components is effective to promote the secondary hydration process of cement and then improve the microstructure and mechanical properties [9-13]. Cong, Zhou, et al. [14, 15] pointed out that coal gangue can enhance cement concrete's mechanical strength by modifying the composition and structure of hydration products. Moreover, He et al. [16, 17] developed high-performance autoclaved aerated concrete produced with recycled wood fiber, coal gangue and rubber powder. This kind of concrete showed excellent mechanical performance. Moreover, the stress-strain relationship, fire resistance and rheological properties were investigated by researchers and they proved that the usage of coal gangue in cement concrete is capable of realizing recycling of waste. Wang, Cheng et al. [18] found that the addition of coal gangue demonstrated a positive effect on concrete's chloride resistance. Furthermore, coal gangue has the ability to improve the resistance of freezing-thawing cycles, drying shrinkage, etc.

Foam concrete is a lightweight concrete material fabricated by mixing bubbles and cement-based materials [19-21]. Although it has low mechanical properties and strength, it has good heat preservation and insulation effect. Due to this reason, it is usually applied in the lower bearing wall, partition walls in buildings. Coal gangue possessing excellent thermal insulation is added into concrete to manufacture foam concrete. Wu et al. [22] developed an efficient method to use coal gangue as building materials and found that high-calcium coal gangue with coal gangue was a non-hazardous building product and the proposed autoclaved curing can actually fix heavy metals. Gao et al. [23] proposed that coal gangue can be utilized as an alternative to coarse aggregate in structural concrete. Meanwhile, a design method to produce cleaner reinforced concrete and concrete-filled steel tube with coal gangue was proposed by considering the coal gangue replacement ratio. Although, some studies on the preparation methods and mechanical performance of concrete with coal gangue have been conducted [24-26], little attention was paid to study the preparation and the mechanical performance of cement foamed concrete mixed with coal gangue power. Limited research on the relationship between volume density and compressive of coal gangue powder cement-based material was reported.

In this paper, the rheological properties of coal gangue cement foam mortar were determined. The change of apparent viscosity with time was also considered. The relationship between foam volume content and volume density was obtained. Moreover, the compressive strength of coal gangue cement mortar after Natural curing for 3 d, 7 d and 28 d were tested. This study will make efforts to protect the environment by using coal gangue in cement foam mortar.

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Table1

Particle passing percentage of cement

Types \ Particle size/*um*	0.3	0.6	1	4	8	16	32	64
Cement	0	0.33	2.66	15.01	28.77	46.64	72.73	93.59
Sand	0	0	0	0	0	0	20	100

Table2

Chemical composition of cement and coal gangue/%

Oxide	MgO	Al_2O_3	Fe_2O_3	CaO	SiO_2	SO_3	R_2O	MnO
Cement	1.73	5.47	3.94	62.23	20.86	2.66	0.48	0
Coal gangue	2.15	31.60	8.68	6.65	42.38	0.78	3.89	1.25
Sand	/	/	0.02	/	99.6	/	/	/

Table 3

Mixing proportion of cement foamed mortar mixed with coal gangue (%)

Types	Cement	Coal gangue powder	Water	Foam	Thickening agent	Water-reducing agent
A-1	28.9	57.8	10.7	2.6	0.025	0.4
A-2	29.7	59.5	8.0	2.6	0.025	0.6
B-1	34.0	50.9	12.5	2.6	0.025	0.8
B-2	35.1	52.7	9.6	2.6	0.025	0.4
C-1	41.1	41.1	15.2	2.6	0.025	0.6
C-2	42.9	42.9	11.6	2.6	0.025	0.8
A0-1	78.7	1.574	21.3	7.08	0	0.3
A0-2	78.7	1.574	21.3	7.08	0	0.45
A0-3	78.7	1.574	21.3	7.08	0	0.6
A1-1	78.7	1.574	21.3	7.08	0.025	0.3
A1-2	78.7	1.574	21.3	7.08	0.025	0.45
A1-3	78.7	1.574	21.3	7.08	0.025	0.6
B0-1	73.0	0.787	27.0	7.08	0	0.4
B0-2	73.0	0.787	27.0	7.08	0	0.6
B0-3	73.0	0.787	27.0	7.08	0	0.8
B1-1	73.0	0.787	27.0	7.08	0.025	0.4
B1-2	73.0	0.787	27.0	7.08	0.025	0.6
B1-3	73.0	0.787	27.0	7.08	0.025	0.8

2. Experiments

2.1. Raw materials

Ordinary Portland cement (Swan brand produced by Yatai Group Harbin Cement Co., Ltd) with a strength grade of 42.5 MPa was used in this study. The particle passing percentages and cement chemical compositions are listed in Table 1 and Table 2, respectively. Coal gangue powder with a fineness modulus of 2.75 was used as fine aggregates. The coal gangue used in this experiment was obtained from a mining area at Chenming District, Yichun city. A light yellow polycarboxylic acid superplasticizer with 40% solid content was used. This study's foaming agent was a light yellow, viscous, liquid and aromatic plant foaming agent. The ratio of foaming agent to water was 1:30.

2.2. Mixing proportion and specimens preparation

Table 3 shows the mixing proportion of cement foamed mortar mixed with coal gangue. 18 groups of specimens named A-1 to C-2 were prepared. Water-reducing agent in the mixture ranged from 0.3 % to 1.6. First, the weighed cement, sand, coal gangue powder, water and water reducing agent were added into the Hobart A200C mixer and agitated at 140 rpm for 2 minutes. Then all mixtures including the weighed foam were added and agitated at 285 rpm for another 2 minutes. After the stirring, fresh paste was applied in testing the slump. After the preparation of fresh cement slurry, a steel cone (60 mm (bottom diameter × 36 mm (upper diameter × 60 mm (height)) was utilized to measure the fresh paste's slump flow. Additionally, a DV-II+ viscometer with No. 63 Rotor with Rotation speed of 5 rpm was provided to test the apparent viscosity of fresh paste. The left fresh mixture was poured into molds to form specimens with a size of 70.7 mm ×70.7 mm × 70.7 mm. The compressive strength was conducted according to Chinese standard GB/T17671-1999. The average value of the compressive strength of 6 samples was applied for this study.

3. Results and discussions

3.1. Composition and particle size of coal gangue

Figure 1 shows the X-ray diffraction spectrum of coal gangue. It could be observed that coal gangue had a continuous XRD peak, which indicated that coal gangue contained a certain percentage of amorphous impurities. Besides, a strong diffraction peak corresponding to quartz (SiO_2) could be found, indicating a high content of SiO_2 quartz crystals in coal gangue. Therefore, coal gangue's addition was effective to increase its activity in cementitious materials and promote the second hydration of cement, thus increasing the later strength of coal gangue foam mortar.

Figure 2 shows the particle size distribution of coal gangue powder after grinding 90 min. The particle size of coal gangue powder ranged from 0.5 *μ*m to 100 *μ*m. About half of coal gangue powder was smaller than 4.552 *μ*m. The fine coal gangue powder indicated high activity.

3.2. Rheological properties

Figure 3 shows the slump flow of fresh coal gangue mortar, as shown in Figure 3 that the slump flow of the fresh mixture increased with the increasing dosage of water-reducing agent.

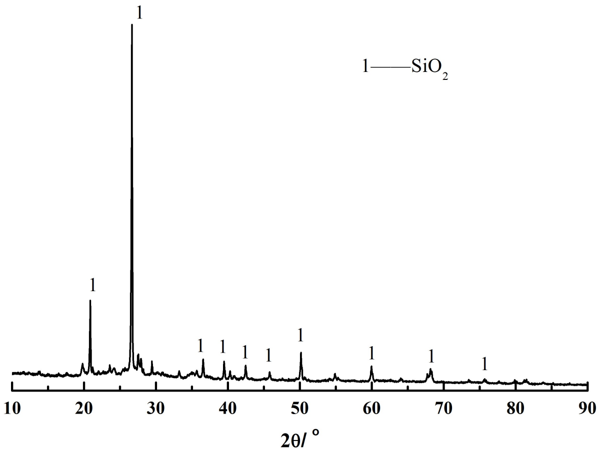


Fig. 1 - XRD patterns of coal gangue.

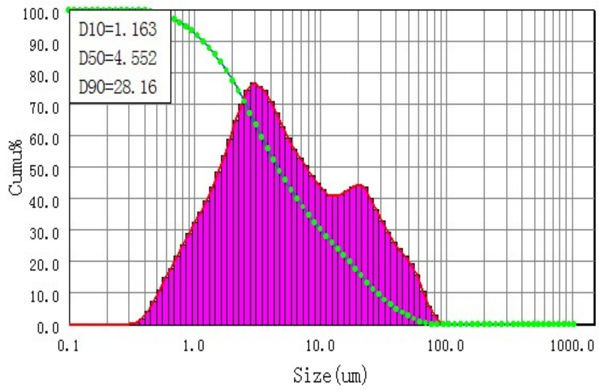


Fig. 2 - Distribution of particle size of coal gangue powder.

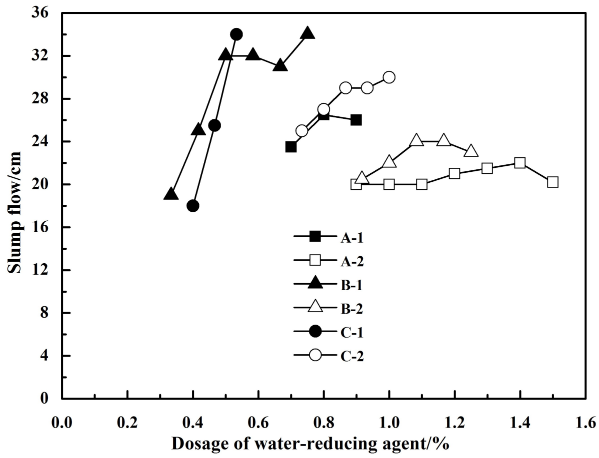


Fig. 3 - The slump flow of foam mortar with coal gangue powder.

Moreover, the increasing water-cement ratios led to ascending the slump flow. Additionally, the addition of coal gangue powder was effective in descent the fluidity of fresh mixture. This could be attributed to the fact that the increasing dosage of water-reducing agent was able to release the free water wrapped by cement leading eventually to decreasing the fluidity of fresh paste [27-29]. However, the coal gangue powder with glassy surface containing fine particle size and occupying bigger specific surface area might imbibe some free water inducing the decline of fresh cement mortar's slump flow and increasing of viscosity [30].

In the following research, all fresh mixtures' slump flows were kept in the scope of around 22 cm. Figure 4 shows the relationship between water-cement ratio and the dosage of water-reducing agent. As shown in Figure 4 that the amount of water-reducing agent decreased with the increasing water-cement ratios due to more free water by higher water-cement ratios [31].

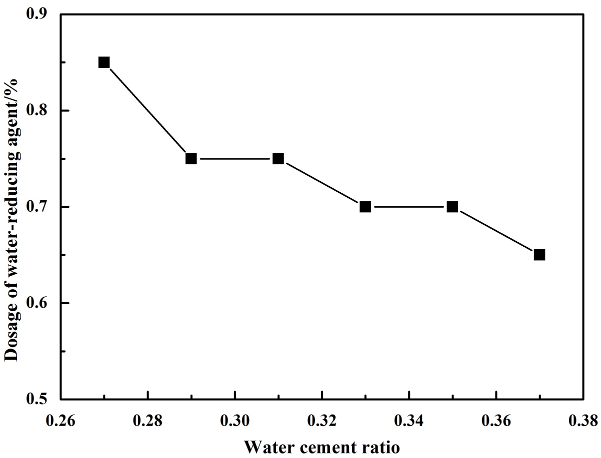
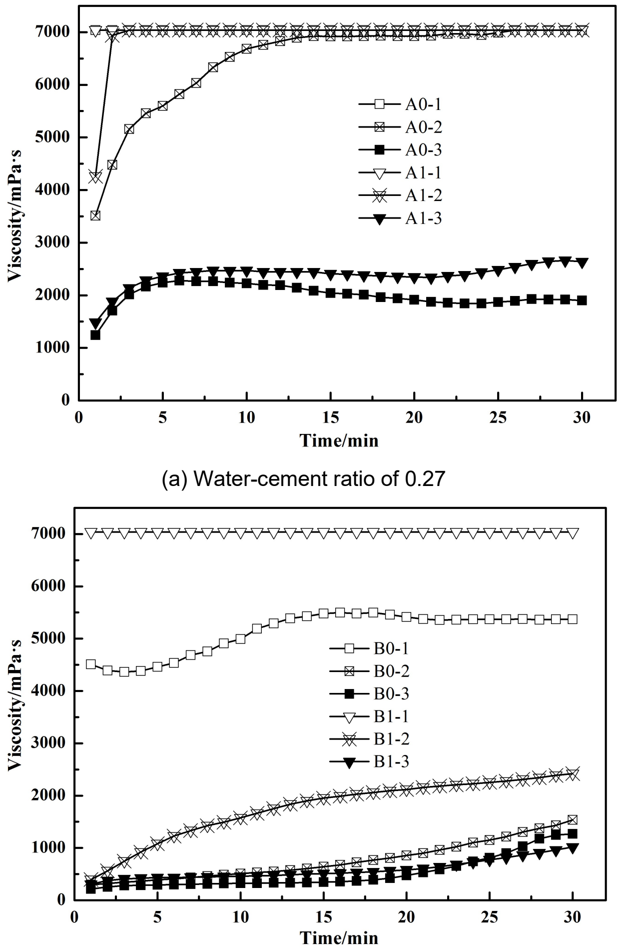


Fig. 4 - Relationship between water cement ratio and water-reducing agent.

Figure 5 shows the apparent viscosity of fresh mixture with different time. As shown in Figure 5 that the apparent viscosity increased with time. When water-cement ratios are 0.27, all groups' apparent viscosities rose to the highest and remained unchanged after time reached 10 min. However, when water-cement ratio was 0.37, apparent viscosities continued to grow with the increasing time. The increasing water-cement ratios, water-reducing agent and the addition of thickening agent were able to decrease the apparent viscosity.



(a) Water-cement ratio of 0.27

(b) Water-cement ratio of 0.37

Fig. 5 - Apparent viscosity of fresh mixture with different time.

3.3. Compressive strength

Figure 6 shows the compressive strength of cement foamed mortar mixed with different dosages of coal gangue. As illustrated in Figure 6, the compressive strength of foamed mortar descended with the increasing dosage of coal gangue due to its weak bonding ability and large pores [32]. As shown in Figure 6, at a ratio of water to material of 0.27, the decent ratio of compressive strength was in the range between 11.4% to 72.3%, while the ratio decreased to the range between 9.4 % to 52.1 % at a ratio of water to material of 0.37. Moreover, with the increase of curing age and decrease of water-cement ratio, the compressive strength of foamed mortar improves. It could be attributed to the enhanced hydration degree and the reduction of porosity [33]. Thus, in the following study, all specimens were cured for

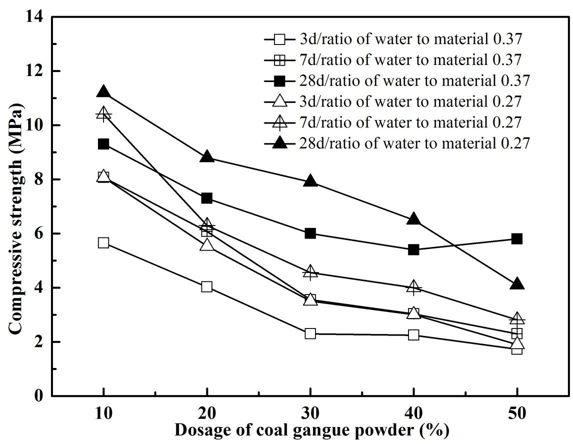


Fig. 6 - The compressive strength of cement foamed mortar mixed with different dosage of coal gangue powder.

28 days. Meanwhile, the water-cement ratio was 0.27 and the content of coal gangue powder was 30 %. From Fig. 6, it could be observed that as the coal gangue powder increases from 40% to 50%, the compressive strength of the cement foamed mortar with a ratio of water to materials of 0.37 improved due to the secondary hydration process of cement by high dosage of SiO_2 and Al_2O_3 in

coal gangue (In this study, the coal gangue powder contained 31.6 % Al_2O_3 and 42.38 % SiO_2, which promoted the secondary hydration process of cement).

Figure 7 shows the relationship between volume density and foam content of gangue foam mortar. As shown in Figure 6, the volume density of gangue foam mortar decreased linearly with foam's addition. The descending speed decreased with the increasing water-cement ratio and the cement-sand ratio. As shown in Figure 6, each group's fitting degree is higher than 0.9. The relationship between volume density and foam content of gangue foam mortar fit well linear equation.

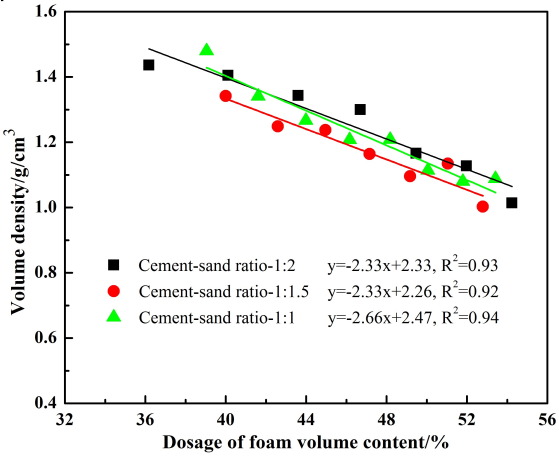


Fig. 7 - Relationship between volume density and dosage of foam content of gangue foam mortar.

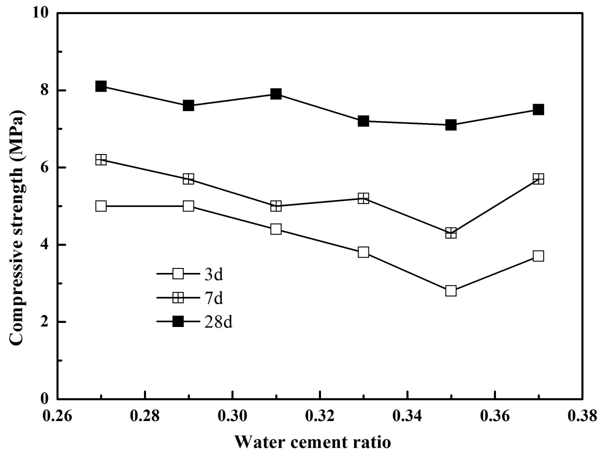
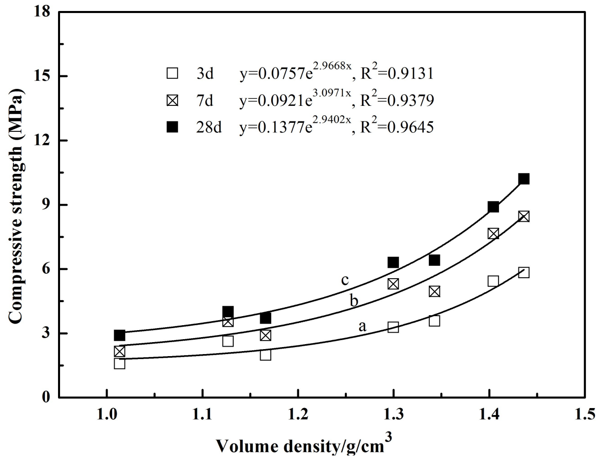
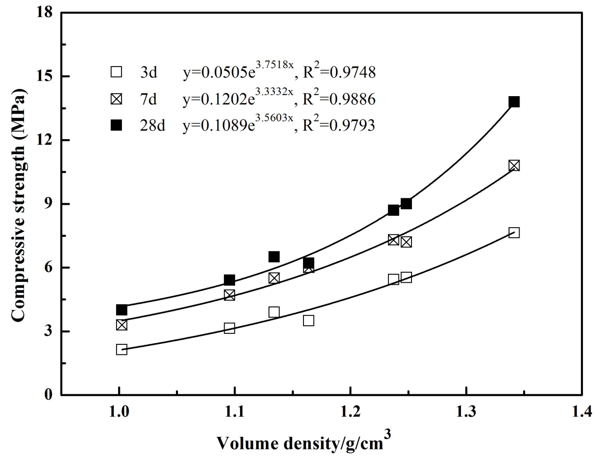


Fig. 8 - Compressive strength of specimens with different water-cement ratio and curing age.

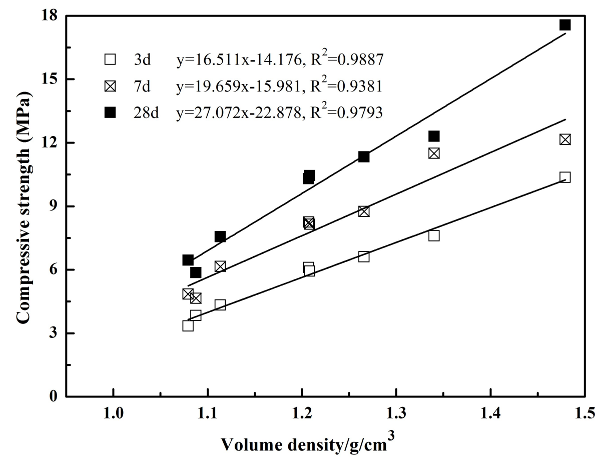
Figure 8 shows the compressive strength of specimens with different water-cement ratio and curing age, as shown in Figure 8, the compressive strength of specimens decreased first and then increased with the increasing water-cement ratio. Specimens with water-cement ratio of 0.35 exhibited the lowest compressive strength of all water-cement ratios. This might be attributed to the fact that when water-cement ratio of specimens was low enough, the hydration was insufficient, a lot of unhydrated cement particles existed in



(a) Cement-sand ratio of 1:2 and water-cement ratio of 0.27



(b) Cement-sand ratio of 1:1.5 and water-cement ratio of 0.27



(c) Cement-sand ratio of 1:1.1 and water-cement ratio of 0.27

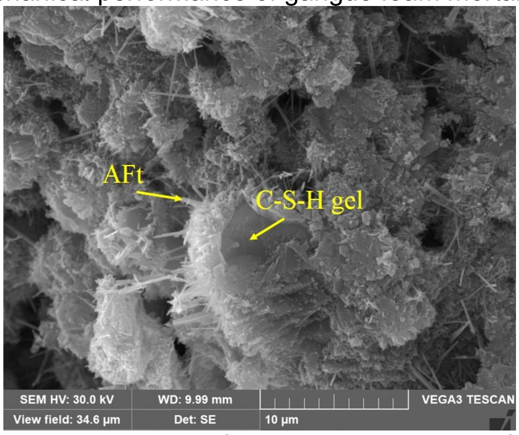
Fig. 9 - The relationship between compressive strength and volume density.

specimens leading to decreasing the compressive strength of specimens [34-36]. However, when water-cement ratio was higher than 0.35, the compressive strength of specimens ascended with the increasing water-cement ratio due to the sufficient hydration of cement. As shown in Figure 8 that the increasing curing age led to improving the compressive strength [37-39].

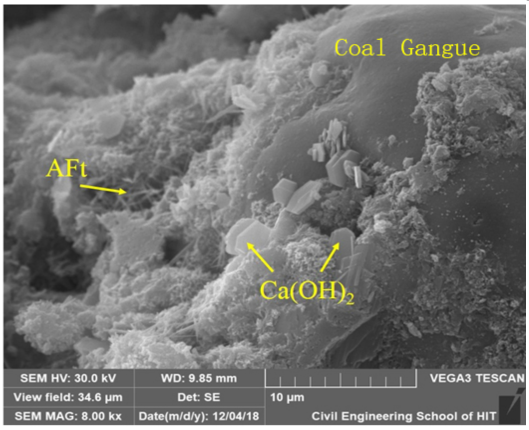
Figure 9 shows the relationship between compressive strength and volume density of specimens with curing ages of 3 d, 7 d and 28 d respectively. As shown in Figure 9, compressive strength of specimens increased with the volume density. Compared Figure 9(a) with Figure9 (b) that the compressive strength of specimen decreased with the increase of cement-sand ratio and the water-cement ratio. The increasing curing age led to improving the compressive strength of specimen. When cement-sand ratios were 1:2 and 1:1.5, the relationship fit well with exponential function. However, the relationship of specimens fit well with linear function.

3.4. Microscopic observations

Figure 10 shows the scanning electron microscope (SEM) images of gangue foam mortar with cement-sand ratios of 1:2 and 1:1.5 respectively and the water-cement ratio of 0.27 whose curing age was 28 d. It could be found that the loose flocculent structures in Figure 10 (a) can be seen clearly, while the structures of hydration products in Figure 10 (b) were denser. In Figure 10 (b), hydration products of $Ca(OH)_2$ could be observed clearly. Results indicated that the microstructure of specimens became denser with the decreasing cement-ratios. Therefore, the decreasing cement-sand ratio led to improving the mechanical performance of gangue foam mortar.



(a) The cement-sand ratio of 1:2 and water-cement ratio of 0.27



(b) The cement-sand ratio of 1:1.5 and water-cement ratio of 0.27

Fig. 10 - SEM microstructure photos of gangue foam mortar.

4. Conclusions

In this study, the rheological performance and compressive strength of cement foamed mortar mixed with coal gangue power were investigated. Based on the findings, the following conclusions can be summarized:

Slump flow of fresh coal gangue power foamed cement mortar firstly increased and then remained stable with the addition of water-reducing agent.

The addition of coal gangue power caused a negative effect on the fluidity and compressive strength of foamed cement mortar. The dosages of coal gangue powder led to the decreased compressive strength of 9.4 % ~ 52.1 % for the foamed cement mortar with a water to material ratio of 0.37 to 11.4 % ~ 72.3 % for the foamed cement mortar to material ratio of 0.27.

Compressive strength of foamed cement mortar decreased linearly with foam content and ascended in the exponential or linear functions with volume density. Moreover, cement-sand ratio led to tightening the microstructure of specimens.

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