Durability and Microstructure of High-Strength Mortar Produced with High Loss-On-Ignition Fly Ash and Silica Fume

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Abstract. To save natural resources and protect the environment, the use of fly ash (FA) with a high loss on ignition (LOI) and silica fume (SF) in producing high-strength mortar (HSM) is the objective of this study. The effect of FA with high LOI on the durability and microstructure of HSM was investigated. All HSMs were designed with a water-to-binder ratio of 0.24, and the amount of SF is 20% total amount of binder materials. The reference mixture was designed without FA, while four others were created by using FA to replace 15, 30, 45, and 60% cement. Test results indicated that the mortar quality was decreased with increasing high FA content. However, with the presence of SF, all mortars in this study still showed good quality with compressive strength of above 50 MPa and rapid chloride ion penetration value of below 1000 Coulombs. Many free-FA particles and impurities, which were observed in the scanning electron microscopy image of HSM samples with high FA content, are causes leading to a reduction in the mortar quality. In addition, the relationships between some properties of HSM were also established.

Keywords: High-strength mortar · Fly ash · High loss on ignition · Durability · Microstructure

1 Introduction

Cementitious materials are considered the most common materials used in the world just after water [1]. Along with the explosion of urbanization, the consumption of concrete and mortar is increasing rapidly. Consequently, some kinds of natural resources like limestone, river sand, and coal are gradually depleted due to cement and concrete production. The cement production process consumes a large number of natural resources and releases a lot of polluted gases into the air, leading to the warming of the earth [2]. In Vietnam, natural sand is gradually becoming a non-renew.

able resource because of over-exploitation [3]. On the other hand, industrial waste from thermal power plants is another social concern relating the environmental pollution. In that context, many studies have been conducted to return fly ash and bottom ash as

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cement and sand replacement in producing concrete and mortar [4–6]. However, most previous studies used fly ash with a low LOI [7], satisfying the specification indicated in ASTM C618 (the LOI is lower than 6%). The use of FA with high LOI in the production of mortar and concrete has been investigated in some previous studies [8–10]. While the compressive strength of concrete containing high LOI FA was adequate to that of the control concrete [8], the effect of the high LOI FA on the compressive strength of mortar was negative [10]. The use of fly ash with a high LOI of above 6% is still limited in the literature. The quality of raw ingredients has a strong influence on the quality of concrete and mortar. Therefore, the use of a local FA with a high LOI in producing mortar should be investigated.

Besides recycling industrial waste into construction materials, creating high-strength materials is another way to save natural resources. In this study, FA from a local thermal power plant with a high LOI was used to replace a part of cement in producing high-strength mortar. Silica fume was also used to minimize the negative influence of FA with high LOI. The compressive strength and other properties that affected the mortar's durability such as ultrasonic pulse velocity (UPV), water absorption, and rapid chloride ion penetration (RCPT) were investigated. The microstructure of these mortars was also examined using scanning electron microscopy (SEM).

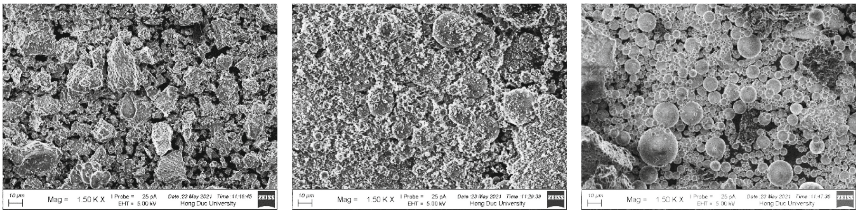
2 Materials and Experimental Methods

2.1 Materials

SEM images and chemical compositions of Nghi Son PCB40 cement, silica fume (SF), and fly ash (FA) are presented in Figs. 1 and 2, respectively. It is noticed that PCB cement is a popular type of cement in practice. Even though PCB cement has included mineral admixture, the use of FA to replace a part of a common cement is still necessary. The specific gravities of these binder materials were 3.12, 2.21, and 2.16, respectively. It is noticed that the LOI of FA was 6.9%, higher than the specification stipulated by ASTM C618 (lower than 6%). The strength activity index of FA was 76%. Some unburnt impurities are observed in Fig. 1c, and its large scale is shown in Fig. 3. As seen in Fig. 3, the surface image of the impurity indicates its high porosity, explaining the lowest specific gravity of FA among the three binder materials. Therefore, SF was added to create high-strength mortars and enhance the strength and durability of mortars incorporating FA with high LOI. The natural river sand, tap water, and superplasticizer (SP) with densities of 2630, 1000, and 1150 kg/m^3 were used, respectively. The SP used was type G in accordance with ASTM C494, which is similar to the one used in the previous study [8]. The dosage of SP was adjusted to ensure all the fresh mortar mixtures have a flow diameter of 18 $\pm$ 2 cm.

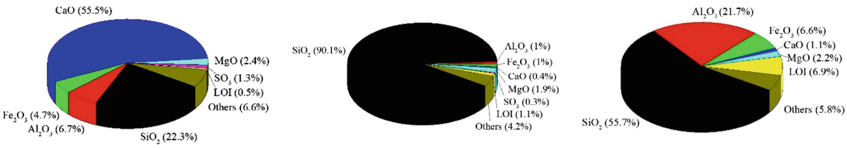
2.2 Mixture Proportions

Firstly, the reference mixture (HSM-00) without fly ash was designed with a water-to-binder ratio (w/b) of 0.24, which value is similar to the previous study [11]. The mass percentage of cement and SF were 80% and 20% total amount of binder materials,



(a) PCB40 (b) SF (c) FA

Fig. 1. SEM images of cementitious materials



(a) PCB40 (b) SF (c) FA

Fig. 2. Chemical compositions of cementitious materials

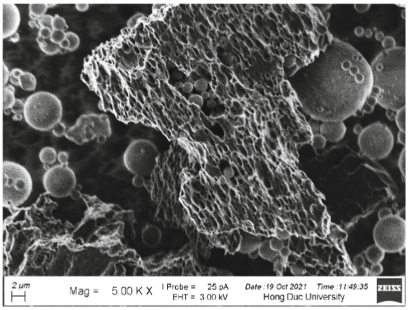


Fig. 3. Impurity of FA under SEM observation

respectively. The amount of sand was equal to the total amount of the binder. Then, four other mixtures were formed by replacing 15, 30, 45, and 60% of cement with FA, denoted as HSM-15, HSM-30, HSM-45, and HSM-60, respectively. It is noticed all HSMs were designed with a flow diameter of 18 ± 2 cm, and the SP was used to adjust this value (Table 1).

2.3 Sample Preparation and Test Methods

The mixing process was conducted similarly to the previous study of Peng et al. [12]. After mixing, the flow diameter was checked based on ASTM C1437, and the SP dosage was changed to ensure the flow diameter in the range of 18 ± 2 cm. While the cubic samples of 5 cm were cast for compressive strength and water absorption tests, the cylinder samples with a diameter of 10 cm and a height of 20 cm were cast for ultrasonic pulse velocity and rapid chloride ion penetration measurement. The compressive

Table 1. Mixture proportions of HSM

Mixtures	w/b	Material proportions (kg)					
		PCB40	SF	FA	Sand	Water	SP
HSM-00	0.24	816	204	0	1020	245	15.7
HSM-15		694		122			13.3
HSM-30		571		245			12.6
HSM-45		449		367			11.9
HSM-60		326		490			9.3

strength, water absorption, UPV, and RCPT were tested in accordance with ASTM C109, C642, C597, and C1202, respectively. All tests were conducted at 28 and 56 days, and the value presented herein is the average of three measurements. The microstructure of these HSMs was examined on the broken pieces from the compression test at 28 days.

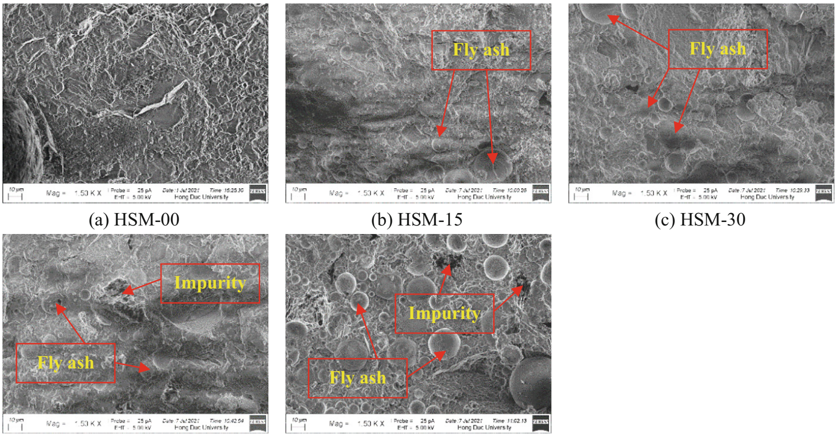
3 Results and Discussion

3.1 SEM Observations

The SEM morphologies of all the HSM samples at 28 days are shown in Fig. 4. According to Figs. 3e and 4d, many free-FA particles are detected in the SEM images of the samples with high FA replacement levels. This finding means that a part of FA existed as a fine aggregate instead of joining in the pozzolanic reaction. A similar result has been indicated in the previous study when the FA replacement level was high [13]. Moreover, some impurities are seen in Figs. 3e and 4d, correspond to HSMs with high FA contents. As shown in Fig. 4, while the SEM morphology of the reference sample without FA shows a high density, the morphologies of HSMs with FA are higher porosity than that of the HSM-00. These phenomena will yield the degradation quality of HSMs with high FA contents, which will be presented in the following sections.

3.2 Compressive Strength

The compressive strengths of all HSMs at 28 and 56 days are shown in Fig. 5. In general, the compressive strength of a mortar at 56 days was higher than that value at 28 days. This is due to the hydration and pozzolanic reactions continuously happening with curing time. According to Fig. 5, the effect of replacing cement with FA with high LOI on the mortar properties is negative. At 56 days, the compressive strengths were reduced by 12.3, 25.7, 35.1, and 49.4% corresponding to FA replacement levels of 15, 30, 45, and 60%. The reduction of compressive strength is due to the use of FA with high LOI. The impurities and free-FA particles mentioned in the previous section are the causes of compressive strength loss. It is noticed that the impurities and unreacted-FA found in Figs. 3 and 4 are related to the low strength activity index of FA. However, the 56 day compressive strength of the mortar containing 60% FA was 50.13 MPa, which is still



(a) HSM-00 (b) HSM-15 (c) HSM-30

(d) HSM-45 (e) HSM-60

Fig. 4. SEM morphologies of HSM samples at 28 days

significantly higher than conventional mortar used in practice (around 7.5–30 MPa as specified by TCVN 4314–2003 [14]). Besides, the presence of SF particles maintained the high strength of these mortars due to their filler and pozzolanic effects [15].

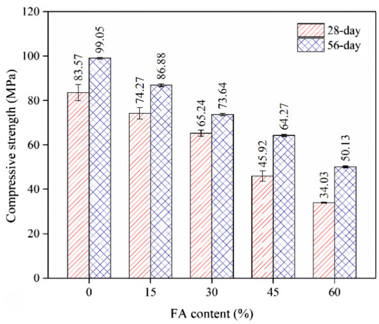


Fig. 5. Compressive strength of HSM samples

3.3 Ultrasonic Pulse Velocity

Ultrasonic pulse velocity test is used to assess the uniformity, density, and appearance of voids and cracks in the mortar samples. These characterizations have a significant effect on the durability of mortar. Figure 6 shows the UPV values of all the mortar samples at 28 and 56 days. Similar to compressive strength, the UPV values increased with curing time and decreased with increasing the FA content. The previous study [16] has indicated that the UPV value is closely associated with the sample's density. As stated above, the SEM morphology of the mortar sample was high porosity with increasing FA replacement level (Fig. 4), resulting in a reduction of UPV values. However, at 28 days, all HSMs in this study have a UPV value of above 3500 m/s, indicating good quality based on the classification from the previous study [17]. Similar to compressive strength, the FA with high LOI has a negative effect on the UPV value, but the high UPV values of these mortars in this study are due to the addition of SF. Both the filler and pozzolanic effects of SF contributed to reducing the porosity of the mortar sample, resulting in a high UPV value [15].

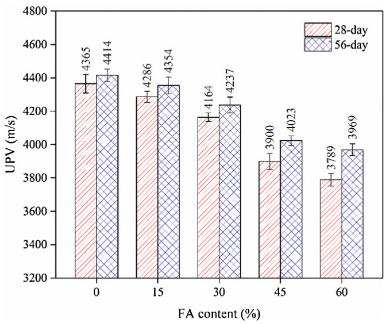


Fig. 6. UPV of HSM samples

3.4 Water Absorption

The water absorption values of all HSM samples at 28 and 56 days are shown in Fig. 7. As expected, the water absorption at 56 days was lower than the water absorption at 28 days, which is due to the hydration reaction and pozzolanic reaction of cement, FA, and SF that was continuously happened during the curing time. As increasing the FA content, the water absorption of HSMs raised. The increment of water absorption is related to the impurities and free-FA observed in the SEM images (Fig. 4). The cohesion of the impurities and free-FA with other ingredients of the mortar mixture is not good, so the water easily penetrated into the mortar samples.

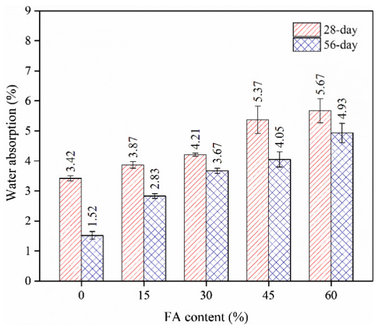


Fig. 7. Water absorption of HSM samples

3.5 Rapid Chloride Ion Penetration

Figure 8 shows the rapid chloride ion penetration levels of all HSM mixtures, which are indexed by the total charges passed through the sample during 6 h. Similar to the water absorption, the RCPT value was reduced with curing time and increased with increasing the FA replacement level. In the mortar sample with high water absorption, the chloride ion also easily penetrated through the mortar sample, resulting in high RCPT values. This result is related to using FA with high LOI, as aforementioned. However, due to the presence of SF and its filler and pozzolanic effects [15], all HSMs in this study have RCPT values of below 1000 Coulombs, indicating an excellent resistance to chloride attack based on the classification of ASTM C1202.

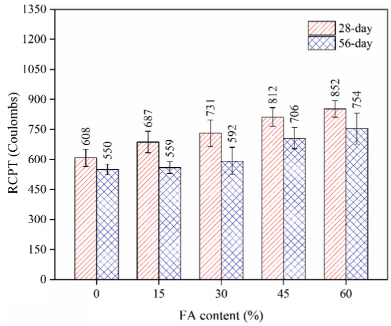


Fig. 8. RCPT of HSM samples

3.6 The Relationship Between Compressive Strength and UPV

As mentioned above, both compressive strength and UPV, which reflect the mortar quality, had a close relationship with the sample density. A relationship between the compressive strength and UPV values at 28 and 56 days are established and shown in Fig. 9. These relationships are described by the linear Eqs. (1) and (2), respectively. It means that the sample with a high UPV value will result in high compressive strength.

$$y = 12.14x + 3365 \tag{1}$$

$$y = 10.02x + 3450 \tag{2}$$

3.7 The Relationship Between Water Absorption and RCPT

As stated above, the mortar sample with high water absorption will result in a high RCPT value. The relationship between water absorption and RCPT values at 28 and 56 days are shown in Fig. 10 and are described by Eqs. (3) and (4), respectively.

$$y = 98.68x + 293 \tag{3}$$

$$y = 23.05x^2 - 83.91x + 620 \tag{4}$$

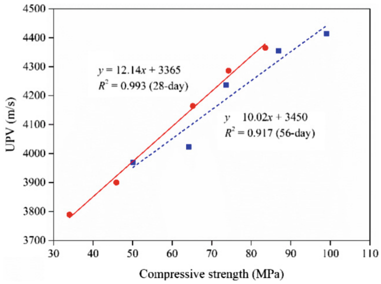


Fig. 9. The relationship between compressive strength and UPV of HSM samples

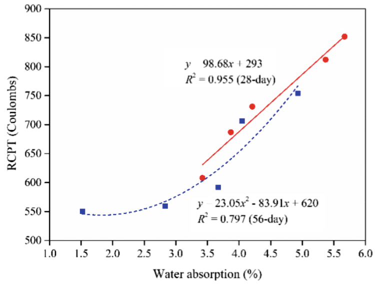


Fig. 10. The relationship between water absorption and RCPT of HSM samples

4 Conclusions

This study investigates the use of FA with high LOI incorporating SF in producing HSM. Based on the experimental outcomes, some brief conclusions were drawn as follows.

1. The use of FA with high LOI has a strong effect on the quality of the mortars. As increasing FA content, the compressive strength and UPV of the mortars decreased; meanwhile, the water absorption and RCPT values increased.
2. Although the quality of the mortars was significantly affected by FA with high LOI, the addition of SF can minimize this negative effect. All the HSMs using FA with high LOI still have a good quality with compressive strength of above 50 MPa and an RCPT value of below 1,000 Coulombs.
3. Many free-FA particles and impurities were detected in the SEM images of the HSM samples containing high FA content. They are causes for the reduced quality of the mortars.

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