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Incorporation of High Loss-on-ignition Fly Ash in Producing High-strength Flowable Mortar

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Abstract

A large amount of fly ash with a high loss on ignition (over the maximum allowance value stipulated by ASTM C618) is being released and increasing daily in Vietnam. The recycling of this fly ash is still limited, while a big remaining part is disposed of in storage yards, causing environmental pollution. On the other hand, the demand for high-strength mortar as a repair material is increasing for high-rise buildings and important projects, gradually depleting natural resources. However, the application of this fly ash in the production of mortar is restricted in the literature. In this study, local fly ash with a high loss on ignition is used to replace 0%, 15%, 30%, 45%, and 60% cement content in producing high-flowability and high-strength mortar. Changes in the fresh and hardened mortar properties were systematically investigated using samples produced with various fly ash contents. Test results indicate that the effect of impurities in fly ash on the mortar's workability can be neglected due to the spherical shape of fly ash. The unit weight, thermal conductivity, and drying shrinkage of mortars decreased with increasing fly ash content. Although some other properties of mortar are reduced due to the use of high loss-on-ignition fly ash, all mortars produced in this study still showed good quality with the presence of silica fume. In addition, the relationships between compressive strength and flexural strength with ultrasonic pulse velocity were established to predict the strength of mortar in a non-destructive method.

Keywords

high-flowability mortar, high-strength mortar, raw fly ash, high loss on ignition, silica fume

1 Introduction

Nowadays, the consumption and demand for cement are mushrooming as large projects and high-rise buildings are being constructed along with the rapid urbanization in many developing countries. Aside from that, the globe is facing a relentless situation relating to environmental contamination where the global carbon dioxide footprint is at a dangerous level, and the cement and construction industry is partially responsible. On the other hand, a large amount of fly ash and bottom ash, by-products from thermal power plants, are increasing day by day, as reported in previous studies [1–3]. Approximately 186 million tons of these ashes are released annually in Thailand, Malaysia, and India. In Vietnam, 25 coal thermal power plants discharged about 16.4 million tons of fly ash and bottom ash into the environment in 2020 [4]. Although around 47% of fly ash in total has been recycled [5], a big remaining part is disposed of in landfills, leading to the risk of overloading the storage yards and possibly spreading out, causing environmental pollution. Therefore, in the last few decades, research has been oriented on finding sustainable building materials as partial or entire replacement of cement with fly ash to make good environmental sense.

In the Thanh Hoa province of Vietnam, the Nghi Son coal thermal power plant releases about 1700 tons of fly ash per day. Due to the high loss on ignition [4], a small part of this local fly ash is recycled in the production of unfired building bricks. The majority of the remaining is stored in landfills and needs to be treated or recycled to avoid environmental pollution. On the other hand, around 5 million tons of cement are consumed to make concrete and mortar annually for local urbanization. Consequently, a large volume of natural resources, such as limestone, is

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depleted. Moreover, the demand for high-strength mortars used as a repair material for high-rise buildings and important projects, especially in coastal areas, is increasing. Therefore, using fly ash with a high loss on ignition to produce high-strength mortars for the local construction industry is necessary. It contributes to the partial treatment of industrial waste, minimizing environmental pollution, and also helps to save natural resources.

The use of fly ash in producing mortar and concrete was widely studied by many researchers all over the world [6, 7]. It is stated that the physical, mechanical, and durable properties of mortars depend on the properties of the used fly ash [8–11]. Meanwhile, the quality of fly ash is variable in different thermal power plants depending on the quality of coal and combustion technology. Table 1 shows the property comparison of fly ash from different sources over the world. As shown in Table 1, the composition of fly ash from different sources is variable. It is noticed that the loss on ignition of most fly ash used in previous studies [1, 2, 9, 12, 13] is lower than 5%, except for the fly ash sourced from Vietnam [4]. Likely, the unburnt impurities in fly ash may negatively affect the properties of concrete and mortar. Therefore, ASTM C618 [14] has to limit the loss on ignition of fly ash used in concrete to lower than 6%. This fly ash is considered the selected fly ash with good quality. Meanwhile, the fly ash with a high loss on ignition [4], referred to as low quality, has just been applied to produce unfired building bricks. Their application rather than in unfired building bricks such as concrete and mortar needs to be clarified [15–17]. However, the use of fly ash with a high loss on ignition in high-strength mortars is still limited in the literature. It is projected that the high loss-on-ignition fly ash may negatively affect the properties of mortar [15, 17]. Thus, an innovative design mix proportion for mortar mixture instead of the conventional one is needed.

Reactive powder concrete (RPC) is a construction material made of very fine aggregate and powder with high reactivity and ultra-high performance [18, 19]. This material has significantly higher compressive and flexural strength values than ordinary concrete, good heat resistance, high fire resistance, durability, and high resistance to aggressive chemical agents [20–23]. With its superior performance, as indicated, RPC has also been extensively applied in many sectors, such as civil, nuclear power, marine, and military facilities, as well as petroleum structures. However, the workability of RPC is low because of the low water-to-cement ratio [24]. It is noticed that mortar also consists of fine materials like compositions of RPC. Liu and Huang [24] and Lee et al. [25] have developed high-flowability and high-strength mortar based on RPC by increasing the water-to-binder ratio to 0.35 and even 0.65 to get the desired flow value. On the other hand, fly ash with a spherical shape is known to increase mortar mobility. Therefore, it is interesting to use fly ash in high-flowability and high-strength mortar to increase the workability without increasing the water-to-binder ratio. Similar to RPC, the use of silica fume in high-strength mortar mixtures can minimize the strength loss of mortar due to the use of fly ash with a high loss on ignition. Thus, this study develops high-flowability and high-strength mortar based on the design method of RPC.

Based on the literature review, the application of high loss-on-ignition fly ash in producing high-strength mortar is still limited. In order to treat a part of solid industrial waste from local thermal power plants, reduce environmental

Table 1 Comparison of the composition of fly ash from different sources

Composition (%)	Thailand (Chindaprasirt et al. [1])	Malaysia (Rafieizonooz et al. [2])	Vietnam (Ngo et al. [4])	Taiwan (Hwang and Hsieh [9])	China (Peng et al. [12])	Turkey (Yazıcı et al. [13])
SiO_2	38.7	47.6	51.48	60.58	51.7	42.1
Al_2O_3	20.8	23.8	20.18	18.54	32.1	19.4
Fe_2O_3	15.3	7.42	7.07	11.39	6.1	4.6
CaO	16.6	10.7	1.99	5.24	3.7	27.0
Na_2O	1.3	2.16	-	0.51	-	-
TiO_2	0.5	2.92	-	-	-	-
MgO	1.3	1.5	1.23	1.67	1.0	1.8
K_2O	2.1	1.68	-	1.23	-	1.1
SO_3	2.6	0.76	-	0.58	0.2	2.4
LOI*	0.8	-	15.89	4.9	1.2	1.3

*LOI: loss-on-ignition

pollution, and minimize the depletion of natural resources, the main objective of this study is to investigate the use of local fly ash with a high loss on ignition in the production of high-flowability and high-strength mortar as a repair material. The mixed proportion of the high-strength mortar in the present study was designed based on that of RPC. The effect of this fly ash content on the fresh and hardened mortar properties such as workability, unit weight, compressive strength, flexural strength, ultrasonic pulse velocity, water absorption, resistance to chloride attack, drying shrinkage, and thermal conductivity was symmetrically investigated. Moreover, the microstructure of mortar was also examined.

2 Experimental program

The experimental program includes five steps, as shown in Fig. 1.

2.1 Materials

The mortars produced in this study were a mixture of cement, silica fume (SF), fly ash (FA) sourced from the Nghi Son coal power plant in Vietnam, natural river sand, superplasticizer (SP), and tap water. Silica fume was used in the mixtures to obtain a compressive strength level of at least 60 MPa. The physical and chemical compositions of the binder materials are shown in Table 2. It is noticed that cement has the highest density among these binder materials, followed by silica fume and fly ash. The loss on ignition of fly ash is 6.91%, higher than 6% as a maximum allowance stipulated by ASTM C618 [14], which may affect the mortar quality and will be discussed later. The X-ray diffraction (XRD) pattern of FA is shown in Fig. 2. Both Fig. 2 and Table 2 indicate that the main compositions of FA are stable crystals of quartz (SiO_2) and mullite (Al_2O_3). The natural river sand, with a size ranging from 0.14 mm to 0.63 mm, a density of 2.63, water absorption capacity of 0.42%, is used as fine aggregate. It is noticed that the concept of RPC was applied to design the mix proportion for the mortars in this study, so the particle size of sand was selected as similar to the size of fine aggregate in the previous study [23]. The superplasticizer with a density of 1.15 is used to ensure the flow diameter target of around 18 ± 2 cm (Table 3).

The microstructure of cement, silica fume, and fly ash has been observed using the scanning electron microscopy (SEM) technique, as illustrated in Figs. 3–5, respectively.

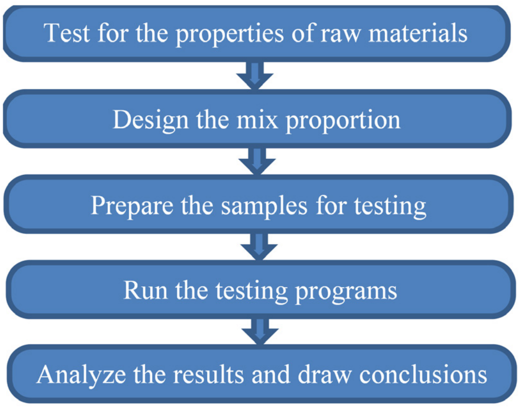

Fig. 1 Experimental procedures

Table 2 Physical and chemical properties of binder materials

Items	Cement	Silica fume	Fly ash
Density (g/cm^3)	3.12	2.21	2.16
Composition (%)			
SiO_2	22.30	90.1	55.73
Al_2O_3	6.68	0.98	21.67
Fe_2O_3	4.73	1.02	6.58
CaO	55.45	0.44	1.06
MgO	2.4	1.86	2.17
SO_3	1.28	0.30	0.01
P_2O_5	0.31	0.14	0.21
LOI	0.45	1.12	6.91

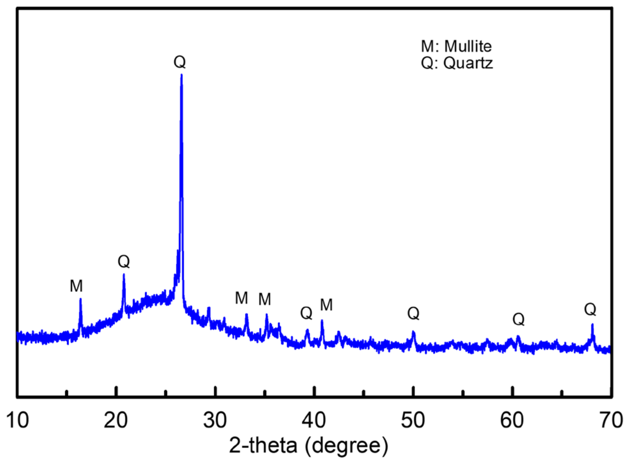

Fig. 2 XRD pattern of FA

Table 3 Mix proportions

Mix	W/B	Mix proportions (kg/m^3)						Flow diameter (cm)
		Cement	SF	FA	Sand	Water	SP	
FA00		845	211	0	1056	211	24	17
FA15		707	208	125	1039	208	23	19
FA30	0.20	572	204	245	1021	204	23	20
FA45		443	201	362	1007	201	20	20
FA60		317	198	476	991	198	19	20

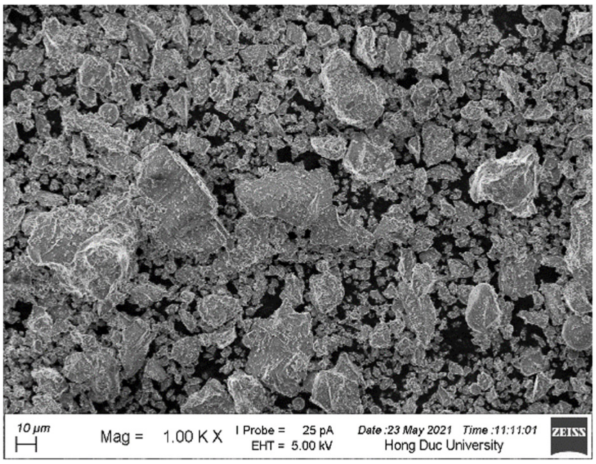

Fig. 3 SEM observation of cement

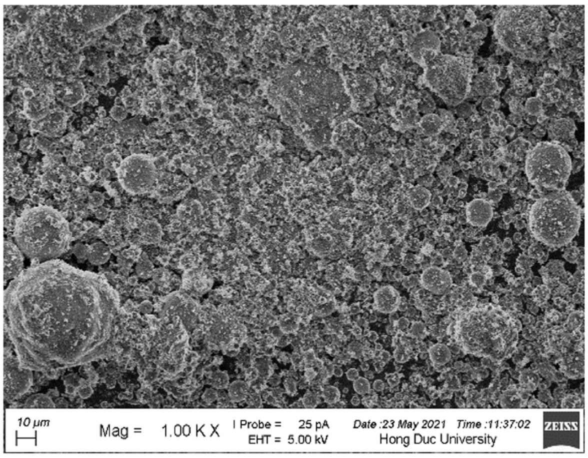

Fig. 4 SEM observation of silica fume

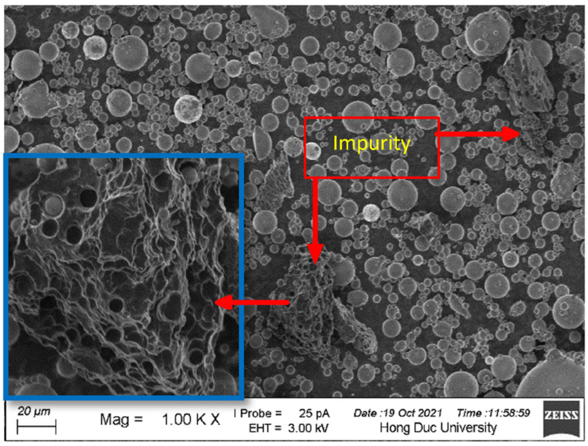

Fig. 5 SEM observation of fly ash

The particle shape of cement is irregular, while fly ash is spherical with different sizes. Silica fume consists of many very fine particles, with some particles have a shape like spherical, as shown in Fig. 4. As aforementioned, some unburnt impurities with high porosity are observed in Fig. 5, which is associated with the high loss on ignition of fly ash.

2.2 Mixture proportions and preparation

An experimental program was carried out in the laboratory to test the mortar specimens using different proportions of fly ash. The reference mixture named FA00 was designed first with a water-to-binder ratio of 0.20 and using only cement and silica fume as binder materials. The silica fume and sand contents are selected as 0.25 and 1.0 total amount of binder materials by mass. After that, four other mixtures were designed by replacing 15, 30, 45, and 60% cement with fly ash, referred to as FA15, FA30, FA45, and FA60, respectively. The proportions of raw materials in these mixtures are shown in Table 3. It is noticed that SP content has been used to control the workability through the flow diameter of 18 ± 2 cm in the mixing process. As illustrated in Fig. 5, fly ash with a spherical shape can increase the workability of mortar. Thus, SP content is slightly reduced by increasing the fly ash content in the mixtures.

The mixing process is similar for all batches of the tested mixture. It consists of two main steps: (i) mixing drying materials for three minutes, (ii) introducing the water and SP, and mixing for several minutes until the homogeneity of the mixture is achieved. After mixing, the homogeneous mortar was poured into the steel molds for specimen fabrication under table vibrating and hand tamping. After 24 hours, the specimens were de-molded and stored in water at room condition until the tests.

2.3 Test methods

After mixing, the fresh mortar properties, such as workability and unit weight, were measured according to ASTM C1437 [26] and ASTM C138 [27], respectively. Next, the three-point bending tests were carried out on the prismatic specimens with the dimensions of 40×40×160 mm to determine the flexural strength of mortar in compliance with ASTM C348 [28]. For each mixture, the flexural strength is the average value of a set of three specimens of the same batch. After each bending test, two half specimens were used to perform the compression test complying with ASTM C349 [29]. Therefore, the compressive strength is an average value of six specimens of the same batch for each mixture. After the compression test, the fracture specimens of mortar were collected to perform the SEM observation.

Water absorption of the mortar specimens was measured according to ASTM C642 [30] using the cubic specimens with the dimensions of 50 × 50 × 50 mm. The cylinder specimens with a diameter of 100 mm and height of 200 mm were used for the ultrasonic pulse velocity (UPV) test complying with ASTM C597 [31] and thermal conductivity tests using the ISOMET-2014 device. The cylinder specimens with a thickness of 50 mm, which were cut from the cylinders of 100 mm diameter and 200 mm height, are used to measure the rapid chloride ion penetration through the total charge passed in coulombs during six hours according to ASTM C1202 [32]. The prismatic specimens with the dimensions of 25 × 25 × 285 mm were used for measuring the drying shrinkage. This test was performed following ASTM C490 [33], and the drying shrinkage values of mortar specimens were recorded for up to 56 days. The flexural strength, compressive strength, and UPV tests were conducted at 3, 7, 14, 28, and 56 days, while water absorption, thermal conductivity, and rapid chloride ion penetration tests were conducted at 28 and 56 days. The values reported herein are the average values of at least three specimens.

3 Result and discussion

3.1 Fresh properties of reactive powder mortar

The unit weights of all fresh mortar mixtures with different proportions of fly ash are presented in Fig. 6. The unit weight of the reference mixture (FA00) is equal to 2.24 T/m^3. When increasing the FA proportion from 0% to 60%, the unit weight of fresh mortar reduced from 2.24 T/m^3 to 2.08 T/m^3. This phenomenon is due to the lower density of fly ash (2.16 T/m^3) than that of cement (3.12 T/m^3) as shown in Table 2. In other words, the replacement of cement with fly ash results in reducing the unit weight of fresh mortar. This finding is similar to the result from a previous study [16]. It is also noticed that the measured unit weight of mortars shown in Fig. 6 is 93–96% of the theoretical unit weight presented in Table 3. This phenomenon is due to the air content, and voids are naturally available inside the mortar specimens; meanwhile, the presented values in Table 3 were calculated based on the specific gravity of raw materials. A lower measured value than a theoretical one has been reported in several studies [3, 34].

On the other hand, with the flow diameter target of 18 ± 2 cm for all mixtures, the SP content is slightly reduced with increasing fly ash content (Table 3). It is noticed that a small amount of water was absorbed by the high porosity impurities in fly ash (Fig. 5), reducing the workability of mortar. However, the spherical shape of fly ash increases the workability of mortar. In this case, the effect of the high loss on ignition of fly ash on the workability of mortar is negligible. Thus, the use of fly ash not only reduces SP content but also reduces the fresh unit weight of mortars.

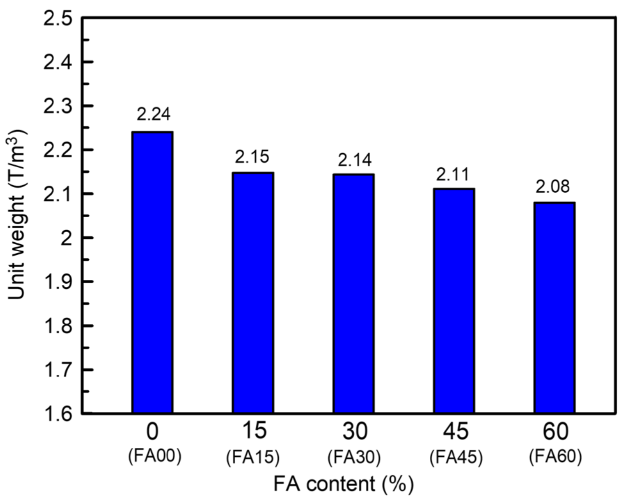

Fig. 6 Effect of FA content on unit weight

3.2 Compressive strength

Fig. 7 shows the compressive strength development of mortars with various fly ash proportions versus time. The 28-day and 56-day compressive strengths of the reference mixture were 98.7 MPa and 109.7 MPa, respectively. Meanwhile, the 28-day and 56-day compressive strengths of fly ash mortars ranged from 40 MPa to 87.9 MPa and 58 MPa to 102.6 MPa, respectively. According to Fig. 7, fly ash content shows a negative effect on the compressive strength of mortars. At any time of the test, the compressive strength of mortars reduced with increasing the fly ash proportion. For example, in the case of a 15% fly ash proportion (mixture FA15), the 28-day compressive strength of the mortar is reduced by 11% compared to that of the reference mortar (mixture FA00) (87.9 MPa versus 98.7 MPa). In the case of a 60% fly ash proportion, the 28-day compressive strength of the mortar significantly decreased up to 40% in comparison to the reference mixture. This finding is similar to experimental results from

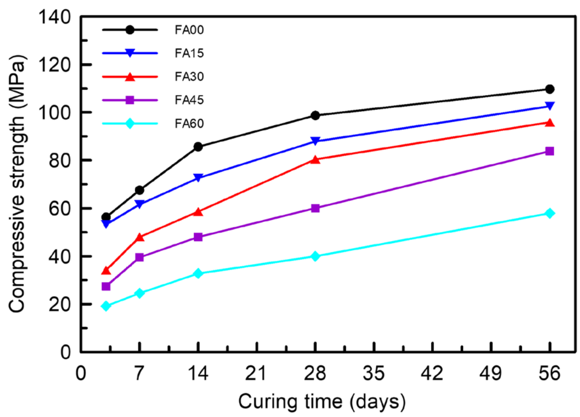

Fig. 7 Effect of FA content on compressive strength

a study conducted by Yiğiter et al. [35], in which the compressive strength of RPC is reduced by around 36% since using fly ash to replace 60% cement in the RPC. It is noticed that the fly ash used in Yiğiter's study [35] had a loss on ignition of 1.3%, significantly lower than that of fly ash used in the present study (6.91%). Hence, the compressive strength degradation rate of fly ash mortars in this study is slightly higher than that in Yiğiter's study. Moreover, in comparison with the concrete produced with high loss-on-ignition fly ash from a previous study [15], the compressive strength of the mortar in this study is significantly higher. This outcome is due to the addition of silica fume in the mix proportion.

In the beginning, the mortar with high FA content (FA45 and FA60) shows a significantly lower compressive strength than others. After 28 days, these mixtures exhibited a significant increase rate in compressive strength. In general, the reduction in compressive strength of fly ash mortar is attributable to insufficient progress of pozzolanic reaction [35], especially for fly ash with high loss in ignition used in the present study. Furthermore, the main compositions of fly ash used are quartz and mullite, which exist in crystalline form with lower activity than in the amorphous form [10]. The pozzolanic reaction of fly ash slowly happens in the beginning ages, but that strongly occurs in the more prolonged stage [36]. Although the compressive strength of mortar decreases with increasing fly ash content, all fly ash mixtures have a 28-day compressive strength of higher than 60 MPa, except the FA60 mixture. The maintenance of this high strength is due to the use of silica fume to compensate for the strength loss caused by the effect of fly ash with a high loss on ignition. To produce a mortar with a compressive strength of higher than 60 MPa, the recommended fly ash proportion for practical use is not more than 45%.

3.3 Flexural strength

Fig. 8 shows the flexural strength of all mortars with different proportions of fly ash. Similar to compressive strength, the flexural strength of mortars decreased when increasing fly ash content. For example, at 56 days, the flexural strength of mortar reduced from 14.5 MPa to 9.8 MPa, corresponding to fly ash proportion increased from 15% to 60%. The low flexural strength of fly ash mixtures is related to pozzolanic reaction and the quality of local fly ash used in this study, as aforementioned, which will be clarified in the next section. The flexural strength of those mortars in this study ranges from 9.8 MPa to 17.1 MPa,

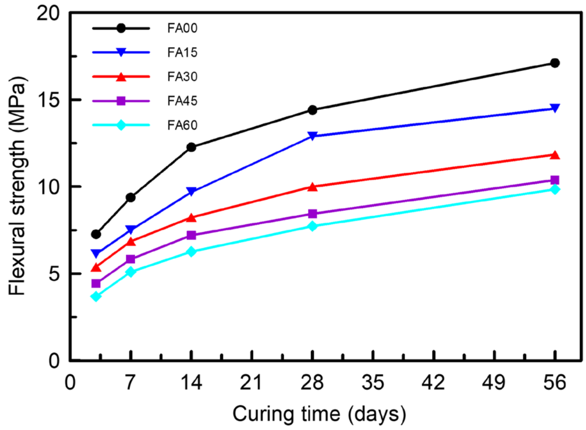

Fig. 8 Effect of FA content on flexural strength

similar to the flexural strength of mortars cured in the standard condition tested by Erdogdu et al. [18], but this is lower than those values reported by Yiğiter et al. [35]. This is because the samples in Yiğiter's study were cured under autoclave conditions with pre-pressure and high temperature, while the samples in the present study were cured in water as the standard condition. On the other hand, the flexural strength of concrete produced with high loss-on-ignition fly ash in the previous study [15] was around 2.7-6.3 MPa, significantly lower than reported values from the present study. Again, this finding is due to the presence of silica fume.

3.4 SEM observation

The microstructures of mortars with fly ash replacement levels of 0%, 30%, and 60% are shown in Figs. 9, 10, and 11, respectively. For the reference sample with free-fly ash (Fig. 9), some free silica fume particles (with shapes like spherical) are observed. It proves that a few silica fumes did not join the hydrate reaction to form C-S-H gels under standard conditions. Therefore, the compressive strength and flexural strength of mortars in this study were lower than those in the previous studies [13, 35]. It is noticed that the RPC samples in previous studies were cured under autoclave conditions with pre-pressure and high temperature, thus most binders were activated, resulting in high compressive and flexural strengths. Meanwhile, the mortar samples in the present study were cured in water as a standard condition. Moreover, some unburnt impurities in fly ash are recognized in Fig. 10. When the fly ash replacement level increased up to 60%, many unreacted fly ash particles are detected in Fig. 11. Besides the low activity of fly ash used in this study, these findings are related to the decrease in the compressive strength and flexural strength of fly ash mortars as aforementioned.

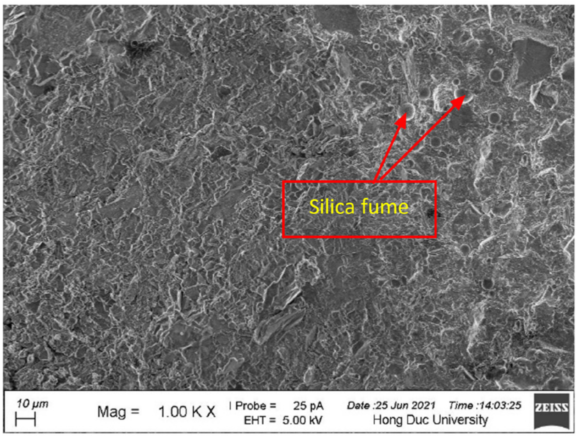

Fig. 9 SEM micrograph of FA00

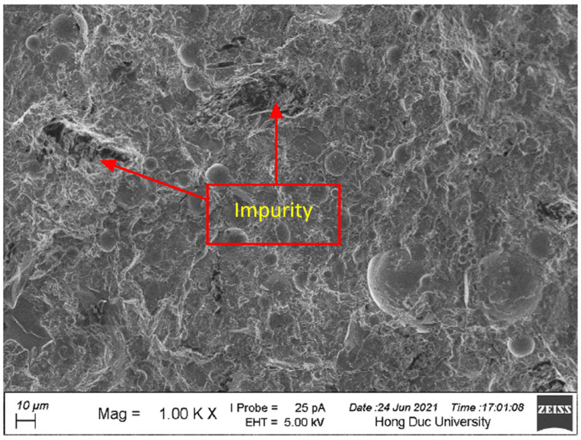

Fig. 10 SEM micrograph of FA30

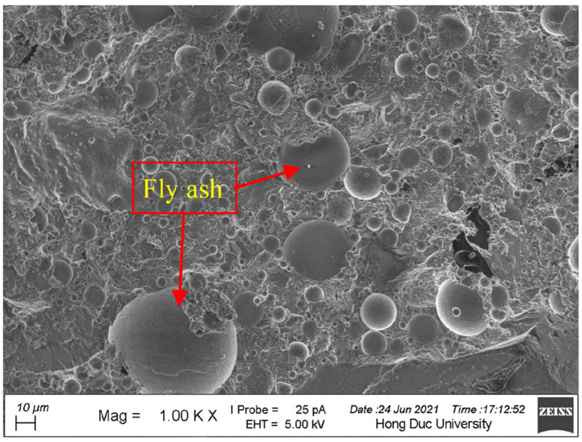

Fig. 11 SEM micrograph of FA60

3.5 Ultrasonic pulse velocity

In order to evaluate the relative quality of hardened mortar related to the mechanical and durability properties, the ultrasonic pulse velocity (UPV) test was used. The UPV results are presented in Fig. 12 for all tested mortars at 28 and 56 days. The UPV values ranged from 4168 to 4467 m/s, corresponding to the compressive strengths at 28

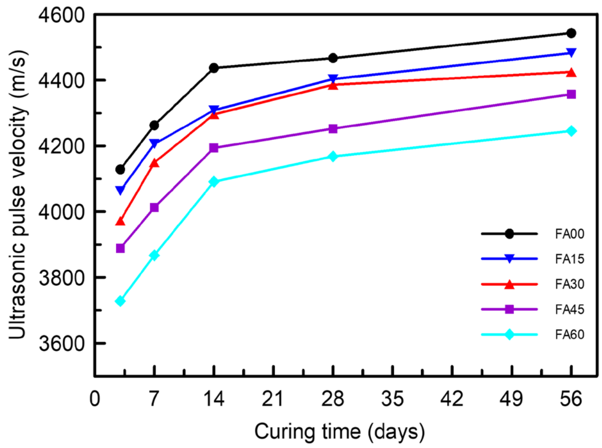

Fig. 12 Effect of FA content on UPV

days ranging from 40 to 98.7 MPa. Based on the study conducted by Solís-Carcaño and Moreno [37], if the UPV value is higher than 4100 m/s, the concrete is considered of high quality regardless of the quality of the aggregates used. In other words, all mortars produced in this study have a good quality with UPV values higher than 4100 m/s. According to Fig. 12, the UPV values reduced when the fly ash proportion increased. As stated in a study conducted by Bogas et al. [38], the UPV values of concrete are strongly related to its density and compressive strength. In this study, the reference mortar had the highest unit weight, showing the highest UPV value. Increasing fly ash content reduces the unit weight of mortars, resulting in a decrease in UPV values. On the other hand, the high porosity of impurities in fly ash may also negatively influence the UPV value of mortars.

3.6 Correlation between compressive strength, flexural strength, and UPV

As mentioned above, the mortar strengths (compressive and flexural strength) and UPV values have close relationships. Therefore, the relative quality of mortars is possibly evaluated through UPV values. Fig. 13 shows the correlations between UPV and compressive strength, while Fig. 14 shows the relationship between UPV and flexural strength. As compressive or flexural strength increases, the UPV value of mortar also increases. These relationships are described by linear regressions, with the coefficients of determination ranging from 0.84 to 0.99. The results show that the compressive strengths of fly ash mortars are strongly related to their UPV values at 28 and 56 days. It demonstrates that the ultrasonic technique is a potential non-destructive method for assessing the mechanical properties (e.g., compressive strength, flexural

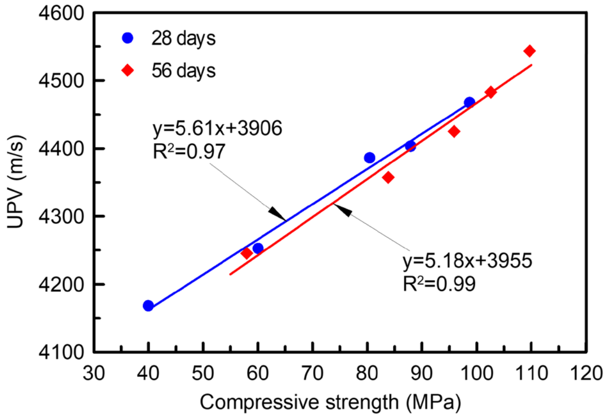

Fig. 13 Correlation between UPV and compressive strength

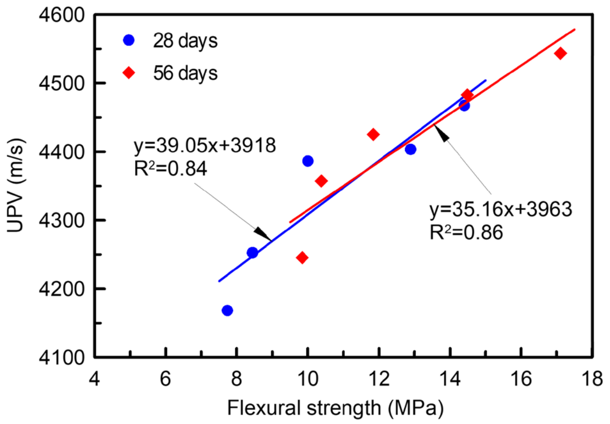

Fig. 14 Correlation between UPV and flexural strength

strength) of high-strength mortars, especially when the fly ash replacement level is not controlled, and the number of casted or core specimens is limited. Figs. 13 and 14 are also used to predict the compressive and flexural strength of high-strength mortars based on UPV values.

3.7 Water absorption

Permeability is a crucial durable property of mortar that is indirectly reflected through water absorption. The mortars with low water absorption will have a high resistance to chemical attacks from deteriorative substances. Fig. 15 shows the water absorption of all tested mortars at 28 and 56 days of age. For the reference mortar, the water absorption was equal to 2.5% on average at 28 days and decreased to 1.5% at 56 days. The water absorption of all mortars in this study ranged from 2.5-5.2% and 1.5-4.9% at 28 and 56 days of age, respectively, which are low values, indicating good impermeable capacity. The presence of fly ash induces an increase in water absorption of mortars, from 3.7% to 5.2% for the measurements at 28 days, when the fly ash replacement level ranges from 15% to 60% in the mixture. The negative effect of fly ash on the water absorption of mortars is likely due to unreacted fly ash and unburnt impurities. With a high porosity, the impurities absorbed water, causing an increment in the water absorption of fly ash mortars. However, with very fine particles, silica fume can fill the void inside mortars, reducing its water absorption. Thus, all mortars in this study have a low water absorption capacity.

The water absorption is reduced for the measurements carried out on the specimens at 56 days compared to the measured values at 28 days. It can be explained that the mortar's compressive strength developed with curing time due to forming hydration products, then the microstructure of mortars is consequently denser. At this time, the reduction in water absorption of mortars using a 15–30% fly ash replacement level is observed.

3.8 Rapid chloride ion penetration

The rapid chloride ion penetration (RCPT) test was conducted to examine the resistance capacity of mortars to chloride attack. Fig. 16 shows the measured results of the

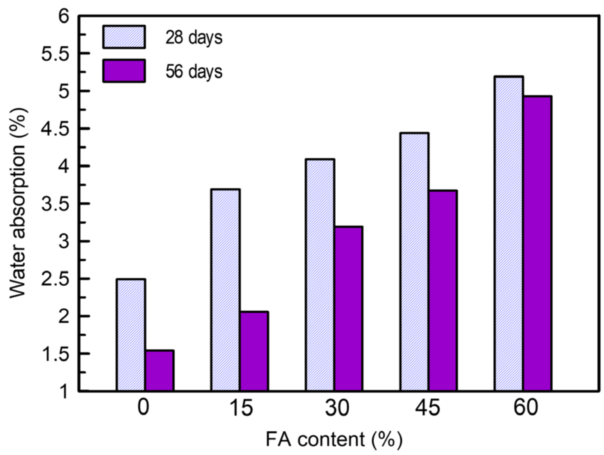

Fig. 15 Effect of FA content on water absorption

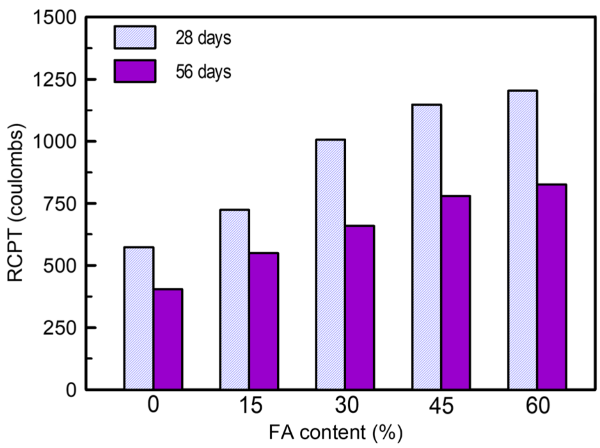

Fig. 16 Effect of FA content on RCPT

RCPT test at 28 and 56 days. The RCPT values of mortar specimens at 28 days are significantly higher than those of the identical specimens at 56 days. The microstructure of mortars is denser along with curing time due to the formation of hydration products. Therefore, the mortar specimens become more impermeable and can prevent the penetration of chloride ions into themselves. On the other hand, the reference mortar had a lower RCPT value than the mortar made with fly ash at any time. The unreacted fly ash and unburnt impurities negatively affected the properties of mortars as well as the RCPT results. However, the presence of silica fume reduces their negative effect on the RCPT of mortars. As a result, the RCPT values of all mortars tested in this study are lower than 1500 coulombs, which is a low chloride ion penetration level according to American standard ASTM C1202 [32].

3.9 Drying shrinkage

The drying shrinkage can be considered a fundamental problem of reactive powder products due to the use of high cement and silica fume content [39], which causes the formation of micro-cracks and affects the durable properties of mortar. Fig. 17 shows the drying shrinkage values of all mortars tested up to 56 days. The measured values show that the drying shrinkage increased rapidly from the first measurement to 14-day curing. Next, it continued increasing with a slow rate from 28-day curing. With the high cement content, the reference mixture (FA00) showed the highest drying shrinkage compared to fly ash mixtures at any time. It means that the drying shrinkage of mortar is reduced with increasing fly ash proportion. It can be explained that the presence of fly ash caused the lower hydration rate of cementitious paste in concrete [40], leading to low heat release and low drying shrinkage. Thus, the use of fly ash is an interesting solution for reducing the drying shrinkage that contributes to the limitation of earlier cracks in the mortar.

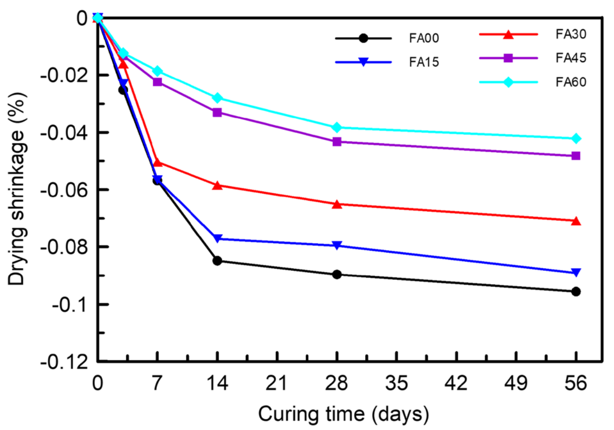

Fig. 17 Effect of FA content on drying shrinkage

3.10 Thermal conductivity

Fig. 18 shows the obtained results of the thermal conductivity test under saturated surface dry conditions for all mortars at 28 and 56 days. These values range from 1.4 to 2.0 W/m.K. There is no considerable difference in the measured values between 28 and 56 days of age. In general, the thermal conductivity reduced with increasing the proportion of fly ash. However, the reduction becomes significant if the cement replacement level is more than 30%. As a finding from a previous study [41], the thermal conductivity of concrete is related to its density. Therefore, the reference mixture (FA00) with the highest unit weight showed the highest thermal conductivity, and the fly ash mixtures with a lower unit weight yielded a lower thermal conductivity than the reference mixture. In addition, the high porosity of impurities in fly ash may cause the degradation of the thermal conductivity of fly ash mortars.

4 Conclusions

In this study, the use of fly ash with a high loss on ignition (over 6%) in the production of high-flowability and high-strength mortars is investigated. This study aims to produce mortars with a flow diameter of 18 ± 2 cm and compressive strength higher than 60 MPa. Some brief conclusions based on experimental work are summarized as follows:

1. Despite the negative effect of impurities in high loss-on-ignition fly ash, the workability of mortar increased slightly with increasing fly ash content.

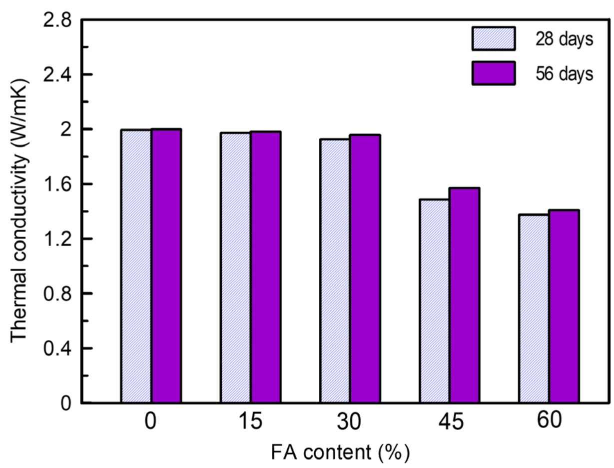

Fig. 18 Effect of FA content on thermal conductivity

2. The benefit of using high loss-on-ignition fly ash is that it reduces the unit weight, thermal conductivity, and drying shrinkage of mortars.
3. Although the use of raw fly ash with a high loss on ignition could reduce some properties of mortars, all fly ash mortars tested in this study still showed a good quality through the 56-day compressive strength of 58–102.6 MPa, the flexural strength of 9.8–14.5 MPa, UPV of above 4100 m/s, water absorption of 1.5–4.9%, and high resistance to chloride attack. It means that the fly ash with a high loss on ignition could be used to replace a part of cement in producing high-flowability and high-strength mortars with the addition of silica fume.
4. The correlations between compressive strength and flexural strength with UPV were described by linear regressions, which were used to estimate the mortar's compressive and flexural strengths based on UPV values in a non-destructive method.
5. To produce a mortar with a 28-day compressive strength of higher than 60 MPa, the fly ash proportion is recommended not to exceed 45%.

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