Journal of Marine Science and Technology

Volume 27 | Issue 2 Article 9

INFLUENCE OF FLY ASH FINENESS AND HIGH REPLACEMENT RATIOS ON CONCRETE PROPERTIES

Shihwen Hsu
Department of Fire Science, WuFeng University, Chiayi County, Taiwan, R.O.C

Maochieh Chi
Department of Harbor and River Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C., jackchi@wfu.edu.tw

Ran Huang

Journal of Marine Science and Technology, Vol. 27, No. 2, pp. 161-169 (2019)
DOI: 10.6119/JMST.201904_27(2).0009

INFLUENCE OF FLY ASH FINENESS AND HIGH REPLACEMENT RATIOS ON CONCRETE PROPERTIES

Shihwen Hsu[1], Maochieh Chi[2], and Ran Huang[3]

Key words: fly ash, fineness, cement replacement ratio, rapid chloride penetration test, mercury intrusion porosimetry.

ABSTRACT

The influence of fly ash (FA) fineness and a high cement replacement ratio on concrete properties was investigated. Class F FA with an original fineness of 3,150 cm^2/g (3F) and a high fineness of 5,690 cm^2/g (5F) was used; high cement replacement ratios of 30%, 40%, 50%, and 60% by FA with different levels of fineness (two groups: 3F30, 3F40, 3F50, 3F60, and 5F30, 5F40, 5F50, 5F60 by weight of cement) were selected to produce the blended cement concrete. Tests regarding the heat of hydration, compressive strength, water absorption, rapid chloride penetration, and Mercury intrusion porosimetry were performed. The FA with fineness of 5,690 cm^2/g improved concrete properties more effectively than did the FA with fineness of 3,150 cm^2/g. The compressive strengths of concretes with FA of 40% or less (3F30, 5F30, 5F40) were higher than that of ordinary Portland cement at 91 days. This indicates that the cement replacement ratio by FA should not exceed 40%. The incorporation of FA reduced the maximum heat of hydration, total charge passed, and capillary pores of concrete. Based on the results, FA concrete with fineness of 5,690 cm^2/g and a cement replacement ratio of 40% had the most influential properties.

I. INTRODUCTION

Fly ash (FA) is an industrial byproduct generated in electric power plants during the combustion of coal for energy production. The use of FA as a supplementary cementitious material (SCM) is increasing gradually because of its excellent structural performance, environmental kindliness, and energy conservation (Berry and Malhotra, 1982; Soni and Saini, 2014). FA has a spherical and smooth surface, which can lead the ball bearing and filling effects to enhance the interfacial zone between the aggregate and matrix. Thus, the addition of FA as a binder reduces capillary pores and increases the compressive strength of pastes, mortars, or concrete (Slanička, 1991; Payá et al., 1995; Prinya Chindaprasirt, Jaturapitakkul, and Sinsiri, 2005; Ahmaruzzaman, 2010). Moreover, the incorporation of FA within Portland cement causes a pozzolanic reaction between the active SiO_2 and Al_2O_3 of the FA and the $Ca(OH)_2$ produced through cement hydration. The formation of additional C-S-H and C-A-H (Calcium-Silicate Hydrates Containing Aluminium) gels results in a higher compressive strength and increased durability (Liu et al., 2000; Kiattikomol et al., 2001; Tangpagasit et al., 2005; Fanghui et al., 2015; Saha, 2018). Saha (2018) reported that concrete with FA as a binder reduced the porosity and minimized water sorptivity and chloride permeability.

Kiattikomol et al. (2001) revealed that FA fineness was the main factor affecting the strength activity index of FA-cement mortar. The use of finer FA leads to more favorable mechanical properties of concrete as compared with coarse FA (Erdoğdu and Türker, 1998; Chindaprasirt et al., 2004; Arel and Shaikh, 2018). In general, increasing the fineness of FA could increase the hydration reaction of the binder and thus increase the compressive strength of the FA mortar or concrete (Kiattikomol et al., 2001; Prinya Chindaprasirt et al., 2005; Fanghui et al., 2015; Somna, Jaturapitakkul, and Amde, 2012; Feng, Sun, and Yan, 2018; Arel and Shaikh, 2018). Finer FA has a higher specific surface area; it is more reactive and has a greater pozzolanic index to consume more lime at a certain stage (Myadraboina et al., 2017).

Apart from FA fineness, the FA cement replacement ratio also has a considerable influence on the properties of blended cement mortar or concrete (Chindaprasirt et al., 2005; Mehta and Monteiro, 2006; Sinsiri et al., 2010; Fanghui et al., 2015; Hsu et al., 2018). Concrete with high-volume FA (HVFA) has recently received increasing attention as an ecologically friendly concrete. However, one disadvantage of using FA is the slow development of early compressive strength, especially in HVFA concrete. The early compressive strength decreases if the replacement ratio exceeds 40% in FA concrete, because the amount of lime is insufficient to react with the large quantity of pozzolana in HVFA concrete (Mehta and Monteiro, 2006; Myadraboina et al., 2017). A 15%-25% FA replacement level is recommended for normal-

Paper submitted 12/19/18; revised 01/24/19; accepted 03/27/19. Author for correspondence: Maochieh Chi (e-mail:jackchi@wfu.edu.tw).
[1] Department of Fire Science, WuFeng University, Chiayi County, Taiwan, R.O.C.
[2] Department of Harbor and River Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.

strength concrete by the American Concrete Institute (ACI Committee 211, 2008). However, some studies (Carette, A, Chevrier, and Malhotra, 1993; Malhotra and Mehta, 2002) have revealed that concrete with 50% or more cement replaced by FA can produce sustainable, high-performance concrete mixtures. Thus, the problems of cement replacement by FA and low early compressive strength require solutions.

Despite the fact that the effects of the fineness and cement replacement ratio of FA on the properties and durability of mortar or concrete have been addressed by previous researchers (P. Chindaprasirt, Chotithanorm, Cao, and Sirivivatnanon, 2007; Zhao, Sun, Wu, and Gao, 2015; Myadraboina et al., 2017; Thomas, 2018), whether the coarse fraction of FA can take part in a pozzolanic reaction and whether FA fineness influences the physical properties, pore structure, and microstructure of concrete remain unclear. Hsu et al. (Hsu et al., 2018) investigated the effect of ground FA fineness and the replacement ratio on the properties of blended cement mortar with three fineness values of 4,610 cm^2/g, 5,690 cm^2/g, and 6,300 cm^2/g and four replacement ratios of 0%, 10%, 15%, and 20% by weight of cement. The highest compressive strength, lowest water absorption, and smallest porosity were obtained for the mortar with a fineness of 5,690 cm^2/g and a 20% replacement ratio of FA. Therefore, it is possible to maximize the cement replacement ratio of FA with a fineness of 5,690 cm^2/g. In this study, FA with a fineness of 5,690 cm^2/g and cement replacement ratios of 30%, 40%, 50%, and 60% of FA were selected to present an advanced understanding of the influence of FA fineness and a high replacement ratio on the heat of hydration, compressive strength, water absorption, rapid chloride-ion penetration, and porosity of FA concrete.

II. EXPERIMENTAL PROGRAM

1. Materials

Type I Ordinary Portland cement (OPC) conforming to American Society for Testing and Materials (ASTM) C 150, Type I ("ASTM C 150. Standard Specification for Portland Cement. American Society for Testing and Materials," 2017) was used. The specific gravity was 3.14 and its specific surface area was 3650 cm^2/g. Class F FA according to ASTM C 618 ("ASTM C 618. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. American Society for Testing and Materials," 2015) was used to replace the OPC. FA with two fineness values, original FA (OFA) with a specific surface area of 3,150 cm^2/g and ground FA (GFA) with a surface area of 5,690 cm^2/g, was obtained from the Mailiao Six Light Naphtha Cracker Plant in Yunlin County, Taiwan. The abbreviations 3F and 5F were used to identify the fineness values of FA of 3,150 cm^2/g and 5,690 cm^2/g, respectively. The specific gravity and specific surface area of OPC and FA are listed in Table 1.

The cumulative passing percentage curves for cement and FA with fineness of 3,150 cm^2/g (3F) and 5,690 cm^2/g (5F) are displayed in Fig. 1. The particle size distributions (PSDs) for cement, 3F, and 5F were determined through laser diffraction particle size analysis; the PSD curves are illustrated in Fig. 2. As shown in Fig. 2, Cement (OPC) has a two-modal distribution, and it is characterized by d_{10} = 1.93 μm, d_{50} = 15.96 μm, and d_{90} = 36.88 μm, which are finer than the FA with a fineness of 3,150 cm^2/g (3F) used in this work. FA with a fineness of 3,150 cm^2/g (3F) also has a two-modal distribution, which is characterized by d_{10} = 2.78 μm, d_{50} = 31.96 μm, and d_{90} = 83.01 μm. FA with a fineness of 5,690 cm^2/g (5F) has a lognormal distribution, which is characterized by d_{10} = 0.96 μm, d_{50} = 3.02 μm, and d_{90} = 8.35 μm. It is evident that FA with a fineness of 5,690 cm^2/g (5F) is finer than the others, with more than 90% of particles less than 10 μm. Chindaprasirt et al. (P. Chindaprasirt et al., 2004) noted that the high fineness is normally positive for the pozzolanic reactivity of the material and

Table 1. Specific gravity and specific surface area of OPC and FA.

Physical properties	OPC	3F*	5F*
Specific gravity	3.14	2.18	2.58
Specific surface area (cm^2/g)	3,650	3,150	5,690

* The abbreviations 3F and 5F were used to identify the fineness values of FA of 3,150 cm^2/g and 5,690 cm^2/g, respectively.

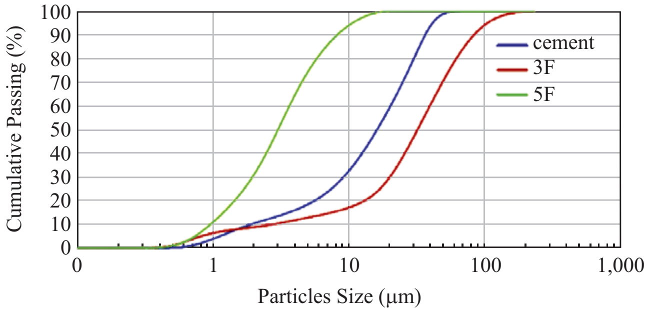

Fig. 1. Cumulative passing percentage curves for cement and FA with fineness of 3,150 cm^2/g (3F) and 5,690 cm^2/g (5F).

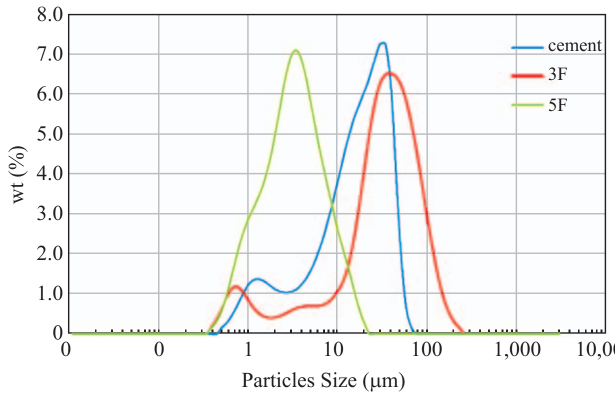

Fig. 2. Particle size distribution curves for cement and FA with fineness of 3,150 cm^2/g (3F) and 5,690 cm^2/g (5F).

Table 2. Chemical compositions of OPC and FA*.

Chemical compositions (%)	OPC	FA
Calcium oxide, CaO	62.0	6.6
Silicon dioxide, SiO_2	19.7	53.4
Aluminum oxide, Al_2O_3	4.7	25.1
Ferric oxide, Fe_2O_3	3.0	6.8
Sulfur trioxide, SO_3	2.7	0.6
Sodium oxide, Na_2O	0.3	0.3
Potassium oxide, K_2O	0.7	0.8
Magnesium oxide, MgO	4.6	2.0
Loss on ignition, L.O.I.	1.4	2.8
Others	0.9	1.6

*The percentage of free lime within FA is approximately 4.35%.

Table 3. Mix proportions of OPC and FA concrete (kg/m^3).

Mix No.	Water	Cement	FA	Sand.	CA*	Slump (cm)
OPC	203	420	0	792	946	15
3F30	203	294	126	739	946	18.5
3F40	203	252	168	722	946	18
3F50	203	210	210	704	946	13
3F60	203	168	252	687	946	12
5F30	203	294	126	739	946	18
5F40	203	252	168	722	946	16
5F50	203	210	210	704	946	12
5F60	203	168	252	687	946	11.5

*CA: coarse aggregate

the packing effect as well as for filling the voids in the cement matrix.

Table 2 lists the chemical compositions of Type I OPC and FA, respectively. The sum of the major elements in FA—SiO_2, Al_2O_3, Fe_2O_3, and SO_3—represented 85.9% of the composition (over 70%), and CaO represented 6.6% of the chemical composition of FA (less than 10%), which was classified as Class F in accordance with ASTM C 618 ("ASTM C 618. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. American Society for Testing and Materials," 2015).

River sand with gradations conforming to ASTM C33 ("ASTM C33-18 Standard Specification for Concrete Aggregates, American Society for Testing and Materials," 2018) was used as fine aggregate with a density of 2,530 kg/m^3, a fineness modulus of 3.1, and water absorption of 1.86%. The coarse aggregate used was crushed stone with a density of 2,320 kg/m^3 and a fineness modulus of 6.25. The water absorption was 1.24%, and its relative density at the saturated surface-dry condition was 2.68. Tap water provided from the city waterworks of Taipei City in Taiwan was used in this study.

2. Mix Design and Specimen Preparation

Table 3 lists the mix proportions of the OPC and FA concrete. FAs with fineness of 3,150 cm^2/g (3F) and 5,690 cm^2/g (5F) were used to replace OPC at the dosage levels of 0%, 30%, 40%, 50%, and 60% by weight of binder. A water-to-binder ratio (W/B) of 0.485 was selected for all mixes. OPC and FA binders of 420 kg/m^3 were used to design the mix according to ASTM C 192 ("ASTM C 192. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. American Society for Testing and Materials," 2016). These mixes were designated as OPC for the control mix and 3F30, 3F40, 3F50, and 3F60 for the blended cement mixes with FA fineness of 3,150 cm^2/g and cement replacement ratios of 30%, 40%, 50%, and 60%, respectively; blended cement mixes with FA fineness of 5,690 cm^2/g and cement replacement ratios of 30%, 40%, 50%, and 60%, respectively, were designated as 5F30, 5F40, 5F50, and 5F60. First, the dry ingredients were mixed in the required

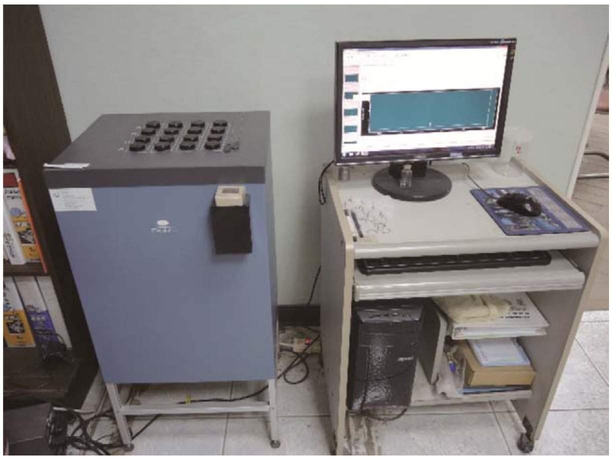

Fig. 3. Setup of an isothermal calorimeter to measure the heat of hydration.

proportions to obtain a uniform mix; subsequently, water was gradually added to the mix, and the specimens were cast. After 24 hours, the prepared specimens were demolded and cured at a temperature of 23°C ± 2°C and relative humidity of 70% ± 5%. The specimens were tested in triplicate sets until the time of testing. As listed in Table 3, the results of the slump obtained for all concrete mixes ranged from 11.5 to 18 cm. The slump of the concrete mixes with FA decreased with an increasing amount of FA. When the cement replacement ratio of FA was over 50%, the slump of the mixes was lower than that of the OPC mix, which had a slump of 15 cm.

3. Methods

1) Heat of Hydration

The heat of hydration was measured in accordance with ASTM C186 ("ASTM C186 Standard Test Method for Heat of Hydration of Hydraulic Cement, American Society for Testing and Materials," 2017; Maage, 1986). The setup of an isothermal conduction calorimeter interfaced with a computer using an automated data acquisition system is illustrated in Fig. 3. Each test was performed on a 10-g sample. The sample was placed into a copper cup with the calorimeter and kept for 48 hours to reach temperature stability. Subsequently, the required amount of water equilibrated in a syringe was injected into the cup. The rates of heat evolution, dQ/dt in mW/g of pozzolana, were measured and recorded by the automated data acquisition system. The total heats evolved were calculated using a combination of the areas under the rate curves.

2) Compressive Strength Test

The compressive strength of concrete was tested in accordance with ASTM C39 ("ASTM C 39. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. American Society for Testing and Materials," 2016). Concrete cylinders ø100 × 200 mm^2 in size were cast and tested at 7, 28, 56, and 91 days. Three specimens of each age were prepared and tested for each mix.

3) Water Absorption

The water absorption of concrete was evaluated in accordance with ASTM C642 ("ASTM C642. Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. American Society for Testing and Materials," 2013). Concrete cylinders ø100 × 200 mm^2 in size were cast and cured at 56 days. After the required curing period, the specimens were dried at 105°C ± 5°C for 24 hours and then cooled, and the dry weight (W_d) was measured. Afterward, the specimens were immersed in water at room temperature until they reached a constant weight, and the saturated weight (W_s) was recorded. The water absorption was computed as follows:

$$WaterAbsorption : WA(\%) = \frac{w_s - w_d}{w_d} \times 100 \qquad (1)$$

where w_d is the weight of the dried specimens before the test, and w_s represents the weight of the dried specimens immersed in water for 24 h.

4) Rapid Chloride Penetration Test

The rapid chloride penetration test (RCPT) of concrete was performed in accordance with ASTM C1202 ("ASTM C 1202. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. American Society for Testing and Materials," 2012). A vacuum-saturated concrete specimen 100 mm in diameter and 50 mm in thickness at the age of 28 or 56 days was placed between two acrylic cells. One cell was filled with a 3.0% NaCl solution, and the other cell was filled with a 0.3 M NaOH solution. A potential voltage of 60 ± 0.1 V was applied for 6 hours. The total charge passed was measured. The recommended chloride-ion penetrability of concrete based on the charge passed is presented in Table 4.

Table 4. Chloride-ion penetrability based on the charge passed recommended by ASTM C 1202.

Charge passed	Chloride-ion penetrability
> 4000	High
2000 ~ 4000	Moderate
1000 ~ 2000	Low
100 ~ 1000	Very low
< 100	Negligible

5) Mercury Intrusion Porosimetry

Mercury intrusion porosimetry (MIP) was performed in accordance with ASTM D4404 ("ASTM D4404 Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry. American Society for Testing and Materials," 2010; Ma, 2014). Specimens 10 × 10 mm^2 were prepared. The volume intruded at each pressure increment was measured to determine the pore size distribution and calculate the total porosity. The drying of samples to remove free water was required before MIP. First, the samples were oven-dried at 105°C for 24 hours after which they were maintained in a desiccator until testing time. The capillary diameter was computed as follows (Kumar and Bhattacharjee, 2003):

$$\text{capillary diameter} : d = \frac{-\Phi \gamma \cos\theta}{p} \qquad (2)$$

where Φ is the shape factor of pores, γ is the surface tension of mercury, and θ and p represent the contact angle of mercury with the solid and applied pressure, respectively.

III. RESULTS AND DISCUSSION

1. Heat of Hydration

The heat of hydration is the heat produced by the mix of Portland cement and water and its subsequent reaction. Generally, hydration heat is not easily released in massive concrete structures such as dams that are subject to high temperatures and extreme stresses. Figs. 4 and 5 exhibit the heat of hydration of the OPC and FA specimens with fineness of 3,150 cm^2/g (3F) and 5,690 cm^2/g (5F) at various cement replacement ratios. As illustrated in Fig. 4, the OPC had a maximum heat of hydration of 2.35 Mw/g, which was higher than that for any other specimen. The maximum heat of hydration for the FA specimens with fineness of 3,150 cm^2/g decreased with an increase of the cement replacement ratio. The maximum heat of hydration for 3F30, 3F40, 3F50, and 3F60 specimens was 1.81, 1.43, 1.19, and 1.03 Mw/g, which is 77.0%, 60.9%, 50.6%, and 43.8% of that of the OPC specimen (2.35 Mw/g), respectively. The incorporation of FA as a cement replacement can reduce the maximum temperature increase in mortar and concrete (Arito, 2018; Choi, Lee, and Monteiro, 2012).

As indicated in Fig. 5, the maximum heat of hydration for FA specimens with fineness of 5,690 cm^2/g also decreased with an increase in the cement replacement ratio. The maximum heat of hydration for the 5F30, 5F40, 5F50, and 5F60 specimens was 1.73, 1.54, 1.33, and 1.18 Mw/g, which is 73.6%, 65.5%,

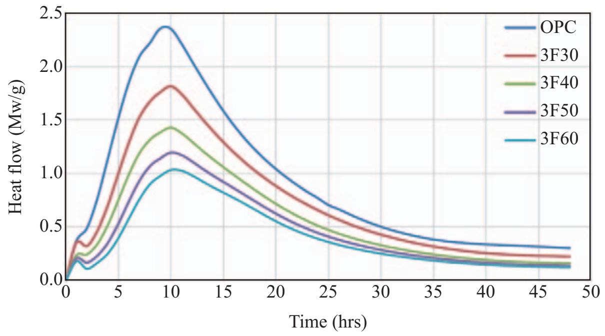

Fig. 4. Heat of hydration of OPC and FA specimens with fineness of 3,150 cm^2/g (3F) at various cement replacement ratios.

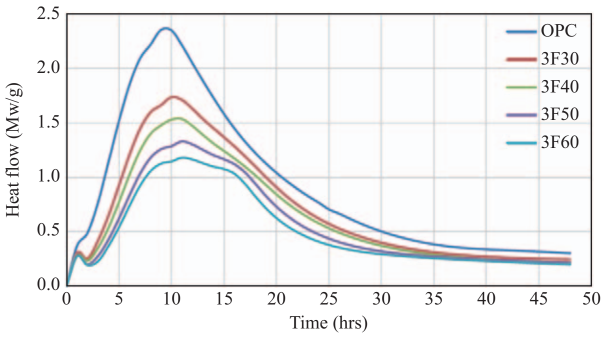

Fig. 5. Heat of hydration of OPC and FA specimens with fineness of 5,690 cm^2/g (5F) at various cement replacement ratios.

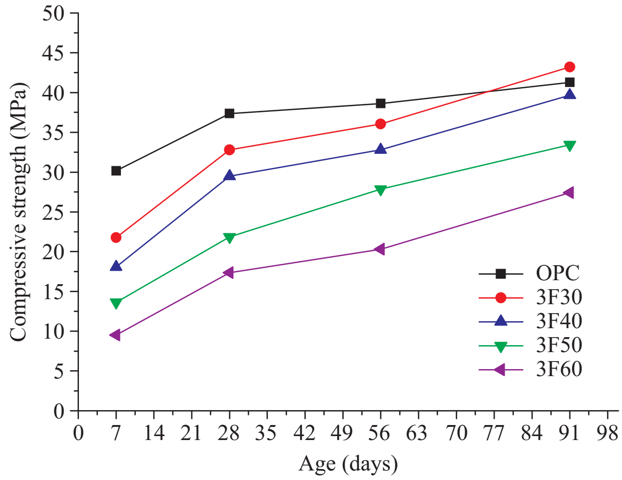

Fig. 6. Compressive strength development of OPC and FA concrete with fineness of 3,150 cm^2/g (3F) at various cement replacement ratios.

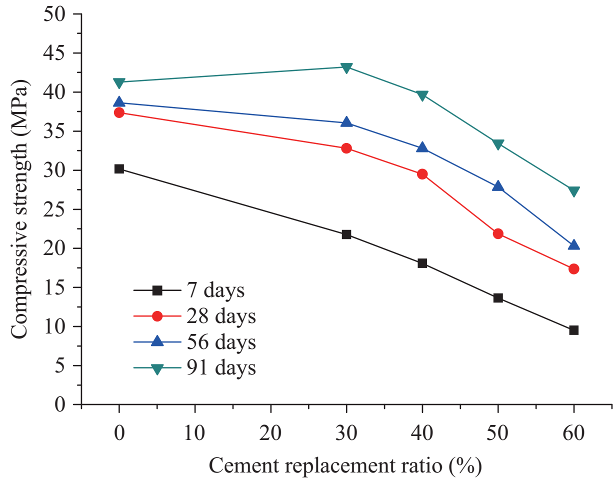

Fig. 7. Compressive strength of the concrete with FA fineness of 3,150 cm^2/g (3F) at various cement replacement ratios.

56.6%, and 50.2% of that of the OPC specimen (2.35 Mw/g), respectively. For FA specimens with the same cement replacement ratio, the maximum heat of hydration increased with an increase in FA fineness, but the increase was negligible. Based on these results, the cement replacement ratio of FA has a significant influence on the heat of hydration regardless of the FA fineness; this finding is consistent with previous research (Choi et al., 2012; Han, Liu, Wang, and Yan, 2014). As the cement replacement ratio increased, the maximum heat of hydration obtained decreased.

2. Compressive Strength

Figs. 6 and 7 present the compressive strength development for OPC and FA concrete with fineness of 3,150 cm^2/g (3F) at various cement replacement ratios. A higher compressive strength was obtained for OPC concrete compared with FA concrete. Meanwhile, increasing the cement replacement ratio reduced the compressive strength of FA concrete. As illustrated in Fig. 6, the compressive strength development of the OPC and FA concrete evolved at a higher rate during the first 28 days; it was followed by a lower rate of compressive strength development through 56 days. After 56 days, the compressive strength development of OPC began to level off, whereas the compressive strength development of FA concrete continued to grow. At 91 days, apart from the FA concrete with a cement replacement ratio of 30% (3F30), the OPC still had a higher compressive strength than the FA concrete, as illustrated in Fig. 7. However, the compressive strength of the 3F30 concrete (43.2 MPa) was close to that of the OPC (41.3 MPa) at 91 days. Increasing the amount of FA reduces the early compressive strength of concrete because a higher amount of FA used as a binder reduces the cement hydration reaction, thus slowing the pozzolanic reaction for FA concrete (Mtarfi, Rais, Taleb, and Kada, 2017).

Figs. 8 and 9 display the compressive strength development of the OPC and FA concrete with fineness of 5,690 cm^2/g (5F) at various cement replacement ratios. As illustrated in Fig. 8, the OPC maintained a higher compressive strength than the other FA concrete during the first 28 days. At 28 days, the compressive strength of the FA concrete with a cement replacement ratio of 30% (5F30) at 37.4 MPa was nearly equal that of the OPC (37.3MPa). After 56 days, the compressive strengths of the FA concrete with cement replacement ratios of 30% and 40% (5F30

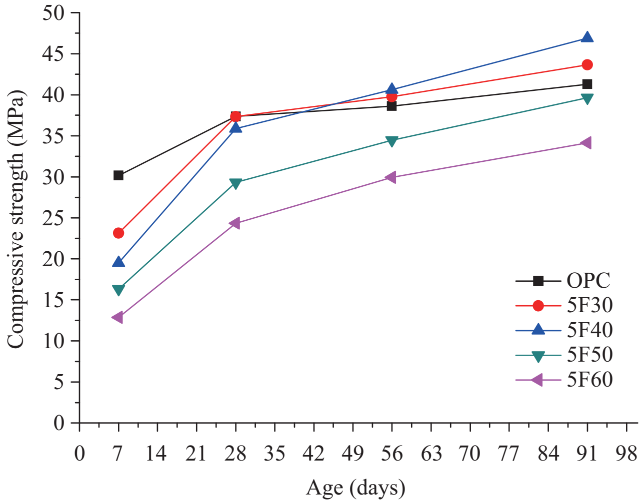

Fig. 8. Compressive strength development of OPC and FA concrete with fineness of 5,690 cm^2/g (5F) at various cement replacement ratios.

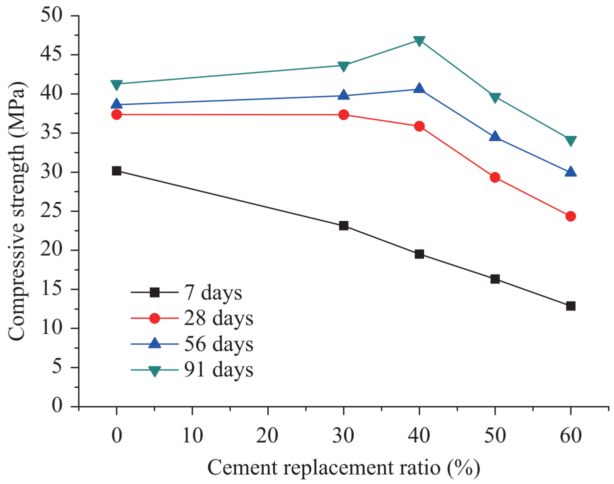

Fig. 9. Compressive strength of the concrete with FA fineness of 5,690 cm^2/g (5F) at various cement replacement ratios.

and 5F40) were higher than that of the OPC. At 91 days, the compressive strengths of 5F30 and 5F40 concrete were markedly higher than that of the OPC, as demonstrated in Fig. 9. The 5F40 concrete had a higher compressive strength (46.9MPa) than that of the 5F30 concrete (43.7MPa). The OPC was in the middle, with a compressive strength of 41.3 MPa. The 5F50 and 5F60 concretes were on the other end of the scale, with compressive strengths of 39.7 MPa and 34.1 MPa at 91 days, respectively F.

Based on the test results, it indicated that the fineness and cement replacement ratio of FA are two key factors influencing the compressive strength of concrete. The increasing compressive strength of concrete with FA results from the filling effect and pozzolanic effect (CIsaia et al., 2003). When the FA was classified as a fine FA, the FA concrete with classified fly ash has higher compressive strength than that with (Chindaprasirt et al., 2005). Therefore, the concrete with a fineness of 5,690 cm^2/g and an FA cement replacement ratio of 40% had the highest compressive strength at 91 days.

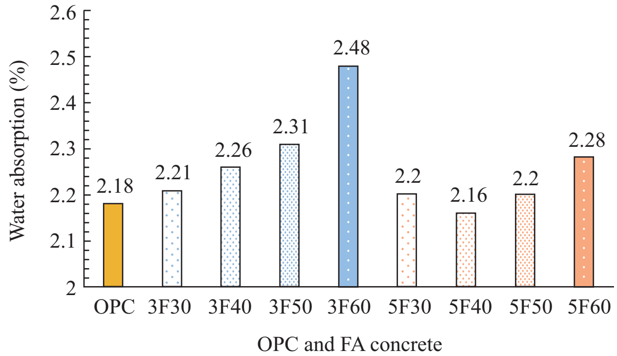

Fig. 10. Water absorption of OPC and FA concrete at 56 days.

3. Water Absorption

Water absorption is defined as the amount of water absorbed under identified conditions. Fig. 10 represents the water absorption of the OPC and FA concrete with fineness of 3,150 cm^2/g (3F) and 5,690 cm^2/g (5F) at various cement replacement ratios by FA at 56 days. As illustrated by Fig. 10, the water absorption of the FA concrete with fineness of 3,150 cm^2/g (3F) increased with an increase in the cement replacement ratio, varying from 2.21% to 2.48%; whereas the OPC had a water absorption rate of 2.18%. For the FA concrete with fineness of 5,690 cm^2/g (5F), the water absorption values at cement replacement ratios of 30%, 40%, 50%, and 60% (5F30, 5F40, 5F50, and 5F60) were 2.20%, 2.16%, 2.20%, and 2.28%, respectively; therefore, the FA concrete with a high fineness of 5,690 cm^2/g (5F) and a cement replacement ratio of 40% (5F40) had the lowest water absorption. The FA concretes with fineness of 5,690 cm^2/g (5F30, 5F40, 5F50, and 5F60) had lower water absorption than those with fineness of 3,150 cm^2/g (3F30, 3F40, 3F50, and 3F60). This reveals that an increase in FA fineness results in a decrease in water absorption. The trend of the water absorption is consistent with the results of the compressive strength test. The concrete with a fineness of 5,690 cm^2/g at a cement replacement ratio of 40% (5F40) had the lowest water absorption compared with the others, including the OPC.

4. RCPT

The RCPT was conducted on 28-day and 56-day concrete specimens containing two finenesses of FA and various cement replacement ratios. The purpose of the test was to evaluate the performance of these concrete specimens compared with the OPC without FA. The results of the RCPT for the OPC and FA concrete at 28 days are presented in Fig. 11. For the OPC, 5,136 C passed; for the FA concrete with fineness of 3,150 cm^2/g at cement replacement ratios of 30%, 40%, 50%, and 60% (3F30, 3F40, 3F50, and 3F60), 2,042, 1,565, 1,302, and 1,886 C passed; and for the FA concrete with fineness of 5,690 cm^2/g at the cement replacement ratios of 30%, 40%, 50%, and 60% (5F30, 5F40, 5F50, and 5F60), 835, 638, 749, and 1,631 C passed,

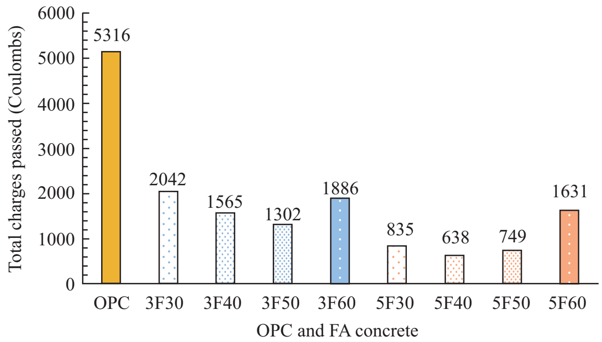

Fig. 11. Total charge passed of OPC and FA concrete at 28 days.

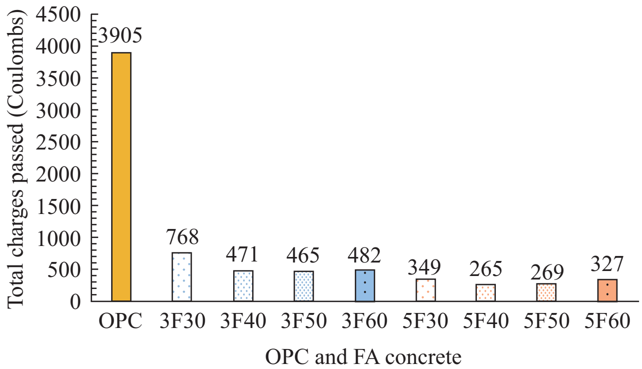

Fig. 12. Total charge passed of OPC and FA concrete at 56 days.

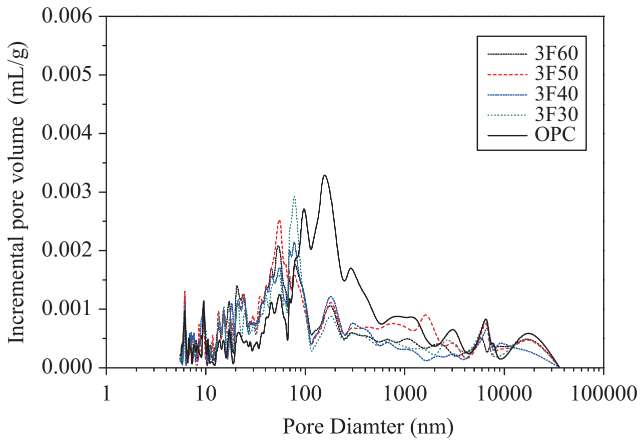

Fig. 13. Relationship between incremental pore volume and pore diameter of OPC and FA concrete with fineness of 3,150 cm^2/g at different cement replacement ratios at 56 days.

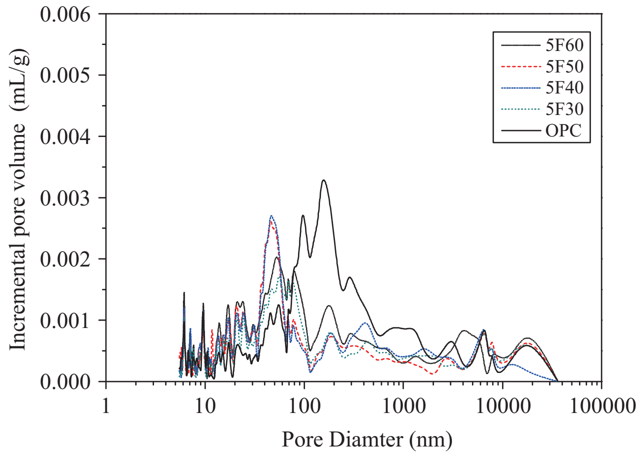

Fig. 14. Relationship between incremental pore volume and pore diameter of OPC and FA concrete with fineness of 5,690 cm2/g at different cement replacement ratios at 56 days.

respectively. This result verified that the incorporation of FA results in drastic reductions in the total charge passed. According to ASTM C1202, the OPC exhibits high chloride-ion penetrability; however, the FA concrete with 3,150 cm^2/g fineness displays moderate to low chloride-ion penetrability, and the FA concrete with 5,690 cm^2/g fineness presents low to very low chloride-ion penetrability.

Fig. 12 displays the results of the RCPT for the OPC and FA concrete at 56 days. For the OPC, 3,905 C passed, indicating moderate chloride-ion penetrability. The total charge passed for the FA concrete with fineness of 3,150 cm^2/g at the cement replacement ratios of 30%, 40%, 50%, and 60% (3F30, 3F40, 3F50, and 3F60) was 768, 471, 465, and 482 C, whereas for FA concrete with fineness of 5,690 cm^2/g at the cement replacement ratios of 30%, 40%, 50%, and 60% (5F30, 5F40, 5F50, and 5F60), 349, 265, 269, and 327 C passed, respectively, indicating extremely low chloride-ion penetrability. Therefore, FA concrete with high fineness has the low total charge passed compared with those of the FA concrete with original fly ash. It can be concluded that the FA fineness and cement replacement ratio of FA concrete mainly determine the ease with which chloride ions can move into concrete.

The degree of hydration of cementitious material is related to the internal pore structure, which is influenced by the water-to-binder ratio, fineness, and curing temperature. Plante and Bilodeau (Plante and Bilodeau, 1989) reported that the chloride-ion permeability decreased with the moist curing time for plain and silica fume concrete, and the use of SCM significantly reduced the chloride-ion permeability of concrete. In this study, when the curing time increased from 28 to 56 days, a chloride permeability reduction of 24% was obtained for the OPC, a chloride permeability reduction of 62%-75% was obtained for the FA concrete with a fineness of 3,150 cm^2/g, and a chloride permeability reduction of 58%-80% was obtained for the FA concrete with a fineness of 5,690 cm^2/g. In addition, the incorporation of high FA fineness and a high cement replacement ratio further reduces the total charge passed.

5. MIP

Figs 13 and 14 display the relationships between incremental pore volumes and pore diameter of the OPC and FA concrete with fineness of 3,150 cm^2/g and 5,690 cm^2/g at different cement replacement ratios at 56 days. In Fig. 13, two peaks of incremental pore volumes can be observed. The first peak for

Table 5. Capillary pore and gel pore intrusion volumes of OPC and FA concrete.

Mix No.	Cumulative Intrusion Volume (ml/g)	Capillary Pore Intrusion Volume (ml/g)	Gel Pore Intrusion Volume (ml/g)
OPC	0.05628	0.05595	0.00033
3F30	0.05050	0.04966	0.00084
3F40	0.05106	0.04899	0.00207
3F50	0.05986	0.05700	0.00286
3F60	0.05803	0.05452	0.00351
5F30	0.04706	0.04531	0.00175
5F40	0.04170	0.03862	0.00308
5F50	0.05277	0.04820	0.00457
5F60	0.06280	0.05879	0.00401

the capillary pores of the 3F30, 3F40, 3F50, and 3F60 concrete is located at 51.8 nm with incremental pore volumes of 0.00167 mL/g, 0.00190 mL/g, 0.00215 mL/g, and 0.00215 mL/g, respectively. The second peak for the capillary pores of the 3F30, 3F40, 3F50, and 3F60 concrete is located at 77.1 nm with incremental pore volumes of 0.00313 mL/g, 0.00233 mL/g, 0.00192 mL/g, and 0.00188 mL/g, respectively. These values are lower than those of the OPC mortar, which are 0.00298 mL/g at 95.4 nm at the first peak and 0.00349 mL/g at 151.1 nm at the second peak. This reveals that the incorporation of FA was more effective at reducing capillary pores than was the OPC. The cement replacement ratio of FA with fineness of 3,150 cm^2/g for concrete was less than 50%.

In Fig. 14, the first peak for the capillary pores of the 5F30, 5F40, 5F50, and 5F60 concrete is located at 51.8 nm with incremental pore volumes of 0.00137 mL/g, 0.00258 mL/g, 0.00254 mL/g, and 0.00209 mL/g, respectively. The second peak for the capillary pores of the 5F30, 5F40, 5F50, and 5F60 concrete is located at 77.1 nm with incremental pore volumes of 0.00175 mL/g, 0.00109 mL/g, 0.00114 mL/g, and 0.00191 mL/g, respectively. The results reveal that the cement replacement ratio for FA with fineness of 5,690 cm^2/g for concrete was less than 60%. Therefore, concrete with FA fineness of 5,690 cm^2/g was more effective at reducing the pore diameter than was the concrete with FA fineness of 3,150 cm^2/g.

The capillary pore (10 nm-10 μm) and gel pore (5.7-10 nm) intrusion volumes of the OPC and FA concrete with fineness of 3,150 cm^2/g and 5,690 cm^2/g at different cement replacement ratios at the age of 56 days are listed in Table 5. For the FA concrete with fineness of 3,150 cm^2/g, the capillary pore intrusion volumes of the 3F30 and 3F40 concrete were lower than that of the OPC. When the cement replacement ratio by FA was over 50%, the capillary pore intrusion volume could not be reduced, because of the quantities of $Ca(OH)_2$ during the pozzolanic reaction were insufficient. For the FA concrete with fineness of 5,690 cm^2/g, the capillary pore intrusion volumes of the 5F30, 5F40, and 5F50 concrete were lower than that of the OPC. When the cement replacement ratio by FA was over 60%, the capillary pore intrusion volume increased. The use of FA with fineness of 5,690 cm^2/g was more effective at reducing the capillary pore intrusion volume than the use of FA with fineness of 3,150 cm^2/g. The trend of the cumulative intrusion volume reduction is similar to that of the capillary pore intrusion volume.

IV. CONCLUSIONS

This study investigated the effects of FA fineness and high replacement ratios on concrete properties. The heat of hydration, compressive strength, water absorption, total charge passed, and pore structures of FA concrete were compared with OPC for reference. The following conclusions can be drawn from the present study.

1. The incorporation of FA reduces the maximum heat of hydration, total charge passed, and capillary pores of concrete. An increase in the cement replacement ratio results in a decrease in the maximum heat of hydration of the concrete. FA concrete with fineness of 5,690 cm^2/g is more effective for a low pore diameter than is FA concrete with fineness of 3,150 cm^2/g.
2. The compressive strengths of concretes with FA ratios of 40% or less (3F30, 5F30, and 5F40) are higher than that of OPC at the age of 91 days. The trend of the water absorption is consistent with that of the compressive strength.
3. The FA fineness and cement replacement ratio have a significant influence on concrete properties. FA concrete with fineness of 5,690 cm^2/g and a cement replacement ratio of 40% has the most effective properties.

REFERENCES

ACI 211.4R (2008). Guide for selecting proportions for high-strength concrete using Portland cement and other cementitious materials. ACI 211-committee.

Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. Progress in Energy and Combustion Science 36(3), 327-363.

Arel, H. Ş., and F. U. A. Shaikh (2018). Effects of fly ash fineness, nano silica, and curing types on mechanical and durability properties of fly ash mortars. Structural Concrete 19(2), 597-607.

Arito, P. (2018). Influence of mix design parameters on restrained shrinkage cracking in non-structural concrete patch repair mortars. Ph.D. Dissertation, University of Cape Town, South Africa.

ASTM C33-18 (2018). Standard Specification for Concrete Aggregates, American Society for Testing and Materials.

ASTM C186 (2017) Standard Test Method for Heat of Hydration of Hydraulic Cement, American Society for Testing and Materials.

ASTM C642 (2013). Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. American Society for Testing and Materials.

ASTM C 39 (2016). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. American Society for Testing and Materials.

ASTM C 150 (2017). Standard Specification for Portland Cement. American Society for Testing and Materials.

ASTM C 192 (2016). Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. American Society for Testing and Materials.

ASTM C 618 (2015). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. American Society for Testing and Materials.

ASTM C 1202 (2012). Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. American Society for Testing and Materials.

ASTM D4404 (2010). Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry. American Society for Testing and Materials.

Berry, E. E., and V. M. Malhotra (1982). Fly ash for use in concrete-A critical review. Journal of the American Concrete Institute 77(2), 59-73.

Carette, G. A. B., R. L. Chevrier and V. M. Malhotra (1993). Mechanical properties of concrete incorporating high volumes of fly ash from sources in the U.S. ACI Materials Journal 90(6), 535-544.

Chindaprasirt, P., C. Chotithanorm, H. T. Cao and V. Sirivivatnanon (2007). Influence of fly ash fineness on the chloride penetration of concrete. Construction and Building Materials 21(2), 356-361.

Chindaprasirt, P., S. Homwuttiwong and V. Sirivivatnanon (2004). Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. Cement and Concrete Research 34, 1087-1092.

Chindaprasirt, P., C. Jaturapitakkul and T. Sinsiri (2005). Effect of fly ash fineness on compressive strength and pore size of blended cement paste. Cement and Concrete Composites 27, 425-428.

Choi, S. J., S. S. Lee and P. J. M. Monteiro (2012). Effect of fly ash fineness on temperature rise, setting, and strength development of mortar. Journal of Materials in Civil Engineering 24(5), 499-505.

CIsaia, G., A. L. G. Gastaldini and R. Moraes (2003). Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete. Cement and Concrete Composites 25(1), 69-76.

Erdoğdu, K. and P. Türker (1998). Effects of fly ash particle size on strength of Portland cement fly ash mortars. Cement and Concrete Research 28(9), 1217-1222.

Fanghui, H., W. Qiang and F. Jingjing (2015). The differences among the roles of ground fly ash in the paste, mortar and concrete. Construction and Building Materials 93, 172-179.

Feng, J., J. Sun and P. Yan (2018). The Influence of ground fly ash on cement hydration and mechanical property of mortar. Advances in Civil Engineering 2018, 1-7.

Han, F., R. Liu, D. Wang and P. Yan (2014). Characteristics of the hydration heat evolution of composite binder at different hydrating temperature. Thermochimica Acta 586(20), 52-57.

Hsu, S., M. Chi and R. Huang (2018). Effect of fineness and replacement ratio of ground fly ash on properties of blended cement mortar. Construction and Building Materials 176, 250-258.

Kiattikomol, K., C. Jaturapitakkul, S. Songpiriyakij and S. Chutubtim (2001). A study of ground coarse fly ashes with different finenesses from various sources as pozzolanic materials. Cement and Concrete Composites 23(4-5), 335-343.

Kumar, R. and B. Bhattacharjee (2003). Study on some factors affecting the results in the use of MIP method in concrete research. Cement and Concrete Resaerch 33, 417-424.

Liu, B., X Y.ie, S. Zhou and Q. Yuan (2000). Influence of ultrafine fly ash composite on the fluidity and compressive strength of concrete. Cement and Concrete Research 30, 1489-1493.

Ma, H. (2014). Mercury intrusion porosimetry in concrete technology: tips in measurement, pore structure parameter acquisition and application. Journal of Porous Materials 21, 207-215.

Maage, M. (1986). Strength and heat development in concrete, influence of fly ash and condensed silica fume. The second International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, American.

Malhotra, V. M. and P. K. Mehta (2002). High-Performance, High-Volume Fly Ash Concrete. Supplementary Cementing Materials for Sustainable Development: Inc. Ottawa, Canada.

Mehta, P. K. and P. J. M. Monteiro (2006). Concrete Microstructures, Properties and Materials. Prentice-Hall, Englewood Cliffs, NJ.

Mtarfi, N. H., Z. Rais, M. Taleb and K. M. Kada (2017). Effect of fly ash and grading agent on the properties of mortar using response surface methodology. Journal of Building Engineering 9, 109-116.

Myadraboina, H., S. Setunge and I. Patnaikuni (2017). Pozzolanic Index and lime requirement of low calcium fly ashes in high volume fly ash mortar. Construction and Building Materials 131, 690-695.

Payá, J., J. Monzó, E. Peris-Mora, M. V Borrachero, R. Tercero and C. Pinillos (1995). Early-strength development of Portland cement mortars containing air classified fly ashes. Cement and Concrete Research 25(2), 449-456.

Plante, P. and A. Bilodeau (1989). Rapid chloride ion permeability test: data on concrete incorporating supplementary cementing materials. International Concrete Abstracts Portal 114, 625-644.

Saha, A. K. (2018). Effect of class F fly ash on the durability properties of concrete. Sustainable Environment Research 28(1), 25-31.

Sinsiri, T., P. Chindaprasirt and C. Jaturapitakkul (2010). Influence of fly ash fineness and shape on the porosity and permeability of blended cement pastes. International Journal of Minerals, Metallurgy, and Materials 17(6), 683-690.

Slanička, Š. (1991). The influence of fly ash fineness on the strength of concrete. Cement and Concrete Research 21(2-3), 285-296.

Somna, R., C. Jaturapitakkul and A. M. Amde (2012). Effect of ground fly ash and ground bagasse ash on the durability of recycled aggregate concrete. Cement and Concrete Composites 34(7), 848-854.

Soni, D. K. and J. Saini (2014). Mechanical properties of high volume fly ash (HVFA) and concrete subjected to evaluated 1200˚C temperature. International Journal of Civil Engineering Research 5(3), 241-248.

Tangpagasit, J., R. Cheerarot, C. Jaturapitakkul and K. Kiattikomol (2005). Packing effect and pozzolanic reaction of fly ash in mortar. Cement and Concrete Research 35(6), 1145-1151.

Thomas, M. (2007). Optimizing the use of fly ash in concrete. Department of Energy Office of Scientific and Technical Information, University of New Brunswick, USA.

Zhao, H., W. Sun, X. Wu and B. Gao (2015). The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures. Journal of Cleaner Production 95, 66-74.