Construction and Building Materials 176 (2018) 250–258

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of fineness and replacement ratio of ground fly ash on properties of blended cement mortar

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HIGHLIGHTS

- Ground FA resulted in significant improvement in compressive strength.
- FA decreased the water absorption and capillary pores of blended cement mortars.
- Finer FA was more effective at reducing the intensity of $Ca(OH)_2$ than OFA.
- FA fineness and replacement ratio have a major effect on the properties of mortars.
- Mortars with 20% FA of 5690 cm^2/g fineness have the highest strength.

ARTICLE INFO

Article history:
Received 15 January 2018
Received in revised form 29 April 2018
Accepted 6 May 2018

Keywords:
Fly ash
Fineness
Replacement ratio
Mercury intrusion porosimetry (MIP)
Scanning electron microscopy (SEM)
X-ray diffraction (XRD) analysis

ABSTRACT

This study presents an experimental investigation on the effect of ground fly ash fineness and replacement ratio on properties of blended cement mortar. Class F fly ash was ground into three different fineness values of 4610 cm^2/g, 5690 cm^2/g, and 6300 cm^2/g with ball grinding machine and used as a replacement ratios of 0%, 10%, 15%, and 20% by weight of cement to produce the blended cement mortars. Compressive strength test, water absorption, mercury intrusion porosimetry (MIP) test, scanning electron microscopy (SEM), and X-ray diffraction (XRD) analysis were performed. Test results show that the use of fly ash resulted in significant improvement in compressive strength and substantial decrease in water absorption and capillary pores for blended cement mortars compared to OPC mortar. The mortars with fineness value of 5690 cm^2/g and FA replacement ratio of 20% has the highest compressive strength and lowest water absorption and smallest porosity. The XRD analysis showed that $Ca(OH)_2$ is one of the hydration products during the hydration reaction. When fly ashes were incorporated into the blended cement mortars, the intensity peaks of $Ca(OH)_2$ in the XRD patterns decreased. The increasing replacement ratio of fly ash decreased $Ca(OH)_2$. Based on the results, both the fly ash fineness and the fly ash replacement ratio have a significant influence on the properties of blended cement mortar.

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1. Introduction

Concrete is the main building material that will continue to be in demand far into the future. As the demand for infrastructure development rises, the consumption of concrete would keep increasing [1,2]. Ordinary Portland cement (OPC) is a binding material which plays an important role in making concrete and mortar. However, it is known that every ton of OPC produced emits on average a similar amount of CO_2 into the atmosphere, or altogether relatively 6% of all man-made carbon emissions, which is harmful to the environment [3]. To overcome the problem, utilizing the supplementary cementitious materials (SCMs) as partial replacement has been incessantly studied because of its economical, ecological and technical benefits [4].

Fly ash (FA), an industrial by product, has been successfully used in concrete industry since over 50 years, principally as an mineral admixture in OPC concrete or as a component of blended cement [5,6]. The use of FA combined with OPC causes a pozzolanic reaction between glassy phase of FA and $Ca(OH)_2$ generated from the hydration of OPC, which results in the formation of additional C-S-H gel and leads to higher density and strength [7]. Actually, the compressive strength of the concrete with FA is considerably higher than that of OPC concrete only at late ages and the FA concrete exhibits lower strength than OPC concrete at the ages of 7 and 28 days. The compressive strength of mortar is contributed

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https://doi.org/10.1016/j.conbuildmat.2018.05.060
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from hydration reaction, filling effect, and pozzolanic reaction [8]. However, lower strength development rate at early age limits the application of blended cement composites with high volumes of FA [9], which is often used to replace usually 30% of the mass of OPC in a concrete mixture [2]. Akcaozoğlu and Atis [10] investigated the effect of granulated blast furnace slag (GBFS) and fly ash addition on the strength properties of lightweight mortars and found that the use of FA at the same replacement ratio improved flow value, but decreased compressive and flexural tensile strength values compared to OPC specimens.

The porosity and pore size of blended cement paste were significantly influenced by the replacement level of fly ash and its fineness [11,12]. The fine fly ash is more reactive and its use resulted in a denser cement matrix and better mechanical properties of mortar [13]. Mehta [14] tested 11 fly ashes from different sources and found that the calcium content and particle size distribution were the crucial parameters governing the strength development rate. Slanicka [15] and Paya et al. [16] reported that the concrete with finer fraction of FA had a higher compressive strength than that without FA and the one with coarser FA reduced the compressive strength of concrete. The finer FA is more reactive and has greater pozzolanic index and consumes more lime at a certain age [17]. Chousidis et al. [18] indicated that the performance of hardened fly ash concrete depends on the CaO and SiO_2 contents, fineness, free lime and sulfate ions content. Despite the previous studies for the effect of fly ash on properties and durability of blended cement mortars or concrete [19]. However, few researchers were found to deal with the fineness of fly ash on the physical properties, pore structure and microstructure of blended cement mortars. This present study attempts to provide an advanced understanding of the influence of the fly ash fineness and the replacement ratio on the compressive strength, water absorption, porosity, and XRD analysis of blended cement mortars.

2. Experimental program

2.1. Materials

The main binder materials used in this study consisted of Ordinary Portland cement type I (OPC) according to ASTM C 150 [20] and fly ash (FA). Fly ashes were obtained from Mailiao Six Light Naphtha Cracker Plant, located in the Yunlin county of Taiwan, and were classified into Class F as prescribed by ASTM C 618 [21]. The physical properties and chemical compositions of OPC type I and FA with different fineness are given in Tables 1 and 2, respectively. The original fly ash (OFA) was ground into three different fineness with ball grinding machine. The abbreviations OFA, 4FA, 5FA, and 6FA were used to identify fineness values of FA as 3150 cm^2/g, 4610 cm^2/g, 5690 cm^2/g, and 6300 cm^2/g, respectively. The specific gravity of OFA and FA with different fineness varied between 2.18 and 2.58. The amount of CaO of FA was 6.6%. The FA was classified into Class F as prescribed by ASTM C 618 [21] because the sums of the major components SiO_2, Al_2O_3, and Fe_2O_3 were 85.3%, which were over 70%. That FA with different fineness values had the similar physical and chemical properties was reported by previous research [22–24]. The loss on ignition (LOI) of FA was 2.8% which was consistent with the limitation of 6% as identified by ASTM C618 [21]. River sand used in this study has a density of 2540 kg/m^3, a fineness modulus of 3.1, and an absorption of 2%. The physical properties of river sand are given in Table 3. Water used in this study was tap water provided from city waterworks of Taipei (Taiwan).

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 fly ash is about 4.35%.

2.2. Mix design and specimen preparation

Mix proportions of OPC and FA composites is given in Table 4. Fly ashes with three different fineness were used to replace OPC at dosage levels of 0%, 10%, 15%, and 20% by weight of binder. The water to binder ratio (W/B) was kept at a constant of 0.485 in all samples. Mixing of OPC and FA with 523 kg of binders per cubic meter according to ASTM C 192 [25] were designed. All mortars were mixed in a mechanical mixer and properly compacted by a vibration table (vibrations per min = 3000 Hz) for 15 s according to ACI 309R [26]. The fresh specimens were covered with polyethylene sheet to prevent evaporation and were kept in mold at relative humidity of 90% RH and room temperature of 23 °C. After 24 h, the specimens were removed from the mold and cured in saturated lime water until the time of testing. For each mixture, 50 mm cubes were prepared for compressive strength test and water absorption test, 10 mm cubes were made for mercury intrusion porosimetry (MIP) test.

2.3. Methods

2.3.1. Scanning electron microscopy (SEM)

The morphology of OPC and FA specimens was investigated by a HITACHI S-4100 microscope with an energy dispersive Spectroscopy (EDS). Prior to SEM analyses, representative samples were air-dried first, followed by resin impregnation. The impregnated specimens were crushed and softly polished with sand paper down to 0.25 μm.

2.3.2. Compressive strength test

Compressive strength test of the specimens was conducted on the specimens according to ASTM C109 [27]. For each mixture, three 50x50x50 mm cubic specimens were prepared and tested at the ages of 3, 14, 28, and 56 days to determine the average compressive strength.

2.3.3. Water absorption

Water absorption was made in accordance with ASTM C642 [28]. For the water absorption test, the specimens were dried in

Table 1
Physical properties of OPC and FA.

Physical properties	OPC	OFA	4FA	5FA	6FA
Specific gravity	3.15	2.18	2.46	2.58	2.56
Specific surface area (cm^2/g)	3640	3150	4610	5690	6300

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