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The effect of using fly ash on the strength and hydration characteristics of blended cements

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HIGHLIGHTS

- FA has a high pozzolanic activity.
- FA contributes to the consumption of $Ca(OH)_2$ formed during the hydration of PC.
- The acceleration of the pozzolanic reaction at 28 days is confirmed by analyses.
- The long-term strengths of FA blended cements are affected in a positive way.

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ABSTRACT

The present study is aimed at investigating the combined effects of the compressive strength and hydration development of blended cements which contain fly ash. In the first stage, chemical, physical, X-Ray diffraction (XRD) and Fourier transforms infrared spectroscopy (FT-IR) analysis were performed in order to determine the characteristics of Portland cement and fly ash. In the second stage, the compressive strength of cement mortars and setting time, water demand and volume expansion of cement pastes were identified according to the standard cement experiments. In the last stage, XRD, FT-IR, thermal and scanning electron microscope analyses were performed in order to determine the hydration of cement pastes. Consequently, the addition of FA in Portland cement contributes to the consumption of $Ca(OH)_2$ which is formed during the hydration of cement and leads to the formation of cementitious products, like C–S–H. Therefore, the compressive strength of fly ash blended cement mortars increased at later ages compared to the early ages.

1. Introduction

Fly ash, blast furnace slag, silica fume, pumice, zeolite and diatomite improve the properties of cement and concrete, so that they have been used in the construction sector for years as mineral admixtures [1–6]. Fly ash (FA) is an industrial waste material, and is the most widely used additive to cement and concrete [7–9].

The use of FA in cement and concrete provides a number of advantages. Because of the small sizes of FA particles, the cement pastes produced with FA became smoother, which allows better bonding between aggregate and cement, and results in a more durable and impervious concrete [10,11]. Because FA particles are hard and round shape, concrete's workability increases without adding extra water [12]. The hydration products of FA with calcium hydroxide ($Ca(OH)_2$) reduce the pores, in this way more strength and durable concrete is obtained [13–15]. Since FA is enriched with SiO_2 and Al_2O_3, this industrial waste material can be transformed into zeolite-like crystalline materials as a result of chemical treatment [16]. In addition, FA positively affects sulfate resistance, hydration heat, alkali–silicate reactions, and abrasion resistance [17–19]. Furthermore, with the use of FA in concrete significant energy savings and reductions in CO_2 emission is provided and resources are conserved [20,21].

FA does not enter the reaction with water without an alkaline activator. The role of FA in the process of hardening of the concrete is relatively understandable. Notwithstanding FA–cement–water system hydration mechanism is sufficiently understood, the hydration quantity determination for FA–cement is not yet clarified [22]. Therefore, this study was performed to determine the hydration of cement with and without addition of FA using various testing methods such as X-ray diffraction (XRD), Fourier transforms infrared spectroscopy (FT-IR), thermal (DTA–TG) and scanning electron microscopy (SEM) analyses.

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2. Materials and methods

In this study, Portland cement (CEM I 42.5 R), FA, standard aggregate and tap water of Zonguldak–Eregli were used. Portland cement (PC) was obtained from Bolu Cement Factory. FA was obtained from Catalagzi thermal power plant in Zonguldak (Turkey).

In the study, six different cements were produced by substituting 5%, 10%, 15%, 20% and 25% FA with the reference Portland cement. These samples were coded as R, 5FA, 10FA, 15FA, 20FA and 25FA, respectively.

ARL 8680 S XRF was used in chemical analyses of PC and FA. Particle size analyses were done using Malvern Hydro 2000 G. Toni Technik 6565 Blaine device was used to determine surface areas (Blaine). Quantachrome MVP-3 device was used to determine for specific gravities. The mineralogical analyses were examined using a Rikaguminiflex XRD device. Bruker Vertex 70 spectrometer was used for FT-IR analyses between the wave lengths range of 400–4000 cm^{-1}. DTA–TG analyses were done with apparatus type Perkin Elmer S II by heating from 20 °C to 1000 °C with 20 °C/min steps. SEM images were determined using JEOL JSM 6060LV device.

Cement mortar and paste samples were prepared according to TS EN 196-1 standard [23]. The setting time, water demands and volume expansion tests of cement pastes were made according to TS EN 196-3 standard [24].

For compressive strength tests, 450 g Portland cement, 1350 g standard sand and 225 ml of water were mixed in order to produce each mortar mixture according to TS EN 196-1 [23]. The mixed mortars were then poured into moulds of size 40 × 40×160 mm. Compressive strength tests were performed at the ages of 2, 7, 28, 56 and 90 days according to TS EN 196-1 [23].

3. Results and discussion

3.1. Chemical analysis

Chemical analyses of PC and FA are given in Table 1.

According to chemical composition of raw materials used in the experiments, the PC consists of CaO with higher proportion and Al_2O_3, Fe_2O_3 and SO_3 compounds with lower proportion (Table 1).

According to the chemical analysis, the main component of FA is SiO_2. The sum of S + A + F is 85.74 (which is higher than 70% according to ASTM C) and the amount of CaO is less than 10%, so that FA is in Class F type (low calcium). Besides, it is in Class V type (silica-like FA) according to TS EN 197-1, because the amount of reactive lime is less than 10% (2.58%) [25]. Since the amount of reactive silica is 39.52% (which is higher than 25%) V Class FA satisfies all conditions. Furthermore, potassium oxide (K_2O) in FA have a higher amount of K^+ ions than sodium oxide (Na_2O), it shows that rich with K^+ ions (Table 1).

3.2. Physical analysis

In physical analysis, particle size distribution, specific gravity and Blaine values were determined. Particle size distribution of PC and FA are shown in Fig. 1 and the same raw materials and physical properties of the FA blended cements are given in Table 2.

Particle size distribution, specific surface (Blaine) and specific gravity of each material was different from each other.

Table 1
Chemical specifications of PC and FA.

Materials	PC	FA
Chemical composition: wt.%		
SiO_2 (S)	21.34	54.35
Al_2O_3 (A)	4.84	24.33
Fe_2O_3 (F)	3.72	7.08
CaO	60.77	3.02
MgO	1.3	2.46
SO_3	3.3	0.37
Na_2O	0.14	0.73
K_2O	0.45	1.82
Cl^-	0.0071	0.0057
Loss on ignition	2.83	1.20
S + A + F	–	85.74
Reactive CaO	–	2.58
Reactive SiO_2	–	39.52

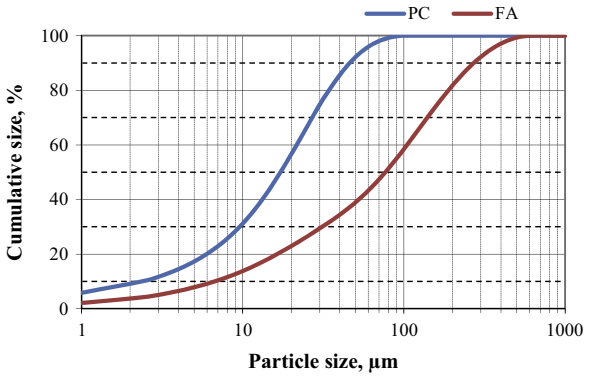

Fig. 1. Particle size distributions of PC and FA (under sieve).

Table 2
Physical specifications of materials.

Materials	Specific gravity (g/cm^3)	Blaine (cm^2/g)
PC	3.10	3885
FA	2.00	4150
5FA	3.06	3962
10FA	3.00	3940
15FA	2.95	4105
20FA	2.89	4198
25FA	2.83	4215

When compared with FA, the particle size values of PC are smaller (Fig. 1). According to 90% under sieve ratio, PC and FA have particle sizes of 45, and 280 µm, respectively. It is determined that according to 45% screen under sieve ratio, PC and FA have particle sizes of 18 and 65 µm, respectively.

The Blaine values of FA are higher in comparison to cement (Table 2). The reason for this is show that FA has a porous structure.

FA, which has a low specific gravity, decreases the specific gravity of the cement mixture obtained by the substitution of FA to PC. Since the specific gravity of PC is 3.10 g/cm^3, it is decreased to 2.83 g/cm^3 with the substitution of 25% FA (Table 2). When the FA is blended with PC, the specific gravity values of the FA blended cements also decrease.

3.3. X-ray diffraction (XRD) analysis

XRD analyses of PC and FA are shown in Fig. 2.

XRD analyses reveals that, PC was composed of mainly C_3S (alite), C_2S (belite), C_3A and brownmillerite. It is also observed that the mineralogical composition of FA is amorphous and crystal phases are formed. Mullite ($3Al_2O_3{\cdot}2SiO_2$) is formed by the aluminum silicates that are present in FA, and SiO_2 in the structure is also present in quartz form. On the other hand, iron is present in the hematite (Fe_2O_3) form. Sanidine, which is a feldspat mineral, causes K^+ elements to be in the structure. It is also observed that the amorphous phase reaches its maximum when 2θ is between 20 and 35°. So that, the amorphous phase has silica-like characteristics since it is close to the maximum peak value of quartz crystal (Fig. 2).

According to XRD results, it can be concluded that FA has irregular (amorphous) mineralogical structure whereas PC has regular (crystal) mineralogical structure.

3.4. Fourier transform infrared spectroscopy (FT-IR) analysis

Surface structures of the molecules are determined by FT-IR analysis and the results obtained from these analyses are shown in Fig. 3 schematically.