HBRC Journal (2015) 11, 321–327

Housing and Building National Research Center

HBRC Journal

http://ees.elsevier.com/hbrcj

Physico-chemical characteristics of blended cement pastes containing electric arc furnace slag with and without silica fume

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Received 11 December 2013; revised 19 June 2014; accepted 2 July 2014

KEYWORDS

Electric arc furnace slag (EAFS);
Silica fume (SF);
Thermal analysis;
Phase composition

Abstract Filled-pozzolanic cement pastes were made by different replacements of OPC by electric arc furnace slag (EAFS) with silica fume (SF) at water/cement ratio of 0.27. The pastes were hydrated up to 90 days. At each time interval, the physico-chemical characteristics of the hardened cement pastes were studied and related to the structure of the hardened pastes and the role of EAFS replacement as a filler in the hardened OPC-EAFS pastes. It was found that the optimum replacement of OPC by EAFS for the improvement in hydraulic properties of filled cement pastes is 6%. High replacement of OPC by EAFS (10% or 15%) causes a notable deterioration in the compressive strength at all ages of hydration. The replacement of EAFS in Mix (90% OPC + 10% EAFS) by 4% SF causes a marked improvement in the mechanical properties for the hardened pastes of Mix (90% OPC + 6% EAFS + 4% SF). The DSC thermograms for all pastes indicated the formation of nearly amorphous calcium silicate hydrates, calcium sulphoaluminate hydrates, calcium aluminate hydrates and portlandite. The SEM micrographs showed that the partial substitution of OPC by EAFS and/or SF leads to more dense structures as compared to the neat OPC paste.

Introduction

Manufacturing of Portland cement (PC) is a resource exhausting, energy intensive process that releases large amounts of the green house gas (CO_2) into the atmosphere. At present, efforts have been made to enhance the use of cementitious materials such as pozzolana and other industrial wastes to partially replace Portland cement [1,2]. The term pozzolana was defined as siliceous/aluminous materials, either natural or artificial, which react chemically with calcium hydroxide (CH) or with materials that can release calcium hydroxide (Portland cement clinker) in the presence of water to form compounds that

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Peer review under responsibility of Housing and Building National Research Center.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.hbrcj.2014.07.002

possess cementitious properties. Fly ash (FA), rice husk ash (RHA), silica fume (SF), slag and also calcined clay in the form of metakaolin (MK) are good examples of pozzolanic materials [3–6].

Condensed silica fume (SF) is a byproduct of silicon or ferrosilicon alloy industries. It consists of 95% amorphous silica with a very high surface area; these characteristics increase its pozzolanic activity [7,8]. Metakaolin (MK) is ultrafine artificial pozzolana powdered form of anhydrous alumino-silicate derived from the calcination of raw kaolin at a specific temperature range to form a phase transition which is highly disordered, amorphous and with pozzolanicity [9].

Slag represents one of the industrial wastes of various metal extractions and refining processes. In the specific case of making steels, the slag is generated at 3 different stages of processing and accordingly classified as: blast-furnace slag, electric arc furnace slag and ladle slag [10]. The electric arc furnace slag (EAFS) has a chemical composition more close to that of the cement clinker compared to the ground granulated blast-furnace slag (GGBFS). Hence, recently it was shown that it has potential application as a partial substitute for raw materials in clinker production. Addition of up to ~20% EAFS in the kiln feed was found to improve burnability index of the raw material mix [11]. The cementitious and pozzolanic behaviour of electric arc furnace steel slag, both as received and treated, has been studied. The as received slag was completely crystalline with monticellite as the predominant phase. Treatment of this slag, remelting and water quenching, results in several phases with merwinite as the dominant phase with an increase in basicity index which is more hydraulic [12].

Hydration of multi-blended cements composed of (OPC-FA-SF-MK), (OPC-MK-GGBFS) and (OPC-SF-GGBFS) mixes was studied. The results have shown that even 40 wt.% replacement of OPC by the pozzolanic materials does not deteriorate the compressive strength. This is attributed to that the pozzolanic material acts as a filler as well as, pozzolana which increases the formation of the C–S–H phase [13–17].

The object of this work is to study the hydration characteristics of OPC-EAFS blends with SF. The hydration characteristics were investigated by the determination of compressive strength, chemically combined water and free lime contents at different hydration ages. In addition, the phase composition was examined using DSC. The morphology and microstructure of some selected cement pastes were also examined using SEM.

Experimental

Materials

Ordinary Portland cement (OPC) used in this study was supplied from South Valley Cement Company, Egypt, with a Blaine surface area of 2945 $cm^2\ g^{-1}$. Electric arc furnace slag (EAFS) was supplied from Ezz Flat Steel Company, Egypt, with the same Blain surface area of OPC. The chemical oxide compositions of OPC and EAFS are shown in Table 1. Condensed silica fume (SF) was supplied from ferro-silicon company, Kom-Ombo, Egypt. Silica fume particles are spherical and have an average diameter of about 0.1 μm. It consists of 95% amorphous silica with a specific surface area $2 \times 10^5\ cm^2\ g^{-1}$. The chemical composition of SF is shown in Table 1.

Preparation of the hardened blended cement pastes

Different cement pastes were prepared using a W/S ratio of 0.27. Each paste was prepared by mixing the dry mix with the required amount of water for about 3 min. After complete mixing, the resulted paste was moulded in 1 inch cubic moulds, cured in 100% relative humidity for 24 h and then demoulded and cured under water at room temperature up to 90 days. Table 2 shows the mix designations and their compositions.

Methods of investigation

Compressive strength tests were performed after 1, 3, 7, 14, 28 and 90 days. At each curing time, three cubes of each mix were subjected to compressive strength test and the average value was recorded as $kg\ cm^{-2}$. This was accomplished using a Ton-industrie machine (West Germany) with a maximum load of 60 tons. After the determination of compressive strength the crushed specimens of the hardened cement pastes were then ground and the hydration reaction was stopped using the method described in an earlier publication [18]. Samples were then dried at 80 °C for 3 h in CO_2-free atmosphere and maintained in a desiccator containing soda lime and $CaCl_2$ until the time of testing.

Hydration kinetics was studied by the determination of chemically combined water and free lime contents at different ages of hydration using the ground dried samples according to the methods reported in earlier investigation [18,19].

The phase composition of the formed hydrates was investigated for some selective samples by differential scanning calorimetric (DCS) technique. Also, the morphology and microstructure of hydrated phases were examined using a JSM-5410 scanning electron microscope (SEM).

Results and discussion

Compressive strength

Fig. 1 shows the results of compressive strength versus age of hydration for all of the investigated hardened pastes made of neat OPC and OPC – EAFS blends. Obviously, the values of compressive strength of the neat OPC paste increase continuously with the age of hydration. This increase is mainly

Table 1 Chemical oxide compositions of OPC and EAFS, mass %.

Oxide/mass %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Cr_2O_3	Mn_2O_3	TiO_2	L.O.I
OPC	20.46	5.14	3.53	61.28	2.8	0.2	0.11	2.82	–	0.11	0.33	3.15
EAFS	13.9	5.82	36.1	33.4	5.71	0.2	–	0.3	0.73	2.82	0.6	–
SF	94.7	0.26	0.25	1.13	–	0.36	2.45	0.6	–	–	–	–