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Physico-mechanical properties of composite cement pastes containing silica fume and fly ash

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Abstract This works aims to study the effect of partial substitution of ordinary Portland cement (OPC) by silica fume (SF) and fly ash (FA) on the physico-mechanical properties of the hardened OPC–FA–SF composite cement pastes. The OPC was partially replaced by 20% and 30% fly ash along with 5% and 10% silica fume. The phase composition of the hydration products was investigated using XRD and DTA techniques. It was found that, the increase of FA content in OPC–FA–SF composite cement decreases the water consistency values and increases the setting times. On the other hand, the increase of SF content leads to increase the water of consistency and decrease the setting times. The partial substitution of OPC by FA and SF leads to higher porosity values with a consequent decrease in the compressive strength values especially during the early ages of hydration. At the later ages of hydration, however, the OPC–FA–SF cement pastes possess total porosity and compressive strength values close to those of the neat OPC paste. The lower of free lime contents were obtained for OPC–FA–SF composite cement pastes with the formation of further additional amounts of CSH as a result of the pozzolanic reaction. The results showed also that, the physico-mechanical properties of composite cement paste [OPC (65%)–FA (30%)–SF (5%)] were improved at later ages.

Introduction

Manufacturing of Portland cement is a resource exhausting, energy intensive process that releases large amounts of the green house gas CO_2 into the atmosphere. Production of 1 ton of Portland cement requires about 2.8 tons of raw materials, including fuel and other materials. As a result of decarbonation of limestone, manufacturing of 1 ton of cement generates about 1 ton of green house gas. Davidovits et al. [1] reported that the amount of carbon dioxide released during the

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chemical reactions, the cement content of CO_2 emission based on the calcinations of limestone could reach up to 1800 million tons in the year 2000 BaU (Business as Usual). At present, efforts have been made to promote the use of pozzolans to partially replace Portland cement. Pozzolana is a natural or artificial material containing silica in a reactive form. ASTM C618 [2] describes Pozzolana as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to exhibit hydrated cementitious properties [3,4]. The main hydration product of alite and belite in Portland cement is a calcium silicate hydrate (CSH) of colloidal dimensions, it is highly cementitious and represents about 60 to 65 wt.% of the total solids in a fully hydrated Portland cement. The other hydration product is about 20 wt.% portlandite, which usually occurs as large hexagonal crystals, and contributes little to the cementitious properties of the system. In addition, being relatively more alkaline than the other hydration products, it is easily subjected to attack by water or acidic solution, thus reducing the durability of Portland cement systems to such environments [5]. The reaction of pozzolanic materials with lime is called the ''pozzolanic reaction'' which is slow at ordinary temperature. Generally, amorphous silica reacts much more rapidly than the crystalline form. It is pointed out that calcium hydroxide is converted into cementitious material by the use of pozzolanic materials. The use of pozzolanic materials as a blended component of Portland Pozzolana cement production is generally associated with significant savings in energy and reducing the solid wastes [6]. Utilization of various types of by-products or waste materials such as fly ash, slag, silica fume, rice husk ash and limestone dust as additives in concrete results in better chemical resistance, higher strength or better durability.

Silica fume is a by-product of the silicon smelting process. It is used to produce silicon metal and ferrosilicon alloys by reducing quartz in an electric arc furnace. Silica fume is characterized by its small spherical particles, very high surface area and have a high content of glassy phase silicon dioxide (SiO_2). The results of microstructure of the hydrated blended cement containing silica fume, indicated that it is a highly active Pozzolana and increases the resistance to sulfate attack for cement pastes [7]. Silica fume is known to produce a high strength concrete, and is used in two different ways: as a cement replacement, in order to reduce the cement content, and as an additive to improve concrete properties (in both fresh and hardened states) [8].

Fly ash is widely used in blended cements, and is a by-product of coal-fired electric power plants [9]. Two general classes of fly ash can be defined: low-calcium fly ash (LCFA: ASTM class F) produced by burning anthracite or bituminous coal; and high-calcium fly ash (HCFA: ASTM class C) produced by burning lignite or sub-bituminous coal. LCFA is categorized as a normal Pozzolanic material consisting of silicate glass, modified with aluminum and iron. LCFA requires $Ca(OH)_2$ to form strength developing products (pozzolanic reactivity), and therefore is used in combination with Portland cement, which produces $Ca(OH)_2$ during its hydration. It lowers the heat of hydration and improves the durability when used in concrete as a cement replacement. It also contributes to concrete strength by pozzolanic and filler effects [10–12]. Fly ash is characterized by its cheapness which reduces the unit cost of cement and concrete, and its positive effects, such as lower water demand [12], lower hydration heat [13,14], reduced bleeding [15], and satisfactory durability [8,16,17].

The combination of silica fume and fly ash in a ternary cement system (i.e., Portland cement being the third component) should result in a number of synergistic effects, some of which are obvious or intuitive, as follows:

- Silica fume compensates for low early strength of concrete with low CaO fly ash,
- Fly ash increases long-term strength development of silica fume concrete,
- Fly ash offsets increased water demand of silica fume,
- Low CaO fly ash compensates for higher heat release from silica fume concrete and
- The relatively low cost of fly ash offsets the increased cost of silica fume.

Experimental

The materials used in this study were ordinary Portland cement (OPC) supplied from Suez Portland Cement Company (Suez, Egypt), condensed silica fume (SF) provided from Ferro-Silicon Alloys Company (Edfo-Aswan, Egypt) and fly ash (FA) obtained from Geos Company (India). The chemical analysis of these materials is shown in Table 1.

The water of consistency and setting times (initial and final) for the fresh cement pastes, made of each cement blend, were determined using Vicat Apparatus according to ASTM: C191 [18].

To prepare fresh cement pastes made of OPC–FA–SF cement blends, some amount of each cement blend was placed on a smooth, non-absorbent surface, and a crater was formed in the center. The required amount of mixing water (water of consistency) was poured into the crater by the aid of a trowel. The dry cement was slightly troweled over the remaining to absorb the water for about one minute. Continuous and vigorous mixing was done for only three minutes. The fresh cement paste was placed into one inch cubic molds, manually pressed into the corners and along the surface of the mold until a homogeneous paste was obtained. After the top layer was compacted and pressed with hand, the surface of the paste was smoothed by the aid of a thin edged trowel. Immediately after molding, the specimens were first cured in a humidity chamber at 100% R.H. at room temperature 23 ± 1 °C for 24 h then the cube specimens were demolded and curing was continued under tap water up to 3, 7, 28, 90 and 180 days, ASTM: C191 [18].

At each hydration time, all pastes were tested for their compressive strength, total porosity, free lime and phase composition of the formed hydration products.

A set of three cubic specimens of the same cement pastes and curing time were used for the determination of compressive strength according to ASTM C-150 [19].

The total porosity of the hardened cement pastes was determined according to Copeland and Hayes [20].

After the compressive strength determination, removal of free water was accomplished by using a stopping solution from 1:1 mixture by volume of methyl alcohol and acetone[21]. At any time a representative sample of the cement paste, about