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Effect of silica fume fineness on the improvement of Portland cement strength performance

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HIGHLIGHTS

- Interaction between SF fineness and amorphous SiO_2 on mortars has been assessed.
- The mortar compressive strength rises with the SF fineness increase.
- SF size distribution is a key factor regarding the compressive strength development.
- The addition of fine SF to PC improves the microstructure of hardened pastes.
- Higher strength and lower permeability have been assessed.

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ABSTRACT

This paper presents both a study on the effect of silica fume (SF) fineness on the pozzolanicity of blended cement and a method for improving coarse SF performance in making high-strength and high-performance concrete. The coarse SF, having a 45 μm sieve residue of 32.11%, yields a low pozzolanic reaction. In order to enhance its quality, the coarse SF was ground until the average particle size was reduced to a 45 μm sieve residue of 4.13% and 0.98%. It was then mixed with Portland cement type CEM I 52.5 N-SR 3 by a weight of 25% to determine the strength activity index for it to be used to produce high-performance concrete.

The pozzolanic reaction and quantitative influence of SF fineness on the mechanical strength in the SF containing composite cement system were examined in detail. XRF results indicated that reactive SiO_2 content has a clear influence on pozzolanic performance, though not as important as the SF grain size. Several methods, including the pozzolanicity test (EN 196-5:2011), chemical analysis (XRF) and strength activity index techniques, were used comprehensively for evaluation of the SF containing composite cement system.

The results suggest that the SF with high fineness is suitable for use in making CEM II/A–D cement in percentages of SF lower than 10%, according to the European Standard EN 197-1:2011 in producing a good quality, high-strength and high-performance concrete.

1. Introduction

Silica fume (SF) composed of submicron particles of silicon dioxide is produced by an electric arc furnace as a by-product of the smelting process in the production of metallic silicon or ferrosilicon in the alloys industry. The reduction of high-purity quartz to silicon at temperatures up to 2000 °C produces SiO_2 vapours which oxidise and condense in the low-temperature zone to tiny particles consisting of 85–99% amorphous silica [2]. Then, SF is composed of submicron particles of silicon dioxide which occur as almost-perfect spheres with diameters ranging from 20 to 500 nm [1]. It is estimated that current global output of SF is, at most, between one and 1.5 million tonnes per year [58].

Portland cement (PC) is unquestionably the primary cementitious material now used in construction. However, SF has been used as a high pozzolanic reactive cementitious material to make

Abbreviations: EDXA, energy dispersive X-ray analysis; HPC, high-performance concrete; PC, Portland cement; SF, silica fume; SCM, supplementary cementitious material; XRF, X-ray fluorescence.

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high-performance concrete (HPC). Moreover, it may be said that SF is the key ingredient for producing such high-performance concrete. This addition in PCs, such as CEM II/A–D according to the European Standard EN 197-1:2011 [18] has been shown to give rise to physical and chemical effects on the microstructure of hardened pastes, leading to improved properties well recognised in concrete technology, such as higher strength [4,10,27] and lower permeability [63]. Therefore, HPC has increasingly been used in civil engineering work because it allows reduction of the size of structural elements, which is essential in high-rise building. In addition to this, such HPC use is now growing in conditions of a severe nature [48,5]. In summary, the benefits obtained when utilising SF include substantial increases in compressive strength and increased durability of hardened concrete when added in optimum amounts [36,50,55,35,60,10]. Particularly, the main advantages of using SF are higher mechanical strength (high early compressive strength, high tensile strength, high flexural strength and modulus of elasticity, increased toughness and high bond strength) [10,61] and enhanced durability (sulphate resistance [61,65], higher electrical resistivity, low permeability to chloride and increased resistance to chemical attack, seawater resistance [28], freeze–thaw resistance [64] abrasion resistance [49], controlling expansion due to alkali–silica reaction [12] and good fire resistance [47]).

Therefore, SF is used in construction to make HPC for highway bridges, marine structures, parking decks, and bridge deck overlays. Furthermore, SF is utilised to manufacture shotcrete for use in rock stabilisation, mine tunnel linings, and rehabilitation of deteriorating bridge and marine columns and piles. Furthermore, SF is applied for oil well grouting and in a wide variety of cementitious repair products, among other applications.

In the case of some pozzolanic materials such as fly ash, a correlation between pozzolanic properties determined by using the compressive strength of mortars and the fineness and the soluble silica was identified [62]; the effect of the soluble silica content was found to be more significant than the effect of their fineness at later ages [56].

The purpose of this study is to evaluate the influence of SF reactive SiO_2 and grain size on SF reactivity. The pozzolanicity test method was complemented by another widely accepted method, the strength activity index for strength performance quantification, with the aim of clarifying the pozzolanic reaction and effects of SF on the hydration process of SF-containing composite cement system. Hence, the study focused on two sections: the effects of SF fineness on the evolution of pozzolanic reaction and strength performance quantification.

2. Experimental programme

2.1. Materials

Materials used in this study consisted of PC type CEM I 52.5 N-SR 3 according to the European Standard EN 197-1:2011 [18], fine aggregates (sand), silica fume and distiled water at 20 °C. Two brands of SF, namely SF I and SF II, in powder form were used. Both of them conformed to the mandatory requirements of the European Standard EN 13263-1:2005+A1:2009 [15] issued by the European Committee for Standardisation (Comité Européen de Normalisation, CEN). High-quality standardised sand was used as the aggregate (a German standardised sand, NORMASAND) in all mortar mixtures. The aggregates used in mortar mix proportioning composed of 100% sand (0–4 mm). Distiled water was used throughout the experimental programme.

2.2. Chemical analyses

The work was performed by utilising X-ray fluorescence (XRF) combined with chemical analyses for CaO and OH^- content determination, for $Ca(OH)_2$ quantification. Chemical analyses of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, SO_3, K_2O, Ti_2O_5, P_2O_5 were performed by XRF with a Bruker S8 Tigger 4 kW model. Determination of reactive SiO_2, which is active for pozzolanic reactions, was performed according to the Spanish Standard UNE 80225:2012 [3].

2.3. Evaluation of the pozzolanic activity of SF

Evaluation of the pozzolanic activity of SF was assessed by chemical and mechanical testing. The chemical evaluation was performed by the method described in the European Standard EN 196-5:2011 [19], and the CaO and OH^- concentrations determined in accordance with the European Standard EN 196-2:2005 [16] at seven and 15 days. The mechanical testing was based on the strength activity index determined and according to the European Standard EN 450-1:2012 [20].

2.4. Compressive strength testing. Strength activity index

Mechanical strength was tested according to the European Standard EN 196-1:2005 [17]. In order to determine the strength activity index, SF was added to mixes PC:SF (75:25) and specimens with only PC.

The specimens for strength measurement were cast in prismatic $40 \times 40 \times 160\ mm^3$ moulds, consolidated for 120 s on a jolting table and then covered (to minimise water evaporation) and kept in a humid cabinet. Distiled water was used as the mixing water during the preparation of the mortar specimens. The moulds were stripped after 24 h, and then the specimens were immersed in lime-saturated water at 20 °C until testing. The testing age was carried out after one, two, seven and 28 days. For each age, three specimens of each mixture were tested for compressive strength and the mean value of these measurements reported.

2.5. Grinding of SF

The SF I (A) was very finely ground in order to evaluate the fineness effect on hydration reactions and then passed through a 45 μm sieve for use in mortar preparation. Ground SF I (A) were named as SF I (B) and SF I (C). Therefore, SF I (A) with a 45 μm sieve residue of 32.11% was ground prior to use up to a fineness equivalent to a 45 μm sieve residue of 4.13% and 0.98% (SF I (B) and SF I (C), respectively). A slow-setting PC of similar fineness was used (CEM I 52.5 N-SR 3 according to European Standard EN 197-1:2011).

2.6. Particle size distribution

Particle size distribution curves of the materials were obtained by using a Mastersizer 2000 (Malvern Instruments, Ltd. Mastersize 2000 Version 5.40 – Fraunhofer Method). Particle analysis was also carried out, by using an Alpine sieve with 45-μm size sieve.

3. Results and discussion

3.1. Chemical composition of materials

The oxide analyses for cement CEM I 52.5 N-SR 3 and SF samples SF I and SF II are presented in Table 1. The fraction of SiO_2

Table 1
Chemical composition of cement CEM I 52.5 N-SR 3 and SF samples SF I and SF II.

Oxides	Cementitious materials (%)		
	Portland cement	SF I	SF II
Silicon dioxide, SiO_2	19.06	94.49	93.97
Aluminium oxide, Al_2O_3	2.092	0.252	0.620
Ferric oxide, Fe_2O_3	4.84	0.084	0.410
Calcium oxide, CaO	66.16	0.452	0.660
Magnesium oxide, MgO	1.005	0.278	1.160
Potassium oxide, K_2O	0.296	0.448	0.790
Sodium oxide, Na_2O	0.249	0.186	0.250
Sulphur trioxide, SO_3	3.366	0.130	0.340
Titanium oxide, TiO_2	0.109	–	–
Manganese oxide, Mn_2O_3	0.098	–	–
Phosphorus oxide, P_2O_5	0.148	–	–
Loss on ignition (500 °C)	0.36	0.51	0.350
Loss on ignition (975 °C)	2.12	2.89	1.520
Reactive SiO_2	–	82.50	93.90
Al_2O_3/Fe_2O_3 ratio	0.43		
	Clinker Compounds		
$C_3S + C_2S$	83.0		
C_3A	2.5		
C_4AF	14.1		
	Fineness		
Surface area, SSA (m^2/kg)	479	21,892	28,200
45 μm sieve residue (Alpine)	0.48	32.11	0.37