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Long term durability performance and mechanical properties of high performance concretes with combined use of supplementary cementing materials

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HIGHLIGHTS

- Combined use of SCMs did not result in better performance in compressive strength than separate use.
- Combined use of SCMs did not result in better performance in durability parameters.
- Combined use of SCMs did not result in better performance in sulphuric acid or acetic acid resistance.
- Abrasion resistance is only slightly influenced by SCM addition.
- Metakaolin activates more Portlandite for the pozzolanic reactions than silica fume.

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ABSTRACT

Supplementary cementing materials (SCMs) contribute to the hydration of Portland cement by physical phenomena (e.g. nucleation effect) or by chemical reactions (e.g. pozzolanic activity). The partial substitution of Portland cement with SCMs can significantly reduce the CO_2 emission during the production of concrete and, therefore, can make concrete a more sustainable and environmental-friendly material. Durability of concrete is considerably improved by the incorporation of SCMs. Due to the pozzolanic activity and the filling effect, use of SCMs can result high performance concrete having both enhanced mechanical characteristics and reduced permeability that leads to improved durability. Combined use of SCMs of ternary composition of SiO_2-Al_2O_3-CaO (e.g. blastfurnace slag and fly ash) can lead to extraordinarily favourable durability performance of concretes at even large cement substitution ratios, however, very few experimental data exist on the combined use of silica dominated and alumino-silicate dominated SCMs (e.g. silica fume combined with metakaolin) at increased cement substitution ratios. Most important aim of the present research was to reveal if there is any advantage of the combined use of silica fume and metakaolin.

1. Introduction

Technical literature provides experimental evidence for a long time that supplementary cementing materials (SCMs) contribute to the hydration of Portland cement by physical phenomena (e.g. nucleation effect) or by chemical reactions (e.g. pozzolanic activity) [1–7]. Since concrete is the most widely used construction material due to its favourable durability to cost ratio, it is high priority in concrete technology to enhance sustainability of concrete with the partial substitution of Portland cement by SCMs. Supplementary cementing materials are mostly silicate based materials and majority of them is industrial waste. The partial substitution of Portland cement with SCMs can significantly reduce the CO_2 emission during the production of concrete and, therefore, can make concrete a more sustainable and environmental-friendly material.

Some of the SCMs are silica dominated (e.g. silica fume, waste glass powder, perlite powder, quartz powder), some are alumino-silicates (e.g. activated clays, metakaolins) and some are ternary composition of SiO_2-Al_2O_3-CaO (e.g. slags and fly ashes) [8–15]. The most important characteristics of SCMs are: chemical composition, fineness (specific surface) and degree of crystallinity. SCMs react mostly with the $Ca(OH)_2$ formed during hydration of Portland cement, and extra cementitious products are produced.

Durability of conventional concrete can significantly decline when subjected to severe environments, due to the electrochemical corrosion of embedded reinforcement and/or the physical

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degradation of concrete itself. Durability of concrete is considerably improved by the incorporation of SCMs. Due to the pozzolanic activity and the filling effect, use of SCMs can result high performance concrete having both enhanced mechanical characteristics and reduced permeability that leads to improved durability [16–20].

Although, the pozzolanic reactions of SCMs have generally the same basis (i.e. reactions with calcium hydroxide), the structure of the hydration products, the rate of the pozzolanic reactions and, therefore, the magnitude and time development of the improvement of physical properties of the hardened cement paste are quite different for the different SCMs [21–26]. It is also a frequent question that what can be the optimum amount of the SCM used. Earlier studies indicated that the combined use of blast-furnace slag and pulverized fly ash (i.e. SCMs of ternary composition of SiO_2-Al_2O_3-CaO) can lead to extraordinarily favourable durability performance of concretes at even large cement substitution ratios [27–30]. To the author's knowledge, however, very few experimental data exist on the combined use of silica dominated and alumino-silicate dominated SCMs (e.g. silica fume combined with metakaolin) at increased cement substitution ratios.

2. Research objectives

The aim of the present experimental study was to investigate the effect of the combined use of commercially available silica based SCM (silica fume) and alumino-silicate based SCM (metakaolin) on long term mechanical properties and durability of high performance concretes (HPC). For this purpose, replacement of Portland cement at various percentage levels was examined under laboratory conditions on hardened concrete specimens. In total, thirteen different mixtures of HPC were studied.

3. Materials and methods

3.1. Constituent materials and mixtures

A typical Portland cement (CEM I 42.5N) according to European Standard EN 197-1:2011 [31] was used for the present studies. X-ray Diffraction (XRD) pattern of the binder is given in Fig. 1 indicating the peaks of the most important clinker minerals.

A commercially available metakaolin (in the form of powder) was used as alumino-silicate based SCM. XRD pattern of the rather amorphous metakaolin is given in Fig. 1 indicating some visible peaks of Kaolinite (K), Muscovite (M) and Quartz (Q). Ratio of the main oxide components was found by X-ray Fluorescence Spectrometry (XRF) to be 53.0% SiO_2, 41.7% Al_2O_3 and 0.52% Fe_2O_3.

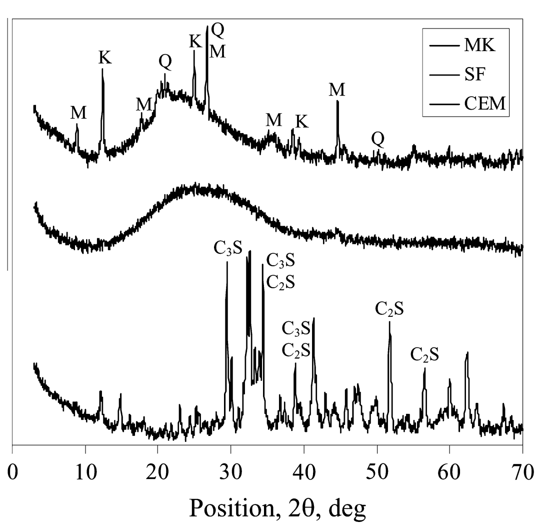

Fig. 1. XRD patterns of the cement, silica fume and metakaolin used for the present studies.

A commercially available silica fume (in the form of slurry) was used as silica based SCM. XRD pattern of the silica fume is given in Fig. 1 indicating the almost completely amorphous structure of the material with no visible peaks.

Particle size distribution curves of the cement, metakaolin and silica fume used in the present studies are shown in Fig. 2.

Quartz sand and gravel was used for the preparation of concretes (maximum aggregate size was 16 mm). Three nominal grading fractions according to European Standard EN 12620:2002+A1:2008 [32] were used: sand 0/4 mm, small gravel 4/8 mm and medium gravel 8/16 mm.

The water/binder ratio was selected to be w/b = 0.40 with constant CEM + SCM amount of 325 kg/m^3. The relatively low binder content was selected with the purpose of reaching enhanced durability performance.

The targeted consistence of the fresh concrete was 600 mm flow that was set by polycarboxylic ether based superplasticizer admixture conforming EN 934-2:2009 +A1:2012 European Standard [33]. The actual consistence achieved was found in the range of 588–604 mm flow that demonstrated the effective use of the selected superplasticizer admixture.

One reference concrete mix and twelve concrete mixes with different amount of SCMs were prepared. The cement substitution ratio for silica fume was 3 m%, 5 m%, 10 m% and 15 m%. The cement substitution ratio for metakaolin was 10 m%, 17 m%, 25 m% and 33 m%. For the combined use of the SCMs the following cement substitution ratios were applied: metakaolin/silica fume (MK/SF) ratio of 7/3 (m%/m%), 12/5, 17/8 and 25/8 to reach a total cement substitution ratio of 10 m%, 17 m%, 25 m% and 33 m%, respectively.

Steel moulds were used for the preparation of the test specimens. Specimens were standard cubes (150 × 150 × 150 mm) for the compressive strength testing, for the watertightness testing, for the air permeability testing and for the electrical resistance testing; prisms of 70 × 70 × 150 mm for the water absorption testing, for the immersion type freeze-thaw testing and for the dissolution testing in acidic solutions; and cylinders of ∅100 × 50 mm for the rapid chloride penetration testing. Specimens for the de-icing salt scaling tests and for the Bauschinger-Böhme type abrasion tests were prepared either from the standard cubes or from the prismatic specimens. All the specimens were stored under water for 7 days and under laboratory atmosphere afterwards.

3.2. Test methods

The laboratory testing of the specimens has been started at the age of 28 days. Compressive strength tests were performed by a universal closed-loop hydraulic testing machine according to European Standard EN 12390-3:2009 [34] at a constant loading rate of 11.25 kN/s applied on the standard cube specimens. The compressive strength tests were repeated at the age of 180, 300 and 600 days.

Watertightness tests were carried out at specimen age of 180 days as water penetration test according to European Standard EN 12390-8:2009 [35], however, the applied water pressure was increased to 8 bar rather than 5 bar; water pressure was applied for 72 h.

Water absorption tests were carried out by the full saturation of specimens immersed in water until reaching constant mass after being oven dried. Time development of the increase of absorbed water content was continuously recorded. The apparent porosity (i.e. water content in V% that corresponds to the atmospheric water saturated condition) was evaluated after reaching constant mass of the specimens. Water absorption tests were performed at the age of 28 days and 300 days.

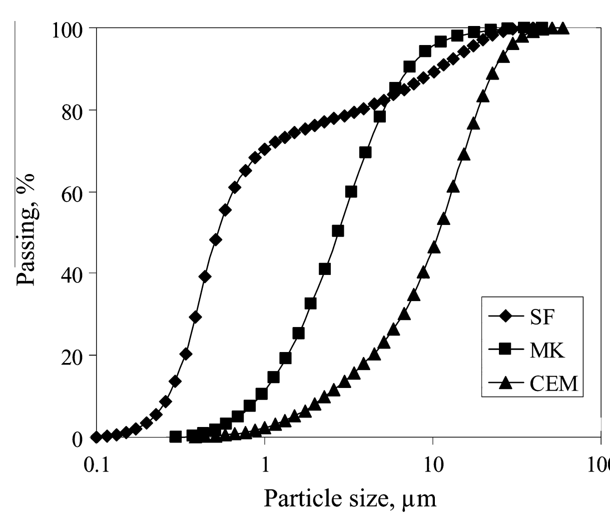

Fig. 2. Particle size distribution curves of the cement, silica fume and metakaolin used for the present studies.