Assessment of the long-term performance of SCC incorporating different mineral admixtures in a magnesium sulphate environment

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HIGHLIGHTS

• Mechanical, physical and chemical results were followed during 4 years.
• Mechanisms of damage were studied using mineralogical and microstructural analysis.
• Expansion of ordinary concrete correlate with the amount of gypsum and ettringite.
• Long-term weakness of SCC with limestone was related to the presence of thaumasite.
• Higher C-S-H decalcification occurred in SCC containing fly ash or natural pozzolan.

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ABSTRACT

The effects of mineral admixture type on the behaviour of self-consolidating concrete (SCC) in magnesium sulphate environments were investigated over the course of 4 years of exposure. Three mineral admixtures (limestone filler, fly ash and natural pozzolan) representing a wide range of compositions were used in the study. Twelve formulations covering three strength classes (30, 50 and 70 MPa) and four concrete mixtures were studied. Mass loss with physical deterioration, and dimensional and compressive strength changes due to magnesium sulphate attack were determined through microstructural analysis. The sulphate profiles of sulphur, magnesium, silicon, calcium and aluminium elements were also quantified through analyses of the samples. A complementary analysis by phase assemblages was performed on the degraded layers of concrete specimens. These test results indicate that the mineral admixture type greatly affects the durability performance of SCC under magnesium sulphate exposure. Among the tested mineral admixtures, natural pozzolan showed better long-term durability performance in the magnesium sulphate environment. The interaction between vibrated concrete and SCC is related to the nature of the mineral admixtures.

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1. Introduction

Self-consolidating concrete (SCC) is characterised by its ability to compact itself by means of its own weight, with little or no vibration and without segregation or bleeding. It fills all recesses, reinforcement spaces and voids, even in highly reinforced concrete members. Recently, this type of concrete has gained wide use in many countries. Because of the advantages it offers, SCC is increasingly being used in civil engineering structures such as substructures, infrastructure and industrial floors that are regularly subjected to aggressive environmental conditions.

External sulphates are highly soluble salts that are considered to be one of the major problems affecting concrete structures. The results of sulphate attack are generally related to the volume change, cracking and hence the deterioration of concrete. Magnesium sulphate (MgSO4) is responsible for the fastest, most severe attacks on concrete [1]. According to Golop and Taylor [2], magnesium sulphate is more severe than sodium sulphate. Their spectrum media is wide, and they usually originate from underground water, soil, seawater or industrial wastewater. The magnesium sulphate reacts with double action, with the ions SO42- reacting with the aluminate (or portlandite) to form gypsum and ettringite. The ions Mg2+ may

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react with OH\textsuperscript{-} to form brucite [Mg(OH)\textsubscript{2}] or cause a partial replacement of calcium by magnesium in Calcium Silicate Hydrate (C-S-H). The Magnesium Silicate Hydrate (M-S-H), thus formed, has no binder properties and the hydrated paste becomes soft and incoherent [3,4].

Deterioration due to magnesium sulphate is a well-known occurrence in ordinary concrete, and there have been numerous studies conducted into its effects [5–9]. However, the composition of SCC is quite different than that of ordinary concrete. The mixture design of SCC usually incorporates an efficient high-range water-reducing admixture, possibly a viscosity-modifying admixture, controlled coarse aggregate volume fraction and a large amount of mineral admixture. The influence of the nature and volume of mineral admixture content in SCC appears to be fundamental to understanding the behaviour of the material in a magnesium sulphate environment. However, there is very little information in the literature on the behaviour of SCC under MgSO\textsubscript{4} attack. Yusal and Sumer presented an experimental study on the influence of replacement of Portland cement with fly ash (FA), granulated blast furnace slag (GGBS), limestone powder (LP), basalt powder (BP) and marble powder (MP) on the magnesium sulphate attack durability of high-strength SCC [10]. The rate of attack was evaluated by visual examination and the reduction in compressive strength of samples immersed for 400 days in 10% magnesium sulphate solution. According to the results of this study, incorporation of FA, GGBS, LP and MP substantially improved the resistance of SCCs against MgSO\textsubscript{4} attack. In a recent publication, Hassan et al. studied the assessment of magnesium sulphate attack on SCC containing rice husk ash (RHA) and GGBS, with cement replacement levels of 5–15% [11]. Specimens were immersed in 5% MgSO\textsubscript{4} solution for 7 days of curing. Compressive strength, length change, and mass loss were investigated over 118 days. Results of this study showed that adding FA, RHA, and GGBS to SCC improves its resistance to magnesium sulphate attack. These studies reveal the need for further comprehensive studies on the assessment of SCC incorporating high volumes of mineral admixtures under magnesium sulphate attack, especially for a long-term exposure period.

This paper presents a detailed mechanical, physical and microstructural study into the effects of strength class and nature of mineral admixture on the behaviour of SCC in a magnesium sulphate environment. Twelve concrete mixtures with three strength classes were produced for the study. Three typical mineral admixtures (i.e., fly ash, natural pozzolan and limestone filler) were used in the production of the SCC mixtures, representing a wide range of chemical compositions. Ordinary concrete mixtures (OC) with similar strength grades were also produced for comparison purposes. The degree of magnesium sulphate attack was evaluated by visual inspection and by assessing mass change, dimensional variation and compressive strength change of concrete specimens immersed in the reference medium (fresh water) and in 5% magnesium sulphate solution for 1440 days (4 years). Microstructural changes within the different layers of degraded samples were analysed using scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses. Sulphate profiles were performed with backscattered electron imaging from the surface towards the core of the concrete samples, avoiding aggregates. The mechanisms of damage were studied using a microanalysis graphical treatment of the infected and uninfected zones [12].

2. Experimental program

2.1. Materials

Portland cement CEM I-52.5, complying with European Standards EN 197-01 [13] (similar to ASTM C150 Type I cement [14]), was used as part of the cementitious materials in the production of SCC. Siliceous round sand with a maximum grain size of 4 mm and crushed silico-calcareous rocks with 12.5 mm maximum size were used as fine and coarse aggregates. The specific gravity and water absorption properties of round sand and crushed rocks were 2.6% and 1.2%, and 2.66% and 0.5%, respectively. Three types of mineral admixtures were used in the SCC mixtures: a limestone filler characterised by its high degree of fineness, a natural pozzolan from a volcanic deposit site, and a silico-aluminate Class-F fly ash. The superplasticizer (SP) used was an acrylic copolymer with a density of 1.06 and chloride ion content of <0.1%.

Four concrete recipes (ordinary concrete (OC), SCC with limestone filler (SCCLF), SCC with natural pozzolan (SCCPZ) and SCC with fly ash (SCCF)) (12 concrete mixtures in total) were prepared, covering three strength classes (30, 50, and >70 MPa). All of the various data related to the materials were taken into account for determining the SCC mix design using Bétonlab-Pro software [17]. Bétonlab-Pro combines several behavioural models calibrated from a wide range of concrete types, with the granular structure described by the compressible stacking model.

A fixed amount of binder (cement + mineral admixtures) equal to 520 kg/m\textsuperscript{3} was selected. In each strength class, the concretes were formulated from the same components, with the same granular skeleton and constant water to binder (W/B) ratio. A comparison was then carried out using the same mechanical strength. The amount of superplasticizer was selected to obtain a slump flow as close to 670 ± 20 mm as possible for all SCC mixtures. In order to get the same strength classes as in OC, the OC formulation was realised using the Deux-Gourisse method [18]. Table 2 gives the mixture proportions of the concretes investigated. As seen in the table, the mixtures are labelled based on their ingredients; for example, mixture SCC70LF had a compressive strength class of 70 MPa and contained limestone filler.

2.3. Preparation and testing

Compressive strength and mass changes before and after immersion in the magnesium sulphate solution were monitored on 10 × 10 × 10 cm concrete cube specimens. Prismatic specimens with 7 × 7 × 28 cm dimensions were prepared to determine expansion amount after immersion. All specimens were demoulded after 24 h and cured in a controlled chamber at 20 ± 2 °C and 95% relative humidity. Slump-flow, L-box, V-funnel and air content tests were conducted in the fresh state to determine the properties of SCC in accordance with the tests recommended by the AFGC [19]. In the hardened state, after 28 days of curing, the initial mass, compressive strength and length of the specimens were determined before immersion in the sulphate solution. Two mediums were used for immersion: a fresh water tank (reference medium) and a water tank containing 5% magnesium sulphate solution. The temperature of the solution was maintained at 22 ± 2 °C. The testing procedure was conducted according to the ASTM C1012-04 [20] and the method outlined by Melita [21]. The pH of the sulphate solution was maintained within a range of 6.0–8.0 by adding a suitable amount of sulphuric acid solution (0.1 N H\textsubscript{2}SO\textsubscript{4}). In addition, the aggressive solutions were totally renewed every 8 weeks. Samples were immersed for 4 years in the magnesium sulphate and fresh water solutions. To evaluate the effect of the various mineral admixtures on the durability of SCC exposed to magnesium sulphate solution, visual (photos), mechanical (compressive strength), physical (change of mass and length), and mineralogical (XRD) investigations were performed. Chemical and microstructural studies were also carried out using SEM coupled to EDS and microanalyses of polished surfaces.

3. Experimental results

3.1. Concrete properties in fresh state and compressive strength before immersion

Table 3 presents the workability and basic mechanical properties of twelve SCC mixtures. The results of the SCC mixtures listed in Table 3 can be interpreted according to the limits of the standard for SCC tests recommended by the AFGC [19]. The SCC mixtures had good filling ability with a slump-flow equal to 670 ± 20 mm and V-funnel flow times between 5.8 and 7 s. All SCC mixtures showed acceptable passing ability based on L-box and fill-box results, which ranged between 0.80 and 0.90 and 79% and 96.2%, respectively.

When 7-day compressive strength test results were compared, a significant difference between SCCLF and other concretes was observed. The improved strength of SCCLF at an early age can be attributed to the formation of calcium carboaluminate hydrate, which led to a decrease in the total porosity and accelerated the hydration rate of the cement paste [22]. From the 28-day test