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Properties of self-consolidating concrete made utilizing alternative mineral fillers

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HIGHLIGHTS

- SCC mixtures prepared using four different materials as mineral filler were studied.
- All four mineral fillers can be alternatively used to produce high performance SCC.
- Information presented in the paper can be used to produce economical mixtures of SCC.

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ABSTRACT

Self-consolidating concrete (SCC) is a concrete material possessing an ability to take formwork shapes and pass through congested reinforcement bars without being vibrated, making it a 'smart concrete' material. However, the high cost of SCC resulting from the use of mineral fillers and high cement content has been a main factor impeding the widespread use of this smart material. Consequently, there is a need to investigate the use of low cost materials in the production of SCC to ensure adoptability of SCC in concrete construction. This paper presents the results of a study conducted to develop and evaluate the performance of four SCC mixtures using different combinations of filler materials, such as silica fume, natural pozzolana and metakaolin, in conjunction with limestone powder. The developed SCC mixtures exhibited high strength (compressive, tensile, bond and elastic modulus), excellent shrinkage behavior and good durability characteristics (high corrosion resistance and related indices). The findings of this study indicated the possibility of producing cost-effective and high-performance SCC mixtures using the mineral fillers considered in this study.

1. Introduction

Unusual construction circumstances in Japan in the 1980s incited a team of engineers to develop a smart concrete material, which was later named as self-consolidating concrete (SCC). SCC possesses the ability to take form shapes and pass flow through congested reinforcement bars without any mechanical aid, thus eliminating the risk of concrete honeycombing and other defects resulting from poor compaction [1]. As a result of its phenomenal fluidity, SCC easily flows through obstructions and narrow sections to fill-in the forms by its self-weight, yet free of any objectionable segregation or bleeding.

While the material components of SCC are generally the same as for conventionally vibrated concrete (CVC), the major difference lies in relative quantities of the component materials, such as the high amount of superplasticizer (SP) for the required level of flowability, the high powder content to act as "lubricant" for the coarse aggregates, and high fine aggregate content to assist workability and enhance stability of the mixture against segregation [2]. Given the aforementioned peculiarities of SCC, for those in Europe, India and other parts of the world where filler materials, like fly ash (FA) and silica fume (SF) are available at little or no cost, the only cost raising component in SCC remains the SP (and in some cases stabilizer also). However, in the regions where these materials are not available, the cost of SCC increases – thus making it uneconomical. Therefore all attempts to develop SCC with alternative locally available materials will always count as welcome developments towards making the SCC economical. Some of the prospective materials for use as mineral filler for the production of SCC include: limestone powder (LSP), calcined clay/metakaolin (MK), and natural pozzolana (NP).

Limestone powder (LSP) is a by-product (quarry dust) of the quarrying process of carbonate rocks; hence its main component

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is calcium carbonate, $CaCO_3$. Although LSP does not possess pozzolanic property [3,4], its use in concrete offers many technical benefits, among which are increase in early strength and bleeding control [4,5], improvement of the concrete workability and excellent densification of concrete microstructure [4–6]. LSP improves the deformability and viscosity of SCC, as well as reduction of SCC porosity. Because of these positive impacts of LSP on the properties of SCC coupled with its economic benefits, it forms a major component of many SCC mixtures. However, there are little or no published information on the performance of SCC made with the limestone quarry dust (herein denoted as LSP in the paper).

Metakaolin (MK), a product of calcination of kaolinitic clays, is another effective pozzolana which improves strength and durability properties of concrete [7–13]. Recent studies on the incorporation of MK in SCC mixtures [8,9] showed that MK improves the compressive strength and durability of SCC mixtures, but may raise the plasticizer requirements when large quantities are used [8].

Natural pozzolana (NP) is a raw or calcined natural material having pozzolanic properties, which are among the oldest construction materials [14]. A natural pozzolana of volcanic origin is usually composed of mainly silica and alumina with low contents of calcium and iron oxides. Though the pozzolanic activity of NP is slow according to several studies [14–16], its beneficial contribution in improving the durability characteristics and ultimate strength [14,17–19] had made it the focus of several studies on the development and performance of concrete mixtures. However only few studies [9,19,20] have recently considered the use of NP in SCC.

Silica fume (SF) is a byproduct generated from the carbothermic reduction of quartz and quartzite in electric arc furnaces in the production of silicon and ferrosilicon alloys [21]. This siliceous material, containing 85–95% SiO_2 with very fine vitreous particles [21], is so popular with its ability to improve the strength and durability properties of concrete to the extent that many modern high-performance concrete mixtures incorporate SF as an important admixture [22]. Several studies [23–26] on the fresh and mechanical properties of SCC incorporating silica fume have been reported in the literature. However, the cost of SF is very high in regions because of importation factors, and as such many local researchers have sought to get locally available replacements for producing concrete.

The aim of this study was to explore the feasibility of producing high performance SCC utilizing the combinations of the filler materials that have not been commonly utilized thus far. This will consequently help in reducing the cost of production of SCC. Four different combinations of the mineral fillers, namely LSP, SF, NP and MK were considered in this study. Since LSP is commonly used as mineral filler in SCC, it was common in each of the four combinations of the mineral fillers. The mechanical properties (compressive strength, splitting-tensile strength, bond strength and modulus of elasticity), drying shrinkage behavior, and durability characteristics (water permeability, rapid chloride permeability (RCP), electrical resistivity and corrosion resistance) of the developed SCC mixtures were investigated and the experimental results presented and discussed.

2. Experimental Program

2.1. Materials

Type I cement, complying with ASTM C 150 was used. The SF used in this study was sourced from Saudi Ready Mix Company, a local supplier. The NP used was a volcanic ash, complying with the specifications of ASTM C 618, obtained from local volcanic sites in the eastern province of Saudi Arabia. The LSP was sourced from a local limestone quarry. Raw clay from a local source was calcined to obtain MK. The clay was thermally activated in a furnace at 850 °C and then ground with laboratory pulverizer to a fineness of passing #100 (150 μm) sieve. The properties of powder materials (cement and mineral fillers) used are shown in Table 1.

The coarse aggregate used in this study was crushed limestone sourced from a local quarry. It had a maximum aggregate size of 20 mm, specific gravity of 2.60 and water absorption of 1.4%. Dune sand was used as fine aggregate. Its specific gravity was 2.56, while its water absorption was 0.4%. Fig. 1 shows the grading of coarse and fine aggregates used.

A new generation polycarboxylic-based ether hyperplasticiser (superplasticizer (SP)) was used in all the trial mixtures while the stabilizer/viscosity modifying admixture (VMA) used was an aqueous solution of a high-molecular weight synthetic copolymer. Both the SP and VMA were kindly supplied by Saudi BASF for Building Materials Co., Ltd., Al-Khobar. The SP and VMA properties are also shown in Table 1.

2.2. Mixture parameters

In this study, the properties of four SCC mixtures prepared utilizing LSP and other three mineral fillers were studied. Table 2 shows the parameters used in the preparation of four SCC mixtures. As can be seen from Table 2, mix design parameters were fixed for all the four SCC mixtures, except the quantities of superplasticizer and stabilizer dosages required for each mixture to achieve self compactability. These dosages were obtained by trials on the concrete mixtures until the rheological parameters attained satisfactory levels. Table 3 shows the designation used for the selected four SCC mixtures.

The weights of constituent materials for producing one cubic meter of SCC mixtures, calculated using the absolute volume method, are presented in Table 4. As indicated in Table 4, the mixture L-20 was used as a control mixture, containing 20% LSP, while the other three mixtures contain other fillers in binary combination with LSP, still maintaining the total filler content of 20% of the total powder. Unlike the other three mixtures in which each of the two fillers were 10% of the total powder content, LM-15-5 was made with only 5% MK (and 15% LSP to keep total filler same 20% like others) due to the low mixture workability observed in the preliminary work with 10% MK. As more than one trial was made on each of the trial mixtures in order to achieve the SCC mixtures with acceptable self-compactability, only the optimum dosages of VMA and SP for each mixture were shown in Table 4.

2.3. Evaluation of self-compactability

Three self-compactability tests were performed on each of the SCC mixtures. These tests included: slump flow and V-funnel test for filling-ability and U-box test for passing-ability. All these three tests were conducted in accordance with the guidelines provided by EFNARC for SCC [27]. Segregation resistance was evaluated by visual judgment. According to EFNARC [27], visual observation of a flowing concrete on the flow table can offer some indication of its segregation resistance. Emphasis was laid on observing band of mortar or cement paste without coarse aggregate at the perimeter of the pool of concrete on the flow table. In line with this, 'mortar band width' criteria were set, based on long-term segregation behavior of previously tested mixtures. The 'mortar band width' criteria employed in this study, for classifying mixtures with respect to their stability, is shown in Table 5.

2.4. Evaluation of hardened properties

Mechanical properties were evaluated in terms of compressive strength, splitting-tensile strength, bond (pull-out) strength and static modulus of elasticity. The drying shrinkage of the SCC specimens was also assessed. The durability characteristics of the developed SCC were evaluated by measuring water permeability, rapid chloride permeability (RCP), and electrical resistivity. Further, reinforcement corrosion was monitored by measuring corrosion potential and corrosion current density of reinforced concrete 'lolly-pop' specimens frequently for about 15 months while exposing them to chloride solution during this period. Table 6 summarizes the specimen size and test methods for evaluating the mechanical properties and durability characteristics of the selected SCC mixtures.

3. Results and Discussion

3.1. Self-compactability

The flow characteristics of the developed mixtures are shown in Table 7. The optimum SP and VMA dosages that gave these acceptable flow properties were used in preparing the respective test specimens for evaluating the mechanical properties and durability characteristics.

From the flow results in Table 7, it can be seen that L-20, ML-S-10 and LN-10-10 required nearly same volume of SP and VMA. However, LM-15-5 required an increased volume of SP and VMA. Consequently, except a clear benefit that can be seen in this blend over others in terms of mechanical properties and/or durability