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Effect of various supplementary cementitious materials on rheological properties of self-consolidating concrete

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HIGHLIGHTS

- The effect of binder type and content on the benefits of SCM in SCC was investigated.
- Metakaolin was able to increase the plastic viscosity of SCC by 90%.
- Silica fume and blast furnace slag reduced the plastic viscosity of SCC.
- Yield stress of the mixtures with SCM was higher than that of the control mixtures.

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ABSTRACT

In design of self-consolidating concrete (SCC) for a given application, the mixture's rheological parameters should be adjusted to achieve a given profile of yield stress and plastic viscosity. Supplementary cementitious materials (SCM) can be useful for this adjustment in addition to their other advantages. In this study, the rheological properties of 57 SCC mixtures with various SCM were investigated for a constant slump flow value. For this aim, various amounts of silica fume (SF), metakaolin (MK), Class F fly ash (FAF), Class C fly ash (FAC) and granulated blast-furnace slag (BFS) were utilized in binary, ternary, and quaternary cementitious blends in three water/binder ratios. Results showed that SF and BFS decreased plastic viscosity and V-funnel time values in comparison with mixtures containing only Portland cement (PC). However the opposite tendency was observed when MK, FAC and FAF were incorporated with PC. Substitution of PC with SF, MK and FAC increased high range water reducer (HRWR) demand in the SCC mixtures having constant slump flow. Use of SCM in SCC mixtures increased yield stress values. Good correlations were established between plastic viscosity and V-funnel flow time values for all *w*/*b* ratios.

1. Introduction

SCC is one of the innovative concrete that is progressively used for experimental jobs and actual projects. It can flow readily under its own weight and self-consolidate without any mechanical vibration. Such a concrete must achieve magnificent deformability, and great stability to ensure high filling capacity of the formwork, even in a very congested structural member.

Yield stress and plastic viscosity are considered as two main parameters that define concrete rheology. SCC has a low yield stress and a moderate viscosity to ensure good consolidation and a highly fluid mixture without any segregation among constituents, especially between the binder phase and aggregate. A low yield stress and a moderate viscosity can be achieved by an increase in paste volume for a given rheology of paste and dosage of high-range water-reducer (HRWR) [1–3]. One of the ways to increase the paste volume is to replace some part of the Portland cement (PC) with supplementary cementitious materials (SCM). In addition to the enhancement of mechanical properties and durability, the use of SCM, such as silica fume (SF), fly ash (FA), metakaolin (MK) and granulated blast-furnace slag (BFS) can improve rheological properties by adjusting the rheological parameters for a given application. In other words, plastic viscosity or yield stress can be tailored according to the desired performance in a variety of civil engineering applications by the utilization of SCM. Moreover, use of by-product SCM, like FA and BFS, can decrease the cost of SCC and the amount of the CO_2 production related to the use of PC in concrete [4–13].

Despite the above-mentioned advantages of SCM in SCC, they may also weaken SCC properties compared to the plain SCC containing no SCM. For instance, SF and MK significantly increase

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early strength and considerably reduce the permeability of SCC but may impair the required workability in fresh concrete. On the contrary, BFS generally decreases early strength but improves workability. Due to these opposite effects, combinations of SCM have found significant importance in concrete technology [14–17]. Assaad [10] studied the rheological behavior of SCC containing SF, BFS and FA. It was reported that mixtures containing binary cement (PC + SF), ternary cement (PC + SF + FA) and quaternary cement (PC + SF + FA + BFS) showed lower plastic viscosity values than corresponding plain SCC mixtures. In another research, the effects of SCM on the rheological properties of cement grouts were tested by Khayat et al. [6]. It was concluded that the partial substitutions of cement with FA and BFS increased the plastic viscosity compared to that of the reference grout made without any SCM, regardless of the HRWR dosage. However in the case of SF, decrease in plastic viscosity was visible.

In recent years, there has been a growing interest in the use of MK and SF as SCM to produce SCC. However, only a limited number of studies are available about the rheological properties of SCC containing MK. In a recent study, Hassan et al. [18] investigated the yield stress and plastic viscosity of SCC containing MK and SF. They proposed that the addition of MK and SF increased the HRWR demand in SCC mixtures having constant slump flow. Moreover, the addition of SF appeared to require more HRWR when compared to MK. It was also found that both plastic viscosity and yield stress increased as percentage of MK was increased. At constant slump flow, plastic viscosity of SF mixtures were similar to that of the control mixture without any SCM. When the HRWR content was kept constant, yield stress increased continuously with an increase in SF content. Besides, as cited by Hassan et al. [18], Mouret and Cyr [19] found that cement paste with MK exhibited high plastic viscosity while cement paste with SF showed lower plastic viscosity than reference cement paste. In another investigation Boukendakdji et al. [20] noted that the SCC mixtures incorporating BFS exhibited low plastic viscosity and low yield stress than the reference mixture containing only PC.

Although a number of studies about the effects of using FA, SF and BFS on the fresh and hardened properties of SCC have been found in the literature, the effect of using these SCM on the rheological properties were discussed only in limited number of studies [10,18,21,22]. Moreover, the potential benefit of using various amounts of SCM in ternary and quaternary combinations with PC on rheological properties of SCC is not well documented. The study presented herein aims at the effect of binder type and content on the benefits of SCM in SCC of different dispersion states that can be used in a variety of civil engineering applications.

The current study focuses on the rheological properties of SCC containing various amounts of SF, FA, MK and BFS as a partial replacement of cement. These SCM were used in binary, ternary, and quaternary cementitious blends to investigate the variations of some properties such as V-funnel flow time, HRWR demand as well as yield stress and plastic viscosity. The mixtures were designed to have three water-binder ratios (*w*/*b*). The rheological parameters were measured with a coaxial cylinder concrete rheometer. This study also aims at comparing the effects of utilization of a viscosity modifying admixture (VMA) to those of SCM.

2. Experimental methods

2.1. Materials

An ordinary Portland cement CEM I 42.5 R, similar to ASTM C 150 [23] Type I cement, was used. Five types of SCM, which are SF, FAC, FAF, MK, and BFS, were also used in binary, ternary, and quaternary cementitious blends. The physical and chemical properties and particle-size distribution of PC, SF, FAF, MK, and BFS are presented in Table 1 and Fig. 1. In addition, the micrographs of SCM and PC are shown in Fig. 2. Crushed limestone was used as aggregate. The maximum particle size was 15 mm and 3 mm for coarse and fine aggregate, respectively. The bulk specific gravity of the coarse and fine aggregates were 2.64 and 2.61, respectively, and their absorption capacities were 0.21% and 0.67%, respectively. A polycarboxylate ether-based HRWR conforming to ASTM C494 Type F of [24] with a specific gravity of 1.1 and solid content of 28% was incorporated in all mixtures. A liquid viscosity-modifying admixture (VMA) was used in some SCC mixtures.

Table 1
Physical and chemical properties of cement and SCM.

	PC	SF	FAC	FAF	MK	BFS
CaO (%)	64.06	0.25	36.56	3.24	0.3	35.2
SiO_2 (%)	17.74	87.92	31.94	59.5	51.1	40.3
Al_2O_3 (%)	4.76	0.4	13.5	18.5	39.1	10.2
Fe_2O_3 (%)	3.17	0.35	4.09	6.96	2.15	0.67
MgO (%)	1.28	3.97	1.42	2.03	0.7	6.9
SO_3 (%)	2.94	0.21	3.86	0.47	0.08	1.4
K_2O (%)	0.8	0.81	0.94	1.93	1.78	0.97
Na_2O (%)	0.45	1.79	1.1	1.27	0.11	1.12
Free lime (%)	2.21	–	2.69	0.42	–	–
Other minor oxides (%)	0.64	1.43	0.91	1.26	0.88	1.34
Loss on ignition (%)	1.95	2.87	2.99	4.32	3.8	1.9
Specific gravity	3.13	2.29	2.73	2.38	2.54	2.97
Blaine fineness (cm^2/g)	3310	–	3470	3220	–	3650
Surface area B.E.T. (m^2/kg)	–	24,520	–	–	15,410	–
Residue 45 μm (%)	4.2	–	17.4	19.5	0.4	1.3

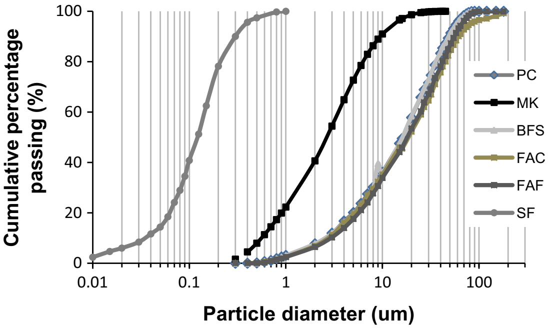

Fig. 1. Particle size distributions of PC and SCM.

2.2. Mix proportions and preparation

As summarized in Tables 2–4 a total of 57 SCC mixtures were designed to have three *w*/*b* (0.44, 0.50, and 0.56) with various binder contents (454.5, 400, and 357 kg/m^3) and a constant water content. For all SCC mixtures the fine aggregate-to-total aggregate ratio, by mass, was set at 0.53. The HRWR dosages used in the mixtures were adjusted to secure an initial slump flow of 650 ± 10 mm. The three control mixtures did not contain any SCM, whereas other mixtures incorporated binary (PC + SF, PC + FAC, PC + FAF, PC + MK and PC + BFS), ternary (PC + SF + BFS, PC + FAC + BFS, PC + FAF + BFS and PC + MK + BFS) and quaternary (PC + SF + FAC + BFS) cementitious blends in which a portion of PC was replaced with the SCM. The replacement levels for various SCM were different: it was 4%, 8% and 12% for SF, 4%, 8%, 18% and 36% for MK, 18% and 36% for FA and only 18% for BFS. In addition, a constant amount of VMA, selected within the recommended dosage range of the manufacturer, was employed for each *w*/*b* ratio to compare the results with the mixtures containing SCM. All substitutions of the cement by SCM were made on the total mass basis of the binder. The mixtures were mixed in batches of 20 L using a rotary planetary mixer. Mixing efficiency, mixer type, mixing sequence, ambient temperature, etc. are the factors affecting the rheology of SCC during its production [25,26]. Therefore, these factors were not changed throughout the study. The mixing materials were kept at approximately 20 ± 2 °C (68 °F) temperature before mixing. Following the end of mixing, mixtures had approximately constant temperatures of 24 ± 2 °C (75.2 °F). The mixing procedure for concrete mixtures consisted of homogenizing the fine and coarse aggregate for 1 min and introducing 35% of the mixing water. Following a rest period of 1 min to allow the saturation of the aggregates, binder and 40% of water were added. After 2 min of mixing, the HRWR diluted with the remaining water was introduced gradually over 2 min. while the mixer was turned on. Following 2 min of rest, the concrete was mixed for 3 additional min.

The mix proportions of VMA-bearing mixtures were similar to that of the control mixtures except that VMA content was 4.6 kg/m^3 for all *w*/*b* ratios and HRWR content was 8, 6, 5.48 kg/m^3 for *w*/*b* ratios of 0.44, 0.50 and 0.56, respectively. The