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Thixotropy and structural breakdown properties of self consolidating concrete containing various supplementary cementitious materials

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In this study, thixotropy and structural breakdown of 57 self-consolidating concrete (SCC) mixtures containing various supplementary cementitious materials (SCM) were investigated by different approaches. The effects of SCM type and content on high range water reducer demand and plastic viscosity were also studied. For these purposes, 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 (w/b) ratios. Results showed that except BFS, use of SCM in SCC mixtures increased thixotropy values in comparison with the mixtures containing only portland cement (PC). Good correlations were established between structural breakdown area and drop in apparent viscosity values for all w/b ratios. The different methods used to evaluate the thixotropy and structural breakdown got more consistent with each other as w/b decreased.

1. Introduction

Utilization of supplementary cementitious materials (SCM) in concrete has a tendency to increase by the future in order to provide greater sustainability in construction industry. SCM such as fly ash (FA), granulated blast-furnace slag (BFS) and silica fume (SF) are widely used in self-consolidating concrete (SCC) due to their several advantages. First of all, the high amount of paste requirement for better flow of SCC is easily achieved by SCM, which is superior to using only portland cement (PC). Also utilization of these SCM in SCC reduces the demand for PC, fine fillers and viscosity-enhancing chemical admixtures in SCC. Many studies [1–5] reported that use of SCM in SCC not only improves the mechanical, durability and long term properties of concrete, but also helps to adjust the rheological and thixotropic properties as well as stability of the fresh SCC for a given application. In other words, plastic viscosity or stability specifications can be tailored according to the desired performance in a variety of civil engineering applications by the utilization of SCM. Additionally, 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. Therefore, use of SCM has become very important in SCC [6,7].

Despite the above-mentioned advantages of SCM in SCC, they may present some deleterious effects on SCC properties compared to the plain SCC containing no SCM. For instance for a constant slump flow, MK may significantly increase plastic viscosity [8] and impair a sharp fall in the workability of fresh concrete although it can considerably reduce the permeability [3] of SCC. On the contrary, BFS may improve workability but it may decrease plastic viscosity of SCC [9,10]. Plastic viscosity of SCC mixtures containing SF could be similar or lower than of the control mixture without any SCM at constant slump flow values while stability and durability aspects are improved [4,5,8]. In addition, replacement of PC by FA in SCC mixtures can increases plastic viscosity [11] but may significantly decrease early strength values [12].

A high amount of plastic viscosity can reduce concrete flowability and workability, whereas a very low viscosity can accelerate the speed of segregation [13]. Moreover, a concrete with a high degree of thixotropy may show high segregation resistance [5] and decrease lateral pressure exerted on the formwork system [14] while high thixotropy may lead to an increase in entrapment of air in fresh concrete and formation of lift lines in multilayer casting [15]. Such opposite effects may be remedied by the combined use of the SCM. Therefore, combinations of SCM in ternary and quaternary cementitious blends have found significant importance in the presented study.

Although a number of studies about the effects of SCM on the fresh and hardened properties of SCC have been found in the

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literature, the effect of using SCM on the thixotropic properties were discussed only in limited number of studies [2,5,16]. Moreover, the potential benefit of using various amounts of SCM in ternary and quaternary combinations with PC on rheological and thixotropic properties of SCC is not well documented. Thus, the effects of different blends of SCM on rheological and thixotropic properties of SCC are presented in this study.

Thixotropy can be defined as a gradual decrease of the viscosity under shear stress followed by a gradual recovery of structure when the stress is removed [17]. The thixotropic behavior of cement paste is related to coagulation, dispersion and re-coagulation of the cement particles [18–20]. Coagulation is a result of the total potential energy interaction between them, which originates from the combined forces of van der Waals attraction, electrostatic repulsion and steric hindrance [19,21,22].

Tattersall and Banfill [21] explained the structural breakdown as follows: When cement particles and water come together, a hydrate membrane immediately covers and links the particles. If the cement paste is sheared, the linkages between them may be broken, separating the particles. The breaking of linkages was considered to be an irreversible process and thus non-thixotropic [21,23].

There are several ways of studying the thixotropy and structural breakdown. By gradually increasing and then decreasing the angular velocity of the viscometer vane, the corresponding torque values will form a hysteresis loop if the mixture is thixotropic. The area between the up and down curves can quantify the thixotropy [21,24,25]. A more widely used method to quantify the thixotropy and structural breakdown is to keep the shear rate constant and observe the change (decrease) in the corresponding torque values in time [21]. This approach can be repeated for several constant shear rates to study the behavior over a wider range of shear rates, enabling a more comprehensive evaluation [5,26]. The thixotropic behavior of the cementitious materials was also studied by evaluating the static yield strengths of the mixtures determined at very low shear rates [27]. Roussel defined a so-called "thixotropy index" as the ratio of the shear stress at rest to the characteristic time of flocculation [14]. The modeling of the time-dependent behavior of the cementitious materials have attracted the attention of many researchers [20–24]. In a recent research, Wallewik [23] showed, by both his model and experimental work, that the time-dependent behavior is governed by both thixotropy (combination of coagulation, dispersion and re-coagulation of the cement particles) and structural breakdown (breaking of chemically formed linkages between the particles). Very detailed reviews for thixotropy and structural breakdown can be found in [19,24,28,29].

In recent years, the study of thixotropy and structural breakdown of SCC has become an interesting area of research owing to the fact that it would help concrete technologists to predict some aspects such as the static stability, segregation resistance, formwork pressure and its decay after casting, air entrapment, surface quality, interlayer bond strength between consecutive concrete layers and pumpability of concrete [15,30–34].

SCC behaves thixotropically showing good segregation resistance and low lateral pressure on formwork whereas it probably can increase entrapped air in fresh concrete and lift lines in multilayer casting, reducing bond strength between layers [15,31,35]. Therefore, for a given application the mixture parameters of SCC should be adjusted to achieve a given profile of thixotropic properties that can take into account the various requirements. Many parameters such as w/b ratio [36], binder type and content [2,37], aggregate characteristics and content [38] can affect the rheological properties, thixotropic and structural breakdown behavior of SCC. Besides the type and dosage of high-range water-reducing admixture (HRWR) [36], type and concentration of viscosity-modifying admixture (VMA) [39] as well as use of set-modifying admixtures [30] are important parameters in this respect.

Cementitious materials characteristics such as concentration, packing density, fineness and incorporation of SCM such as FA, SF and BFS are among the factors that affect the rheology and thixotropy of concrete [14,21,40]. Roussel et al. [41] reported that high thixotropy value in the mixtures containing SCM, like fine silica or limestone particles, is related to nucleation effect of these materials in PC mixtures. In fact, the increase in thixotropy without any workability loss can be obtained if the mixing power is sufficient to break the additional C–S–H bonds created by these products. It was reported that utilization of SCM in concrete increases the internal friction and hence attractive forces among solid particles, which in turn, increase the degree of physical and chemical bonds during cement hydration [14,21,40].

Assaad [2,5] studied the rheological and thixotropic properties of SCC containing SF, BFS and FA. It was reported that mixtures containing a binary cement (PC + SF), a ternary cement (PC + SF + FA) and a quaternary cement (PC + SF + FA + BFS) showed lower plastic viscosity and higher thixotropy values than corresponding plain SCC mixtures in the time interval between 0 and 30 min. However, reduction in the amount of thixotropy was observed in quaternary mixtures up to 150 min. It was also reported that mixtures with higher amount of cement content and lower amount of aggregate showed lower thixotropy values.

In a more recent study, Rahman et al. [16] reported that the use of SF in SCC in the range of 2.5–7.5% by weight of cement did not influence the thixotropy significantly from that of the control mixture. However use of FA in the range of 5–10% by weight of cement was found to increase the thixotropy of the mixture considerably.

In this paper, the rheology, thixotropy and structural breakdown of SCC made with various amounts of SF, FA, MK and BFS as a partial replacement of PC were studied. The aim of the first part of this study is to evaluate the effect of using these SCM in binary, ternary, and quaternary cementitious blends on HRWR demand and rheology. In the second part, the effect of these SCM on the thixotropy and structural breakdown of SCC mixtures was evaluated by different approaches. The effects of the SCM were also compared to those of a VMA. A total of 57 SCC mixtures were designed to have three w/b ratios with various binder contents. The measurements were made with a coaxial cylinder concrete rheometer.

2. Research significance

Rheology, thixotropy and structural breakdown of SCC have been recognized as important tools to be tailored to achieve a multifold set of engineering properties required for successful accomplishment and performance of the intended application. For a given application, the mixture's properties should be adjusted to achieve a given profile of static stability, segregation resistance, formwork pressure, air entrapment, surface quality and interlayer bond strength between consecutive concrete layers. Utilization of SCM in concrete can not only improve the mechanical and durability properties of the mixtures, but also improve rheological and thixotropic properties as well as stability of the fresh concretes [1–3,5]. 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 and thixotropic properties were discussed only in limited number of studies [2,5,16]. Moreover, the potential benefit of using various amounts of SCM in ternary and quaternary blends on thixotropic properties of SCC is not well documented. The study presented herein aims at filling these gaps in the literature.