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Role of Water Film Thickness on Rheological Characteristics of Self-Consolidating Concrete Containing Silica Fume

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ABSTRACT

In previous studies, it has been found that utilization of various supplementary cementations materials has significant effect on rheological properties of self-consolidating concrete. The present study aims to extend the role of water film thickness on rheological characteristics of self-consolidating concrete containing silica fume. For this purpose, relation between T_{50} flow time, V-funnel flow time and plastic viscosity with water film thickness of self-consolidating concrete mixtures containing different amounts of silica fume has been investigated. Results, showed that the rheological parameters can be closely related to the thickness of excess water around the solid particles.

Keywords: *Water film thickness, Rheology, Self-consolidating concrete, Silica fume.*

1. Introduction

Previous studies [1-3] revealed that the usage of fine supplementary cementitious materials (SCM) in self-consolidating concrete (SCC) helps to adjust the rheological and thixotropic properties of the fresh SCC for a given application. In other words, rheological performance of SCC can be tailored according to the desired performance in a variety of civil engineering applications by the utilization of SCM, in addition to their numerous profits. The rheological performance of a concrete mix is highly dependent on flowability of the cement paste portion, which in turn is governed mainly by the water/binder ratio, type and amount of SCM that has been used [2, 4]. At micro scale level, the thickness of the water films coating the cement particles governs the consistence of cement paste [5]. When the ultrafine SCM fills the voids between cement grains, the packing density of solid particles increases and some of the water entrapped can be freed as excess water (the water in excess of that needed to fill the voids) to form water films coating the solid particles to provide lubrication. On the other side, owing to high fineness of fine SCM, the addition of SCM would significantly increase the surface area of the solid particles that would be coated with water films [6, 7]. In this regard a method for calculating the average thickness of water film coating the solid particles taken as the excess water to solid surface area ratio has been developed as water film thickness (WFT) [8]. In recent years, due to increasing usage of SCM in concrete, the study role of WFT up on rheological performane of mortar and concrete has become an interesting area of research owing to the fact that it would help concrete technologists to predict a mortar or concrete mix design based on WFT [8, 9]. Although a number of studies about the role of WFT on the fresh and hardened properties of concrete have been found in the literature. However there is lack of the experimental information about the role of WFT on rheology of SCC containing SCM. The present study aims to extend the role of WFT on rheological characteristics of SCC containing silica fume (SF).

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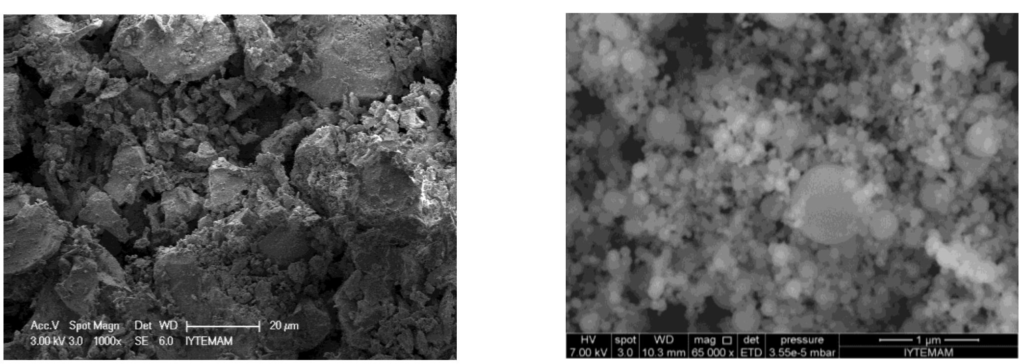
2. Materials

The cement used was an ordinary Portland cement (PC), CEM I 42.5 R. The physical and chemical properties of PC and SF is presented in Table 1. In addition, the micrographs of PC and SF inspected by a scanning electron microscope (SEM) are shown in Fig. 1. Crushed limestone aggregate with maximum particle size of 15 mm and 4 mm, respectively for coarse and fine aggregate, were employed. 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 high-range water-reducer (HRWR) with a specific gravity of 1.1 was used in all mixtures.

Table 1: Physical and chemical properties of PC and SF.

Parameters	PC	SF
CaO, %	64.06	0.25
SiO_2, %	17.74	87.92
Al_2O_3, %	4.76	0.4
Fe_2O_3, %	3.17	0.35
MgO, %	1.28	3.97
SO_3, %	2.94	0.21
K_2O, %	0.8	0.81
Na_2O, %	0.45	1.79
Free lime, %	2.21	—
Other minor oxides, %	0.64	1.43
Loss on ignition, %	1.95	2.87
Specific gravity	3.13	2.29
Blaine Fineness, cm^2/g	3310	—
Surface area B.E.T., m^2/kg	—	24520
Residue on 45 μm sieve, %	4.2	—



(a) (b)

Fig. 1: SEM images of a) PC and b) SF

3. Mixtures proportions

As summarized in Table 2, one control mixture without any SCM and 3 SCC mixtures with SF were designed to have a constant w/b of 0.44 and total binder content of 454.5 kg/m^3. 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 control mixture contained only PC whereas other mixtures were incorporated with SF in which a portion of PC was replaced with the SF. All substitutions of the cement by SF were made on the total mass basis of the binder. The mixtures were designated according to the type and the amount of cementitious materials included. For example, 4SF shows the mixture containing 4% SF.

Table 2: Mix proportions of mixtures substituted with SF (kg/m^3).

Mixture ID	Water	PC	SF	HRWR	Aggregates, (SSD)	
					Fine	Coarse
Control	200	454.5	—	5.75	883	783
4SF	200	436.5	18	6.70	880	778
8SF	200	418.5	36	7.50	875	774
12SF	200	400	54.5	8.0	870	771

4. Testing procedure

The measurement of fresh SCC properties was started as soon as mixing of all materials was finished (9 minutes after the initial contact of water with cement). The slump flow values were represented by the mean diameter (measured from two perpendicular directions) of the concrete spread after lifting the standard slump cone. The final diameter was determined in the slump flow test, and the time required for the concrete to spread to a diameter of 500 mm (T_{50}) was recorded. The V-funnel flow time test consisted of a V-shaped container with an opening of 65×65 mm at the bottom and 500×65 mm at the top. Determination of rheological parameters was carried out with the concrete rheometer (ConTec 4SCC) shown in Fig. 2.

Fig. 2: ConTec 4SCC rheometer.

4.1. Evaluating plastic viscosity

Rheological parameters to determine the most appropriate measurement parameters were determined by trial-and-error. As a result of trials and literature search, the impeller was rotated at six different speeds (0.70, 0.55, 0.40, 0.25 and 0.10 rps). Measuring sequence started from the highest speed to the lowest speed. Each speed continued 8 seconds. However, the torque values obtained during the last 6 seconds were used in calculating the average torque value corresponding to that speed. Since the rheometer can take 4 torque data per 1 second, 6x4 = 24 data were averaged. Hereby torque-rotation speed chart was generated, for each concrete mixture. Bingham model was constructed by adding a linear trend line to the data. The intersection point of the trend line with the torque axis corresponds to apparent yield stress (g) and the slope of the trend line is determined as torque plastic viscosity (h). The h values obtained from such figures drawn for each mixture were turned to plastic viscosity (Pa. s) after multiplying with special coefficients recommended by the manufacturer of the rheometer.

4.2. Determination of water film thickness

Concrete becomes workable when the content of water exceeds the volume required to fill the voids among the solid particles. Therefore, the extra water film will have a dispersive effect, and the existence of this lubricating layer on the solid particles reduces the friction between them by pushing away from each other. According to this theory, the WFT can be calculated as follows [9]:

$$u'_w = u_w - u_{min} \tag{1}$$

$$A_S = A_C \times R_C + A_{Sf} \times R_{Sf} + A_{FA} \times R_{FA} + A_{CA} \times R_{CA}$$

$$\text{WFT} = \frac{u'_w}{A_S}$$

where u'_w, u_w and u_{min} are respectively the excess water ratio, the water ratio of concrete mix and the minimum voids ratio of solid particles and A_S , A_C, A_{Sf}, A_{FA}, A_{CA} are respectively the specific surface area of the solid particles, cement, SF, fine and coarse aggregate while R_C, R_{Sf}, R_{FA} and R_{CA} are respectively the volumetric ratios of cement, SF, fine and coarse aggregate to the total solid volume.

5. Experimental results

5. 1. T_{50} flow time

T_{50} flow time is a test to assess the flow ability and the flow rate of SCC in the absence of obstructions. T_{50} flow times obtained from SCC mixtures is presented in Table 3. These values are in the range of 1.1–2 seconds. As shown in Table 3, T_{50} flow time reduced when SF was incorporated in the binder system. The mixture containing 12% SF, led to the greatest reduction in T_{50} flow time. The correlation between the T_{50} flow time and WFT is shown in Fig. 3. As expected, the T_{50} flow time decreases with the increase in water film thickness. This can be explained by the

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greater inter-particle distance among particles due to the higher water amount surrounding them. The increase in the excess water thickness enhances the mobility of the mixture and reduces the internal friction among particles, leading to a reduction in T_{50} flow time.

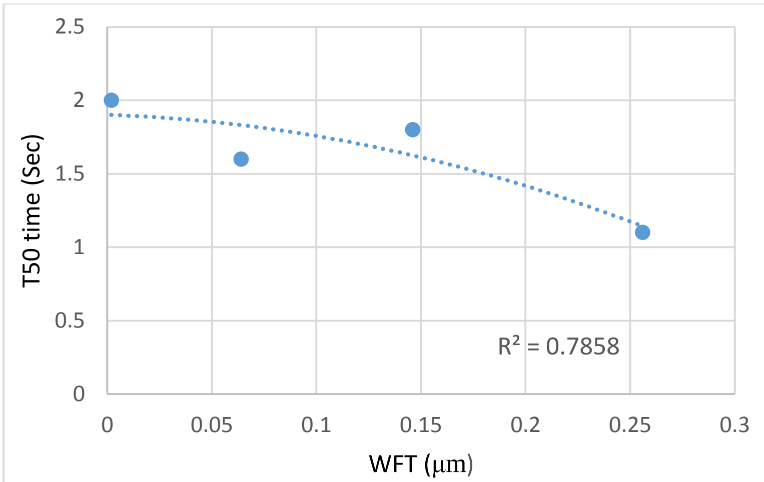

Fig. 3: Correlation between T_{50} flow time and water film thickness.

Table 3: Rheological properties and water film thickness of the SCC mixtures.

Mixture ID	w/b	T_{50} flow time (sec)	V-funnel flow time (sec)	Plastic viscosity (Pa.s)	WFT (μm)
Control	0.44	2	16	174	0.0019
4SF	0.44	1.6	15	150.8	0.064
8SF	0.44	1.8	13	107.7	0.146
12SF	0.44	1.1	8	74.3	0.256

5.2. V-funnel flow time

The V-funnel flow time test can be applied to evaluate indirectly the flow ability and viscosity of SCC. In fact, this time value characterizes the rate of flow and is affected by the potential deformability of concrete. The V-funnel flow times obtained from SCC mixtures are presented in

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Table 3. These values were ranged from 8 to 16 seconds. The relationship between the V-funnel flow time and water film thickness for mixtures with an approximate slump flow value of 650 mm is shown in Fig. 4. As shown in this figure, there is a good relation between the V-funnel flow time and thickness of water film. Similar to the discussions made for the correlations of the T_{50} flow time, the friction between the solid particles and their possibility of collision decreases as the water thickness around them increases. This can have resulted in an easier flow of the mixture from the V-funnel orifice with lower probability of collision.

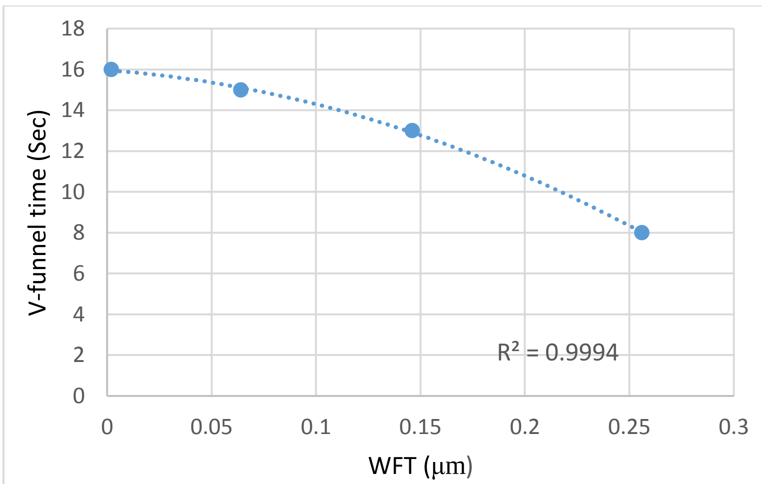

Fig. 4: Correlation between V-funnel flow time and water film thickness.

5.3. Plastic viscosity

Plastic viscosity is considered as main parameter that define concrete rheology. SCC has a moderate viscosity to ensure a highly fluid mixture without any segregation among constituents, especially between the binder phase and aggregate. The test results for plastic viscosity measurements are given in Table 3. As seen in this Table, plastic viscosity was reduced when SF was incorporated in the binder system. 12% replacement of SF showed greatest reduction in plastic viscosity values. The correlation between the plastic viscosity and water film thickness of SCC mixtures yielded a high coefficient of determination (R^2= 0.99). As can be observed from Fig. 5, the plastic viscosity value decreases with the increase in WFT. This is an expected observation since the friction between the particles and their possibility of collision decrease with the increase in water film thickness around the particles, resulting in lower resistance to flow and lower plastic viscosity.

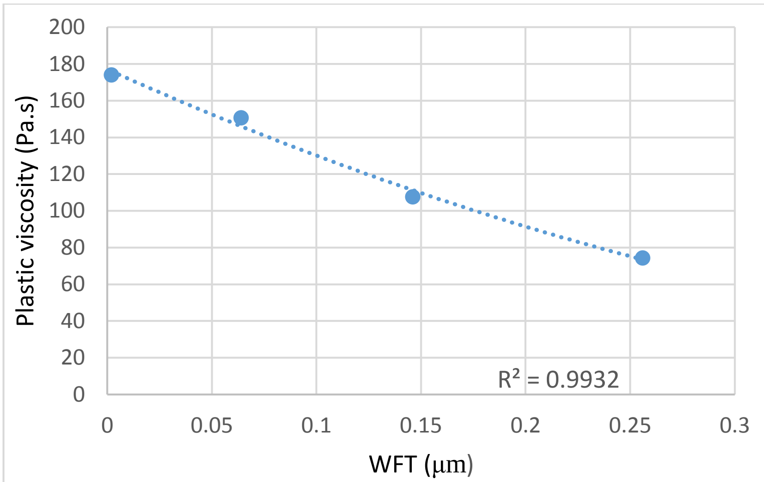

Fig. 5: Correlation between plastic viscosity and water film thickness

6. Conclusion

The correlation between the plastic viscosity and water film thickness of SCC mixtures containing SF, yielded a high coefficient of correlation. Also, good relation between the V-funnel flow time and water film thickness has been established. According to the results, it can be concluded that the rheological parameters can be closely related to the thickness of excess water around the solid particles.

Based on the results of this investigation, several SCC mixtures covering a wide range of SCM can be used to establish relationship between the excess water layer and rheological properties. This can facilitate the modelling of the flow characteristics and reduce the number of trial batches for concrete mix design needed to ensure high deformability and stability, with savings in time, manpower, and materials.

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