論文 Viscosity Eguation for Highly-Flowable Mortar Containing Limestone Powder

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ABSTRACT: A mathematical model based on the sediment volume theory is proposed to predict the viscosity of "equivalent" self-compacting concrete mortar containing limestone powder. The accuracy of the proposed equation is evaluated using various mortar mixtures. The high predicted-to-measured values confirm the good accuracy of the proposed model to predict viscosity of fluid mortar.

KEYWORDS: Highly-flowable mortar, limestone powder, viscosity, sediment volume theory, self-compacting concrete

1. INTRODUCTION

Self-compacting concrete (SCC) can be used to rationalize the manufacturing, improve productivity of concrete placement and provide better working environment by eliminating vibration noise. The successful placement of SCC to achieve required mechanical properties, durability, and structural performance requires that the concrete should be able to deform and undergo change in shape under its own weight and pass through various obstacles without exhibiting segregation and blockage.

In general, for a given coarse aggregate content, a proper viscosity for mortar is required to ensure a homogenous suspension, thus reducing the inter-particles collision and flow resistance and avoiding the local coalition and blockage during placement. Furthermore, the viscosity of mortar controls the deformability speed that affects the casting duration required to achieve a given filling capacity.

The measurement of this physical parameter involves the use of a viscometer and consists in determining the flow curve of material. The flow curve is then used to estimate the viscosity by fitting the experimental data to a given rheological model. Such procedure may require special cares to minimize the experimental error. On the other hand, such a procedure may not be suitable for practical purposes. Therefore, a mathematical model for estimating the viscosity of mortar may provide an attractive toll that can be used to establish a guideline in selecting suitable mortar mixtures that can be used to proportion SCC.

The main objective of this study is to evaluate the feasibility of using the sediment approach theory proposed by Robinson to predict the viscosity of "equivalent" SCC mortar containing limestone powder. The investigated mixtures are prepared with a fixed water content and various water-to-cement ratios (W/C) of 0.35, 0.40, and 0.45, typically used to proportion structural SCC.

2. MATERIAL PROPERTIES

All mixtures investigated in this study were systematically proportioned using a Japanese ordinary portland cement with a Blaine fineness of 3460 cm^2/g. The limestone powder (LP) used in this study had a specific gravity of 2.7 and a Blaine fineness of 4800 cm^2/g. A well-graded sand with a fineness modulus of 2.6, a specific gravity of 2.61, and an absorption value of 1.21% was employed. The sand was a combined sea and

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crushed sand types of 7:3 proportions, by mass. The sand was first set at the saturated and dry surface state and kept at 20°C room temperature for one 1 day before mixing. A polycarboxylic acid-based polymer was employed for the high range-water reducer (HRWR). The HRWR had a specific gravity of 1.09 and a solid content of 26.5%.

The mortar mixtures were prepared in 2500-mL batches using a Hobart mixer with a rotational velocity of 1000 rpm. The mixing sequence consisted of homogenizing the sand (Sv) and powder (Pv) for 15 seconds, then the HRWR diluted with mixing water was added. The mixture was mixed for 180 seconds. After 60 seconds of rest, the mortar received another 60 seconds of mixing.

3. TEST PROCEDURES

Following mortar mixing, fluidity measurements including slump flow, V-funnel flow time and plastic viscosity were evaluated. The measurement of slump flow was carried out by a mini cone for mortar similar to that specified by JIS R 5201 standard. A V-funnel cone for mortar similar to that proposed by Ozawa et al. was used [1]. The efflux time needed for the sample to flow out was noted. Rheological measurements were performed using a coaxial cylinder viscometer with a gap size of 20 mm and varying the rotational speeds from 5 to 150 rpm, corresponding to shear rates of 1.2 to 40 s^{-1}, respectively. The viscometer was calibrated using standard solution for calibrating viscometer complying with JIS Z 8809 specifications before measurements on mortar. The mortar sample was sheared for 30 s at 150 rpm, corresponding to shear rate of 40 s^{-1}, to ensure an equilibrium state (breakdown) of structure. Rheological profile was then obtained by increasing the rotational velocities from 5 to 150 rpm during 1 minute. Such time is adapted after various preliminary experiments to avoid segregation. The plastic viscosity was, therefore, estimated. All fluidity measurements were carried out after 6 minutes of hydration.

4. EXPERIMENTAL PROGRAM

The experimental program consisted of two different phases. In the first Phase, the required dosages of HRWR to proportion a mortar mixture with slump flow and V-funnel flow time values of 25 cm and 10 s, respectively, were determined. Such optimum dosages are determined on mortar mixtures, which was made with fixed unit water content of 250 kg/m^3, various W/C of 0.35, 0.40 and 0.45, and different percentages of LP ranging between 0 and 50%, by volume of Pv. The HRWR dosage was varied between 0.6 and 2.2%, by mass of cement.

The second phase consists in measuring the plastic viscosity of mixtures containing different percentages of LP. Such values are then used to investigate the feasibility of using the sediment theory to predict viscosity of fluid mortar. All of the investigated mixtures incorporated 0.6% of air deforming agent. Such dosage was experimentally established and found to be sufficient to maintain the entrapped air content lower than 1%.

5. TEST RESULTS AND DISCUSSIONS

5.1 REQUIRED DOSAGES OF HRWR

The objective of the first step of this investigation was to determine the required dosage of HRWR that can be incorporated in mortar mixtures to achieve suitable fresh properties. The targeted mixture is an "equivalent" SCC mortar with a slump flow and V-funnel time values of 25 cm and 10 s, respectively. In general, a mortar mixture with such properties can be suitable to successfully tailor a concrete mixture containing 30% of 20-mm coarse aggregates and achieving adequate self-compactability [2]. For each W/C, the dosage of LP is varied between minimum and maximum values to ensure a powder volume between 16 and 19%, by volume of concrete, as recommended by Japan Society of Civil Engineers [3]. For the 0.35 W/C mixtures, minimum and maximum contents of LP were set at 0 and 20%, by volume of Pv, respectively. Such values were 20 and 30% for the mixtures with 0.40 W/C and 30 and 40% for those proportioned with a 0.45 W/C.

In the case of mixture proportioned with a W/C of 0.35, 1.5% HRWR can be the appropriate dosage to achieve 25 cm slump flow and 10 s flow time. For mixtures prepared with W/C of 0.40 and 0.45, the effective dosages of HRWR is 1.2 and 1%, respectively.

5.2 VISCOSITY EQUATION FOR HIGHLY-FLOWABLE MORTAR

The mixture proportioning and viscosity values of mixtures prepared with various W/C of 0.35, 0.40, and 0.45, by mass, and the corresponding HRWR optimum dosages determined in Phase 1 (section 5.1) are summarized in **Table 1**. For each W/C, the LP dosage was varied to achieve a slump flow between 20 and 30 cm, Even though mixtures with a slump flow varying between 20 and 30 cm may present a difference in rheological properties, such range is selected because it represents, general, the suitable range for "equivalent" SCC mortar.

Table 1 Mixture proportioning and viscosity values of the investigated mortars

	W/C = 0.35 HRWR = 1.5%			W/C = 0.40 HRWR = 1.2%			W/C = 0.45 HRWR = 1.0%		
LP (% of Pv)	Sv (%)	Pv (%)	μ_p (Pa.s)	Sv (%)	Pv (%)	μ_p (Pa.s)	Sv (%)	Pv (%)	μ_p (Pa.s)
0	48.6	23.9	2.5	--	--	--	--	--	--
10	46.0	26.6	3.3	49.3	23.3	2.4	--	--	--
20	42.7	29.9	4.8	46.4	26.2	2.9	49.3	23.3	2.4
30	38.4	34.2	7.1	42.7	29.9	4.3	46.0	26.6	2.8
40	32.7	39.9	12.3	37.7	34.9	6.0	41.5	31.0	4.2
50	--	--	--	30.7	41.9	10.0	35.3	37.2	6.5

As can be observed in **Table 1**, the addition of LP, i.e. an increase in Pv, resulted in an increase in the plastic viscosity, regardless of the W/C and HRWR dosage. Indeed, the increase in Pv may result in an increase in water demand to achieve a given viscosity. On the other hand, for a given water content, the increase in solid concentration results in higher inter-particle frictions and a reduction in the free space into the system.

The mortar can be regarded as a two-modal suspension where the sand particles (solute) are suspended into the paste solution. The viscosity of mortar is therefore related to the viscosity of the paste, the volume of sand, and the degree of agglomeration, which is controlled by the water content, presence of superplasticizer, shape and surface roughness of solid particles. Difficulties in predicting the viscosity of mortar are mainly due to the ignorance of the detailed structure of such a suspension. Indeed, once the cement is in contact with water, various forces, such as hydrodynamic and otherwise are exerted by the particles on each other [4]. The approach proposed in this study to predict viscosity of mortar considers both the solid concentration and void space into the system. The viscosity of a suspension must vary inversely with the void volume. For example, lower viscosity is achieved for suspension with higher W/C, i.e. higher free space. On the other hand, the viscosity is directly related to the solid concentration of the suspension [5,6].

In general, the free space through which particles can move among each others into a packed system is not necessarily identified as the difference between the whole volume and that occupied by the solid particles. The free volume is generally less due to the immobilization of the solvent between suspended particles. This is may be due to the physical trapping of the solvent in inter-particle space. On the other hand, such a phenomena can also be caused by the hydrodynamic forces between particles as already discussed by many authors and reported by Robinson [4]. Accordingly, the free space is stated to be proportional to (1- α ϕ), as shown in **Fig. 1**.

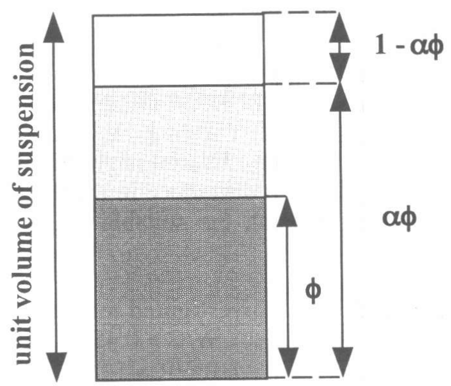

Fig 1. Schematic representation of volumes in a suspension

ϕ is the solid concentration in suspension, α is the relative sediment volume defined as the volume which a sediment will occupy when the particles themselves occupy a unit volume. Thus, the viscosity of mortar mixture can be expressed as:

$$f(\mu) = \frac{g(k,\phi)}{1-\alpha\phi} \quad (1)$$

where k is the packing factor that depends on particle shape and f and g are arbitrary functions that can be determined using experimental data.

For a single-sphere suspension, it was reported that the constants k and α take 2.5 and 0.609 values, respectively [4]. However, for a reactive material, such as portland cement, parameter α may be higher since the volume occupied by cement particles increases when being in contact with water. Indeed, immediately after their contact with water, cement particles interact with water and an adsorbed layer is formed at their surface, thus increases their effective size.

In the present approach, the mortar is considered as a suspension of inert particles of a given volume of sand (Sv) in cement paste solution, and the solid concentration (ϕ) consists in a combination of powder (cement and limestone) and sand. Thus, the free space in the system is related to the variation of Pv and the packing density of sand. For a unit volume of mortar, the free volume can be expressed as (1 - α Pv - β Sv), where the parameter α is the relative sediment volume of powder and β is the apparent packing density of sand. this relation was proposed by some mathematical consideration. α is a function of the reactivity of powder, W/C and the presence of HRWR. For example, higher value can be expected with a system made with reactive cement and combined with low HRWR content and W/C ratio. For example, the use of a reactive cement instead of a normal one may cause an increase in hydration products and therefore in the effective size of particle, thus increase the sediment volume. On the other hand, β is affected by the particle distribution of the sand. Such parameter is calculated using the model proposed by Caquot and adapted by de Larrard for crushed particles and reported by Hu et al [7] as:

$$\beta = 1 - 0.45(\frac{d}{D})^{0.19} \quad (2)$$

where d and D represents the diameter for which 10 and 90% of particles are smaller, respectively. In this study, By using the experimental particles distribution curve of the sand type used in this study and Eq.2, the value of parameter β is 0.70.

Functions f and g are selected based on the highest correlation coefficient to fit the experimental data in **Table 1**. Among several functions, f correspond to the Natural Log of the relative viscosity of mortar defined as $\{Log\frac{\mu_m}{1-\mu_0}\}$, where μ_m is the plastic viscosity of mortar and μ_0 is the viscosity of water (μ_0 = 0.001 Pa.s at a temperature of 20C). On the other hand, the function g is given by the power of powder fraction (Pv^n), and n = 1.03, as proposed by Murata et al. for cement paste [6]. Such functions are found to offers the best-fit response for the measured viscosity values **(Table 1)**.

The incorporation of HRWR in cement-based materials aims to provide higher workability for a given W/C. Indeed, HRWR is generally adsorbed onto cement particles, thus prevent their flocculation and reduce the inter-particles friction. However, given the fact that data presented in this paper is limited, it was not possible to adequately consider the effect of HRWR on viscosity. Therefore, further investigations may be required to consider the effect of HRWR and then adjust the propose model to include the effect of HRWR. The following equation is then proposed to predict the viscosity of mortar:

$$Log(\frac{\mu_m}{1-\mu_0}) = \frac{k\ Pv^{1.03}}{1-\alpha Pv-0.7Sv} \qquad (3)$$

where Pv and Sv are powder and sand fractions, by volume of mortar. The experimental constant k and α are established by least square method and are found to be 1.7 and 1.1, respectively.

5.3 ACCURACY OF THE PROPOSED MODEL

In order to evaluate the accuracy of the proposed model (Eq. 3) to predict viscosity of mortar, supplementary mortar mixtures made with various W/C and HRWR contents are prepared. The mixture proportion and test results are presented in **Table 2**.

Table 2 Mixture proportion of mortars used to evaluate the accuracy of proposed viscosity equation

W/C	LP (% Pv)	HRWR (% of cement)	Sv (%)	Pv (%)	Measured Viscosity (Pa.s)	Predicted Viscosity (Pa.s)	Predicted/ Measured
0.35	0	1.2	48.6	23.9	3.1	2.7	0.86
0.35	0	1.8	48.6	23.9	2.6	2.7	1.02
0.40	20	1.8	46.4	26.2	3.0	3.0	1.01
0.40	30	1.8	42.7	29.9	3.7	3.7	1.01
0.41	15	3.8	50.0	23.8	3.4	2.7	0.80
0.48	45	2.2	40.0	32.8	4.2	4.5	1.07
0.63	45	2.2	50.0	23.8	2.6	2.7	1.04

As can be observed in **Table 2**, the proposed equation predicts well the viscosity of mortar since the predicted values lie close to the measured ones. Furthermore, the scatter between predicted and measured values, each of three different operators carried out three time measurements for given mixtures, is lower than the standard deviation of ± 0.5 Pa.s.

Such value is determined on duplicated mixtures where each mixture is prepared three times as reported in previous study [8].

The worst prediction is obtained with mixture made with 0.41 W/C and 3.8% HRWR. This can be argued by the fact that 3.8% HRWR is over the saturation dosage of HRWR, which is known as the critical dosage beyond which a substantial increase in viscosity can be observed. More accurate prediction may be however achieved by introducing the ratio of HRWR dosage and that corresponding to the saturated level. Further experiments should be carried to adequately establish the effect of HRWR.

On the other hand, the poor prediction observed with mixture proportioned with 0.35 W/C and lower dosage of HRWR corresponding to 1.2% can be due to the flocculated system, thus may result in higher relative sediment coefficient (α) than 1.1. On the other hand, the spread observed with such a flocculated mixture can be due in part to the measurement procedure adopted to determine the rheological profile. Indeed, the shearing time selected to ensure the breakdown of structure may be suitable for some mixtures and may not be for another, such as flocculated one. The adjustable parameters may however require further experiments to accurately establish the experimental constants to better evaluate the validity of the proposed model to predict viscosity of fluid mortar.

6. CONCLUSION

Based on the results presented in this study it can be stated that the proposed model, based on the sediment volume theory, provides accurate prediction of viscosity for "equivalent" self-compacting concrete mortar containing limestone powder. On the other hand, the viscosity of mortar is shown to increase with the powder volume, regardless of the W/C and HRWR content in use.

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