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Rheological properties of highly flowable mortar containing limestone filler-effect of powder content and W/C ratio

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Abstract

The effect of a limestone filler addition in superplasticized cement mortar was investigated. The mixtures considered in this study are highly fluid, yet stable mortars that can be used to proportion self-consolidating concrete (SCC). All the mixtures were proportioned with a fixed unit water content of 250 l and various water–cement ratios varying from 0.35 to 0.45. A limestone filler with a specific surface area of 480 m^2/kg was used at different addition percentages.

This paper reports test results leading to the recommendation of suitable powder contents that can be used to proportion mortar mixtures containing a limestone filler and achieving adequate rheological properties. Test results show that the effect of limestone filler is mainly affected by the W/C and the limestone filler content in use. For a given W/C, the addition of a limestone filler within a certain range did not affect fluidity. However, beyond a critical dosage, the incorporation of some limestone filler resulted in a substantial increase of the viscosity of mortar. An accurate model that can be used to predict the viscosity of such mixtures is proposed and validated on various mixtures.

Keywords: Highly flowable mortar; High-range water reducers; Limestone filler; Self-consolidating concrete; Rheology

1. Introduction

Self-consolidating concrete (SCC) is a new generation of high-performance concrete that can exhibit high deformability and can flow into place under its own weight without any external consolidation and with limited signs of segregation. Deformability of SCC refers to the ability of a fresh mixture to deform and undergo change in shape and to flow around obstacles while maintaining good suspension of coarse particles in the matrix, thus avoiding arching near obstacles and blockage during flow. The design concept of SCC is mainly based on the combination of high deformability and segregation resistance to achieve self-consolidation, facilitate casting, and improve in-situ performance.

The successful development of SCC requires a careful control of mixture parameters, such as the rheological properties of matrix, content of supplementary cementitious materials (SCM), as well as the content and particle size distribution of coarse aggregates. SCC is a multiphase material in which coarse aggregates (solute) are suspended in highly flowable mortar (solution). The flow properties and segregation resistance of SCC are consequently controlled via proper adjustment of the rheology of the mortar and adequate selection of the content of coarse aggregates. For a given type and content of coarse aggregates, proper viscosity of the matrix is required to ensure the homogenous suspension of particles and reduce interparticle collision that can cause a local increase of internal stress and flow resistance [1–5]. The viscosity of cement-based material can be improved by decreasing the water–SCM ratio (w/cm) or using a viscosity-enhancing agent. It can also be improved by increasing the cohesiveness of the paste through the addition of filler, such as limestone [1–3,5,6]. However, excessive addition of fine particles can result in a considerable increase in the specific surface area of the powder, which results in an increase of water demand to achieve a given consistency. On the other hand, for a fixed water content, high powder volume (Pv) increases interparticle friction due to solid–solid contact. This may affect the

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ability of the mixture to deform under its own weight and pass through obstacles [1,2,5,7].

The Japan Society of Civil Engineers Specifications recommend to use an SCM content ranging between 16% and 19%, by volume of concrete, to proportion SCC [1]. SCC mixtures made with a ternary blended cement containing 19% of SCM, by volume, were successfully proportioned for casting highly congested structural sections [5]. It should be noted, however, that the required volume of powder is controlled by the particle size distribution of the aggregate, and for a given particle size distribution of aggregate, the volume of powder must be sufficient to fill the interstitial voids, thus reducing interparticle friction between coarse aggregate.

An advantage of incorporating SCM in SCC lies in the resulting enhancement of particle distribution, reduction of the risk of thermal cracking, as well as the improvement of certain mechanical and rheological properties [8,9]. For example, the use of limestone filler can enhance many aspects of cement-based systems through physical or chemical effects. Some physical effects are associated with the small size of limestone particles, which can enhance the packing density of powder and reduce the interstitial void, thus decreasing entrapped water in the system. For example, the use of a continuously graded skeleton of powder is reported to reduce the required powder volume to ensure adequate deformability for concrete [10]. Chemical factors include the effect of limestone filler in supplying ions into the phase solution, thus modifying the kinetics of hydration and the morphology of hydration products [8].

Partial replacement of cement by an equal volume of limestone filler with a specific surface area ranging between 500 and 1000 m^2/kg resulted in an enhancement in fluidity and a reduction of the yield stress of highly flowable mortar [11,12]. Other investigations have shown that partial replacement of cement by an equal volume of limestone filler varying from 5% to 20% resulted in an enhancement of the fluidity of high-performance concrete having a W/C ratio ranging between 0.35 and 0.41 [13]. This improvement may be due to the increase in W/C or in paste volume. Indeed, for a given water content, partial replacement of cement by an equal volume of a filler results in an increase in W/C. On the other hand, partial replacement of cement by an equal mass of limestone filler results in an increase of powder content, i.e., an increase in paste volume. For example, the partial substitution of cement by 40%, by mass, of limestone filler having a specific gravity of 2.7 yields to a 17% increase in powder volume. Therefore, the sole physical effect of limestone filler on the rheological properties of equivalent SCC mortar is still not well established.

The main objective of the present study is to investigate the effect of a limestone filler addition on the rheological properties of "equivalent" SCC mortar made with a fixed water content and different W/C ratios of 0.35, 0.40, and 0.45. Results of this study can therefore provide a guideline to determine the suitable powder volume necessary to impart adequate fresh properties of a superplasticized mortar that can be used to design SCC. Furthermore, an analytical model that can predict the viscosity of mortar is developed and validated.

2. Research significance

SSC contains a relatively higher powder content than conventional concrete does. Fillers, such as limestone, are used as a portion of total SCM to overcome the increase in temperature due to the hydration of cement and enhance certain properties of SCC. Test results presented in this paper highlight the effect of limestone filler addition on the properties of fresh equivalent SCC mortar proportioned with a fixed water unit content and various W/C values. Suitable powder volumes to achieve adequate properties of mortar that can be used to proportion SCC containing a limestone filler are established.

3. Experimental program

3.1. Materials

All mixtures investigated in this study were systematically proportioned using a Japanese ordinary portland cement with a Blaine fineness of 350 m^2/kg. A limestone filler with a specific gravity of 2.80 and a Blaine fineness of 480 m^2/kg was used. The chemical and physical properties of these materials are given in Table 1.

A well-graded sand with a fineness modulus of 2.6, a specific gravity of 2.65, and an absorption value of 1.2% was employed. The sand was a combination of sea and crushed sand in 7:3 proportions, by mass. The sand was set at the saturated and dry surface states and kept at 20 °C room temperature for 1 day before the mixing procedure.

A polycarboxylic-acid-based polymer was used as the high-range water reducer (HRWR). The HRWR had a specific gravity of 1.09 and a solid content of 26.5%. The

Table 1
Chemical and physical properties of cement and limestone filler

	Cement	Limestone filler
SiO_2	21.2	0.47
Al_2O_3	5.1	0.09
Fe_2O_3	3.0	0.06
CaO	64.9	54.9
MgO	1.6	0.49
SO_3	1.9	0.0
Na_2O eq.	0.72	–
Free CaO	0.7	–
CaCO3	–	98.0
Specific gravity	3.15	2.80
Blaine fineness (m^2/kg)	350	480
C_3S	57.8	–
C_2S	16.4	–
C_3A	8.1	–
C_4AF	8.5	–

polycarboxylic type is a new generation of superplasticizer containing a polyethylene graft chain. The dispersing mechanism of this type of HRWR is mainly explained by steric hindrance due to the adsorbed macromolecule and the oxide graft chain [14].

3.2. Test procedures

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 and powder for 15 s, and then, the HRWR, diluted within the mixing water, was added. The mixture was mixed for 180 s. After 60 s of rest, the mortar received another 60 s of mixing.

Following mortar mixing, the fluidity was evaluated by measuring the slump flow (SF) and V-funnel flow time (FT). The measurement of SF was carried out using a minicone 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. [3] and Okamura et al. [4] was used. The efflux time needed for the sample to flow out was noted. The relative flow area (Γ) and relative FT (Φ) are then calculated as:

$\Gamma = \left(\frac{\mathrm{SF}}{100}\right)^2 - 1$, where SF is the mean slump flow diameter in mm.

$\Phi = \frac{10}{\mathrm{FT}}$, FT is the flow time in s.

A coaxial cylinder viscometer was used to evaluate the rheological parameters. The shear stress (τ) was determined at various rotation speeds varying between 5 and 150 rpm, which correspond to shear rates of 1.2 to 40 s^{-1}. The viscometer was calibrated using the JS 14000 standard solution complying with JIS Z 8809 specifications before carrying out measurements on mortar. The mortar sample was sheared for 30 s at 40 s^{-1} to ensure an equilibrium state (breakdown) of the structure. The rheological profile was then obtained by increasing rotational velocities from 5 to 150 rpm. The plastic viscosity was estimated by fitting the shear stress and shear rate data and assuming a Bingham model. All fluidity measurements were carried out after 6 and 60 min after the first contact between water and cement. Between 6 and 60 min, the fresh mortar samples were protected to prevent evaporation and received limited manual mixing prior to the determination of their fluidity at 60 min.

3.3. Test program

The first phase of this study consists of evaluating the effect of HRWR dosages on the relative flow area and relative V-funnel FT of mortar and determining the optimum dosage of HRWR. The investigated mixtures were proportioned with a fixed unit water content of 250 l, various W/C of 0.35, 0.40, and 0.45, and different addition percentages of a limestone filler. The HRWR dosage varied between 0.6% and 2.2%, by mass of cement.

In the second phase, the impact of adding limestone filler at different dosages on rheological properties of mortar is evaluated. For each W/C and optimum HRWR dosage determined in Phase 1, limestone filler content was varied between 0% and 50%, by volume of powder. Fluidity measurements, including SF, V-funnel FT, and plastic viscosity, were evaluated. All of the investigated mixtures incorporated 0.6% of air-defoaming agent. Such dosage was found to be sufficient to maintain the entrapped air content lower than 1%.

4. Test results and discussions

4.1. Effect of HRWR on relative flow area and relative V-funnel FT

The mixture proportioning and test results obtained in Phase 1 are summarized in Table 2. Figs. 1–3 present the variation of Γ and Φ parameters for mixtures proportioned with a W/C of 0.35, 0.40, and 0.45, respectively. For each W/C, limestone filler is added at minimum and maximum dosages to ensure a powder volume between 22% and 30%, by volume of mortar (these percentages correspond approximately to 16% and 19%, respectively, by volume of a concrete containing 27% to 33% of coarse aggregates), as recommended by the Japan Society of Civil Engineers [1]. For the 0.35 W/C mixtures, the minimum and maximum contents of limestone filler were set at 0% and 20%, by volume of powder, respectively. Such values were 20% and 30% for the 0.40 W/C mixtures, and 30% and 40% for those proportioned with a W/C of 0.45.

Table 2
Mixture proportioning and test results (Phase 1)

W/C	LP (% Pv)	Wv/Pv	HRWR (% cement)	Slump flow (mm)		Flow time (s)	
				6 min	60 min	6 min	60 min
0.35	0	1.1	1.2	220	180	6.9	10.1
			1.5	275	300	5.6	7.3
			1.8	290	290	5.6	6.7
	20	0.85	1.2	195	180	10.8	14.6
			1.5	280	265	8.0	10.2
			1.8	280	290	8.8	11.4
0.40	20	1.0	0.6	110	100	21.0	–
			1.2	270	260	6.2	8.7
			1.8	320	320	5.2	7.1
	30	0.85	0.6	110	100	22.0	–
			1.2	260	240	7.8	11.4
			1.8	330	320	6.5	8.7
0.45	30	0.95	0.6	160	100	10.0	20.2
			1.0	260	250	6.1	8.5
			1.4	330	335	4.5	5.9
	40	0.80	0.6	150	100	13.9	–
			1.0	260	250	8.3	10.3
			1.4	350	340	6.1	7.0

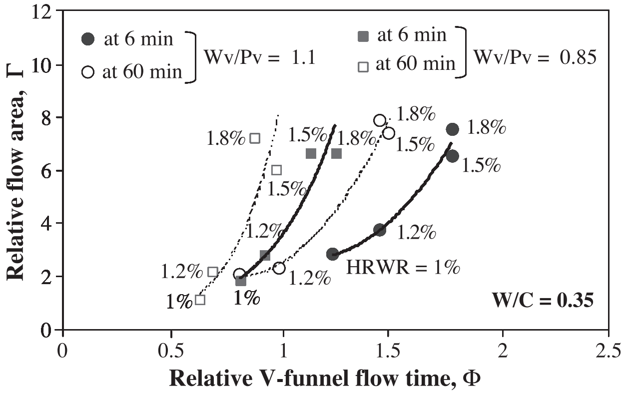

Fig. 1. Effect of HRWR dosage on relative SF and relative V-funnel FT of 0.35 W/C mixtures.

The targeted mixture was a highly flowable, yet stable, mortar that can be used to proportion a SCC. A mortar mixture with Γ and Φ values ranging between 4 and 6, and between 0.95 and 1.05, respectively, can be suitable to successfully tailor a SCC mixture containing 28% to 33% of 20-mm coarse aggregates [15].

As can be seen in Figs. 1–3, the incorporation of the HRWR increased both the Γ and Φ parameters of mortar, regardless of the Wv/Pv. In the case of 0.35 W/C mixtures, the increase of HRWR dosage from 1% to 1.5% resulted in increasing Γ and Φ, regardless of the Wv/Pv (i.e., powder contents of 23% and 29%). The great enhancement is obtained with Γ and a Wv/Pv of 0.85. For example, the increase in HRWR dosage from 1% to 1.2% resulted in increasing Φ from 1.25 to 1.45 (16%) and Γ from 2.8 to 3.7 (32%) of 1.1 Wv/Pv mortar. In the case of 0.85 Wv/Pv mortar, Φ and Γ increased from 0.81 to 0.93 (15%) and from 1.8 to 2.8 (55%), respectively, when the HRWR dosage is increased from 1% to 1.2%. A further increase in HRWR content to 1.5% increased Φ from 1.45 to 1.78 (23%) and Γ from 3.7 to 6.5 (76%) of 1.1 Wv/Pv mortar. An increase in Φ of 34% (increase from 0.93 to 1.25) and Γ of 135% (increase from 2.8 to 6.6) is obtained with 0.85 Wv/Pv mortar. Further increase beyond 1.5% HRWR did not result, however, in a further enhancement in the fluidity of mixtures, regardless of the Wv/Pv. For example, the increase in HRWR from 1.5% to 1.8% did not enhance Φ of 0.95 Wv/Pv mixtures and reduced Γ from 1.25 to 1.14 in case of those proportioned with a Wv/Pv of 0.85.

For 0.40 W/C mixtures, the increase in HRWR dosage from 0.6% to 1.2% resulted in a substantial enhancement in the fluidity of mortar, regardless of powder content. For example, in the case of mortar made with a Wv/Pv of 1, the values of Φ and Γ increased from 0.5 to 1.6 (220%) and 0.3 to 6.1 (1900%), respectively, when the HRWR concentration increased from 0.6% to 1.2%. In the case of 0.85 Wv/Pv mixtures, the Φ increased from 0.5 to 1.3 (160%) and Γ increased from 0.2 to 5.9 (2800%). A further increase in HRWR dosage to 1.5% resulted in limited enhancement in fluidity. In the case of 1 Wv/Pv mixture, the increase in HRWR to 1.5% resulted in 6% and 17% enhancement in the Φ and Γ parameters, respectively. A further increase in HRWR content to 1.8% resulted in mixtures with higher Φ and Γ values that are not included in the targeted range values. On the other hand, the increase in HRWR dosage to 1.8% with 0.40 W/C mortars resulted in mixtures that exhibited excessive bleeding and sedimentation.

In the case of 0.45 W/C mixtures, the increase in HRWR dosage from 0.6% to 1% resulted in a substantial increase in the Φ and Γ parameters. For the 0.95 Wv/Pv mixtures, the increase in HRWR dosage from 0.6% to 1% increased the value of Φ by 65% (from 1 to 1.65) and that of Γ by 300% (from 1.5 to 5.9). In the case of 0.80 Wv/Pv mixtures, the enhancement in Φ and Γ are 70% (from 0.7 to 1.2) and 350% (from 0.2 to 5.9), respectively. Increasing the HRWR dosage beyond 1% resulted in a limited enhancement in Φ and Γ values. For example, the increase of HRWR content to 1.2% increased Φ and Γ values from 1.65 to 1.85 (12%) and 6 to 7.6 (26%), respectively.

As can be seen in Table 1 and Figs. 1–3, all mixtures exhibited good SF retention after 60 min of hydration,

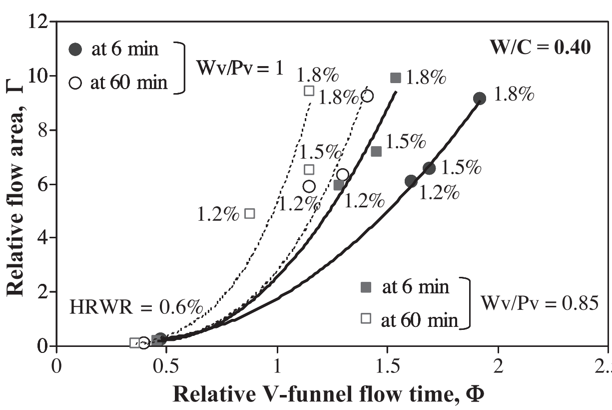

Fig. 2. Effect of HRWR dosage on relative SF and relative V-funnel FT of 0.40 W/C mixtures.

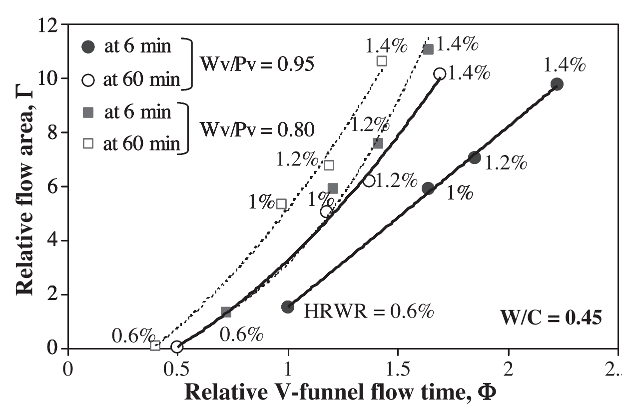

Fig. 3. Effect of HRWR dosage on relative SF and relative V-funnel FT of 0.45 W/C mixtures.

except those made with 0.35 W/C and 0.6% HRWR or those made with 0.45 W/C and a relatively high addition percentage of limestone filler. For such mixtures, a considerable loss of fluidity is observed after 60 min. For example, in the case of the 0.45 W/C mixture containing 30% limestone filler, the relative flow area decreased from 1.5 to 1 (SF from 160 to 100 mm) and the relative FT increased from 1 to 1.64 (FT increased from 10 to 20.2 s). This can be due to the low dosage of HRWR and relatively high volume of powder that result in a higher water demand, which, in turn, result in higher loss of fluidity.

4.2. Effect of powder content on fresh properties of mortar

For each W/C and the HRWR saturation dosage determined in Phase 1, various mixtures are prepared with different limestone filler contents to evaluate the effect of powder volume on the rheological properties of mortar. The investigated mixtures were proportioned with a W/C corresponding to 0.35, 0.40, and 0.45. For a given W/C, the limestone filler is added at different dosages to maintain a powder volume ranging between 20% and 40%, by volume of mortar, and to achieve a Γ value between 4 and 7, corresponding to an SF between 220 and 280 mm. A stable mortar mixture with a SF value of 220 to 280 mm is found to be suitable to design SCC [15].

As can be seen in Fig. 4, for a given W/C and HRWR dosage, the increase in powder content to a certain level did not result in a significant change in the relative flow area, but slightly decreased the relative V-funnel FT. For example, the increase in powder volume from 23% to 26% decreased the Γ and Φ values from 6.8 to 6.5 and from 1.78 to 1.54, respectively, for 0.35 W/C mixtures. Further increase in powder content to 29% did not significantly affect the value of Γ but decreased the value of Φ from 1.78 to 1.25. The increase in powder content beyond 29% resulted, however, in a substantial decrease in both Γ and Φ values. For example, the use of 40% powder content decreased the value of Γ to 2.9 and that of Φ to 0.35.

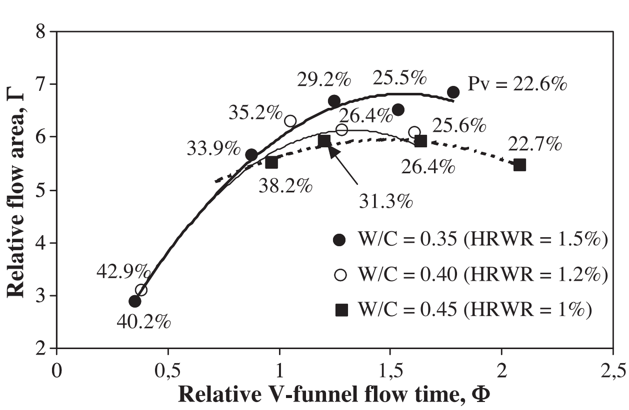

Fig. 4. Effect of powder content on relative SF and V-funnel FT values.

For 0.40 W/C mixtures, the increase in powder content from 26% to 35% did not affect the value of Γ but decreased the value of Φ. The increase in powder volume beyond 35% resulted in a substantial reduction in both Γ and Φ values. In the case of 0.45 W/C mortars, a powder content ranging between 23% and 38% did not result in a significant change in Γ value but decreased Φ. This suggests that the physical effect of the limestone filler on the properties of the fresh mortar depends on the W/C and the addition percentages of limestone filler. It seems that, for a given water content and a fixed W/C, there is an optimum value of powder content that can ensure suitable fresh properties of the mixture. For a W/C of 0.35, an appropriate powder content between 23% and 29%, by volume of mortar, is likely to ensure suitable properties of mixture. For a concrete mixture made with 300 l of coarse aggregate, this range corresponds to 16–20%, by volume of concrete. For 0.40 and 0.45 W/C mixtures, the optimum volume of binder ranges between 25% and 35%, and 23% and 38%, by volume of mortar, respectively.

4.3. Discussion

The use of fillers in multiphase materials, such as cement-based mortar, aims to enhancing the particle distribution of the powder skeleton, thus reducing interparticle frictions and ensuring a better packing density of the system. This can lead to liberating part of the mixing water otherwise entrapped in the system. Among the various parameters, such as the dosage, the reactivity of the limestone filler, and its affinity with the type of HRWR in use (adsorption affinity and dispersing efficiency), the physical effect of limestone filler in highly fluid mortar, such as those investigated in this paper, is associated to the W/C. Indeed, the W/C controls the free space in the system, i.e., the volume of voids in the fresh system and the required volume of fine particles to fill it and enhance the packing density, thus reducing the flow resistance.

Filling the voids in a packed system may improve the arrangement of particles in the system, ensuring a better contribution of the mixing water to achieve adequate fluidity of the mixture. However, at a given concentration higher than the critical dosage, at which close packing is reached, a substantial increase in viscosity is expected. This limit is determined by the volume of the free space into which the added particles can be packed. The increase of viscosity beyond this limit can also be explained by the increase of interparticle friction due to the increase in solid–solid contact.

It should be noted that the optimum mix proportions presented in this paper are valid for the types of limestone filler and HRWR, as well as the particle size distribution of sand used in this study. The methodology and data presented may be used as guidelines to facilitate the optimization procedure of SCC through the proper design of a matrix with suitable properties to achieve good deformation and adequate stability resistance of SCC.

4.4. Viscosity for highly flowable mortar

Unlike unimodal suspensions, such as cement paste, for which the viscosity varies as a function of the solid concentration [16,17], the prediction of the viscosity of a multicomponent suspension, such as a mortar, is more complicated. Indeed, a mortar mixture can be regarded as a bimodal suspension where the sand particles (solute) are suspended into the paste solution. Therefore, the viscosity of mortar is related to the viscosity of the paste, the volume of sand, and the degree of agglomeration, which is controlled by the water content, the presence of superplasticizer, and the shape, as well as surface roughness of solid particles. Difficulties in predicting the viscosity of a mortar mixture are mainly due to ignorance of the detailed structure of such a suspension. Indeed, once the cement is in contact with water, various forces, such as hydrodynamic and others, are exerted by the particles on each other [18].

The approach proposed in this study to predict the viscosity of self-leveling mortars consists in considering the solid concentration in the suspension and the void space of the system. The viscosity of a suspension is proportional to the solid concentration [15–17] and inversely proportional to the free-space volume. For example, suspension with lower solid concentration (higher W/C), i.e., higher free space, exhibits low viscosity.

In general, the free space through which particles can move among each other into a packed system is not necessarily identified as the difference between the whole volume and the volume occupied by the solid particles. The free volume is generally lower due to the immobilization of the solvent between the suspended particles [17]. This may be due to the physical trapping of the solvent in interparticle space. Such a phenomenon can also be caused by hydrodynamic forces between particles. Accordingly, in a unit volume suspension, the free space is stated to be proportional to $(1-\alpha\phi)$, as shown in Fig. 5 (ϕ is the solid concentration in suspension, α is the relative sediment volume, defined as the volume that a sediment will occupy when the particles themselves occupy a unit volume). The viscosity of mortar can then be expressed by the following equation:

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

where k is the packing factor that is a function of the particle shape and interparticle friction, and f and g are arbitrary functions that can be determined using experimental data.

For a single sphere suspension, the constants k and α are reported to be 2.5 and 0.609, respectively [18]. However, for a reactive material, such as Portland cement, the parameter α is expected to be higher than unity because the volume

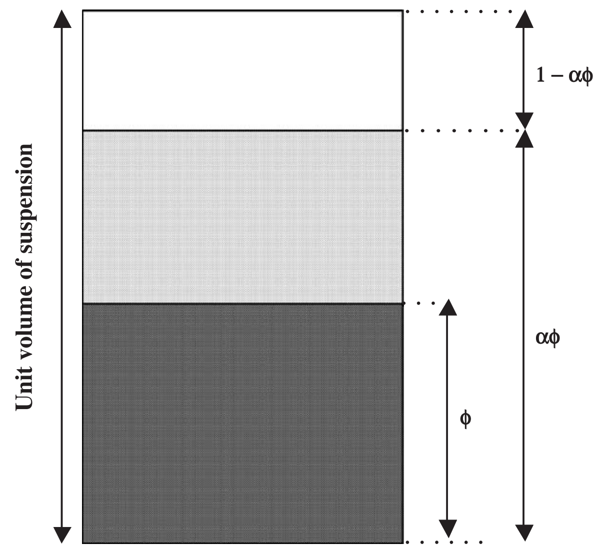

Fig. 5. Schematic representation of volumes in a suspension.

occupied by the cement particles increases when they are 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 increasing their effective size.

A mortar mixture can be regarded as a suspension of inert particles of sand in a cement paste solution. The solid concentration (ϕ) consists of a combination of powder (cement + limestone filler), Pv, and sand particles (Sv). Thus, the free space volume in the system is related to the variation of Pv and the packing density of the sand. For a unit volume of mortar, the free volume can then be expressed as $(1-\alpha\mathrm{Pv}-\beta\mathrm{Sv})$, where α and β are the sediment volume of Pv and the maximum packing density of sand, respectively. The parameter α is a function of the reactivity of Pv, the W/C, and the presence of a superplasticizer. For example, high values of α are expected with a system made with more reactive cement.

The maximum packing density (β) is affected by the particle distribution of the sand. Such a parameter is calculated using the model proposed by Caquot, adapted by de Larrard for crushed particles, and reported by Hu et al. [19] as follows:

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

where d and D represent the diameters for which 10% and 90% of the particles are smaller, respectively. For the sand type used in this study, the value of parameter β was 0.70.

Functions f and g are selected based on the highest correlation coefficient to fit the experimental data. Among several functions, f can be the natural log of the relative viscosity of the mortar, defined as $\{\mathrm{Log}\frac{\mu_m}{1-\mu_0}\}$, where μ_m is the plastic viscosity of mortar and μ_0 is the viscosity of water ($\mu_0=0.001$ Pa s at a temperature of 20 °C). On the other hand, the function g can be expressed as a power of Pv

Table 3
Mixture proportioning of the investigated mortars (Phase 2)

W/C (by mass)	LP (% by mass of cement)	Sv (% by volume of mortar)	Pv (% by volume of mortar)	Slump flow (mm)		Flow time (s)		Viscosity (Pa s)	
				6 min	60 min	6 min	60 min	6 min	60 min
0.35 (HRWR = 1.5%)	0	52.4	22.6	275	300	5.6	7.3	2.5	3.2
	10	49.5	25.5	270	270	6.5	7.8	3.3	4.7
	20	45.8	29.2	280	265	8.0	10.2	4.8	6.4
	30	41.1	33.9	260	230	11.4	15.4	7.1	8.1
	40	34.8	40.2	200	155	28.3	39.5	12.3	13.2
0.40 (HRWR = 1.2%)	10	52.6	23.3	225	260	–	–	2.4	3.0
	20	49.4	26.2	260	260	6.2	8.7	2.9	–
	30	45.3	29.9	300	240	7.8	11.4	4.3	–
	40	39.8	34.9	350	235	9.5	13.5	6.0	7.6
	50	32.1	41.9	430	130	26.1	–	10.0	14.5
0.45 (HRWR = 1.0%)	10	55.1	19.9	200	200	–	7.5	2.3	2.7
	20	52.3	22.7	255	250	4.8	6.4	2.4	3.3
	30	48.6	26.4	260	245	6.1	8.5	2.8	–
	40	43.7	31.3	265	250	8.3	10.3	4.2	–
	50	36.8	38.2	255	220	10.3	17.5	6.5	8.5

fraction (Pv^n), where $n = 1.03$, as proposed by Murata and Kikukawa [16] for cement pastes. Such functions offer the best-fit response for the viscosity values presented in Table 3.

The HRWR is incorporated in cement-based materials to provide higher workability for a given W/C. Indeed, the HRWR polymers are generally adsorbed onto cement particles, thus preventing their flocculation and consequently reducing the interparticle friction. Although the effect of an HRWR on the viscosity of cement-based materials is not quite clear, its effect should be taken into consideration. Therefore, the following equation is proposed to predict the viscosity of self-leveling mortar, such as those used to design SCC:

$$Log\left(\frac{\mu_m}{1-\mu_0}\right) = \frac{k\mathrm{Pv}^{1.03}\left(1-\frac{\mathrm{Sv}}{\mathrm{Pv}+\mathrm{Sv}}\right)^n}{1-\alpha\mathrm{Pv}-0.7\mathrm{Sv}}(1-\lambda\mathrm{HRWR}) \quad (3)$$

where Pv and Sv are powder and sand fractions, respectively, by volume of mortar, and HRWR is the percentage of HRWR. The experimental constants k, n, α, and λ were established by the least-square method and found to be 1.72, 0.22, 1.19, and 0.0057, respectively.

To evaluate the accuracy of the proposed model (Eq. (3)) to predict the viscosity of mortar, additional mixtures made with various W/C and HRWR dosages were prepared using the same materials and test procedures described in the previous sections. The mixture proportioning and test results are presented in Table 4. For each W/C, the HRWR concentration is adjusted to prepare mixtures that can achieve a wide range of SF varying between 100 and 300 mm. As can be observed in Table 4, the deviations between the predicted and measured values are mostly within the standard deviation of ± 0.5 Pa s obtained when measuring the plastic viscosity. Such value was determined on duplicated mixtures and reported in a previous study [11]. High predicted-to-measured-viscosity ratios suggest that the proposed model can accurately predict the viscosity of fluid mortar. The worst prediction is obtained when dealing with the more viscous mixture, such as that prepared with 0.31 W/C. This can be due to the sediment coefficient value (α), which was established for a W/C ranging between 0.35 and 0.45. For a W/C of 0.31, this value can be higher than 1.19. On the other hand, the poor prediction observed when dealing with the 3.8% HRWR mixture can be due to the high dosage of HRWR, which is well over the saturation dosage. Indeed, the saturated dosage of the HRWR is defined as the critical dosage, beyond which a substantial increase in viscosity may be observed. More accurate prediction may, however, be achieved by introducing the ratio of HRWR dosage and that

Table 4
Mixture proportioning of mortar used to evaluate the accuracy of viscosity equation

W/C (by mass)	LP (% by mass of cement)	HRWR (% cement)	Sv (% by volume of mortar)	Pv (% by volume of mortar)	Slump flow (mm)	Measured viscosity (Pa s)	Predicted viscosity (Pa s)	Predicted/measured
0.31	15	2.2	50.0	27.3	100	5.6	3.0	0.53
0.35	0	1.2	48.6	23.9	220	3.1	2.3	0.73
0.35	0	1.8	48.6	23.9	290	2.6	2.3	0.87
0.40	20	1.8	46.4	26.2	320	3.0	2.6	0.85
0.40	30	1.8	42.7	29.9	330	3.7	3.2	0.87
0.41	15	3.8	50.0	23.8	280	3.4	2.3	0.66
0.48	45	2.2	40.0	32.8	270	4.2	4.0	0.94
0.63	45	2.2	50.0	23.8	300	2.6	2.3	0.86

corresponding to the saturated level. Such a saturation amount of HRWR can be experimentally determined using the minislump and Marsh funnel tests [20]. Further experiments may be required to accurately determine the experimental constants for a wide range of W/C to better evaluate the validity of the proposed model to predict the viscosity of self-leveling mortars.

5. Conclusions

Based on the results presented in this paper, the following conclusions can be warranted:

1. The physical effect of limestone filler depends on mixture parameters, especially the W/C and the addition dosage of limestone filler.
2. For a given W/C and HRWR dosage, the addition of limestone filler within a given range did not affect the fluidity of the mixture. However, when used beyond a critical dosage, the addition of limestone filler resulted in a substantial increase in viscosity.
3. Suitable powder contents to proportion equivalent SCC mortar with adequate fresh properties are established for various W/C. For a W/C of 0.35, suitable powder content (cement + limestone filler) ranges between 23% and 29%, by volume of mortar. In the case of 0.40 and 0.45 W/C mixtures, this range is about 25% to 35% and 23% to38%, respectively.
4. A mathematical model is proposed and is shown to be reliable in predicting the viscosity of fluid mortar containing a limestone filler and proportioned with a W/C ranging between 0.35 and 0.45.

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