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Water film thickness, flowability and rheology of cement–sand mortar

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It is well known that the fresh properties of cement paste and cement–sand mortar are governed mainly by three parameters: water content, packing density and solid surface area. However, these parameters vary simultaneously upon any change in the mix composition and hence the evaluation of their individual and combined effects has been a difficult task. Recently, the authors have found that the effects of these parameters on the flowability and rheological properties of cement paste may be evaluated in terms of the water film thickness (WFT) of the solid–water mixture. Herein, this concept of WFT is extended to cement–sand mortar made of sand with a maximum size of 1·18 mm. A number of mortar samples proportioned with different water contents and different sand gradings were produced for packing density, flowability and rheological properties measurements. From the results, the WFT of each sample was determined and the effects of the WFT on the flowability and rheological properties of the mortar were investigated. The good correlations between the flowability and rheological properties with the WFT revealed that the concept of WFT is applicable also to cement–sand mortar.

Introduction

The workability of a fresh concrete mix, taken as composed of a mortar phase and a coarse aggregate phase, is highly dependent on the amount and properties of the mortar phase contained therein. Domone (2006a) pointed out that the coarse aggregate particles in a self-consolidating concrete (SCC) should each be covered by a layer of mortar which must be sufficiently thick and flowable. Lachemi *et al.* (2007) demonstrated that there is a close relationship between the workability of a concrete and the rheology of the mortar phase. For this reason, study on the rheology of the mortar phase is an effective way of predicting the performance of a concrete and it is nowadays quite common to consider the mortar phase as a basis for the mix design of concrete, especially SCC. For example, Billberg (1999) advocated the use of mortar rheology measurements in the mix design of SCC. Likewise, Okamura and Ouchi (2003), who first proposed the idea of SCC, have studied SCC in fine detail with particular interest in the rheology of the mortar phase. As things stand, it is important to study the rheology of mortar, which, apart from being a construction material by itself, is also a major component of concrete.

In fact, throughout the years, a number of studies have been carried out aiming to identify the main parameters governing the rheology of mortar. Quite obviously, the water content should be one of them. In the study conducted by Banfill (1994), it was found that both the yield stress and plastic viscosity of mortar decrease exponentially with the water content or more specifically the water/cement ratio. Concurrently, efforts have also been made to study the influence of the fine aggregate characteristics on the mortar properties. For example, in the same study by Banfill (1994), it was also found that the use of sand containing a higher proportion of fine materials would cause the mortar formed to have a lower workability. In a subsequent study, Banfill (1999) quantified the fineness of sand in terms of certain measures, such as the fraction finer than 300 μm and the fraction finer than 63 μm, and found that the fineness of sand has noticeable effects on the rheology of mortar. Likewise, Westerholm *et al.* (2008) demonstrated that the large amount of fine materials often found in crushed rock fine aggregate would increase the mortar yield stress whereas the particle shape of the fine aggregate would affect the mortar plastic viscosity.

Evidently, the grading and particle shape of the fine

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aggregate have significant effects on the rheology of the mortar formed. However, they do not directly affect the rheology of the mortar. Instead, they affect the packing density and solid surface area, which then exert influence on the rheology of the mortar. For instance, DeSchutter and Poppe (2004) have found that the water demand of a mortar is closely related to the packing density of the fine aggregate and based on this finding postulated that the grading and particle shape of the fine aggregate affect the rheology of the mortar mainly through their effects on the packing density of the fine aggregate. Similarly, Stark and Müller (2007) have found that the plasticiser demand of a mortar would decrease if the packing density of the fine aggregate is increased by improving the grading of the fine aggregate. On the other hand, regarding the solid surface area, Reddy and Gupta (2008) demonstrated that generally a mortar made of finer sand would need a higher water content for a given workability and explained that this is because of the larger solid surface area arising from the finer sand used.

It is now widely recognised that the major parameters governing the rheology of mortar are the water content, packing density and solid surface area. However, the individual and combined effects of these parameters are still not clearly known and many problems have remained despite years of research, because of the following reasons. Firstly, previous studies have focused only on the packing density and solid surface area of the fine aggregate, whereas in actual fact, all the particles in the solid–water mixture, including the fine aggregate and the cementitious materials, should be considered. This was due solely to the lack of a suitable test method for measuring the packing density of cementitious materials or any mixture of particles containing cementitious materials. Secondly, as the cement grading or the aggregate grading or the mix composition of the mortar changed, the water content, packing density and solid surface area all varied at the same time, making it difficult to determine whether the corresponding changes in rheology of the mortar were caused by any individual or combined effects of these parameters.

Dating back to the 1960s, Powers (1968) proposed the excess paste theory that it is the excess paste, namely the paste in excess of the amount needed to fill up the voids between the aggregate particles, that gives the mortar or concrete workability. Following the geometric similarity principle, it may be argued that it is the excess water, namely the water in excess of the amount needed to fill up the voids between the cement particles, that gives the paste flowability. Later, Helmuth (1980) suggested that it should be the thickness of the water films coating the cement particles that governs the consistency of cement paste and that such water film thickness (WFT) may be evaluated simply as the excess water/solid surface area ratio. However, the actual packing densities had not been measured and only the assumed values were used to determine the WFT. Hence, the above suggestion was just a postulation.

More recently, Flatt and Bowen (2006, 2007) have developed a yield stress model called YODEL and successfully applied the model to alumina powder suspensions. This yield stress model was established by correlating the measured yield stress to the solid concentration of the suspension and the packing density of the powder. Although yet to be demonstrated, it should in principle also be applicable to cementitious materials. However, the packing density, which is the key parameter in the model, was estimated using a theoretical packing model rather than actually measured. Without measuring the packing density, the accuracy of the yield stress model is highly dependent on the accuracy of the theoretical packing model adopted.

Following the above line of thought, the authors have, in previous studies, developed a wet packing method for measuring the packing density of cementitious materials (Wong and Kwan, 2008a) and applied the method to determine the excess water (Kwan and Wong, 2008) and excess water/solid surface area ratio (Wong and Kwan, 2008b) of cement paste (note that the excess water/solid surface area ratio may be taken as the WFT). Very good correlations between the rheological properties of cement paste and the WFT have been obtained, thus verifying the postulation that the single most important parameter governing the rheology of a cement paste is the WFT. Similarly, Miyake and Matsushita (2007) have determined the WFT of cement–sand mortar using the conventional dry packing method to measure the packing density of the particles in the mortar. They found that in addition to the WFT, the WFT/particle size ratio also has some effects on the slump and flow of the mortar. However, the dry packing method used to measure the packing density of any material containing cementitious materials is not really appropriate, as agglomeration of the very fine particles due to electrostatic forces between them would tend to cause loose packing and error in the measured packing density (Wong and Kwan, 2008a). Nevertheless, the results so obtained do indicate that there may be a possibility of also applying the concept of WFT to cement–sand mortar.

Herein, an experimental study aiming to apply the wet packing method to determine the packing density of cement–sand mortar and to investigate the combined effects of the water content, packing density and solid surface area on the flowability and rheological properties of cement–sand mortar is presented. In the study, a total of thirty-six mortar samples proportioned with various water contents and fine aggregate gradings were tested. From the respective water content, packing density and solid surface area, the WFT of each mortar sample was determined and then the flowability and rheological properties of the mortar samples were correlated to the WFT to evaluate the effects of the WFT.

The concept of water film thickness

When solid particles are packed together, there exists a certain volume of voids between the particles. In a cement paste, cement–sand mortar or concrete mix, the amount of water added must be at least sufficient to fill up the voids in order not to leave any air in the voids. The water in excess of that needed to fill up the voids is called 'excess water'. It would exist in the form of water films coating the surfaces of the particles. The larger the volume of excess water, the thicker would be the water films and the further apart would be the particles from each other, leading to reduced friction and interaction between the particles and eventually to a higher workability.

Obviously, the excess water can be increased by increasing the water content. However, this would adversely affect the strength and other hardened properties. Strategically, it should be better to increase the excess water by reducing the voids between the particles, or in other words, by increasing the packing density of the particles. In general, the packing density may be improved by optimising the grading (i.e. particle size distribution) of the particles. For instance, when finer particles are added to a pool of coarser particles, the finer particles will fill into the voids between the coarser particles (this is called filling effect) and thus the overall voids volume will be reduced. On the other hand, when coarser particles are added to a pool of finer particles, the coarser particles will occupy an equivalent volume of the finer particles plus the voids between them (this is called occupying effect) and thus the overall voids volume will be reduced as well.

However, any change in the packing density is always accompanied by a simultaneous change in the solid surface area, or vice versa. When adjusting the grading of the aggregate or changing the cement to aggregate ratio to improve the packing density, the solid surface area would also change. If the solid surface area is also increased, then there would be a larger surface area to be coated and for the same amount of excess water, the WFT would be smaller. Therefore, an increase in excess water arising from an improvement in packing density may or may not increase the workability, depending on the simultaneous change in solid surface area and the actual change in WFT. For this reason, we need to consider not just the packing density and the amount of excess water, but also the solid surface area of all the particles in the solid–water mixture.

The WFT could vary from one surface to another and therefore is quite possibly non-uniformly distributed. It is not known yet how the WFT varies within the solid–water mixture. Nevertheless, an average WFT may be evaluated as the excess water/solid surface area ratio (the volume of excess water available to coat the solid surfaces divided by the total solid surface area). The authors (Kwan and Wong, 2008; Wong and Kwan, 2008b) have applied this concept of WFT to cement paste and demonstrated that the average WFT is the major parameter governing the flowability and rheological properties of cement paste. In the present study, this concept is extended for application to cement–sand mortar. When applied to cement–sand mortar, the concept should be similar except that the cement and fine aggregate need to be considered at the same time instead of just the cement alone. For brevity, whenever the WFT is referred to hereafter, it means the average WFT taken as the excess water/solid surface area ratio. The actual evaluation of the WFT is presented in the following paragraphs.

From the measured packing density, the minimum voids volume to be filled with water, expressed in terms of the minimum voids ratio (defined as the ratio of the minimum voids volume to the solid volume of the particles), may be evaluated as:

$$u_{\min} = \frac{1-\tau}{\tau} \qquad (1)$$

where $u_{\min}$ is the minimum voids ratio and τ is the packing density. Having evaluated the minimum voids ratio, the volume of excess water may be determined using the following equation:

$$u'_{\mathrm{w}} = u_{\mathrm{w}} - u_{\min} \qquad (2)$$

in which u'_{w} is the excess water ratio (defined as the ratio of the volume of excess water to the solid volume of the particles) and u_{w} is the water ratio (defined as the ratio of the volume of water to the solid volume of the particles).

For the cement and fine aggregate mixture composed of several different types of particle, denoted by α, β, γ and so forth, the solid surface area A is given by:

$$A = A_{\alpha} \times R_{\alpha} + A_{\beta} \times R_{\beta} + A_{\gamma} \times R_{\gamma} \qquad (3)$$

where A_{α}, A_{β} and A_{γ} are the specific surface areas of α, β and γ, and R_{α}, R_{β} and R_{γ} are the volumetric ratios of α, β and γ (the specific surface area is the ratio of the solid surface area to the solid volume of the particles and the volumetric ratio is the ratio of the solid volume of the particles to the total solid volume of the mixture). With the value of solid surface area so obtained, the combined effects of the excess water and the solid surface area may be considered in terms of the excess water/solid surface area ratio, which is denoted by u''_{w} and defined as:

$$u''_{\mathrm{w}} = \frac{u'_{\mathrm{w}}}{A} \qquad (4)$$

This excess water/solid surface area ratio is taken as the WFT.

Measuring packing density

Broadly speaking, the existing methods for measuring the packing density of solid particles may be classified as: (1) the dry packing method, which measures the packing density under dry conditions; and (2) the wet packing method, which measures the packing density under wet conditions. The dry packing method is commonly used to measure the packing density of aggregate, as stipulated in BS 812: Part 2: 1995 (British Standards Institution, 1995a). The wet packing method has been applied to measure the packing density of cement paste by finding the water ratio at which the consistency of the cement paste, measured in accordance with BSEN 196: Part 3: 1995 (British Standards Institution, 1995b), changes abruptly and taking such a water ratio as the minimum voids ratio for determination of the packing density.

When the dry packing method is applied to very fine particles, including cementitious materials, it has been found that the measured packing density is quite sensitive to the compaction applied (Svarovsky (1987). Moreover, the presence of electrostatic forces under dry conditions would cause agglomeration, leading to loose packing and unreasonably low packing density results (Yu *et al.*, 1997, 2003). Hence, the dry packing method is not really suitable for any particulate system containing very fine particles and should only be applied to relatively coarse particulate systems such as the aggregates. On the other hand, when the wet packing method is applied to cementitious materials, the actual bulk density of the solid–water mixture is often not directly measured and thus the air content in the mixture, which may be significant, is not always accounted for (Lange *et al.*, 1997). Moreover, as explained by Iveson *et al.* (2001), the change in consistency of the solid–water mixture with the water content is gradual and it is generally difficult to determine the water content at which the consistency changes abruptly.

To resolve the above problems, the present authors have recently developed a new wet packing method for measuring the packing density of cementitious materials (Wong and Kwan, 2008a). This new method measures the wet bulk densities and solid concentrations of the cement paste at different water ratios and from the variation of the solid concentration with the water ratio, determines the maximum solid concentration achieved as the packing density of the cementitious materials. It has the advantage that since the packing density is measured under wet conditions, the effects of water and any admixtures present can be incorporated. Furthermore, as the wet bulk density is measured directly, the presence of any air in the cement paste is taken into account and since the measurement is not dependent on consistency observation, no subjective judgement on the change in consistency is needed.

For cement–sand mortar, so far there is no generally accepted method for packing density measurement. Some researchers (Miyake and Matsushita, 2007) have used the dry packing method probably because of its simplicity but, as explained before, the dry packing method is not a suitable method. To this end, the wet packing method was applied in the present study to measure the packing density of mortar. The method is described in detail in the following paragraph.

In each wet packing test, eight to ten samples of mortar were produced at different water/solid (W/S) ratios for packing density measurement (the W/S ratio is actually the same as the water ratio). The mortar samples were produced using the mixer normally used for mortar tests in accordance with BSEN 196: Parts 1-3 (British Standards Institution, 1995b). During mixing, a polycarboxylate-based superplasticiser (SP) was added at the recommended maximum dosage of 3% by liquid mass of the cementitious materials content to disperse the cementitious materials so as to avoid agglomeration. To ensure thorough mixing within a reasonable time, a special mixing procedure of adding the solids to the water so that the mixture was saturated most of the time was adopted. This mixing procedure was developed by the authors in a previous study (Wong and Kwan, 2008a), in which it was found that adding the water and solids to the mixer at the same time could lead to slow or incomplete mixing, especially at a relatively low W/S ratio.

The mixing and testing procedures of the wet packing method are summarised in the following steps.

(a) Set the W/S ratio at which the test is to be carried out (start with a relatively high W/S ratio of 0·8). Weigh the required quantities of water, cement, fine aggregate and SP, and dose each ingredient into a separate container.
(b) Pre-mix the cement and fine aggregate dry.
(c) Add all the water, half of the pre-mixed solids and half of the SP into the mixing bowl and run the mixer for 3 min.
(d) Add the remaining pre-mixed solids and SP in four equal portions into the mixing bowl and each time run the mixer for 3 min.
(e) Transfer the mortar formed to a cylindrical mould, fill the mould to excess and remove the excess with a straight edge. Weigh the amount of the mortar in the mould to measure the wet bulk density.
(f) Repeat steps (a) to (e) at successively lower W/S ratios until the solid concentration calculated from the measured wet bulk density has reached a maximum value and then dropped significantly.

From the wet bulk density, the solid concentration of the particles in the mortar sample can be determined as follows. Let the mass and volume of the mortar in the mould be M and V, respectively (the mould used by the authors is 62 mm diameter and 60 mm high but any other mould of comparable size may also be used). The wet bulk density is equal to M/V. The solid concentration ϕ may be worked out using the following equation:

$$\phi = \frac{M/V}{\rho_w u_w + \rho_c R_c + \rho_f R_f} \tag{5}$$

where ρ_w is the density of water, u_w is the W/S ratio, ρ_c and ρ_f are the solid densities of cement and fine aggregate, and R_c and R_f are the volumetric ratios of cement and fine aggregate to the total solids content. According to equation (5), the value of ϕ is dependent on the W/S ratio of the mortar. Plotting the value of ϕ against the W/S ratio, it can be seen that a maximum value of ϕ exists which may be taken as the packing density of the mortar sample tested.

Measuring flowability

The tests used to evaluate the flowability of mortar were the mini slump cone test and mini V-funnel test. Both the mini slump cone and mini V-funnel tests for mortar may be regarded as reduced scale versions of the slump and V-funnel tests for concrete. The mini slump cone test measures the flow spread of the mortar and the mini V-funnel test measures the discharge rate of the mortar.

There are several versions of mini slump cone test employing slump cones of different dimensions. The version adopted herein is the same as that used by Okamura and Ouchi (2003) and the slump cone dimensions are shown in Fig. 1. The test procedures are detailed in the following steps.

(a) Place the slump cone at the centre of a flat, smooth and level steel plate.
(b) Pour the mortar (prepared by the same mixing procedure as in the wet packing test) into the slump cone until the slump cone is completely filled up and trowel flat the top surface of the mortar with a straight edge.
(c) Lift the slump cone gently and allow the mortar to flow and spread for at least 3 min.
(d) Measure two perpendicular diameters of the mortar patty formed, calculate the average diameter and determine the flow spread of the mortar as the average diameter minus the base diameter of the slump cone.

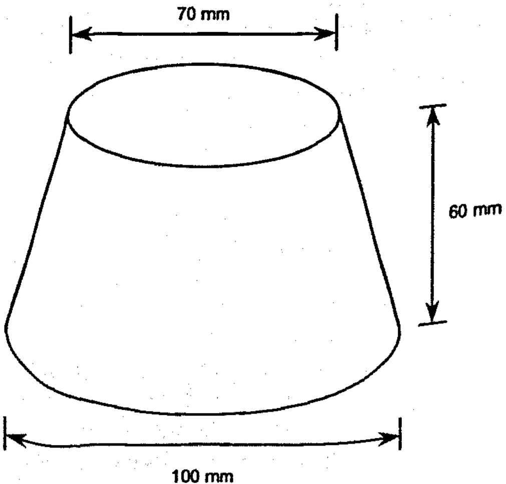

Fig. 1. Mini slump cone

There are also several versions of mini V-funnel test employing V-funnels of different dimensions. The version adopted herein is the same as that used by Okamura and Ouchi (2003) and the dimensions of the V-funnel are shown in Fig. 2. The test procedures are detailed in the following steps.

(a) Mount the V-funnel on a stable stand and close the opening of the V-funnel at the bottom.
(b) Pour the mortar (prepared by the same mixing procedure as in the wet packing test) into the V-funnel until the V-funnel is completely filled up. To minimise air entrapment, pour the mortar slowly along the inner surfaces of the V-funnel.
(c) Open the opening of the V-funnel to let the mortar flow out. Record the time from the start of the flow to the first sight of light through the opening. The recorded time is the flow time of the mortar.

As the flowability of the mortar is inversely proportional to the flow time, the test result is expressed in terms of the flow rate of the mortar calculated as the volume of the mortar sample (equal to 1134 ml) divided by the flow time.

Measuring rheological properties

The vane test was used to evaluate the rheological properties of the mortar. It was carried out using a speed-controlled rheometer equipped with a shear vane,

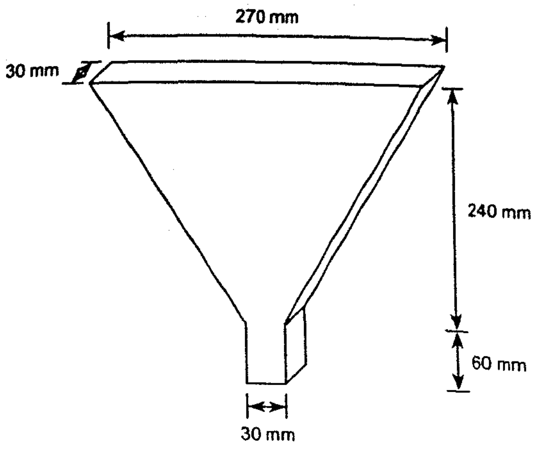

Fig. 2. Mini V-funnel

measuring 20 mm wide and 40 mm long, and a cylindrical container, having an inner diameter of 40 mm, as shown in Fig. 3. The inner wall of the container was profiled with grooves in such a way that the asperity was larger than the largest particle in the mortar sample being tested. This was to minimise slippage of the mortar at the container surface during shearing.

At the onset of the test, the shear vane was concentrically inserted into the mortar sample in the cylindrical container. Then, the shear vane was set to rotate at controlled rotation speed, following the shearing sequence as depicted in Fig. 4. The shearing sequence consisted of two shearing cycles. The first cycle, called the pre-shearing cycle, was to apply pre-shearing to the sample so that all the samples tested had the same shearing history before measurement. The second cycle, called the data-logging cycle, was for the actual measurement. In the data-logging cycle, the rotation speed N [measured in terms of rotations per minute (rpm)] was increased from 0 to 50 rpm in 75 s and then decreased to 0 rpm in another 75 s. During shearing, the torque T (measured in terms of mN m) induced at the shear vane was continuously monitored and regularly logged by a computer. The results obtained at decreasing rotation speed, which are generally more consistent and repeatable, were used for evaluating the rheological properties of the mortar sample.

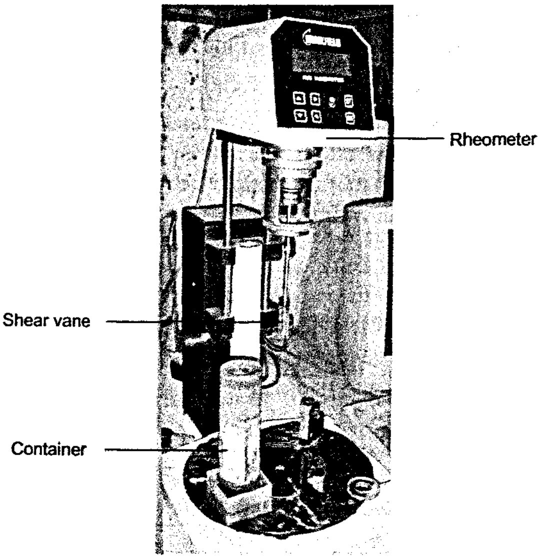

Fig. 3. Rheometer, shear vane and container

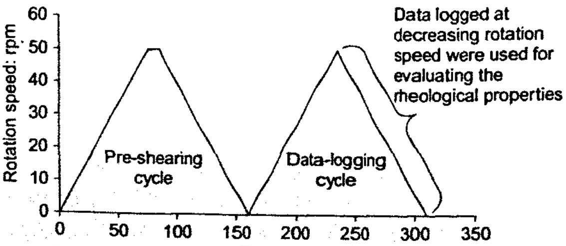

Fig. 4. Shearing sequence of rheological properties measurement

Unlike a rheological test using a rheometer equipped with a coaxial cylindrical rotor which produces uniform shear stress and shear rate within the mortar sample, the present vane test using a rheometer equipped with a shear vane does not produce uniform shear stress and shear rate within the mortar sample. Nevertheless, by neglecting the spatial variations of the shear stress and shear rate, the average shear stress and shear rate in the mortar sample may still be obtained from the induced torque and applied rotation speed (Bauer *et al.*, 2007). It is only that the shear stress–shear rate relation so obtained should not be compared directly with that obtained by any rheometer of a different design.

As the mortar is non-Newtonian, it is customary to describe its rheological properties by either the Bingham model (which assumes that the shear stress–shear rate curve is linear) or the Herschel–Bulkley model (which assumes that the shear stress–shear rate curve follows the power equation). Upon curve fitting using both models, it was found that the experimental results agreed better with the Herschel–Bulkley model, whose shear stress–shear rate relation is given by:

$$\tau = \tau_0 + k\dot{\gamma}^n \tag{6}$$

where τ is shear stress (Pa), $\dot{\gamma}$ is shear rate (s^{-1}), τ_0 is the yield stress (Pa), and k (Pa s^n) and n (non-dimensional) are empirical coefficients. To evaluate the rheological properties of the mortar sample tested, the best-fit curve based on the above equation was first obtained by regression analysis. Then, from the best-fit curve so obtained, the yield stress (taken as the shear stress at a shear rate of zero) and apparent viscosity (taken as the ratio of shear stress to shear rate at a shear rate of 14 s^{-1}) were determined to characterise the rheology of the mortar sample.

Experimental programme

The mortar samples tested resemble the mortar phase of typical SCC (Domone 2006b). Since the cement and fine aggregate have different solid densities and it is the volume rather than the mass that really matters, the mix proportions of the mortar samples were designed on a volumetric basis. On the whole, the mortar samples were designed such that the cement to fine aggregate ratio by solid volume was fixed at 3 to 4 and the W/S ratio by volume was set equal to 0·335, 0·375 or 0·415. In each mortar sample, an ordinary Portland cement (OPC) of strength class 52·5 N was used as the only cementitious material and crushed granite rock fine with a maximum size of 1·18 mm was used as the fine aggregate. The OPC used was tested to have a specific gravity of 3·11 and a Blaine fineness of 361 m^2/kg, whereas the fine aggregate used was tested to have a specific gravity of 2·64 and a water absorption by mass of 1·60%. A polycarboxylate-based SP was added to each mortar sample at the recommended maximum dosage of 3% by liquid mass of the cement content. The SP has a solid mass content of 20% and a specific gravity of 1·03.

The same OPC was used for all the mortar samples but the grading of the fine aggregate was varied by sieving the fine aggregate into four different size classes and blending the four size classes of fine aggregate at various proportions. The four size classes, named as S1, S2, S3 and S4, respectively, had sieve size ranges as depicted in Table 1. Fig. 5 plots the particle size distributions of the OPC and the four size classes of fine aggregate measured by the laser diffraction method. By blending S1, S2, S3 and S4 together at various proportions, twelve different fine aggregate gradings were obtained for producing mortar samples with various packing density and solid surface area. Combining the twelve different fine aggregate gradings (numbered from 1 to 12) with the three different W/S ratios (designated by a, b and c), a total of thirty-six mortar mixes were designed for testing, as presented in Table 2. For easy identification, each mortar mix was assigned a mix number starting with a number denoting the fine aggregate grading and a letter denoting the W/S ratio.

The maximum size of the fine aggregate was limited to 1·18 mm because particles larger than 1·18 mm tend to cause interlocking actions between the particles that might affect the flowability and rheological properties of the mortar. Such particle interactions are larger between larger particles (smaller particles can roll to avoid interlocking whereas larger particles cannot roll easily to avoid interlocking) and thus are generally more significant when the aggregate contains large particles. In this study, particles larger than 1·18 mm were deliberately not added to minimise particle interactions. In a later study, the combined effects of WFT and particle interactions will be investigated by adding larger particles to the mortar.

Table 1. Four size classes of crushed rock fine aggregate

Size class	Sieve size range	
	Sieve retained on	Sieve passed through
S1	75 μm	150 μm
S2	150 μm	300 μm
S3	300 μm	600 μm
S4	600 μm	1·18 mm

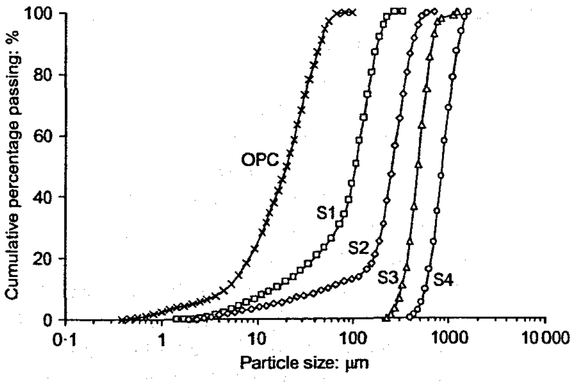

Fig. 5. Particle size distributions of OPC and size classes S1–S4

For each triplet of mortar mixes with the same solid composition (for instance mixes 1a, 1b and 1c have the same solid composition), a wet packing test was carried out to determine its packing density. Then, three mortar samples were produced out of the solid composition at different W/S ratios. Each mortar sample was first subjected to the mini slump cone and mini V-funnel tests to evaluate its flowability and then subjected to the vane test to characterise its rheology. All the tests were carried out in an air-conditioned laboratory with the room temperature controlled at 20 to 22°C. However, it was found that after mixing, due to the mechanical energy applied during mixing, the mortar samples were generally at a temperature of 27 ± 2°C.

Results and discussion

Packing density and excess water ratio

The measured packing densities of the mortar samples are tabulated in the seventh column of Table 2. With the cement to fine aggregate ratio fixed, the packing density of the mortar was dependent mainly on the fine aggregate grading. From the tabulated test results, it is evident that the measured packing densities range from the highest of 0·762 for mix 6 to the lowest of 0·715 for mix 12. Although the range of packing density was only about 6%, which appears quite small, it had significant effects on the excess water ratio of the mortar, as can be seen from the calculated results for the excess water ratio tabulated in the eighth column of Table 2. For instance, at the same W/S ratio of 0·335, mix 6a, which had a packing density of 0·762, was calculated to have an excess water ratio of 0·0224, whereas mix 12a, which had a packing density of 0·715, was calculated to have an excess water ratio of −0·0633 (a negative excess water ratio means that the water added was not sufficient to fill up the voids in the mortar leading to the presence of air in the voids). Hence, a small difference in packing density can cause a large difference in excess water ratio. That is why the packing density must be accurately measured and should be maximised as far as practicable by adjusting the grading of the fine aggregate.

Flowability and rheology

The measured flow spread and flow rate are plotted against the W/S ratio in Fig. 6. It is seen that generally both the flow spread and flow rate increase with the

Table 2. Mix proportions and results of the mortar samples tested

Mix no.	Percentage of different size classes in fine aggregate: %				W/S ratio	Packing density	Excess water ratio	Solid surface area: m^2/m^3	Water film thickness: μm
	S1	S2	S3	S4					
1a	25	25	25	25	0·335	0·725	−0·0441	488 500	−0·0903
1b					0·375		−0·0041		−0·0084
1c					0·415		0·0359		0·0735
2a	20	20	20	40	0·335	0·737	−0·0215	481 700	−0·0445
2b					0·375		0·0185		0·0385
2c					0·415		0·0585		0·1215
3a	0	25	25	50	0·335	0·756	0·0122	466 400	0·0263
3b					0·375		0·0522		0·1120
3c					0·415		0·0922		0·1978
4a	25	25	0	50	0·335	0·730	−0·0343	487 600	−0·0704
4b					0·375		0·0057		0·0116
4c					0·415		0·0457		0·0937
5a	25	25	50	0	0·335	0·719	−0·0552	489 300	−0·1128
5b					0·375		−0·0152		−0·0311
5c					0·415		0·0248		0·0507
6a	0	15	35	50	0·335	0·762	0·0224	462 300	0·0484
6b					0·375		0·0624		0·1350
6c					0·415		0·1024		0·2215
7a	15	0	35	50	0·335	0·751	0·0030	468 900	0·0065
7b					0·375		0·0430		0·0918
7c					0·415		0·0830		0·1771
8a	15	35	0	50	0·335	0·734	−0·0276	483 200	−0·0571
8b					0·375		0·0124		0·0257
8c					0·415		0·0524		0·1085
9a	0	40	60	0	0·335	0·734	−0·0269	474 100	−0·0568
9b					0·375		0·0131		0·0275
9c					0·415		0·0531		0·1119
10a	40	0	60	0	0·335	0·719	−0·0563	491 800	−0·1145
10b					0·375		−0·0163		−0·0332
10c					0·415		0·0237		0·0482
11a	40	0	0	60	0·335	0·727	−0·0405	489 900	−0·0827
11b					0·375		−0·0005		−0·0011
11c					0·415		0·0395		0·0806
12a	50	0	0	50	0·335	0·715	−0·0633	498 700	−0·1270
12b					0·375		−0·0233		−0·0468
12c					0·415		0·0167		0·0334

W/S ratio. These observed phenomena are expected, as it is well known that increasing the water content of a mortar would improve the flowability of the mortar. On the other hand, it is noted that both the flow spread and flow rate vary quite substantially among the mortar mixes with different fine aggregate gradings. This is illustrated by the different lines plotted for the mixes with different fine aggregate gradings. At a W/S ratio of 0·335, the flow spread could range from nearly zero to more than 200 mm due to the use of a different fine aggregate grading. Although at a higher W/S ratio, the range of the flow spread would become smaller, the effect of the fine aggregate grading is still significant. Similar phenomena could be observed for the flow rate. At a W/S ratio of 0·335, the flow rate could range from zero to more than 60 ml/s due to the use of a different fine aggregate grading. Furthermore, the range of the flow rate would not become smaller at a higher W/S ratio. These results indicate that other than the W/S ratio, the fine aggregate grading is also a major parameter governing the flowability of mortar.

The measured yield stress and apparent viscosity are plotted against the W/S ratio in Fig. 7. It is apparent that in general both rheological properties decrease with the W/S ratio. This means that increasing the water content of a mortar would reduce the yield stress and apparent viscosity of the mortar. On the other hand, as for the flowability measures of the mortar, the rheological properties of the mortar also vary quite substantially among the mortar mixes with different fine aggregate gradings, as illustrated by the different lines plotted for the mixes having different fine aggregate gradings. At a W/S ratio of 0·335, the yield stress could range from 5·18 to 28·66 Pa, representing a more than five-fold variation just due to changes in fine aggregate grading. This range would become smaller at a higher

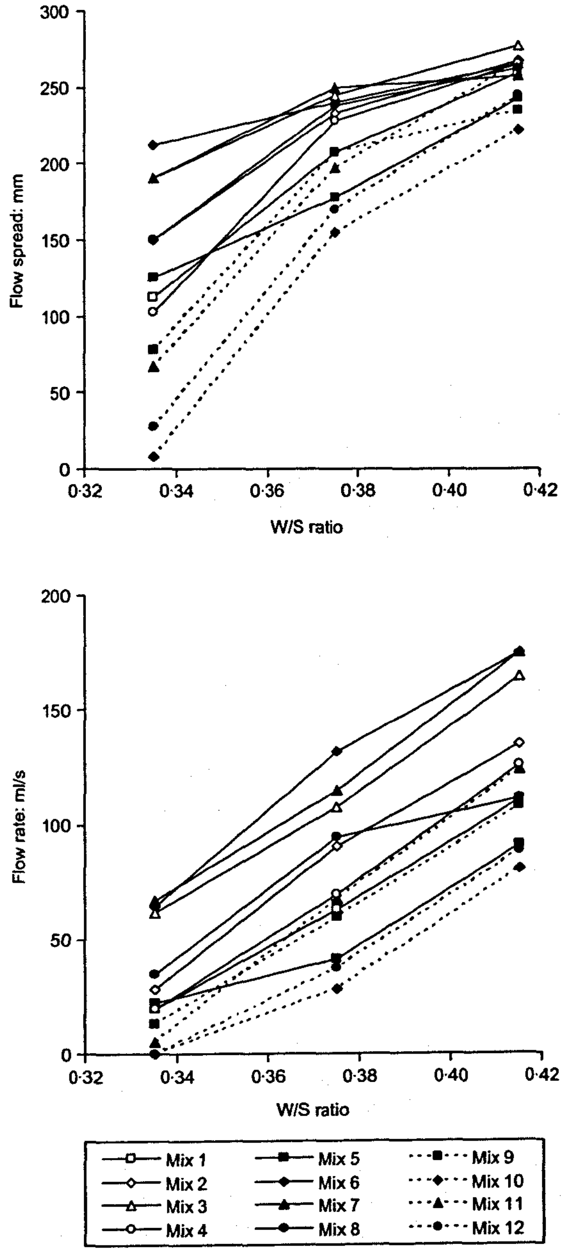

Fig. 6. Flowability plotted against W/S ratio

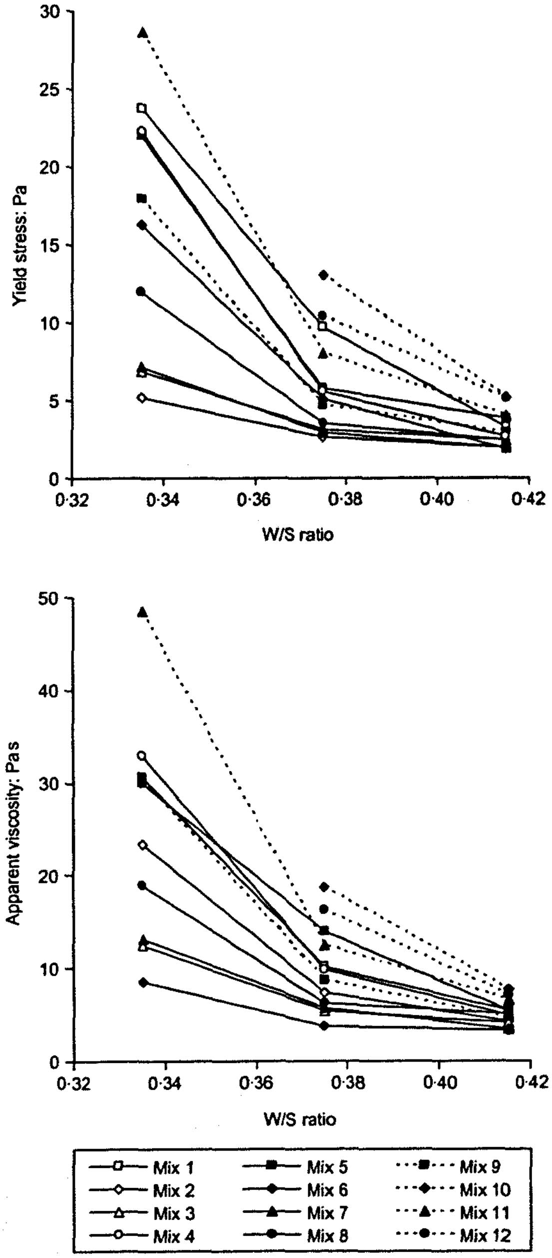

Fig. 7. Rheological properties plotted against W/S ratio

W/S ratio. Similar behaviour was observed for the apparent viscosity. These results show that the W/S ratio is not the sole parameter governing the rheological properties of mortar. The fine aggregate grading also plays a major role, especially at a low W/S ratio.

The flowability and rheology of the mortar samples are somehow inter-related. To study their relationship, the flow spread and flow rate are respectively plotted against the yield stress and apparent viscosity in Fig. 8. From these plots, it can be seen that there is a good correlation between the flow spread and yield stress with an R^2 values of 0·904 and also a good correlation between the flow rate and apparent viscosity with an R^2 values of 0·927. Hence, the flow spread should be governed mainly by the yield stress whereas the flow rate should be governed mainly by the apparent viscosity. The good correlations obtained indicate that the flow spread and flow rate, which can be measured more easily, may be taken as alternative measures of the yield stress and apparent viscosity.

Water film thickness

For evaluation of the WFT, the specific surface area of the cement was determined directly from the Blaine fineness of the cement whereas the specific surface areas of the four size classes (S1, S2, S3 and S4) of fine aggregate were calculated from their respective particle size distributions. Due to the difficulty of

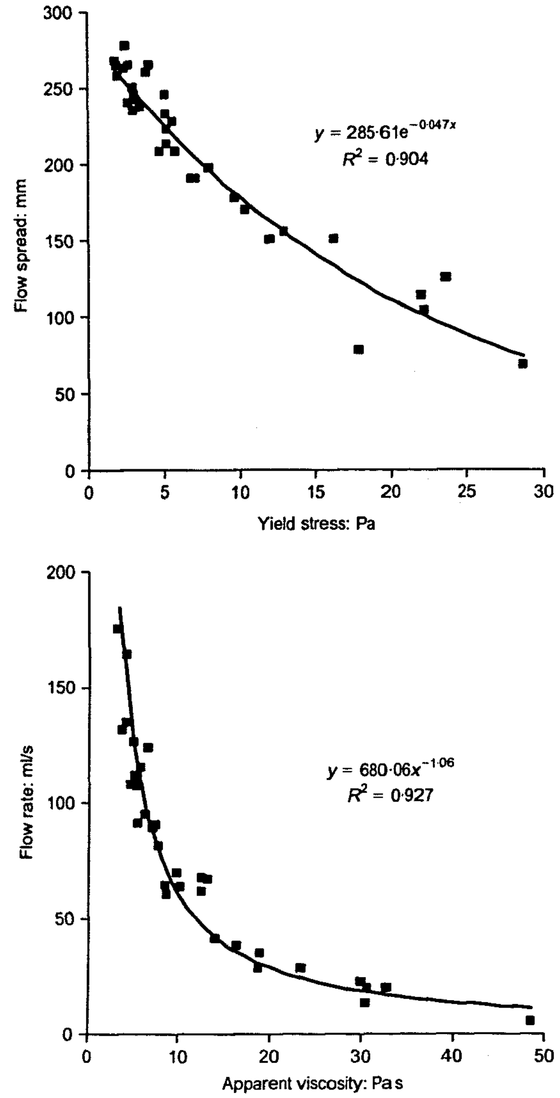

Fig. 8. Flowability plotted against rheological properties

allowing for the effect of particle shape, the aggregate particles were assumed to be spherical when calculating their solid surface areas. Although the actual specific surface areas of the fine aggregate should be larger than the respective calculated values owing to the angularity of the particles, the difference should have little effect on the total solid surface area of the mortar because in general more than 90% of the total solid surface area was contributed by the cement. The solid surface areas so obtained are presented in the second last column of Table 2.

Obviously, both the W/S ratio and fine aggregate grading have major effects on the flowability and rheological properties of mortar. The effect of W/S ratio can be explained quite easily because water is a lubricant and therefore increasing the W/S ratio would improve the flowability and rheological properties. However, the effect of fine aggregate grading cannot be so easily explained. First, there is no simple quantitative measure of aggregate grading. Second, the fine aggregate grading affects the flowability and rheological properties only indirectly through the overall packing density and solid surface area of the mortar. For these reasons, there is, up to now, no simple and generally accepted theory to account for the effect of aggregate grading. Lastly, it should be borne in mind that the effect of the W/S ratio is dependent on the fine aggregate grading whereas the effect of the fine aggregate grading is dependent on the W/S ratio. The combined effects are fairly complicated and yet to be thoroughly investigated for proper modelling. Herein, it is suggested that the combined effects of W/S ratio and fine aggregate grading (or, in other words, the combined effects of water content, packing density and solid surface area) may be evaluated in terms of the WFT, defined as in equation (4). The WFT of the mortar samples so obtained are tabulated in the last column of Table 2.

For the thirty-six mortar samples tested, the WFT ranged from $-0{\cdot}127$ to $0{\cdot}222$ μm. When positive, the WFT has the physical meaning of the average thickness of the water films coating the particles. However, when negative, the WFT no longer has such physical meaning. A negative WFT implies a negative excess water ratio, which in turn implies that the amount of water added is insufficient to fill up the voids between the particles, leading to the presence of air voids in the mortar. The presence of air voids would generate capillary suction and thus increase the cohesiveness and reduce the flowability of the mortar. Hence, when negative, the WFT may be taken as a measure of the amount of air voids per solid surface area in the mortar.

To study the effects of the WFT, the flow spread and flow rate are plotted against the WFT in Fig. 9 and the yield stress and apparent viscosity are plotted against the WFT in Fig. 10. In each graph, a vertical line is drawn at WFT = 0 to demarcate the regions with negative and positive values of WFT. It is found that in each graph, unlike the previous curves plotted against the W/S ratio, the present curves plotted against the WFT for the different mortar mixes all merge to form a single line. For the data presented in each graph, regression analysis has been carried out to derive the best-fit curve, whose equation and R^2 value are printed by the side for easy reference. From these regression analysis results, it can be seen that the correlations of the flow spread, flow rate, yield stress and apparent viscosity to the WFT yielded R^2 values of 0·890, 0·937, 0·893 and 0·821, respectively. Such high R^2 values indicate very clearly that the WFT is the single most important parameter governing the flowability and rheological properties of mortar.

All the curves in Figs 9 and 10 reveal that generally as the WFT increases, both the flowability and rheology of mortar would improve. On the whole, there is a minimum required WFT for the mortar to achieve

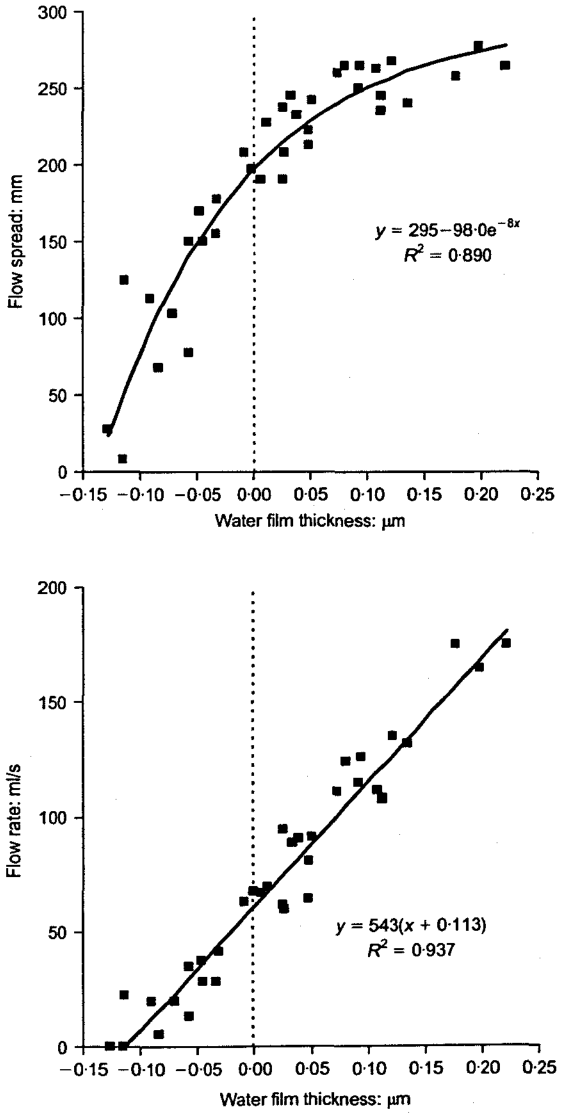

Fig. 9. Flowability plotted against water film thickness

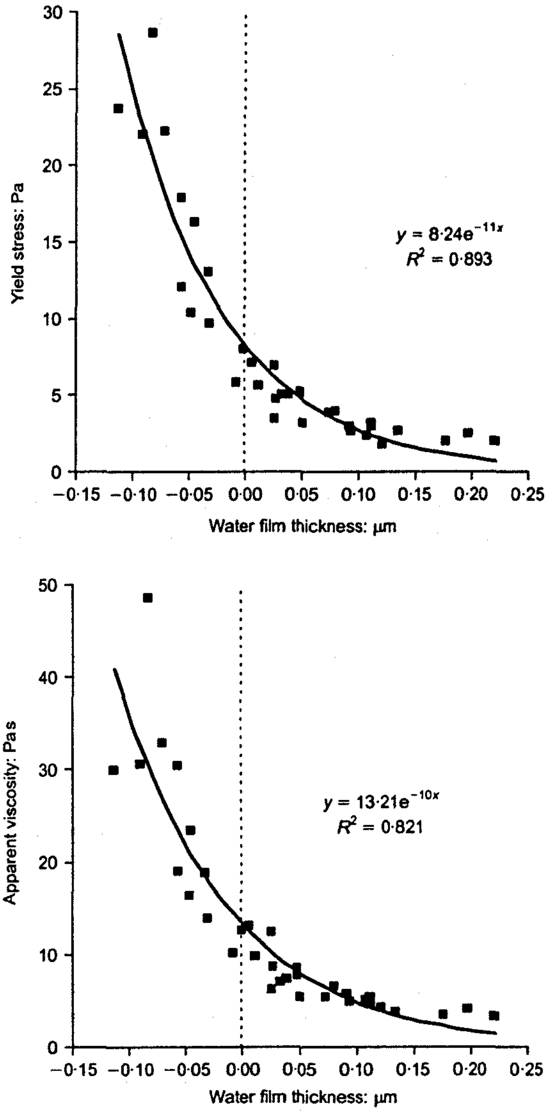

Fig. 10. Rheological properties plotted against water film thickness

reasonably acceptable flowability and rheological properties. Roughly, even when a high workability is not needed, the minimum required WFT is about 0·05 μm. When a higher workability is needed, such as for making high-flow mortar grout or self-consolidating concrete, the required WFT would be higher but further studies are needed before such a required WFT could be established for different types of mortar and concrete. It is anticipated that the required WFT will eventually become the most important parameter to be considered in the mix design of high-performance mortar and concrete.

Conclusions

A total of thirty-six mortar mixes proportioned with twelve different fine aggregate gradings and three different W/S ratios were produced for packing density, flowability and rheology tests. The wet packing method originally developed by the present authors for measuring the packing density of cementitious materials was successfully extended to apply to such mortar mixes. On the other hand, the flowability of the mortar mixes was measured by the mini slump cone and mini V-funnel tests in terms of the flow spread and flow rate, respectively, whereas the rheology of the mortar mixes was measured by the vane test, using a speed-controlled rheometer, in terms of the yield stress and apparent viscosity, respectively.

The measured packing densities varied from 0·715 to 0·762, amounting to about 6% difference. As the cement to fine aggregate ratio was fixed, such variations in packing density were due solely to the changes in fine aggregate grading. However, despite being relatively small, the variation in packing density was found to have great effects on the flowability and rheological properties of the mortar mixes. Hence, the packing density must be accurately measured and should be maximised as far as practicable. On the whole, the test results revealed that both the W/S ratio and fine aggregate grading had major effects on the flowability and rheology of mortar. As expected, the flowability and rheology improved as the W/S ratio increased. However, the effect of the fine aggregate grading was fairly complicated. Moreover, the effect of the W/S ratio was dependent on the fine aggregate grading whereas the effect of the fine aggregate grading was dependent on the W/S ratio.

Nevertheless, since the W/S ratio and fine aggregate grading affect the flowability and rheology of mortar mainly through their effects on the water content, packing density and solid surface area, which together determine the WFT of the mortar, it is apparent that the combined effects of the W/S ratio and fine aggregate grading (or of the water content, packing density and solid surface area) may be evaluated in terms of the WFT. Correlations of the flow spread, flow rate, yield stress and apparent viscosity to the WFT yielded R^2 values of 0·890, 0·937, 0·893 and 0·821, respectively. Such good correlations proved that the WFT is the single most important parameter governing the flowability and rheological properties of mortar.

The correlations also revealed that the minimum required WFT is about 0·05 μm. When high workability is demanded, such as for making high-performance mortar and concrete, the required WFT would be higher but further studies are needed before the required WFT could be established. It is suggested that the required WFT should be adopted as the major parameter to be considered in mortar and concrete mix designs. Lastly, it is recommended that further studies should be conducted to include changing the cement to fine aggregate ratio, adding supplementary cementitious materials and adding larger size particles, in order to investigate the effects of other mix parameters on the WFT and the combined effects of WFT and particle interaction on the mortar/concrete performance.

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