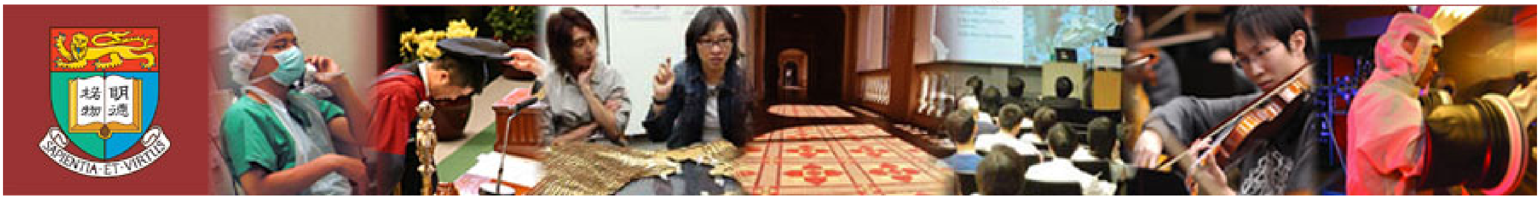

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Effects of packing density, excess water and solid surface area on flowability of cement paste

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Although it has been postulated for many years that it is excess water rather than whole water that lubricates the cementitious materials and governs flowability of paste (excess water is water in excess of that needed to fill up voids), there has been no detailed investigations to study the actual effects of excess water. This was due to the lack of a suitable method for measuring the packing density and voids content of cementitious materials. To resolve the problem, the authors have recently developed a new wet packing method that was applied herein to measure the packing densities and voids contents of cementitious materials containing different amounts of cement, pulverised fuel ash and condensed silica fume. The flowability properties of the paste formed of the cementitious materials with different water contents were also measured and correlated to the excess water contents, each determined as water content minus voids content. The results revealed that whereas an improvement in packing density would increase excess water content, flowability is governed mainly by excess water to solid volume and excess water to solid surface area ratios.

Introduction

The flowability of cement paste is a key factor determining the workability and general performance of concrete. There is no doubt that the single most important parameter affecting the flowability of cement paste is the water content or, more specifically, the water/cementitious materials (W/CM) ratio. Basically, a higher W/CM ratio would lead to a higher flowability. However, the W/CM ratio also affects the strength of concrete and is usually governed by the strength requirement. Hence, to produce a high-performance concrete (HPC) with both high strength and high workability, it is necessary to optimise the flowability at a given W/CM ratio. In fact, in modern HPC,[1] which generally contains supplementary cementitious materials, the flowability of the paste is also affected by the mix proportions and particle characteristics of the cementitious materials, although their actual effects are not yet fully understood. To maximise the flowability of cement paste without increasing the W/CM ratio, it is important to study how the various parameters, especially those related to the cementitious materials, would affect the flowability, or in more general terms the rheology, of the paste.

One major parameter other than the water content that would significantly affect the flowability of cement paste is the particle packing of the cementitious materials. Some years ago, Claisse *et al.*[2] measured the rheological properties of many samples of cement paste formed of different types of cement and showed that the particle size distribution of the cement is a major factor governing the cement paste rheology. They did not give any explanations but the present authors would like to postulate that this was because the particle size distribution affects the particle packing, which in turn influences the cement paste rheology. More recently, in 2003 Lee *et al.*[3] evaluated the fluidity of cement paste containing fly ash of different fineness and found that a blended cement–fly ash system having a wider particle size distribution would yield a better fluidity. This was attributed to the higher packing density achieved with a wider size range. In 2004 Termkhajornkit and Nawa[4] measured the flow spread of cement paste containing different types of fly ash and demonstrated that the flowability of cement paste is dependent on the dry bulk density, taken as a measure of the packing density, of the blended cementitious materials.

As the water added has to first fill up the voids between the solid particles and the water trapped inside the voids is not available for lubrication, it is the excess water, that is the water in excess of that needed to fill

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up the voids, that lubricates the solid particles and contributes to the flowability of cement paste. As the voids content is smaller when the packing density is higher, this explains why the flowability of cement paste is dependent on the packing density of the cementitious materials. The role of the voids content itself is nowadays quite well known. For instance, Mindess *et al.*[5] explained that the addition of a superplasticiser would disperse the flocculated cement particles and reduce the voids content, thereby releasing some of the water inside the voids to reduce the viscosity of the paste. Kong *et al.*[6] also pointed out that the de-flocculation effect of a superplasticiser would improve the cement paste rheology by liberating the water trapped inside the voids for lubrication. On the other hand, Park *et al.*[7] evaluated the effects of fly ash, blast furnace slag and silica fume and showed that through proper mix proportioning, these relatively fine supplementary cementitious materials would fill the voids between the larger cement particles, thereby displacing the water in the voids and enhancing the rheological properties of the paste.

Apart from the packing density and voids content, the surface area of the cementitious materials may also have significant effects on the flowability and rheology of the cement paste. Claisse *et al.*[2] have found from their measurement of cement paste rheology and subsequent data analysis that the yield stress of cement paste would increase with the specific surface area of the cement used and therefore having a larger specific surface area would impair the flowability of the cement paste. Ferraris *et al.*[8] measured the rheology of cement paste containing different types of supplementary cementitious materials and made an attempt to correlate the rheological properties with the mean particle size of the supplementary cementitious materials added. However, although the mean particle size is to some extent an indirect measure of specific surface area, no clear relation between the rheological properties and the mean particle size was found.

From the above, it is evident that the flowability of cement paste is influenced not just by one or two independent parameters but by several inter-related parameters that need to be considered at the same time. For example, the addition of a relatively fine supplementary cementitious material that could fill into the voids of the larger cement particles would improve the packing density, reduce the voids content and increase the excess water content, and thus should have beneficial effects on the flowability. Owing to the reduction in average particle size, however, the specific surface area of the cementitious materials would increase, thereby having adverse effects on the flowability. The net effect is dependent on whether the beneficial or adverse effect is larger. Hence, the various parameters related to the cementitious materials added should not be considered individually. Furthermore, up to now there has been no established test method for direct measurement of the packing density of cementitious materials. Without direct measurement of the actual packing density, the statement that improving the packing density of the cementitious materials would increase the flowability of the cement paste has remained a postulation, which has yet to be verified. These explain the complexity of the issue and why so far the conclusions arrived at in most previous studies are merely qualitative descriptions.

In the present study, in order to resolve the above problems and investigate the combined effects of water content, packing density and other parameters on the flowability of cement paste, a new wet packing method for direct measurement of the packing density of cementitious materials was developed and a comprehensive experimental programme incorporating the newly developed wet packing method performed. In the experimental programme, different mix proportions of ordinary Portland cement (OPC), pulverised fuel ash (PFA) and condensed silica fume (CSF) were blended and the packing densities of the blended mixtures measured. A total of more than 100 samples of cement paste were made from these blended mixtures at different W/CM ratios and the flowability of the paste formed was measured by means of the mini-slump cone and Marsh cone tests. From the experimental data thus obtained, the flowability characteristics of the cement paste were correlated with the water content, excess water content (i.e. water content minus voids content) and specific surface area of the cementitious materials. It was found that whereas the effects of the individual parameters are fairly complicated, the combined effects of the various parameters may be reflected in terms of just two fundamental factors, namely the excess water to solid volume ratio and excess water to solid surface area ratio.

Measuring packing density of cementitious materials

Existing methods of measuring the packing density of solid particles may be classified into two categories: (*a*) the dry packing methods of filling the solid particles into a container and measuring the dry bulk density of the solid particles, such as the one commonly used for aggregates;[9] and (*b*) the wet packing methods of mixing the solid particles with water to form a paste and determining the water demand to achieve a certain arbitrarily chosen level of consistency.[10,11] In the dry packing methods, the packing density is simply determined as the bulk density to solid density ratio. When applied to fine particles (e.g. powders), however, the measured bulk densities are highly sensitive to the compaction effort applied, thus rendering the packing density results unreliable and difficult to interpret.[12] Moreover, among fine particles smaller than 100 μm in size, there often exist strong inter-particle forces that cause agglomeration, leading to loose packing and unreasonably low packing density results.[13] In the wet packing methods, the water demand is assumed to be the same as the minimum amount of water needed to fill up the voids between the solid particles, from which the voids content and packing density may be determined. The assumption that the water demand at a certain level of consistency is the same as the minimum amount of water needed to fill up the voids has never been justified or verified however, and there has been no agreement on the level of consistency at which the water demand should be measured. In addition, the volume of air voids in the paste has been ignored in the packing density calculations.

In view of the aforementioned drawbacks of the existing methods, a new wet packing method was developed and adopted in this study. The basic concept of the new method is to mix the cementitious materials with water at different W/CM ratios to form a paste, measure the wet bulk density of the paste to determine the solid concentration of the cementitious materials and from the variation of the solid concentration with the W/CM ratio determine the maximum solid concentration as the packing density of the cementitious materials. At a high W/CM ratio, the cementitious materials are dispersed in the form of a suspension with low solid concentration, whereas at a low W/CM ratio, the water added is insufficient to fill up the voids causing a large amount of air to be trapped and the cementitious materials to be loosely packed. Between these two extremes, there exists an optimum W/CM ratio at which the solid concentration is a maximum. This maximum solid concentration is the closest packing that the cementitious materials can achieve and is thus taken as the packing density. By measuring the bulk density of the paste, the presence of any air voids is implicitly taken into account. This wet packing method has the advantage that the packing density of the cementitious materials is measured under wet condition with the effects of water and any superplasticiser incorporated. Furthermore, the method directly determines the packing density as the maximum solid concentration that can be achieved instead of the water demand at a certain level of consistency, which is rather arbitrary and not necessarily correct.

To determine the packing density (i.e. the maximum solid concentration), several samples of cement paste are formed of the cementitious materials, starting at a relatively high W/CM ratio and successively reducing the W/CM ratio until the solid concentration had reached a maximum value and then decreased. To ensure thorough mixing of the cementitious materials with water, a special mixing procedure of adding the cementitious materials to the water (note: not adding the water to the cementitious materials) is adopted. All pieces of equipment used complied with BS EN 196: Parts 1–3.[14] The detailed procedures are summarised in the following list.

(*a*) Select the W/CM ratio at which the test is to be carried out. Weigh the required quantities of water, cementitious materials and superplasticiser (if any) and place each ingredient into a separate container.
(*b*) If the cementitious materials consist of several different materials blended together, pre-mix the materials dry.
(*c*) Add all the water and half of the cementitious materials and superplasticiser into the mixing bowl and run the mixer for 3 min.
(*d*) Add the remaining cementitious materials and superplasticiser in four equal portions into the mixing bowl and after each addition run the mixer for 3 min.
(*e*) Transfer the mixture to a cylindrical mould, fill the mould to excess and remove the excess with a straight edge. Weigh the amount of paste in the mould to determine the wet bulk density of the paste.
(*f*) Repeat steps (*a*) to (*e*) at successively lower W/CM ratios until the maximum solid concentration has been obtained.

From the test results obtained, the solid concentration of the cementitious materials in the paste can be determined in the following manner. Let the mass and volume of the paste in the mould be M and V, respectively (the dimensions of the mould used by the authors were 62 mm diameter and 60 mm high, but any other mould of similar size could also be used). The wet bulk density of the paste is equal to M/V. If the cementitious materials consist of several different materials denoted by α, β, γ and so forth, the solid concentration ϕ may be evaluated using the following equation

$$\phi = \frac{M/V}{\rho_w u_w + \rho_\alpha R_\alpha + \rho_\beta R_\beta + \rho_\gamma R_\gamma} \tag{1}$$

where ρ_w is the density of water, ρ_α, ρ_β and ρ_γ are the solid densities of α, β and γ, u_w is the W/CM ratio by volume and R_α, R_β and R_γ are the volumetric ratios of α, β and γ to the total cementitious materials. The maximum value of ϕ so obtained is the packing density of the cementitious materials.

Measuring the flowability of cement paste

The tests used to evaluate the flowability of cement paste are the mini-slump cone test,[15–17] which measures the flow spread of the paste after removal of the mini-slump cone, and the Marsh cone test,[1,18] which measures the time required for a certain volume of paste to flow through the Marsh cone. Details of these two tests are given below.

There are several versions of mini-slump cone tests employing slump cones of different dimensions. The version adopted in the present study was the method used by Okamura and Ouchi,[17] in which the slump cone has the dimensions shown in Fig. 1. The procedures for the test are given in the following list.

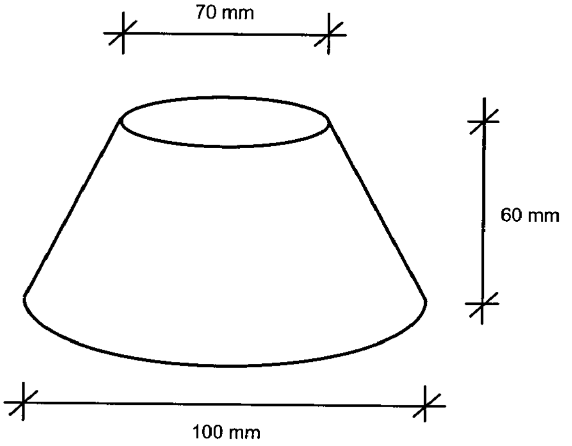

Fig. 1. Mini-slump cone

(*a*) Place the slump cone at the centre of a levelled steel plate.
(*b*) Pour the paste, prepared by the mixing procedure adopted in the wet packing method, into the slump cone and completely fill the slump cone.
(*c*) Lift the slump cone gently and allow the paste to spread till stoppage.
(*d*) Measure the diameters of the paste at two orthogonal directions, calculate the average diameter and determine the flow spread of the paste as the average diameter minus the base diameter of the cone.

There are several versions of the Marsh cone test. The one adopted in the present study was the one specified in BS EN 445: 1997,[18] in which the Marsh cone has dimensions as depicted in Fig. 2. The procedures for the test are given in the following list.

(*a*) Attach the Marsh cone to a stand and place a graduated cylinder underneath the orifice of the cone.
(*b*) Close the orifice and pour 900 ml of paste, prepared by the mixing procedure adopted in the wet packing method, into the cone. To minimise air entrapment, pour the paste slowly along the inner surface of the cone.
(*c*) Open the orifice and record the time required for 300 ml of paste to flow out. The recorded time is the flow time of the paste.

As the flowability is inversely proportional to the flow time, the result is expressed in terms of the flow rate of the paste calculated as 300 ml divided by the flow time to allow easier interpretation. For a dry paste, which took a long time to flow out, the test was stopped after 300 s and the flow rate calculated as the volume of paste collected underneath the cone divided by 300 s.

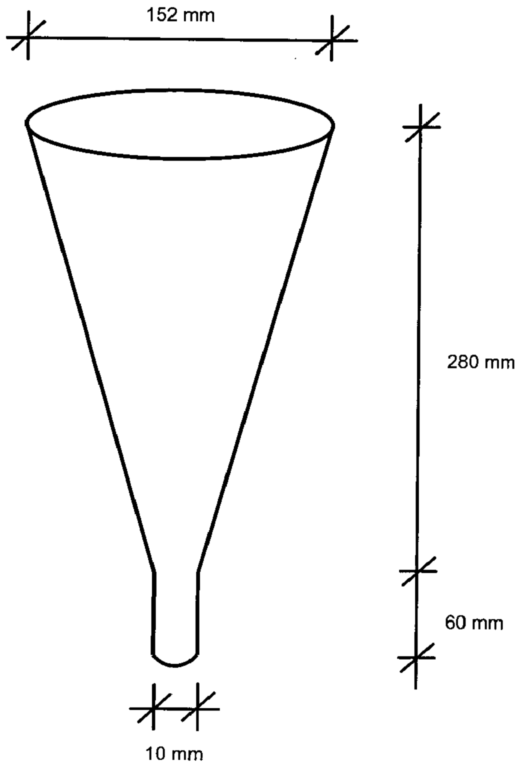

Fig. 2. Marsh cone

Experimental programme

In the experimental programme, twelve blended mixes of cementitious materials containing OPC, PFA and CSF were tested. These mixes were designed such that they could be grouped into four series, named as A, B, C and D. Series A consisted of mixes containing OPC, 0 to 45% PFA and no CSF, whereas series B consisted of mixes containing OPC, 0 to 45% PFA and 15% CSF. In contrast, series C consisted of mixes containing OPC, 0 to 45% CSF and no PFA, and series D consisted of mixes containing OPC, 0 to 45% CSF and 15% PFA. As the cementitious materials have different densities and it is the solid volume rather than the mass of each material that matters, the mix proportions of OPC, PFA and CSF in each mix were designed on a solid volume basis and expressed in terms of the respective ratios of solid volume to the total solid volume of cementitious materials. Details of the mix proportions of the twelve mixes tested are presented in Table 1.

All the cementitious materials employed in the experimental programme were commonly used materials obtained from the market. Compliance testing had been carried out and the results verified that the OPC and PFA complied with BS 12: 1996 and BS 3892: Part 1: 1997, respectively. The CSF was imported from Norway and had been tested by the supplier to comply with ASTM C 1240-03. The relative densities of the OPC, PFA and CSF had been measured in accordance with BS 812: Part 2: 1995 as 3·11, 2·48 and 2·20, respec-

Table 1. Mix proportions of the cementitious materials tested

Series	Mix no.	Mix proportion: % by volume			Packing density	Voids ratio
		OPC	PFA	CSF		
A	A1	100	0	0	0·631	0·585
	A2	85	15	0	0·644	0·553
	A3	70	30	0	0·669	0·495
	A4	55	45	0	0·679	0·473
B	B1	85	0	15	0·709	0·410
	B2	70	15	15	0·730	0·370
	B3	55	30	15	0·749	0·335
	B4	40	45	15	0·750	0·333
C	C1	100	0	0	0·631	0·585
	C2	85	0	15	0·709	0·410
	C3	70	0	30	0·689	0·451
	C4	55	0	45	0·652	0·534
D	D1	85	15	0	0·644	0·553
	D2	70	15	15	0·730	0·370
	D3	55	15	30	0·704	0·420
	D4	40	15	45	0·665	0·504

Note: C1, C2, D1 and D2 are the same as A1, B1, A2 and B2 respectively.

tively. A laser diffraction particle size analyser was used to measure the particle size distributions of the OPC, PFA and CSF and the results obtained are plotted in Fig. 3. The specific surface area of the OPC had been measured in accordance with the air permeability method specified in BS EN 196 Part 6: 1992 as $1{\cdot}05 \times 10^6$ m^2/m^3 (equivalent to 338 m^2/kg), and the specific surface areas of the PFA and CSF were calculated, based on their particle size distributions, as $0{\cdot}86 \times 10^6$ and $13{\cdot}3 \times 10^6$ m^2/m^3, respectively (equivalent to 347 and 6020 m^2/kg, respectively).

A polycarboxylate ether-based superplasticiser was added to each mix. It was a liquid-type superplasticiser having a relative density of 1·03 and a dry mass fraction of 20%. The recommended normal dosage of the superplasticiser, measured in terms of liquid mass, was 0·5 to 3·0% by mass of the cementitious materials. As the cementitious materials have different densities and it is the total solid volume that matters, the superplasticiser dosage was expressed in terms of the liquid mass of superplasticiser per total solid volume of cementitious materials. The dosage of superplasticiser added to each mix was 93·3 kg/m^3, which corresponded to the upper limit of the normal dosage recommended by the supplier.

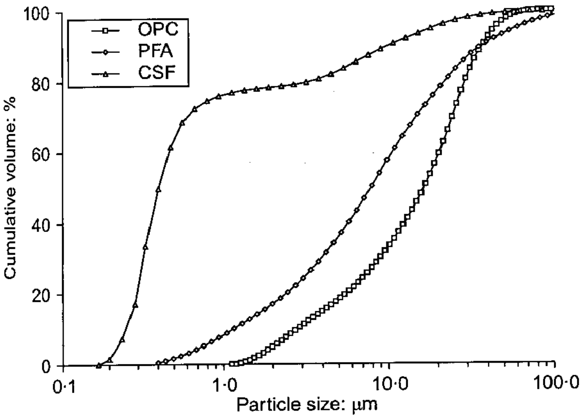

Fig. 3. Particle size distributions of OPC, PFA and CSF

For each mix of cementitious materials, first the wet packing test was carried out to determine the packing density of the cementitious materials and then at least eight samples of cement paste were formed using the cementitious materials at different W/CM ratios ranging from 0·225 to 1·10 by volume for flowability measurement to evaluate the variations of the flow spread and flow rate of the paste with W/CM ratio. As it is the solid volume rather than the mass that is more important, all the W/CM ratios were calculated on a volumetric basis.

Results and discussion

Packing density and flowability

The measured packing densities of the blended mixes tested are tabulated in the sixth column of Table 1. Comparing the packing density results of the mixes with the same CSF content, it can be seen that at the same CSF content, the addition of up to 45% PFA would increase the packing density by several percent. On the other hand, comparing the packing density results of the mixes with the same PFA content, it can be seen that at the same PFA content, the addition of CSF up to 15% would increase the packing density by slightly more than 10% but further addition of CSF to beyond 15% would decrease the packing density. The highest packing density was achieved with 45% PFA and 15% CSF added. From the packing density of each mix, the corresponding voids ratio (the voids volume to solid volume ratio) could be evaluated using the following formula:

$$u = \frac{1 - \tau}{\tau} \tag{2}$$

in which u is the voids ratio and τ is the packing density. The voids ratios so obtained are tabulated in the last column of Table 1 for reference.

The flowability results, namely the flow spread measured by the mini-slump cone test and the flow rate measured by the Marsh cone test, are plotted against the W/CM ratio for series A and B in Fig. 4 and for series C and D in Fig. 5. Comparing the flow spread–W/CM ratio and flow rate–W/CM ratio curves of the mixes with the same CSF content, it is evident that at the same CSF content, the addition of PFA up to 45% would shift the curves to the left. The shifting of the curves to the left is a clear indication of improved flowability at a given W/CM ratio. Bearing in mind that the addition of PFA also increased the packing density, the improved flowability may be attributed to the increase in packing density when PFA was added. This observation provides experimental evidence to verify the postulation that increasing the packing density of cementitious materials would improve the flowability of cement paste.

Comparing the flow spread–W/CM ratio and flow rate–W/CM ratio curves of the mixes with the same PFA content, it is evident that at the same PFA content, the addition of CSF up to 15% would shift the curves to the left and reduce the gradients of the curves and further addition of CSF to beyond 15% would shift the curves to the right and further reduce the gradients of the curves. The shifting of the curves to the left and right are indications of positive and negative changes in flowability at relatively low W/CM ratios whereas the reduction in gradient of the curves reveals a reduced rate of increase in flowability with the W/CM ratio. On the whole, at a W/CM ratio lower than about 0·4, the addition of CSF up to 15% would improve the flowability and further addition of CSF would adversely affect the flowability. However, at a W/CM ratio higher than about 0·6, the addition of CSF would always adversely affect the flowability. Bearing in mind that the addition of CSF up to 15% increased the packing density and further addition of CSF decreased the packing density, the positive and negative changes in flowability at relatively low W/CM ratios may be attributed to the corresponding changes in packing density. On the other hand, the adverse effects on flowability at relatively high W/CM ratios despite improvement in packing density suggest that apart from the packing density there may also be other factors affecting the flowability.

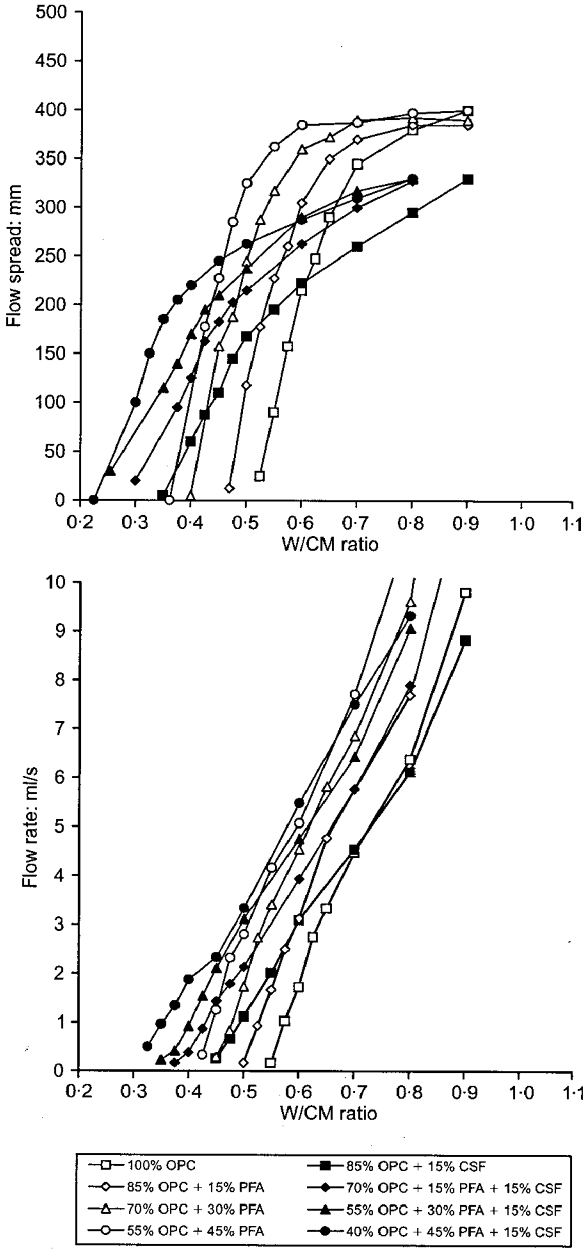

Fig. 4. Flowability plotted against W/CM ratio for series A and B

Effects of excess water ratio

The effects of packing density on flowability may be better explained in terms of the excess water in the paste, which is the water in excess of that needed to fill up the voids between the solid particles. An improved packing density would reduce the voids ratio (see the results in the last two columns of Table 1) and thus for the same amount of water in the paste, there would be more excess water coating and dispersing the solid particles to increase the flowability of the paste. To

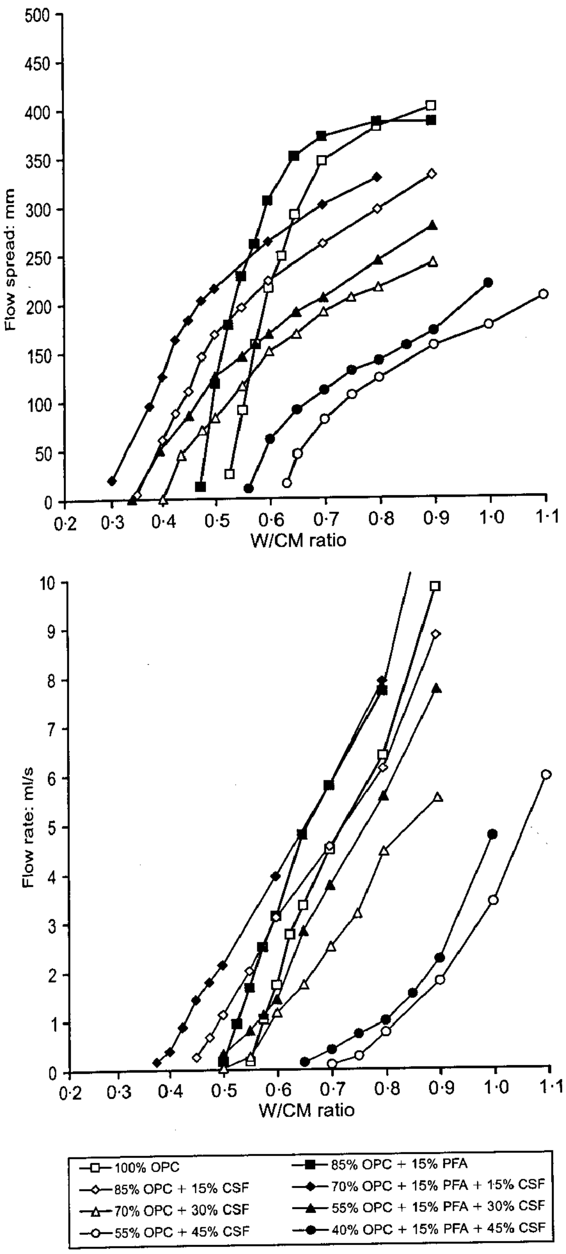

Fig. 5. Flowability plotted against W/CM ratio for series C and D

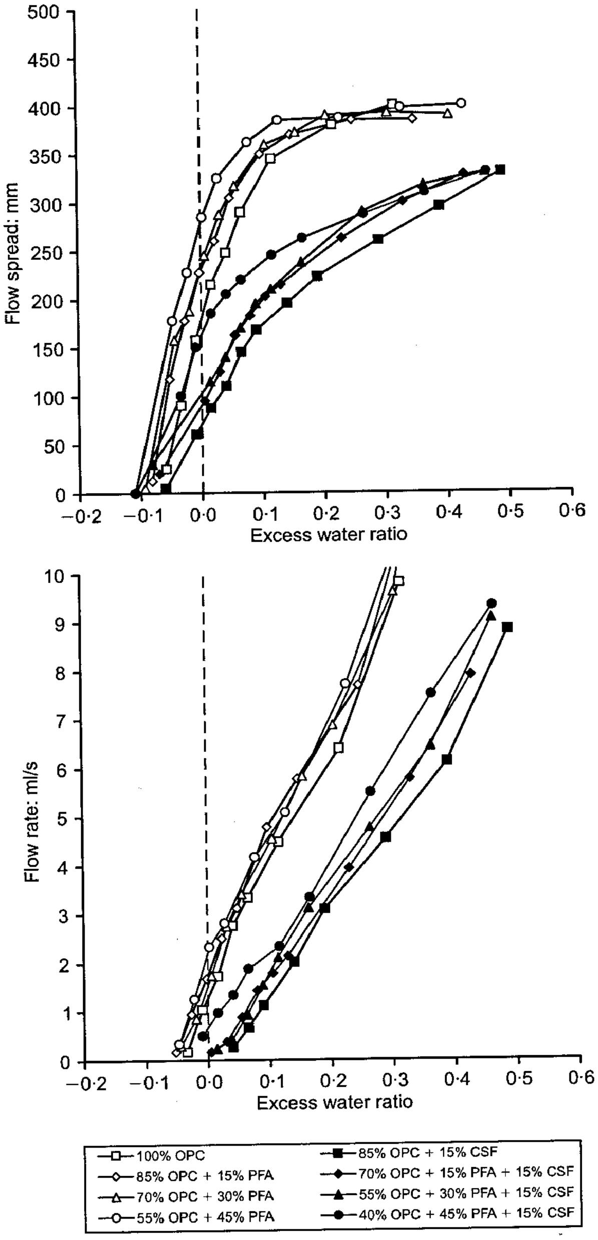

Fig. 6. Flowability plotted against excess water ratio for series A and B

investigate how the excess water influences the flowability, a new parameter called the excess water ratio is herein introduced. The excess water ratio is the volume of excess water per unit solid volume of the cementitious materials and can be calculated as:

$$u'_w = u_w - u \tag{3}$$

where u'_w is the excess water ratio, u_w is the W/CM ratio by volume of the paste and u is the voids ratio of the cementitious materials. Having converted the W/CM ratios to excess water ratios, the flowability results are plotted against the excess water ratio for series A and B in Fig. 6 and for series C and D in Fig. 7. In each figure, a vertical line is drawn at $u'_w = 0$ to demarcate the regions with negative and positive excess water ratios.

From Figs 6 and 7, it can be seen that regardless of whether the excess water ratio was negative or positive, both the flow spread and flow rate increased with the excess water ratio. When the excess water ratio was negative, the flowability was generally quite low. This was because the water added was then not enough to fill up the voids and consequently there were air voids in the paste inducing capillary suction, which rendered the paste rather dry and stiff. As the excess water ratio increased, the amount of air voids decreased and as a result the capillary suction decreased and the paste became more flowable. When the excess water ratio was positive, the flowability was generally much high-

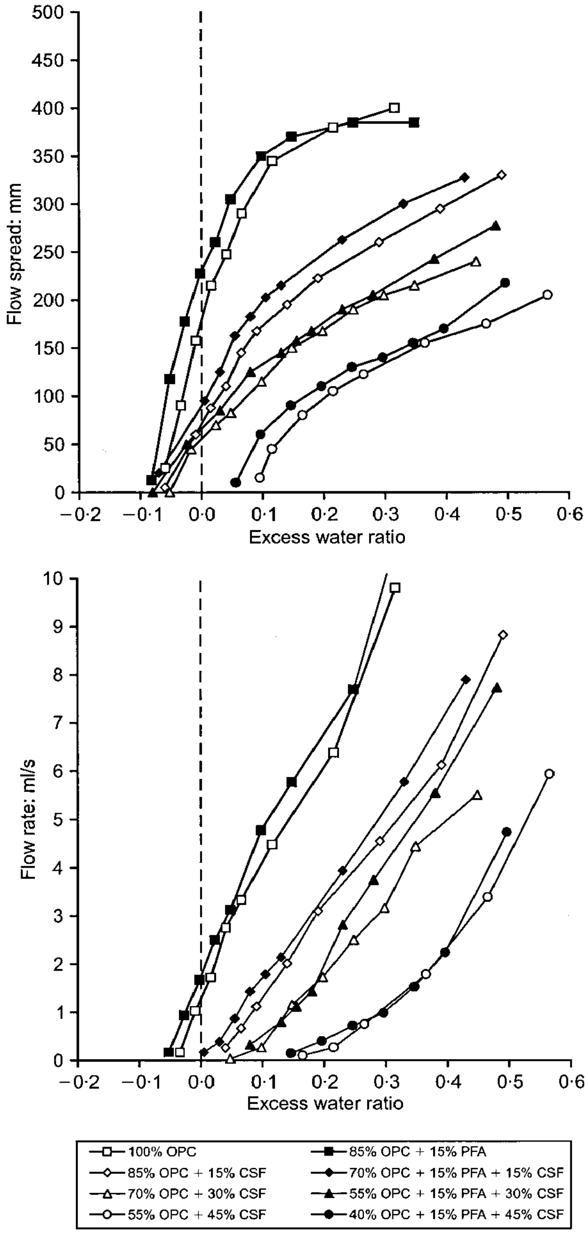

Fig. 7. Flowability plotted against excess water ratio for series C and D

er. This was because the water added was then more than sufficient to fill the voids and consequently there was excess water available for lubricating the solid particles to increase the flowability of the paste. As the excess water ratio increased, the amount of excess water also increased leading to increased thickness of the water films coating the solid particles and therefore higher flowability of the paste.

Comparing the flow spread–excess water ratio and flow rate–excess water ratio curves of the mixes with the same CSF content, it is evident that at the same CSF content, the addition of PFA up to 45% would shift the curves slightly to the left, indicating a slight improvement in flowability at a given excess water ratio. As the increase in packing density has already been allowed for in the excess water ratio, the slight improvement in flowability at a constant excess water ratio may be attributed to the better spherical shape of the PFA particles in comparison with the angular shape of the OPC particles, which alleviated the particle interlocking action and facilitated the rolling action between particles (this is sometimes called the ball-bearing effect) to improve the flowability of the paste.

Comparing the flow spread–excess water ratio and flow rate–excess water ratio curves of the mixes with the same PFA content, it is evident that at the same PFA content, the addition of CSF up to 45% would continuously shift the curves to the right and at the same time reduce the gradients of the curves. The shifting of the curves to the right is an indication that the addition of CSF would, at a constant excess water ratio, always impair the flowability. As the corresponding changes in packing density have already been allowed for in the excess water ratio, the adverse effect on flowability at a constant excess water ratio may be attributed to the observed higher stickiness of the paste samples containing CSF (the stickiness is also called cohesion) during the tests. The high fineness of the CSF might have substantially increased the adhesion between the CSF particles and the mixing water, thus rendering the paste to be more sticky or cohesive and therefore less flowable. On the other hand, the successive reduction in gradient of the curves as the CSF content increased reveals that for the same amount of increase in excess water, the improvement in flowability was dependent on the CSF content. A probable cause was the large surface area of the CSF, which, for the same amount of increase in excess water, would lead to a smaller increase in water film thickness to lubricate the paste.

Effects of excess water to surface area ratio

As the excess water forms a coating of water film on the particle surfaces and the water film thickness is directly proportional to the amount of excess water and inversely proportional to the surface area of the particles, it is proposed to account for the combined effects of excess water and surface area by introducing a new parameter called the excess water to surface area ratio, which is the volume of excess water per unit surface area of the cementitious materials. For a mix composed of several different types of cementitious materials, denoted by α β, γ and so forth, the surface area A is given by:

$$A = A_\alpha \times R_\alpha + A_\beta \times R_\beta + A_\gamma \times R_\gamma \qquad (4)$$

in which A_α, A_β and A_γ are the specific surface areas of α, β and γ, respectively, each expressed as the solid surface area per unit solid volume of the cementitious material. With the value of A so obtained, the excess water to surface area ratio u''_w may be calculated as:

$$u''_{\mathrm{w}} = \frac{u'_{\mathrm{w}}}{A} \qquad (5)$$

It should be noted that when the excess water ratio is positive, the excess water to surface area ratio has the physical meaning of a nominal water film thickness but when the excess water ratio is negative, the excess water to surface area ratio would become a measure of the amount of air voids in the paste per unit surface area of the cementitious materials.

Having converted the excess water ratios to excess water to surface area ratios, the flowability results are plotted against the excess water to surface area ratio for series A and B in Fig. 8 and for series C and D in Fig. 9. It can be seen from these figures that within the whole range of W/CM ratio covered in the study and regardless of whether the water added was enough to fill up the voids, both the flow spread and flow rate increased steadily with the excess water to surface area ratio.

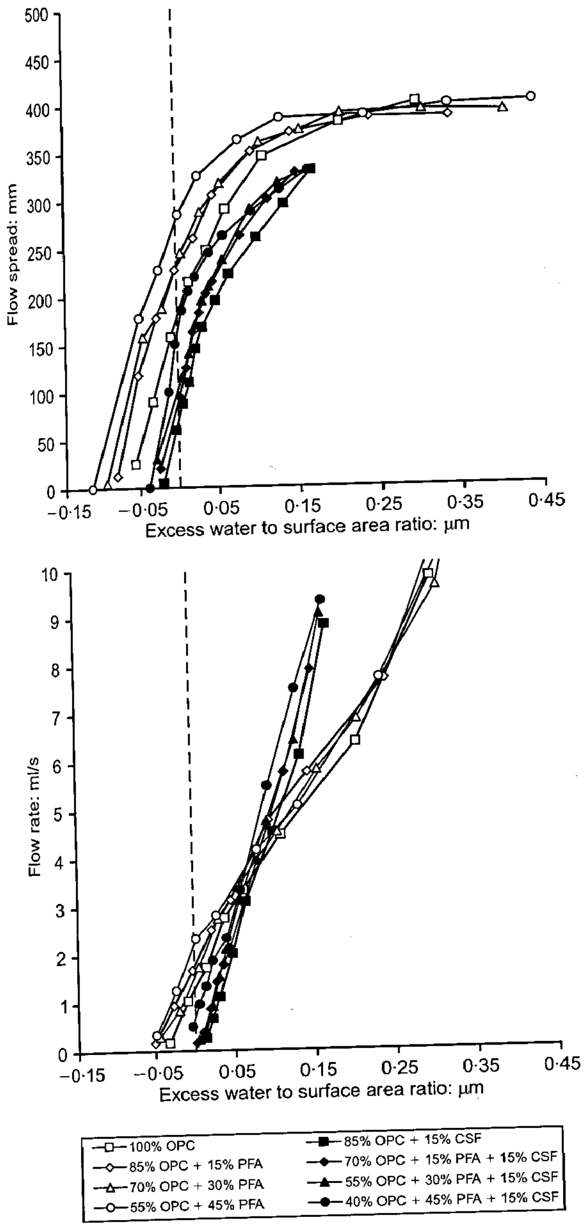

Fig. 8. Flowability plotted against excess water to surface area ratio for series A and B

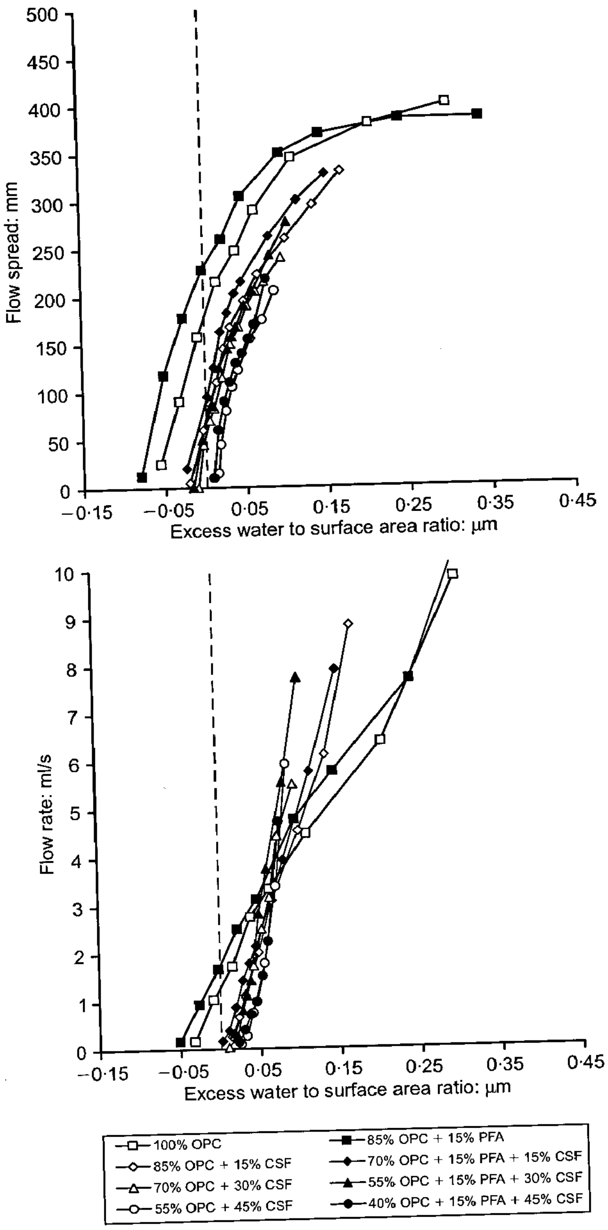

Fig. 9. Flowability plotted against excess water to surface area ratio for series C and D

After allowing for the surface area in the new parameter, the flow spread–excess water to surface area ratio curves have become almost parallel and very close to each other, revealing a definite relatioship between the flow spread and the excess water to surface area ratio. It is therefore evident that the excess water to surface area ratio should be a fundamental factor governing the flow spread of cement paste. Nevertheless, the curves would be slightly shifted to the left upon addition of PFA and to the right upon addition of CSF.

The left shifting of the curves upon addition of PFA was due to the beneficial effect of the rolling action of the PFA particles whereas the right shifting of the curves upon addition of CSF was due to the adverse effect of the increased cohesion arising from the high fineness of the CSF.

On the other hand, the flow rate–excess water to surface area ratio curves become separated into groups, each for mixes with the same CSF content. For mixes with the same CSF content, the curves have the same gradient and are very close to each, revealing a definite relation between the flow rate and the excess water to surface area ratio at a constant CSF content. At an increasing CSF content, the curves would rotate anticlockwise such that the lower parts of the curves would be shifted to the right while the gradients of the curves would become steeper. The right shifting of the lower parts of the curves upon addition of CSF was most probably due to the adverse effect of the increased cohesion arising from the high fineness of the CSF but the steeper gradients of the curves at relatively high CSF contents is difficult to explain. In any case, it is evident that the addition of CSF has different effects on flow spread and flow rate. Flow spread is a static or quasi-static measurement of flowability whereas flow rate is a dynamic measurement of flowability. The velocity of flow is much faster in the flow rate measurement and at such relatively fast velocity, the chances are that the CSF particles would move with the water and roll against the coarser particles to lubricate the cement paste. Further investigation is needed to find out what exactly would happen when a cement paste containing CSF flows at different velocities.

Conclusions

A new wet packing method has been developed and successfully applied to measure the packing densities of 12 mixes of cementitious materials containing different amounts of OPC, PFA and CSF. From these 12 mixes, a total of 121 samples of cement paste were made at different W/CM ratios and their flow spread and flow rate measured by the mini-slump cone and Marsh cone tests. It was found that the addition of PFA would slightly increase both the packing density of the cementitious materials and the flowability of the paste. On the other hand, at a W/CM ratio lower than about 0·4, the addition of CSF up to 15% would increase both the packing density and the flowability, and further addition of CSF to beyond 15% would decrease both the packing density and flowability. The concurrent increase or decrease in packing density and flowability provides experimental evidence to verify the postulation that an improvement in packing density of the cementitious materials is beneficial to the flowability of the cement paste.

From the packing density results, the voids ratio of each mix of cementitious materials and the excess water ratio (i.e. the excess water to solid volume ratio) of each sample of cement paste were evaluated. Correlation of the flow spread and flow rate with the excess water ratio revealed a clear relation between the flowability of cement paste and the excess water ratio, thus verifying the postulation that it is the excess water rather than the whole water that lubricates the cementitious materials and contributes to the flowability. However, the rates of increase of the flow spread and flow rate with the excess water ratio were found to be dependent on the mix proportions and particle characteristics of the cementitious materials, especially the surface area of the cementitious materials.

To account for the combined effects of the excess water in the paste and the surface area of the cementitious materials, a new parameter called the excess water to surface area ratio (or the excess water to solid surface area ratio to emphasise that the surface area is the solid surface area of the particles), which has the physical meaning of a nominal water film thickness, has been introduced. Plotting the flow spread against this parameter for the different mixes, very close and parallel curves were obtained, revealing that the excess water to surface area ratio should be a fundamental factor governing the flow spread of cement paste. Plotting the flow rate against this parameter for the different mixes, several groups of very close curves, each for mixes with the same CSF content, were obtained, indicating that the flow rate–excess water to surface area ratio relation was quite dependent on the CSF content.

Finally, it was also found that apart from the excess water to surface area ratio, which should have included the effects of packing density, excess water and surface area, other parameters such as the particle shape and size of the cementitious materials could also affect the flowability of cement paste, albeit to a lesser extent. For instance, the addition of spherical particles would alleviate particle interlocking and improve the flowability whereas the addition of very fine particles would increase cohesion and decrease the flowability. Further investigations on these effects are recommended.

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