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Concrete mix design based on water film thickness and paste film thickness

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ABSTRACT

In previous studies on the mortar portion of concrete, it has been found that the water film thickness (WFT) and paste film thickness (PFT) have major effects on the performance of mortar. The present study aims to extend the concepts of WFT and PFT to concrete. For this aim, a number of concrete mixes with various paste volumes, water/cement ratios and fine to total aggregate ratios were produced for slump, flow, strength and packing density measurements, and from the results, the combined effects of WFT and PFT on the deformability, flowability and strength of concrete were studied. It was found that whilst the WFT is the key factor governing the above properties of concrete, the PFT also has significant effects and thus is an important factor to be considered in concrete mix design. Lastly, based on the test results, two design charts for concrete mix design were produced.

1. Introduction

In the past 20 years, high-performance concrete (HPC) has advanced so dramatically that nowadays a HPC having high strength (characteristic cube strength up to 100 MPa), high flowability (flow up to 650 mm), high durability (for structures with design life up to 120 years) and high dimensional stability (low heat generation and low drying shrinkage) can be produced for field placement using conventional methods with or without compaction applied. However, there are some major hurdles in further technological advancement. First, the mix design of HPC is still largely by trial mixing, which is tedious, time consuming and much too slow in responding to variations in the properties of the ingredients. Second, the various performance attributes of HPC are often contradictory to each other and thus it is not at all easy to produce a HPC with all round high performance. Last but not the least, there has been little research on the governing factors affecting the performance of HPC.

Early in 1960s, Powers [1] suggested that at macro-scale, successive filling of voids by smaller size particles can increase the packing density of the aggregate. Since it is the excess paste (paste in excess of that needed to fill the voids in the aggregate) that lubricates the concrete mix to provide workability, a higher packing density of the aggregate would for a given paste volume, improve the workability and for a given workability requirement, allow the paste volume to be reduced to improve dimensional stability. Likewise, at micro-scale, successive filling of voids by smaller size particles can increase the packing density of the cementitious materials. Since it is the excess water (water in excess of that needed to fill the voids in the cementitious materials) that lubricates the paste, a higher packing density of the cementitious materials would for a given water volume, improve the flowability and for a given flowability requirement, allow the water volume to be reduced to improve strength and durability. Hence, increasing the packing densities of the aggregate and cementitious materials would generally produce a higher performance concrete.

However, there is so far no generally accepted method of packing density measurement. For fine materials, such as cement and other cementitious materials, and materials containing fines, such as fine aggregates (fines are herein defined as materials finer than 75 μm), due to the existence of inter-particles forces causing agglomeration and loose packing, the measured packing density under dry condition is quite sensitive to the compaction applied and tends to be unreasonably low [2]. In reality, the paste, mortar or concrete is a water–solid mixture. The water and superplasticizer (SP) contained therein may have significant effects on the packing density of the solid particles in the mixture. All in all, the traditional dry packing tests, which do not include the possible effects of water and SP, are not suitable for cementitious materials and fine aggregates.

To resolve the above problems, a new wet packing test for measuring the packing density of cementitious materials under wet condition has been developed several years ago [3]. Later, it was extended for application to fine aggregate [4] and employed to study the effect of packing density on rheology of mortar [5]. Recently, this test was applied to blended fine and coarse aggregate [6]. On the other hand, the accuracy of the wet packing test has

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been verified by checking against established packing models and the results indicated that the differences between theoretical results by the packing models and experimental results by the wet packing test are well within 3% [7,8].

Apart from the packing density, it has been found that the surface area of the particle system also has great effects on the rheology of paste, mortar and concrete. Generally, the larger is the surface area, the lower is the flowability of the paste, mortar or concrete. This may be explained in terms of the thickness of the water films coating the solid particles. For the same amount of excess water, the water film thickness would be smaller and the flowability would be lower when the surface area is larger and vice versa. In this regard, Helmuth [9] has suggested that it should be the water film thickness that governs the consistence of cement paste. Following this line of thought, Zhang et al. [10] pointed out that the water in a cement paste may be divided into two portions: one portion is the filling water, which fills into the voids between solid particles and does not contribute to the fluidity of the paste, while the other portion is the excess water, which forms a water film on the surface of each solid particle and contributes to the fluidity of the paste.

Similarly, it may be inferred that the paste films coating the aggregate particles should have certain effects on the rheology of mortar and concrete. Early in 1940s, Kennedy [11] advocated that the paste has to be more than sufficient to fill the voids between aggregate particles so that there would be excess paste to provide a thin film of paste coating each and every aggregate particle to lubricate the concrete mix. Then in 1960s, Powers [1] proposed the excess paste theory that only the excess paste is contributing to workability. Later, in 1990s, Oh et al. [12] attempted to incorporate the paste film thickness in the mix design of self-consolidating concrete. However, due to the lack of a suitable method for measuring the packing density of fine particles and the lack of studies on the correlation between the rheology of mortar and concrete to the respective paste film thickness, little progress have since been made.

In recent years, with the use of the wet packing test to measure the packing densities of cementitious materials and fine aggregate under wet condition, methods for calculating the water film thickness (WFT) and paste film thickness (PFT) have been successfully developed by the authors' research team. Through various tests on paste and mortar and correlations of the measured rheological and strength properties to the WFT and PFT so calculated, it was found that the WFT is the key factor governing the properties of paste [13,14] while the WFT and PFT are together the key factors governing the properties of mortar [15]. Furthermore, the PFT also has significant effects on the cohesiveness and adhesiveness of mortar [15].

In the present study, the concepts of WFT and PFT are extended to concrete mixes and integrated together to investigate the combined effects of WFT and PFT on the fresh and hardened properties of concrete. For the investigation, an experimental program was launched, wherein concrete mixes with different combinations of paste volume, water to cement ratio and fine to total aggregate ratio were made for testing. The properties of each concrete mix were measured in terms of slump, flow and 28-day cube strength, whereas the packing density was measured by the wet packing test. From the test results, the WFT and PFT were calculated and then the measured slump, flow and 28-day strength were correlated to the WFT and PFT. Lastly, a concrete mix design method based on the WFT and PFT was developed.

2. Experimental details

2.1. Materials

The cement used was an ordinary Portland cement (OPC) of strength class 52.5N complying with BS 12: 1996 [16]. It had been measured in accordance with BS EN 196-6: 2010 [17] to have a Blaine fineness of 354 m^2/kg and measured in accordance with BS 4550: Part 3: 1978 [18] to have a relative density of 3.11. Crushed granite rocks with nominal maximum sizes of 10 mm and 20 mm were used for the coarse aggregate while crushed granite rock fine with a nominal maximum size of 5 mm was used for the fine aggregate. The fine and coarse aggregates had been measured to have the same relative density of 2.56.

For the OPC and the portion of fine aggregate with size smaller than 1.18 mm, a laser diffraction particle size analyzer was employed to measure the particle size distributions. For the portion of fine aggregate with size larger than 1.18 mm, and the 10 mm and 20 mm coarse aggregates, the sieving method was used to determine the particle size distributions. From these particle size distributions, plotted in Fig. 1, the specific surface areas (each specific surface area is the surface area per unit solid volume) of the OPC, the fine aggregate, the portion of fine aggregate with size larger than 75 μm (excluding the portion with size smaller than 75 μm), the 10 mm coarse aggregate and the 20 mm coarse aggregate were calculated to be 1.55×10^6, 5.12×10^4, 1.03×10^4, 642 and 398 m^2/m^3, respectively.

The moisture contents and water absorptions of aggregates were measured and taken into account in the batching of the concrete mixes. The moisture contents of the fine aggregate, 10 mm aggregate and 20 mm aggregate were measured as 1.16%, 0.61% and 0.27%, respectively, while the water absorptions were measured as 1.89%, 1.04% and 0.61%, respectively. All these measurements were carried out in accordance with BS 812: Part 2: 1995 [19].

A third generation polycarboxylate-based superplasticizer (SP) was used for all the concrete mixes. It was a milky white liquid having a specific gravity of 1.05 and containing a solid content of 20%. This type of SP disperses the fine particles in concrete by both electrostatic repulsion and steric hindrance, and is capable of reducing the water demand markedly.

2.2. Mix proportions

A total of 32 trial concrete mixes with various paste volume (PV), water to cement (*W*/*C*) ratios and fine to total aggregate (*F*/*T*) ratios were produced for testing. The concrete mixes were divided into two groups, one with the PV set as 30% by volume of the concrete mix and the other with the PV set as 34% by volume of the concrete mix. In each group of concrete mixes, the *W*/*C* ratio by weight was varied from 0.25 to 0.55 in steps of 0.10 while the *F*/*T* ratio by weight was varied from 0.30 to 0.60 in steps of 0.10. As there were four different *W*/*C* ratios and four different *F*/*T* ratios, there were altogether 4 × 4 = 16 concrete mixes in each group.

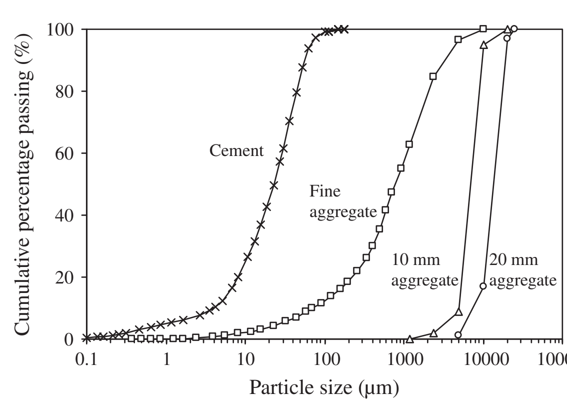

Fig. 1. Particle size distributions of cement, fine aggregate, 10 mm aggregate and 20 mm aggregate.

On the other hand, in all concrete mixes, the 10 mm aggregate to 20 mm aggregate ratio was fixed at 1.0 and the SP dosage (measured in terms of liquid weight) was fixed at 2% by weight of the cement content. For easy identification, each concrete mix was assigned a mix number of PV–*W*/*C* ratio–*F*/*T* ratio, as listed in the first column of Table 1.

2.3. Mixing, casting and testing

A pan mixer was used to mix the ingredients of the concrete mix. The aggregate and the cement were first poured into the mixer and mixed under dry condition for 1 min. Then the water and SP were added separately but at the same time into the mixer and the concrete mix was mixed under wet condition for 3 min. After the mixing was completed, the fresh concrete mix was taken out immediately for slump flow test in order to avoid change of flow properties with time. After the slump flow test, the concrete sample was used to make three 150 mm cubes for cube compression test at the age of 28 days. During casting, the concrete cubes were compacted by the use of a poker vibrator. The total time taken to conduct the slump flow test and cast the cubes was generally within 30 min, during which the workability loss should be insignificant. The three concrete cubes were demoulded at 1 day after casting and cured in lime-saturated water at 27 ± 2 °C until the time of cube compression test.

2.4. Measuring slump and flow

The slump flow tests were to measure the deformability and flowability of the concrete mixes. They were performed using the standard slump cone in general accordance with BS 1881: Part 102: 1983 [20]. To perform the slump flow test, the fresh concrete mix was filled into the slump cone until the slump cone was full, the top surface of the concrete mix in the slump cone was trowelled flat and smooth, and the slump cone was lifted vertically upwards to allow the concrete to slump downwards and flow outwards under its own weight to form a patty. When the concrete mix had stopped deforming and flowing, the slump (the drop in height of the concrete) and the flow (the average of two perpendicular diameters of the patty) were measured. The slump was taken as a measure of deformability (which is a better measure of workability for non-flowable concrete mixes) while the flow was taken as a measure of flowability (which is a better measure of workability for flowable concrete mixes).

Occasionally, due to lack of cohesion of the concrete mix, obvious segregation and separation of the paste/mortar from the coarse aggregate could be observed along the edge of the patty. In such case, since the paste/mortar and the coarse aggregate were not held together and the paste/mortar was able to flow a further distance than the coarse aggregate, there were just paste/mortar and no coarse aggregate particles within a narrow strip along the perimeter of the patty. The width of the strip of patty with no coarse aggregate particles was measured at four perpendicular locations and the four width values so measured were averaged to give the segregation width, which is taken herein as a measure of the degree of segregation of the concrete mix.

2.5. Measuring cube compressive strength

At the age of 28 days, the concrete cubes were tested for their cube compressive strengths in accordance with BS EN 12390-3: 2009 [21]. In order to reduce experimental errors, the measured strengths of the three concrete cubes cast from the same concrete mix and tested at the same time were averaged to give one cube strength result.

2.6. Measuring packing density

The wet packing test developed by the authors' research team [6] was extended to measure the packing density of the portion

Table 1
Experimental results of concrete mixes.

Mix no.	Slump (mm)	Flow (mm)	Segregation width (mm)	28-Day cube strength (MPa)
30-0.25-0.30	10	200	0	100.2
30-0.25-0.40	10	200	0	104.2
30-0.25-0.50	0	200	0	93.5
30-0.25-0.60	0	200	0	93.6
30-0.35-0.30	215	518	35	91.5
30-0.35-0.40	230	488	0	89.1
30-0.35-0.50	165	353	0	84.2
30-0.35-0.60	180	323	0	81.5
30-0.45-0.30	210	645	102	69.4
30-0.45-0.40	250	630	0	73.7
30-0.45-0.50	240	630	0	74.0
30-0.45-0.60	210	575	0	74.6
30-0.55-0.30	255	760	175	47.4
30-0.55-0.40	235	730	84	54.4
30-0.55-0.50	220	665	91	51.5
30-0.55-0.60	225	585	13	48.9
34-0.25-0.30	185	318	0	106.1
34-0.25-0.40	20	200	0	102.2
34-0.25-0.50	18	200	0	96.3
34-0.25-0.60	15	200	0	98.4
34-0.35-0.30	265	695	18	92.1
34-0.35-0.40	260	650	0	91.4
34-0.35-0.50	260	643	0	88.1
34-0.35-0.60	235	576	0	85.0
34-0.45-0.30	260	820	146	61.5
34-0.45-0.40	265	780	121	60.0
34-0.45-0.50	240	725	65	57.5
34-0.45-0.60	235	670	0	61.4
34-0.55-0.30	275	903	132	42.0
34-0.55-0.40	240	838	87	45.3
34-0.55-0.50	240	758	104	45.8
34-0.55-0.60	235	807	38	49.6

of aggregate larger than 75 μm (the portion of aggregate smaller than 75 μm was excluded because it was regarded as fines that would be intermixed with the paste and become un-separable from the paste after concrete mixing) and the packing density of all the solid particles in the concrete mix (cement plus aggregate). To perform the test, around ten samples having the same solid mix proportions and the same SP dosage (2% by weight of cement content) but different water contents (measured in terms of water to solid ratio by volume) ranging from insufficient to more than sufficient to fill the voids between solid particles were produced and their respective solid concentrations ϕ (defined as the ratio of the solid volume to the bulk volume of the particles) and voids ratio u (defined as the ratio of the voids volume to the solid volume of the particles) were measured. In general, as the water to solid (W/S) ratio increased from a relatively low value of about 0.1 (at which the water should be insufficient to fill the voids), the solid concentration first increased with the W/S ratio to a maximum value at an optimum W/S ratio and then decreased, as shown in Fig. 2.

As the test procedures have been presented before in a previous paper [6], only the main features are described herein. First, the solid ingredients were thoroughly mixed with predetermined amounts of water and SP. Then, the water–solid mixture was filled into a container with known volume. During filling, full compaction was applied to the mixture using a poker vibrator to simulate the situation during casting. Finally, the weight of the mixture was measured to evaluate the solid concentration of the mixture. The container used was the same as that stipulated in BS 812: Part 2: 1995 [19] for dry packing tests.

From the bulk volume of the mixture (denoted by V), which is the same as the volume of the container, and the solid volume of the solid ingredients (denoted by V_s), which can be determined from the W/S ratio and the solid volume of each and every solid ingredient in the container, the solid concentration ϕ and voids ratio u can be determined as:

$$\phi = \frac{V_s}{V} \tag{1}$$

$$u = \frac{V - V_s}{V_s} = \frac{1-\phi}{\phi} \tag{2}$$

By plotting the solid concentration ϕ and voids ratio u against the W/S ratio, as shown in Fig. 2, the maximum solid concentration $\phi_{\max}$ and minimum voids ratio $u_{\min}$ could be determined. The maximum solid concentration so obtained was taken as the packing density.

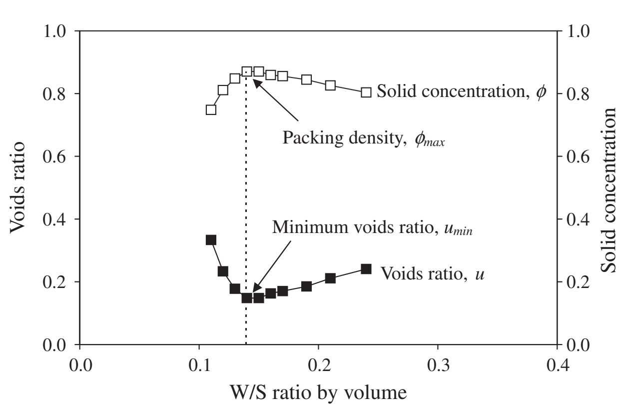

Fig. 2. Voids ratio and solid concentration diagram.

3. Determination of water film thickness and paste film thickness

To determine the water film thickness (WFT) in a concrete mix, it is necessary first of all to measure the packing density of all the solid particles in the concrete (cement plus aggregate). By the wet packing test, the packing density $\phi_{\max}$ and the respective minimum voids ratio $u_{\min}$ of the solid particles can be obtained.

Having obtained the minimum voids ratio $u_{\min}$, the excess water ratio u'_w (defined as the ratio of the volume of excess water to the solid volume of the particles) can be calculated as:

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

where u_w is the water ratio of the concrete mix (defined as the ratio of the volume of water to the solid volume of the particles). On the other hand, the specific surface area of the solid particles A_S (defined as the solid surface area per unit solid volume) is given by:

$$A_S = A_C \times R_C + A_{FA} \times R_{FA} + A_{10\text{mm}} \times R_{10\text{mm}} + A_{20\text{mm}} \times R_{20\text{mm}} \tag{4}$$

in which A_C, A_{FA}, $A_{10\text{mm}}$ and $A_{20\text{mm}}$ are respectively the specific surface areas of cement, fine aggregate, 10 mm aggregate and 20 mm aggregate while R_C, R_{FA}, $R_{10\text{mm}}$ and $R_{20\text{mm}}$ are respectively the volumetric ratios of cement, fine aggregate, 10 mm aggregate and 20 mm aggregate to the total solid volume. With the values of u'_w and A_S so determined, the WFT, which has the physical meaning of being the average thickness of the water films coating the solid particles, may be obtained as:

$$\text{WFT} = \frac{u'_w}{A_S} \tag{5}$$

The steps for determining the paste film thickness (PFT) in a concrete mix are similar. However, since the portion of aggregate smaller than 75 μm tends to be intermixed with the cement and water to become an un-separable part of the paste, there is a necessity to redefine the paste. Herein, it is suggested to redefine the cement paste as the water–cement mixture and the powder paste as the water–powder mixture (in which powder refers to all particles smaller than 75 μm, including the cement and the portion of aggregate smaller than 75 μm). When the aggregate contains particles smaller than 75 μm, the paste should be taken as the powder paste rather than the cement paste. Hence, the paste volume should include the volume of water, the solid volume of cement and the solid volume of the portion of aggregate smaller than 75 μm. For this reason, when determining the packing density of aggregate (fine aggregate plus coarse aggregate) for the purpose of calculating the PFT, the portion of aggregate smaller than 75 μm has to be excluded. From the measured packing density of the remaining portion of aggregate, the minimum voids ratio $u_{A\min}$ of the portion of aggregate larger than 75 μm can be evaluated.

Having evaluated the above minimum voids ratio $u_{A\min}$, the excess paste ratio u'_p (defined as the ratio of the volume of excess paste to the solid volume of the portion of aggregate larger than 75 μm) can be obtained as:

$$u'_p = u_p - u_{A\min} \tag{6}$$

where u_p is the paste ratio of the concrete mix (defined as the ratio of the volume of paste to the solid volume of the portion of aggregate larger than 75 μm). On the other hand, the specific surface area of the portion of aggregate larger than 75 μm A_A (defined as the solid surface area per unit solid volume of the aggregate particles larger than 75 μm) can be calculated from the particle size distribution of the aggregates. With the values of u'_p and A_A so determined, the PFT, which has the physical meaning of being the average thickness of the paste films coating the aggregate particles larger than 75 μm, may be obtained as:

$$\text{PFT} = \frac{u_p\prime}{A_A} \tag{7}$$

4. Experimental results

4.1. Slump and flow

The slump and flow results of the concrete mixes are tabulated in the second and third columns of Table 1 and plotted against the *W/C* ratio for different PV and *F/T* ratios in Figs. 3 and 4, respectively. It is noted that at all PV and *F/T* ratios, the slump increased with increasing *W/C* ratio at a decreasing rate until the slump reached a certain maximum value. The flow also increased with increasing *W/C* ratio at a decreasing rate but the flow kept on increasing within the range of *W/C* ratio covered. Moreover, the slump and flow were generally higher at a higher PV. These observed phenomena are reasonable because increasing the water content by increasing the *W/C* ratio and PV should always improve the deformability and flowability of a concrete. On the other hand, it is noted that at the same *W/C* ratio and PV, the slump and flow decreased with increasing *F/T* ratio, indicating that the *F/T* ratio has certain effects on the deformability and flowability. It may be caused by the corresponding changes of packing density and surface area as the *F/T* ratio varied. Further analysis in this regard will be presented later in the following sections.

During the slump flow test, segregation was sometimes observed, especially at high *W/C* ratio and/or low *F/T* ratio. In such cases, the segregation width was measured, as tabulated in the fourth column of Table 1. From visual observation, it was found that whenever the segregation width was larger than 50 mm, the segregation was rather serious. Hence, a segregation width of larger than 50 mm may be taken as an indication of serious segregation. The concrete mixes which exhibited serious segregation are each marked with a circumscribing circle in Figs. 3 and 4. From these results, it is evident that serious segregation often occurred when the *W/C* ratio was increased to 0.45 or higher and/or the *F/T* ratio was decreased to 0.40 or lower. Hence, at *W/C* ratio $\geqslant$0.45 or *F/T* ratio $\leqslant$0.40, particular care should be taken to avoid serious segregation. It is suggested that when serious segregation occurs, the SP dosage should be reduced and the *F/T* ratio should be increased while the reduction in workability so caused could be compensated by increasing the PV.

4.2. Cube compressive strength

The 28-day cube strength results of the concrete mixes are tabulated in the fifth column of Table 1 and plotted against the *W/C* ratio for different PV and *F/T* ratios in Fig. 5. The variation of the cube strength with the *W/C* ratio reveals that regardless of the PV or *F/T* ratio, the cube strength increased as the *W/C* ratio decreased. Such observed phenomenon is reasonable as the *W/C* ratio is well known to be the governing factor affecting the strength of concrete.

However, the variations of the cube strength with the PV and *F/T* ratio are fairly complicated. From Fig. 5, it can be seen that at *W/C* ratio lower than 0.40, increasing the PV from 30% to 34% slightly increased the cube strength while at *W/C* ratio higher than 0.40, increasing the PV from 30% to 34% slightly reduced the cube strength. This indicates that the effect of PV on the cube strength is dependent on the *W/C* ratio. On the other hand, the *F/T* ratio also has certain effect on the cube strength. Apparently, at given PV and *W/C* ratio, there was an optimum *F/T* ratio for maximum strength. The optimum *F/T* ratio was not constant but tended to be lower at lower *W/C* ratio and higher at higher *W/C* ratio. Since the variations in PV and *F/T* ratio should have induced changes of packing density and surface area, these observations imply that the packing density and surface area may have certain effects on the strength of concrete. Further analysis of the effects of PV and *F/T* ratio will be presented later in the following sections.

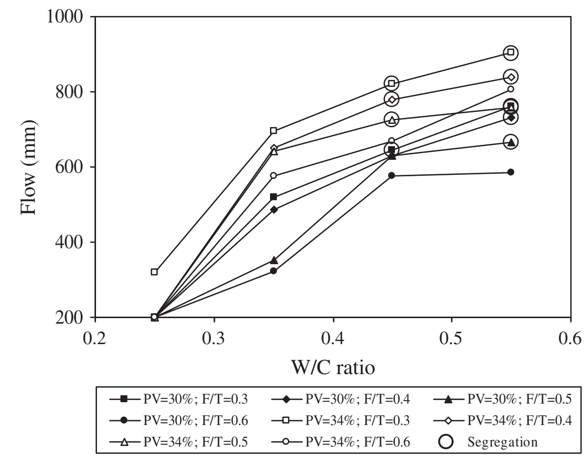

Fig. 4. Flow versus *W/C* ratio.

5. Packing density, excess water/paste and solid surface area

The packing density results of the concrete mixes with different mix proportions of cement, fine aggregate and coarse aggregate are tabulated in the second column of Table 2. These results show that the packing density of all the solid particles in a concrete mix ran-

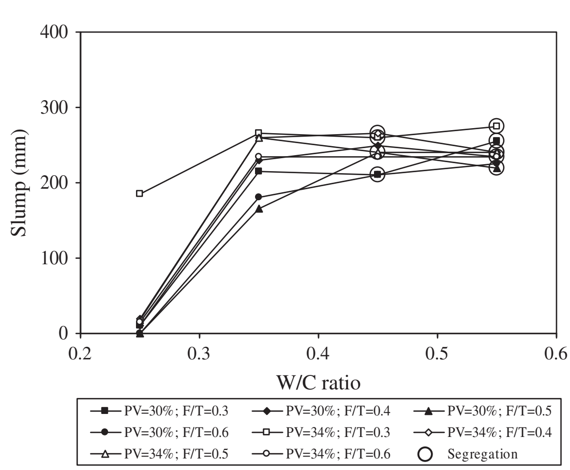

Fig. 3. Slump versus *W/C* ratio.

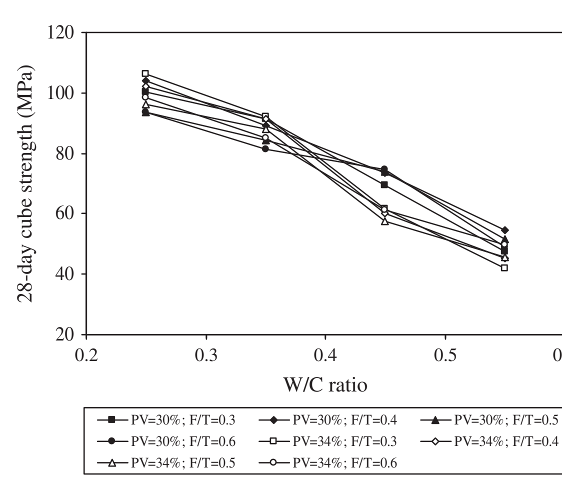

Fig. 5. Cube strength versus *W/C* ratio.

Table 2
Water film thickness of concrete mixes.

Mix no.	Packing density of all solid particles	Water ratio	Excess water ratio	Surface area of all solid particles (m^2/m^3)	Water film thickness (μm)
30-0.25-0.30	0.890	0.159	0.035	306,214	0.114
30-0.25-0.40	0.886		0.030	310,386	0.097
30-0.25-0.50	0.882		0.025	314,517	0.079
30-0.25-0.60	0.880		0.023	318,608	0.072
30-0.35-0.30	0.889	0.191	0.066	271,215	0.243
30-0.35-0.40	0.890		0.067	275,504	0.243
30-0.35-0.50	0.888		0.065	279,751	0.232
30-0.35-0.60	0.882		0.057	283,957	0.201
30-0.45-0.30	0.886	0.217	0.088	243,755	0.361
30-0.45-0.40	0.887		0.090	248,136	0.363
30-0.45-0.50	0.889		0.092	252,474	0.364
30-0.45-0.60	0.879		0.079	256,771	0.308
30-0.55-0.30	0.888	0.237	0.111	221,636	0.501
30-0.55-0.40	0.890		0.113	226,090	0.500
30-0.55-0.50	0.887		0.110	230,502	0.477
30-0.55-0.60	0.884		0.106	234,871	0.451
34-0.25-0.30	0.883	0.184	0.051	351,970	0.145
34-0.25-0.40	0.880		0.048	355,988	0.135
34-0.25-0.50	0.876		0.042	359,967	0.117
34-0.25-0.60	0.873		0.039	363,907	0.107
34-0.35-0.30	0.890	0.222	0.098	312,765	0.313
34-0.35-0.40	0.894		0.103	316,914	0.325
34-0.35-0.50	0.890		0.098	321,023	0.305
34-0.35-0.60	0.879		0.084	325,093	0.258
34-0.45-0.30	0.890	0.253	0.129	281,759	0.458
34-0.45-0.40	0.889		0.128	286,012	0.448
34-0.45-0.50	0.887		0.126	290,224	0.434
34-0.45-0.60	0.883		0.120	294,396	0.408
34-0.55-0.30	0.887	0.278	0.151	256,624	0.588
34-0.55-0.40	0.889		0.153	260,961	0.586
34-0.55-0.50	0.883		0.145	265,257	0.547
34-0.55-0.60	0.881		0.143	269,511	0.531

ged from 0.873 to 0.894 for the concrete mixes tested. Within the range of mix proportions covered, the variation in packing density of all the solid particles in concrete was only about 2%. Nevertheless, it is seen that the maximum packing density generally occurred at a *F*/*T* ratio of 0.30–0.50. On the other hand, the packing density results of the portion of aggregate larger than 75 μm at various *F*/*T* ratios are tabulated in the second column of Table 3. These results show that the packing density of aggregate larger than 75 μm varied slightly with the *F*/*T* ratio. As the *F*/*T* ratio increased from 0.30 to 0.40, the packing density increased from 0.739 to a peak value of 0.743. Then, as the *F*/*T* ratio further increased from 0.40 to 0.60 the packing density gradually decreased from the peak value of 0.743–0.735.

As the water added has to first fill up the voids between the solid particles and it is the excess water that lubricates the solid particles, an increase in packing density would reduce the amount of voids to be filled, increase the volume of excess water and finally improve the deformability and flowability of the water–solid mixture. In the present case, although the range of packing density was not large, the change in packing density did have significant effects on the excess water ratio, as depicted in the third and fourth columns of Table 2.

Likewise, the paste (formed of water, cement and the portion of aggregate smaller than 75 μm) has to first fill up the voids between the larger aggregate particles (those larger than 75 μm) and it is the excess paste that lubricates the larger aggregate particles. Hence, an increase in packing density would reduce the amount of voids to be filled, increase the volume of excess paste and thus enhance the deformability and flowability of the concrete (which may be taken as a paste–aggregate mixture). The paste ratios and excess paste ratios of the concrete mixes tested are tabulated in the third and fourth columns of Table 3, from which it can be seen that the change in packing density did have significant effects on the excess paste ratio.

However, the excess water ratio and excess paste ratio are not the only factors affecting the fresh and hardened properties of concrete. Since the excess water and excess paste would be spread out to cover solid surfaces and a larger solid surface area would lead to thinner water films or paste films, the solid surface areas should also have some effects. To study the effects of the solid surface areas, the specific surface areas of the 32 concrete mixes and the specific surface areas of the fine aggregate larger than 75 μm are calculated from the particle size distributions, and tabulated in the fifth column of Tables 2 and 3, respectively. Since the ingredients in concrete have different specific surface areas (cement > fine aggregate > coarse aggregate), increasing the PV and *F*/*T* ratio, or decreasing the *W*/*C* ratio would increase the specific surface area of the solid particles in concrete, as shown in the fifth column of Table 2, whereas increasing the *F*/*T* ratio would increase the specific surface area of the aggregate larger than 75 μm, as depicted in the fifth column of Table 3.

From the above results, the average water film thickness may be determined as the excess water ratio divided by the specific surface area of solid particles in concrete mix and the average paste film thickness may be determined as the excess paste ratio divided by the specific surface area of the aggregate larger than 75 μm, as tabulated in the last column of Tables 2 and 3, respectively. For brevity, the average water film thickness and average paste film thickness are hereafter referred to simply as the water film thickness (WFT) and the paste film thickness (PFT), respectively.

6. Roles of WFT and PFT

The WFT results reveal that for the concrete mixes with PV ranging from 30% to 34%, *W*/*C* ratios ranging from 0.25 to 0.55 and *F*/*T* ratios ranging from 0.3 to 0.6, the WFT varied from 0.072 μm to 0.588 μm. To better illustrate how the WFT is related

Table 3
Paste film thickness of concrete mixes.

Mix no.	Packing density of aggregate particles >75 μm	Paste ratio	Excess paste ratio	Surface area of aggregate particles >75 μm (m^2/m^3)	Paste film thickness (μm)
30-xx-0.30	0.739	0.477	0.123	3330	37.2
30-xx-0.40	0.743	0.493	0.147	4289	34.3
30-xx-0.50	0.740	0.510	0.158	5260	30.2
30-xx-0.60	0.735	0.526	0.166	6243	26.5
34-xx-0.30	0.739	0.566	0.213	3330	63.9
34-xx-0.40	0.743	0.583	0.238	4289	55.3
34-xx-0.50	0.740	0.601	0.250	5260	47.5
34-xx-0.60	0.735	0.619	0.258	6243	41.4

Note: xx is the *W*/*C* ratio, which in this table may be 0.25, 0.35, 0.45 or 0.55.

to the PV, *W*/*C* ratio and *F*/*T* ratio, the WFT is plotted against the *W*/*C* ratio for different PV and *F*/*T* ratios in Fig. 6. It is seen that the WFT always increased with increasing PV and *W*/*C* ratio but decreased with increasing *F*/*T* ratio. At the same time, the PFT varied from 26.5 μm to 63.9 μm. The PFT is plotted against the PV for different *F*/*T* ratios in Fig. 7. It is observed that the PFT always increased with both the PV and *F*/*T* ratio at a more or less constant rate. Such variations of the WFT with PV, *F*/*T* ratio and *W*/*C* ratio and variations of PFT with the PV and *F*/*T* ratio are in fact the combined effects of the corresponding changes in water or paste content, packing density and specific surface area.

6.1. Effects of WFT and PFT on slump and flow

By plotting the slump and flow against the WFT as shown in Figs. 8 and 9, respectively, it can be seen that basically, at a WFT of around 0.1 μm, the slump was very close to zero and the flow was very close to 200 mm (since 200 mm is actually the diameter at the base of the slump cone, this flow value actually means no concrete flowability). Nevertheless, as the WFT increased, both the slump and flow increased with the WFT at gradually decreasing rates. More importantly, since the data points in Fig. 8 all appear to lie very closely to a certain slump-WFT curve, the WFT should be a major factor affecting the slump of concrete. Likewise, since the data points in Fig. 9 all appear to lie very closely to a certain flow-WFT curve, the WFT should be a major factor affecting the flow of concrete.

However, the data points show quite clearly that at the same WFT, the slump and flow varied significantly with the PFT. In order to investigate the combined effects of WFT and PFT, multi-variable regression analysis has been carried out to derive the best-fit curves for the slump-WFT and flow-WFT relations at various PFT values. For comparison, the best-fit curves so obtained are plotted alongside the data points, and the equations of the best-fit curves and their R^2 value are printed in the figures. From these curves, it is evident that both the slump and flow would increase with the PFT. In other words, the slump and flow are dependent on both the WFT and PFT, although the WFT has a much larger effect and the PFT has only secondary effect. A fairly high R^2 value of 0.947 for the slump and a fairly high R^2 value of 0.954 for the flow have been achieved, proving that the WFT and PFT are together the key factors governing the workability of concrete.

The data points in these figures corresponding to those concrete mixes showing signs of serious segregation in the slump flow test are marked with circumscribing circles. From the marked data points, it can be seen that when the WFT was increased to larger than 0.40 μm, serious segregation often occurred. Hence, at WFT larger than 0.40 μm, care should be taken to avoid segregation by say adding less SP to avoid rendering the cement paste too un-cohesive and/or increasing the *F*/*T* ratio to increase the surface area of the aggregate.

6.2. Effects of WFT and PFT on cube strength

By plotting the 28-day cube strength against the WFT as shown in Fig. 10, it can be seen that in general, the cube strength increased as the WFT decreased until the WFT reached a very low value of about 0.10 μm. Such increase of cube strength with decrease of WFT should be due to the corresponding decrease of *W*/*C* ratio.

On the other hand, the data points show that at the same WFT, the cube strength also varied with the PFT, indicating that the PFT also has certain effect. The effect of PFT on the cube strength is generally larger when the WFT is relatively small (WFT < 0.40 μm) and smaller or even marginal when the WFT is relatively large

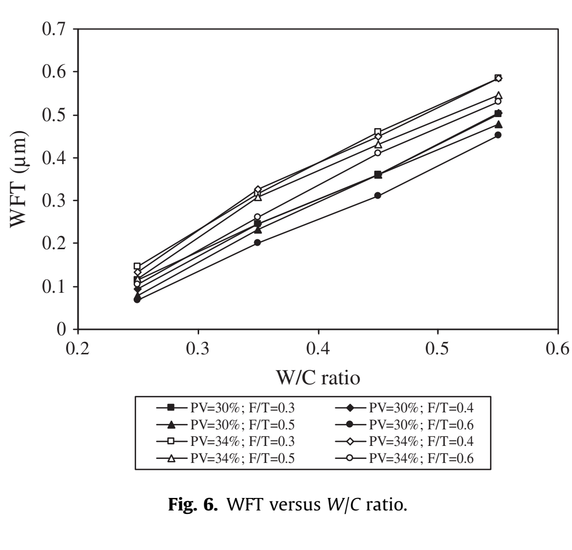

Fig. 6. WFT versus *W*/*C* ratio.

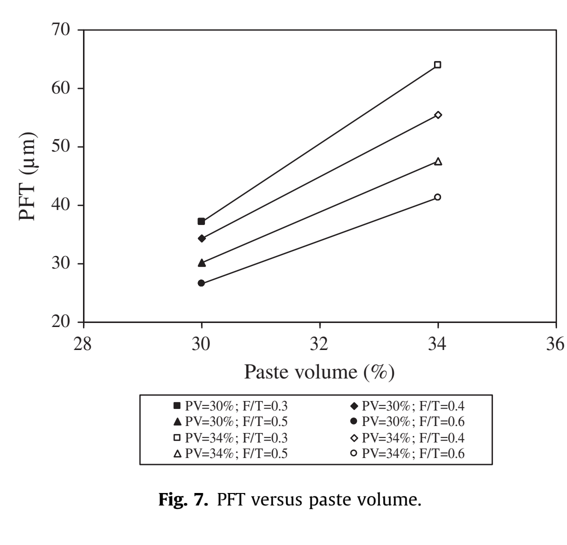

Fig. 7. PFT versus paste volume.

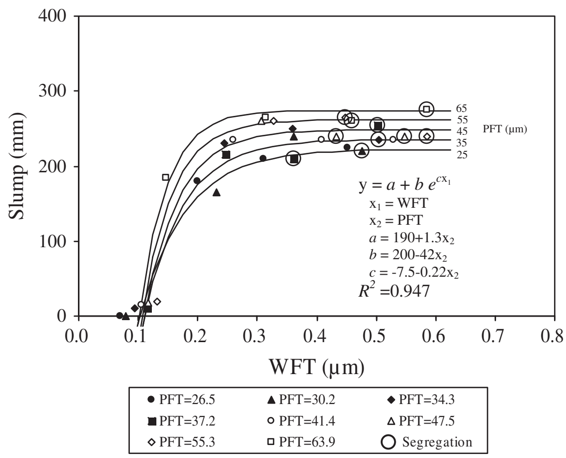

Fig. 8. Effects of WFT and PFT on slump.

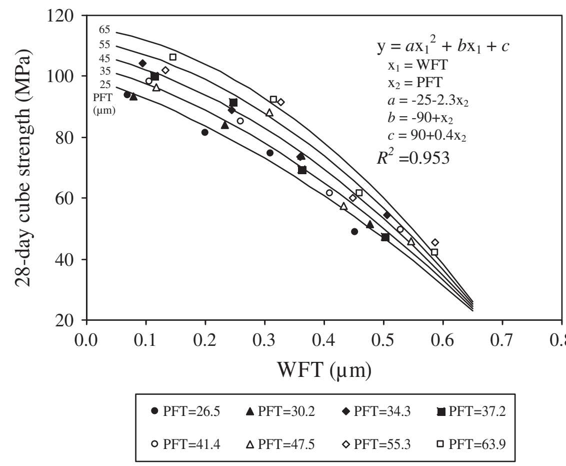

Fig. 10. Effects of WFT and PFT on cube strength.

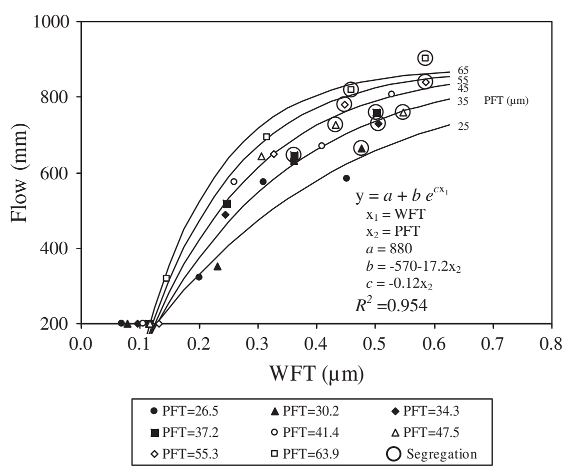

Fig. 9. Effects of WFT and PFT on flow.

(WFT > 0.40 μm). It follows that the effect of PFT on strength is dependent on the WFT. A possible explanation is that at smaller WFT, the paste is less flowable and the concrete mix is less workable, leading to greater difficulties in compaction. In such situation, a larger PFT would allow better consolidation and thus a higher strength to be achieved. At larger WFT, the paste is more flowable and the concrete is more workable, leading to easier compaction. In such situation, a larger PFT is not needed and thus the PFT has little effect on strength.

In order to investigate the combined effects of WFT and PFT, multi-variable regression analysis has been carried out to derive the best-fit curves for the cube strength-WFT relation at different PFT values. For comparison and easy reference, the best-fit curves so obtained are plotted alongside the data points, and the equation of the best-fit curves and its R^2 value are printed in the figure. It can be seen that as the PFT increases, the best-fit curve shifts upwards to yield a higher cube strength at the same WFT. A fairly high R^2 value of 0.953 has been achieved, indicating that the cube strength is governed mainly by the WFT and PFT.

7. Concrete mix design based on WFT and PFT

To develop a concrete mix design method, it is necessary to first identify the major factors governing the performance of concrete, establish a model correlating the various performance attributes to the major factors, and then work out design charts or formulas for back calculating the values of the major factors that would meet with given performance requirements. The major factors are usually taken as the various concrete mix parameters, such as *W*/*C* ratio, *F*/*T* ratio, paste or water volume and certain characterizing parameters of the ingredients. To establish the correlation model, the experiment design approach [22–25], statistical or database approach [26,27] and genetic algorithm approach [28,29] have been adopted. However, because of at least five or six major factors involved, the existing mix design methods are generally quite complicated. Moreover, although the particle size distribution, which determines the packing density and surface area of the particle system, is well known to have significant effects, it remains a difficult task to directly incorporate the particle size distribution (bear in mind that many parameters are needed to define the particle size distribution) in the mix design method.

Since the particle size distribution actually affects the performance of concrete through the corresponding changes of WFT and PFT, it is suggested to allow for the effects of the particle size distribution indirectly in terms of the WFT and PFT. For this reason, the WFT and PFT are taken as the major factors affecting the performance of concrete. Moreover, for modern concrete mixes, which are generally designed to have much higher workability than in the past, it is suggested to measure the workability in terms of the flow. Hence, the performance attributes are taken as the strength and flow of the concrete. The combined effects of the WFT and PFT on the strength and flow of concrete have been statistically analyzed and plotted in Figs. 9 and 10. These two figures are combined together to form the design chart shown in Fig. 11, in which the *x*-ordinate is the WFT, the *y*-ordinate is the PFT and contours of the strength and flow are plotted. From this chart, the strength and flow at a given set of WFT and PFT can be determined simply by locating the point with coordinates (WFT, PFT) in the chart and reading the corresponding values of strength and flow.

For back calculation of the WFT and PFT needed to meet with given strength and flow requirements, the design chart in Fig. 11 is transformed to Fig. 12, in which the *x*-ordinate is the strength, the *y*-ordinate is the flow and contours of the WFT and PFT are plotted. From this chart, the WFT and PFT needed to meet with a given set of strength and flow requirement can be determined simply by locating the point with coordinates (strength, flow) in the chart and reading the corresponding values of WFT and PFT. To the authors' best knowledge, this design chart is the first of its kind. Apart from designing concrete mixes for high-performance concrete, it also helps to improve our basic understanding of the WFT and PFT needed to produce various kinds of high-performance concrete. For instance, the minimum PFT needed to produce a

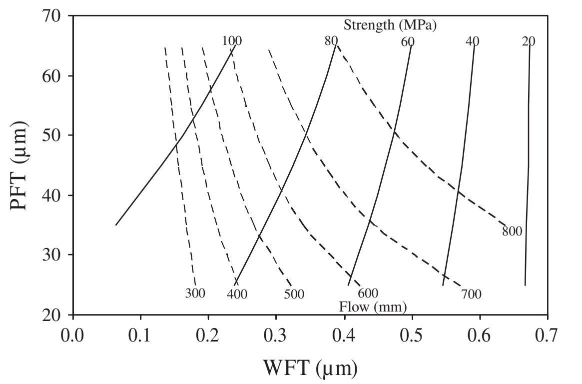

Fig. 11. Design chart for estimating strength and flow from WFT and PFT.

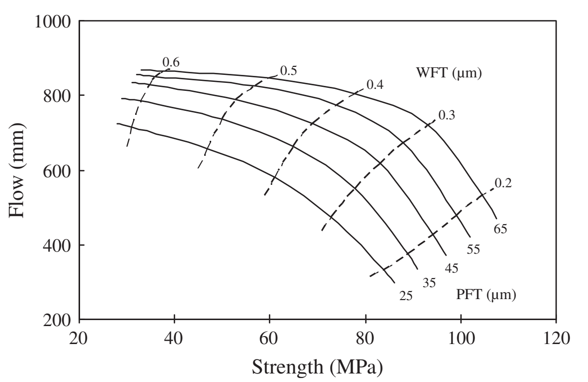

Fig. 12. Design chart for estimating WFT and PFT from strength and flow.

high-strength concrete with a mean cube strength of 100 MPa can be estimated from the chart as 50 μm. Likewise, the minimum PFT needed to produce a high-flowability concrete with a flow of 650 mm and a mean cube strength of 40 MPa can be estimated from the chart as 25 μm.

8. Conclusions

A series of concrete mixes with varying paste volume, water/cement ratio and fine/total aggregate ratio were made for deformability, flowability, cube strength and packing density measurements by the slump flow test, cube compression test and newly developed wet packing test. On the whole, the test results revealed that the paste volume, water/cement ratio and fine/total aggregate ratio all have certain effects on the deformability, flowability and strength of concrete. However, whilst the effect of water/cement ratio is obvious and easy to understand, the effects of the paste volume and fine/total aggregate ratio are not straight forward. On the other hand, it was found that the paste volume, water/cement ratio and fine/total aggregate ratio have relatively small but still significant effects on the packing density of all solid particles in the concrete whereas the fine/total aggregate ratio has significant effects on the packing density of the portion of aggregate larger than 75 μm. It was also found that the segregation stability tended to be lower at a higher water/cement ratio and higher at a higher fine/total aggregate ratio.

In-depth analysis showed that the apparently complicated effects of the paste volume, water/cement ratio and fine/total aggregate ratio are actually caused by the corresponding changes in the packing density, excess water ratio, excess paste ratio and solid surface area of the concrete as a water–solid mixture or a paste–aggregate mixture. Moreover, the combined effects of the packing density, excess water ratio, excess paste ratio and solid surface area may be evaluated in terms of the water film thickness (WFT) and paste film thickness (PFT) of the concrete. Correlations of the slump, flow and 28-day cube strength to the WFT and PFT by multi-variable regression analysis yielded R^2 values of 0.947, 0.954 and 0.953, respectively. Such high R^2 values proved that the WFT and PFT are together the key factors governing the deformability, flowability and strength of concrete. Besides, from the phenomenon that the WFT of all the concrete mixes having serious segregation are generally larger than 0.4 μm, it may be concluded that the WFT also has a major effect on the segregation stability of concrete.

Lastly, a concrete mix design method based on the WFT and PFT was developed and two design charts were produced. The first design chart is for predicting the strength and flow performance of concrete at any combination of WFT and PFT. The second design chart is for determining the required WFT and PFT for meeting with a given set of strength and flow requirements. From these design charts, the minimum PFT for the production of various kinds of high-performance concrete can be estimated directly. With the minimum PFT so estimated, the paste volume needed can then be evaluated simply as the volume of paste needed to fill the voids in aggregate (equal to the volume of voids in the portion of aggregate larger than 75 μm) plus the volume of paste needed to provide the minimum PFT (equal to the PFT times the solid surface area of the portion of aggregate larger than 75 μm).

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