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Flow behaviour of high strength high-performance concrete

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Abstract

The workability of flowable High-Performance Concrete (HPC) is nowadays mainly measured using conventional test methods such as the slump test or the slump-flow test. These single-point tests do not seem sensitive enough to characterize the high-workability of HPC. Due to the fluid consistency and uniformity of fresh HPC, it is possible to describe its flow properties by using a rheological test method. To evaluate the flowability based on rheology, fresh HPC is regarded as a two-phase material composed of a matrix phase and a particle phase. In the study, the effects of materials and proportioning on the rheological properties were investigated experimentally. A new rheometer was established by conducting a two-point test to investigate the flow behaviour of high strength HPC. Test results show that the high strength HPC with good uniformity and without tendency of segregation can possess the properties of rheology according to Bingham's equation. An increase of the fraction of mortar in HPC can lead to a more distinct the rheological behaviour. Moreover, it is found that the application of a rheological method can provide more stable results than any other test method in describing the flowability of high strength HPC.

Keywords: Rheology; Bingham model; High strength high-performance concrete; Mix proportions; Two-point test

1. Introduction

Over the last decade, the High-Performance Concrete (HPC) technology has been the important subject in concrete research since HPC has unique properties and numerous advantages in practical applications. Among them, the fine workability (i.e., easy placing and consolidation) is one of the most representative characteristics. For this reason, the use of such concrete is spreading worldwide quickly.

Nowadays the workability of HPC is mainly evaluated by the slump test [1] or the flow test [2]. An alternative test method adopted in Japan and Taiwan is the slump-flow test [3], which is simply a measurement of the diameter of the concrete after it has collapsed in a standard slump test. However, the validity of a slump test is generally recommended for concrete with a slump value ranging from 25 to 175 mm, corresponding approximately to a consistency ranges from low plastic to medium plastic stage. Therefore, these test methods do not seem appropriate to characterize the workability of HPC with high flowability, since its slump value is usually more than 200 mm. Moreover, it is practically known that concretes with the same slump value or flow value may have different workability. To evaluate the rheological property solely based on these test results can possibly be misleading.

In contrast, the use of rheology is much more sensitive to characterize the viscous behaviour of HPC [4,5]. Especially, when Tattersall [6] introduced his two-point test apparatus in 1973, it is an important milestone forward. Since then, a number of researchers have proposed various apparatuses to characterize the flow properties of fresh concrete [7–15]. However, in order to keep pace with technological progress and to provide a pertinent characterization of the flow behaviour of HPC, the rheological apparatus seem to have room for improvement. There is an urgent need to take a more basic and reliable approach to the testing of the workability of this new generation of materials.

From a practical viewpoint, fresh concrete can be regarded as a two-phase material, composed of a matrix phase and a particle phase, and its flow behaviour can be assumed to depend mainly on the viscosity of matrix and the volume percentage of aggregate. Therefore, a preliminary test on the characteristics of the matrix itself such as flowability or viscosity is required. In the study, the dosage of superplasticizer for paste (with pozzolanic materials consisting of fly ash and slag) was

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first investigated. Then, the influence of the fraction of sand on the viscosity of paste was tested. Finally, the flow behaviour of high strength HPC was studied by adding various quantities of coarse aggregate into mortar mixes. On the other hand, based on the two-point test proposed by Tattersall [8], a rheometer for fresh HPC was established to examine the flow behaviour of fresh HPC under various mix proportions. Test results show that it is practicable to use this apparatus to quantify the rheological properties of fresh high strength HPC.

2. Experimental program

2.1. Materials and test variables

Materials used in the experiments consisted of type I Portland cement, coarse aggregate with a maximum size of 12.7 mm, fine aggregate with a fineness of 2.90, G-type superplasticizer, and cementitious materials of class F fly ash (LOI = 4.0) and slag (LOI $\sim$ 0) with Blaine values equal to 2070 and 3990 cm^2/g, respectively. The superplasticizing admixture is HICON HPC 100 conforming to ASTM C-494-Type-G (color: dark down, pH: 7 ± 1, density: 1.1 kg/l, solid content: 42 ± 2%).

In all the tests, the supplementary cementitious materials were used to replace cement by mass. Other variations of concrete mix proportions included the filling ratio of sand and the coarse aggregate content. All the test variables are listed as follows:

- Mixed ratio of cementitious materials (by weight):
  Series A (Cement:Slag:Fly ash = 7:2:1),
  Series B (Cement:Slag:Fly ash = 6:3:1),
  Series C (Cement:Slag:Fly ash = 7:0.5:2.5).
- Water-to-binder ratio $W/B = 0.28$, 0.30.
- Superplasticizer-to-binder ratio $\mathrm{SP}/B = 0.5$–4.0%.
- Filling ratio of sand (f_V, volumetric proportion of sand to paste): $f_V = 30$–60%.
- Volumetric proportion of coarse aggregate (ϕ_G) in mix: $\phi_G = 30\%$, 35%, 40%.

2.2. Mix proportions and measurements

The mix proportions for paste and mortar with $W/B = 0.28$ are summarized in Tables 1 and 2. To measure the flowability of the paste and the mortar, the rheological measurements were conducted by using a set of commercially available viscometer (Brookfield HBVD-II+ mode viscometer, together with a #4 RV/H spindle). The rotational speed of spindle was controlled in a stepwise manner as 100, 50, 20, 10 and 5 rpm.

Some of the mix proportions for high strength HPC are illustrated in Table 3. The rheological measurements were conducted by using a self-established FHPCM rheometer. This rheometer is fully automatic to record the torque on the spindle at different rotating speeds. During the test, the rotation of the spindle was initially set to a maximum speed then reduced in a stepwise manner, since the time to obtain equilibrium at each rate of shear will be shorter by going from a higher to a

Table 1
Mix proportions of paste (for $W/B = 0.28$)[a]

Mix number	SP/B (%)	C (kg/m^3)	W (kg/m^3)	SP (kg/m^3)	F (kg/m^3)	SL (kg/m^3)
P28A-1	0.5	1125	450.1	8.04	160.7	321.5
P28A-2	1.0	1117	446.8	15.96	159.6	319.2
P28A-3	1.5	1109	443.6	23.77	158.4	316.9
P28A-4	2.0	1101	440.4	31.46	157.3	314.6
P28A-5	2.5	1093	437.3	39.05	156.2	312.4
P28A-6	3.0	1086	434.2	46.53	155.1	310.2
P28A-7	4.0	1070	428.2	61.17	152.9	305.9
P28B-1	0.5	960	448.0	8.00	160.0	480.0
P28B-2	1.0	953	444.7	15.88	158.8	476.5
P28B-3	1.5	946	441.5	23.65	157.7	473.1
P28B-4	2.0	939	438.4	31.31	156.6	469.7
P28B-5	2.5	933	435.3	38.87	155.5	466.4
P28B-6	3.0	926	432.2	46.31	154.4	463.1
P28B-7	4.0	913	426.3	60.89	152.2	456.7
P28C-1	0.5	1096	438.3	7.83	391.4	78.3
P28C-2	1.0	1088	435.2	15.54	388.6	77.7
P28C-3	1.5	1080	432.2	23.15	385.9	77.2
P28C-4	2.0	1073	429.2	30.65	383.2	76.6
P28C-5	2.5	1065	426.2	38.05	380.5	76.1
P28C-6	3.0	1058	423.3	45.35	377.9	75.6
P28C-7	4.0	1044	417.5	59.65	372.8	74.6

[a] *Notes*: C = cement; SL = slag; F = fly ash; SP = superplasticizer; W = water; S = sand; $B = C + \mathrm{SL} + F$.

Table 2
Mix proportions of mortar (for $W/B = 0.28$)[a]

Mix number	f_V (%)	C (kg/m^3)	SL (kg/m^3)	F (kg/m^3)	SP (kg/m^3)	W (kg/m^3)	S (kg/m^3)
M28A1	30	841	240.3	120.1	30.04	336.4	606.9
M28A2	35	810	231.4	115.7	28.92	323.9	681.9
M28A3	40	781	223.1	111.6	27.89	312.4	751.4
M28A4	45	754	215.4	107.7	26.93	301.6	816.2
M28A5	50	729	208.2	104.1	26.03	291.5	876.7
M28A6	55	705	201.5	100.8	25.19	282.1	933.2
M28A7	60	683	195.2	97.6	24.40	273.3	986.3
M28B1	30	718	358.8	119.6	29.90	334.8	606.9
M28B2	35	691	345.5	115.2	28.79	322.4	681.9
M28B3	40	666	333.1	111.0	27.76	310.9	751.4
M28B4	45	643	321.6	107.2	26.80	300.2	816.2
M28B5	50	622	310.9	103.6	25.91	290.2	876.7
M28B6	55	602	300.9	100.3	25.07	280.8	933.2
M28B7	60	583	291.5	97.2	24.29	272.1	986.3
M28C1	30	820	58.5	292.7	29.27	327.8	606.9
M28C2	35	789	56.4	281.9	28.19	315.7	681.9
M28C3	40	761	54.4	271.8	27.18	304.4	751.4
M28C4	45	735	52.5	262.4	26.24	293.9	816.2
M28C5	50	710	50.7	253.7	25.37	284.1	876.7
M28C6	55	687	49.1	245.5	24.55	275.0	933.2
M28C7	60	666	47.6	237.8	23.78	266.4	986.2

[a] *Notes*: f_V = filling ratio; C = cement; SL = slag; F = fly ash; SP = superplasticizer; W = water; S = sand; $B = C + \mathrm{SL} + F$.

Table 3
Mix proportions of concrete (for $W/B = 0.28$)[a]

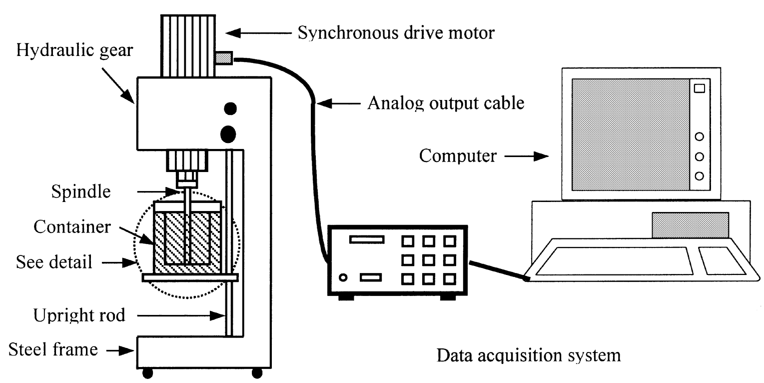
Blend of Series A, SP/B = 2.5% and mortar content = 60%								
Mix number	f_V (%)	C (kg/m^3)	SL (kg/m^3)	F (kg/m^3)	SP (kg/m^3)	W (kg/m^3)	S (kg/m^3)	A (kg/m^3)
C28A1-1	30	505	144.2	72.1	18.02	201.8	364	1036
C28A1-2	35	486	138.8	69.4	17.35	194.4	409	1036
C28A1-3	40	469	133.9	66.9	16.73	187.4	451	1036
C28A1-4	45	452	129.3	64.6	16.16	181.0	490	1036
C28A1-5	50	437	124.9	62.5	15.62	174.9	526	1036
C28A1-6	55	423	120.9	60.5	15.11	169.3	560	1036
C28A1-7	60	410	117.1	58.6	14.64	164.0	592	1036
Blend of Series B, SP/B = 2.5% and mortar content = 60%								
Mix number	f_V (%)	C (kg/m^3)	SL (kg/m^3)	F (kg/m^3)	SP (kg/m^3)	W (kg/m^3)	S (kg/m^3)	A (kg/m^3)
C28B1-1	0.30	431	215.3	71.8	17.94	200.9	364	1036
C28B1-2	0.35	415	207.3	69.1	17.27	193.5	409	1036
C28B1-3	0.40	400	199.9	66.6	16.66	186.6	451	1036
C28B1-4	0.45	386	193.0	64.3	16.08	180.1	490	1036
C28B1-5	0.50	373	186.6	62.2	15.55	174.1	526	1036
C28B1-6	0.55	361	180.5	60.2	15.04	168.5	560	1036
C28B1-7	0.60	350	174.9	58.3	14.57	163.2	592	1036
Blend of Series C, SP/B = 2.5% and mortar content = 60%								
Mix number	f_V (%)	C (kg/m^3)	SL (kg/m^3)	F (kg/m^3)	SP (kg/m^3)	W (kg/m^3)	S (kg/m^3)	A (kg/m^3)
C28C1-1	0.30	492	35.1	175.6	17.56	196.7	364	1036
C28C1-2	0.35	474	33.8	169.1	16.91	189.4	409	1036
C28C1-3	0.40	457	32.6	163.1	16.31	182.7	451	1036
C28C1-4	0.45	441	31.5	157.5	15.75	176.4	490	1036
C28C1-5	0.50	426	30.4	152.2	15.22	170.5	526	1036
C28C1-6	0.55	412	29.5	147.3	14.73	165.0	560	1036
C28C1-7	0.60	400	28.5	142.7	14.27	159.8	592	1036

[a] *Notes*: f_V = filling ratio; C = cement; SL = slag; F = fly ash; SP = superplasticizer; W = water; S = sand; A = aggregate.

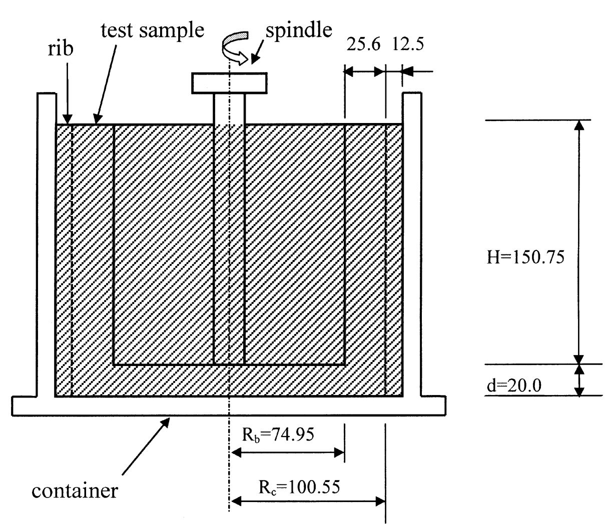
lower rate of shear [8]. To ensure the stability of the results, a 10-second record was taken 20 s after a certain rotating speed is set. The relationship between the mean value of the torque and the corresponding spindle speed is then obtained. In addition to the rheological measurement, a parallel slump test and slump-flow test was also carried out for comparison.

2.3. Test apparatus

The torsional rheometer (FHPCM), modified according to Mk II [8], has several mechanical components. The major setup includes a synchronous drive motor, a hydraulic gear, a spindle, a sample container, and data acquisition system. All the parts are mounted on a steel frame as shown in Fig. 1. It is fully automatic and controlled by a computer, in which a software program has been developed for control of signals between computer and rheometer. The principle of the measurement is that the torque, allowing for stationary rotation of a spindle immersed in a viscous flowing material, is a function of the viscosity (or the extent of flowability) and the rotational speed of the spindle (N). As the spindle rotates at an angular speed ($\Omega = 2\pi N$), which does not exceed a critical value, a laminar shear flow of the sample occurs within the gap between the spindle and the container. Consequently, the torque (T) required to rotate the spindle is the sum of that due to shear in the annulus (T_A), and in the disc-shaped space under the bottom of the spindle (T_B). For a sample conforming to the Bingham model, the flow in the annulus and the flow under the bottom of the spindle can be described by the Eq. (1) for a coaxial-cylinder viscometer and the Eq. (2) for a parallel viscometer, respectively [16]:



(a)



(b)

Fig. 1. The FHPCM rheometer apparatus. (a) General arrangement of apparatus. (b) Detail of spindle and container (dimension in mm).

$$T_A = \frac{[\tau_0 \ln(R_c/R_b) + \Omega\mu]}{(1/R_b^2 - 1/R_c^2)} 4\pi H, \tag{1}$$

$$T_B = \frac{2\pi\tau_0 R_b^3}{3} + \frac{\pi\mu\Omega R_b^4}{2d}, \tag{2}$$

where τ_0 and μ are the yield shear and the coefficient of plastic viscosity of the sample, respectively, H the height of spindle, R_b the radius of the spindle, R_c the radius of the sample container, and d the gap under the spindle. By combining Eqs. (1) and (2), and at the same time, substituting Ω with $2\pi N$ (N is the rotational speed of the spindle in revolution per second), the total torque can be determined as follows:

$$T = \left[\frac{2\pi R_b^3}{3} + \frac{4\pi H \ln(R_c/R_b)}{(1/R_b^2 - 1/R_c^2)}\right]\tau_0 + \left[\frac{8H\pi^2\mu}{(1/R_b^2 - 1/R_c^2)} + \frac{\pi^2 R_b^4 \mu}{d}\right]N. \tag{3}$$

On the other hand, for Bingham material the relation between the torque T and the rotational speed of the spindle N is of the form:

$$T = g + hN, \tag{4}$$

where g is the intercept on the torque axis and h the slope of the line. These two constants are analogous to the yield shear τ_0 and the plastic viscosity μ, respectively. By comparing Eqs. (3) and (4), one has

$$g = \left[\frac{2\pi R_b^3}{3} + \frac{4\pi H \ln(R_c/R_b)}{(1/R_b^2 - 1/R_c^2)}\right]\tau_0, \tag{5}$$

$$h = \left[\frac{8\pi^2 H}{(1/R_b^2 - 1/R_c^2)} + \frac{\pi^2 R_b^4}{d}\right]\mu. \tag{6}$$

Therefore, the units of g and h can be transferred into fundamental units of yield shear (Pa) and plastic viscosity (Pa s), respectively, expressed as follows:

$$\tau_0 = \frac{g}{\left[\frac{2\pi R_b^3}{3} + \frac{4\pi H \ln(R_c/R_b)}{(1/R_b^2 - 1/R_c^2)}\right]}, \tag{7}$$

$$\mu = \frac{h}{\left[\frac{8\pi^2 H}{(1/R_b^2 - 1/R_c^2)} + \frac{\pi^2 R_b^4}{d}\right]}. \tag{8}$$

2.4. Calibration of the apparatus

Calibration of the FHPCM rheometer was conducted by using malt sugar with known flow properties. At the beginning, the shear stress-shear rate relationship (Fig. 2) was obtained experimentally by using a coaxial cylinders viscometer (Brookfield HBVD-II+ mode viscometer). On the same sample, the relationship between the torque and the rotating speed was then established by the FHPCM (Fig. 3) to further determine the value of h (the slope of the T–N relationship). Based on Eq. (8) with given instrument dimensions ($R_b = 0.075$ m, $R_c = 0.10$ m, $d = 0.02$ m, $H = 0.15$ m) and h value, the coefficient of plastic viscosity (μ) of the calibration fluid by the FHPCM rheometer is achieved. Table 4 shows

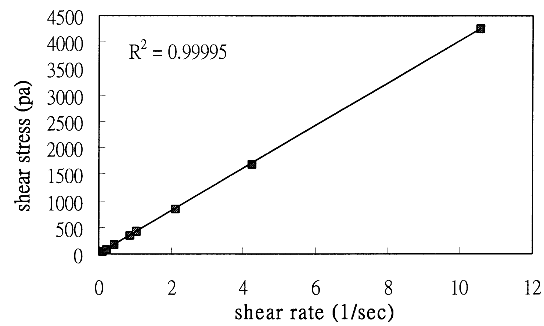


Fig. 2. Flow curve obtained in the Brookfield viscometer.

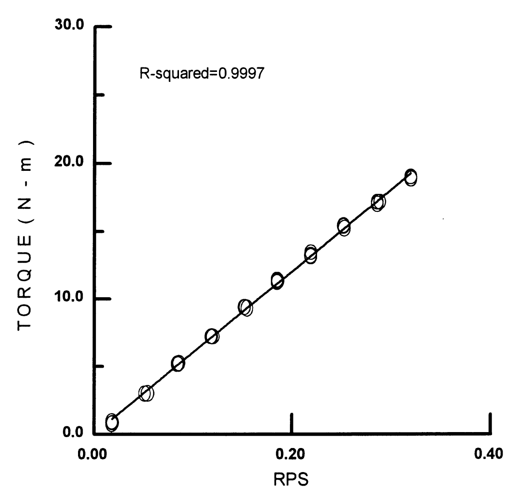


Fig. 3. Flow curve obtained in the FHPCM rheometer.

Table 4
Calibration result

Fluid	Temperature (°C)	h value (N m s) [slope of T vs. N]	Plastic viscosity μ (Pa s) [Eq. (8)]	Viscosity v (Pa s) [Brookfield]
Malt sugar	27.9	60.25	365.1	400.0

that the viscosity values from the measurements of two different rheometers are rather close. The relative difference is within 9%.

3. Results and discussion

3.1. Maximum dosage of superplasticizer for paste

To ensure that the paste is under a fine flowability condition with a given W/B ratio and a given blend of cementitious, it is necessary to find an appropriate dosage of added superplasticizer (SP/B). In the study, the flowability is evaluated based on the result of viscosity measurement of the cement paste. Since the paste generally behaves as a non-Newtonian fluid, however, an "apparent viscosity" is measured. By varying the SP/B ratio for the cementitious blends (Series "A", "B" and "C"), the proper value of SP/B can then be obtained.

As shown in Fig. 4, the apparent viscosity of Series C pastes at various shear rates decreases as the SP/B ratio increases (Similar trends are also found for the blends of Series A and B). Since the effect of added superplasticizer is to promote electrostatic repulsion of anions absorbed on the surface of cement paste, it will thus lead to a decrease in apparent viscosity. When the SP/B ratio of paste is enough to exhibit sufficient flowability, the effect of further addition of superplasticizer is insignificant, and may even decrease the flowability. This value, known as the saturation dosage, is taken as the maximum dosage of superplasticizer. Based on the results in Fig. 5, the maximum dosage of superplasticizer are found and illustrated in Table 5 for specified W/B and blends of cementitious.

To compare the extent of flowability for the three types of blends, the viscosity of all the pastes with $W/B = 0.28$ and SP/$B = 2.5\%$ are measured. It shows in Fig. 6 that the most viscous paste is the Series C blend, while the paste of Series B is the least. Comparing the composition of Series C to that of Series A (see Table 5), replacing slag by an equal amount of mass of fly ash results in an increase of the volume of cementitious material. In addition, the fly ash has a greater loss of ignition. Therefore, the water requirement in the paste of Series C will be increased. This leads to the situation that less free water is available for the lubrication of the particles, and thus increases the viscosity of the paste and results in less flowability. On the other hand, Fig. 6 also shows that the apparent viscosity of Series B paste is less than that of Series A. It is obviously due to the similar reason since the extent of water absorption for slag is less than that of cement.

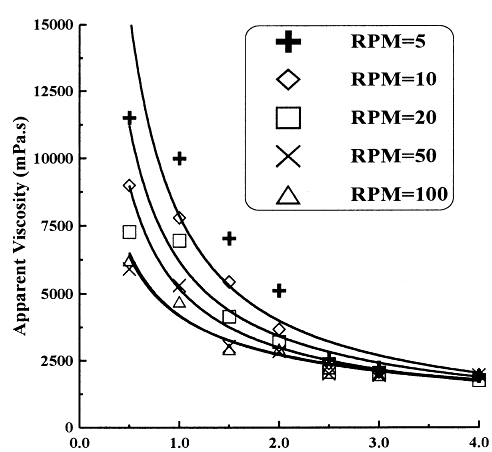


Fig. 4. Effect of superplasticizer dosage on the viscosity of pastes.

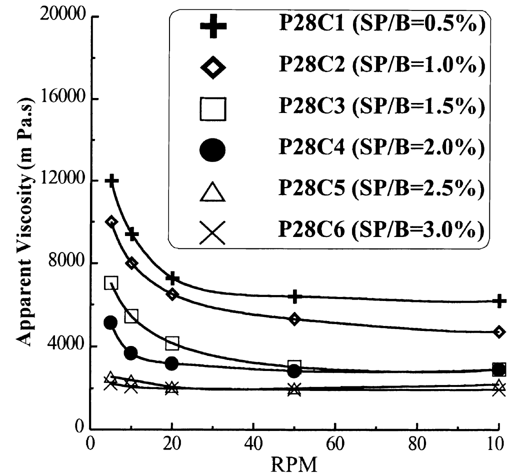


Fig. 5. Relations between the rotational speed of spindle and the viscosity of paste.

Table 5
The maximum dosage of SP/B for paste

W/B	The blended ratio of cementitious materials	SP/B (%)
0.28	Series A (cement:slag:fly ash = 7:2:1)	2.5
0.28	Series B (cement:slag:fly ash = 6:3:1)	2.5
0.28	Series C (cement:slag:fly ash = 7:0.5:2.5)	2.5
0.30	Series A (cement:slag:fly ash = 7:2:1)	2.0
0.30	Series B (cement:slag:fly ash = 6:3:1)	2.0
0.30	Series C (cement:slag:fly ash = 7:0.5:2.5)	2.5

3.2. Filling percentage of sand in mortar

To evaluate the flowability of mortar, the filling ratio of sand (f_V) is used as an indication factor for the determination of the amount of sand that can be incorporated into the cement paste up to the limit imposed by flowability [11]. The flowability of mortars, with

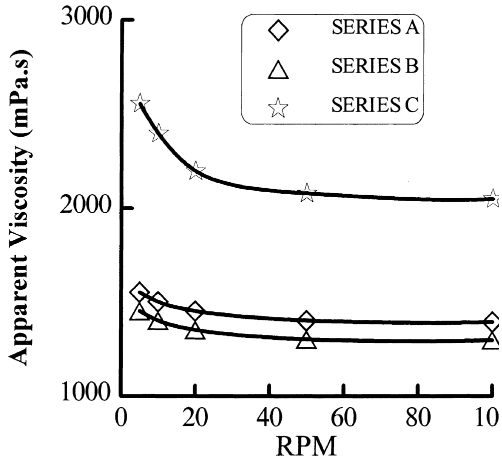


Fig. 6. Apparent viscosity versus rpm curves for pastes.

$W/B = 0.28$, $SP/B = 2.5\%$ and the 3 types of blended cementitious, was tested according to ASTM C230 without jolting of the sample. The apparatus for the flow spread test consists of a mold as a frustum of cone, 50 mm high with diameters of 70 mm at top and 100 mm at the base. The result in Fig. 7 indicates that the flow value of mortar decreases as f_V increases. The reason is increasing sand content reduces the coating thickness of paste around the sand particles and thus decreases its flowability due to the increase of inner friction and interlocking between sand particles. On the other hand, the largest flow value of mortar is found with a blend of Series B and the smallest with Series C. This tendency is consistent with the result of the tests of pastes.

As was mentioned previously, the apparent viscosity, which is measured at a single shear rate (or single point), is the representative of the viscosity of a non-Newtonian liquid. Such test measurements may not, in principle, be capable of providing full description of workability. Nevertheless, it indeed reveals a useful indicative, as the shear rate in the test remains the same as the effective rate of shear on the job [8]. In the experiments, the shear rate is selected as 1.05 s^{-1} as it is close to the shear rate while mortar flowing [17,18]. The relationship between mortar flow values and the apparent viscosity of mortar measured at a shear rate of 1.05 s^{-1} is shown in Fig. 8. It reveals that the flow value of mortar decreases roughly linearly with an increase of the apparent viscosity. Considering convenience of grouting HPC, for instance, to have a mortar flow value beyond 300 mm, the apparent viscosity of mortar should be less than about 6000 mPa s.

3.3. Appropriate percentage of coarse aggregate in high strength HPC

Three different volume percentages of coarse aggregate (30%, 35% and 40%) are added to the mortar to explore the range of HPC proportions leading to fine workability, which is verified by performing a slump-flow test. According to the test results in Table 6, the type of mortars (in shaded area), with the blend of Series A and $f_V = 30$–60%, are considered capable of producing flowable concrete by adding adequate quantity of coarse aggregate, in which: "flowable" is defined as a condition that the slump value is greater than 235 mm and the slump-flow value is greater than 500 mm. For mortars with a blend of Series B, the cases that f_V is between 30% and 35% are excluded from the appropriate proportions since they are relatively less viscous. In contrast, since the consistency of the mortars with a blend of Series C and f_V between 50% and 60% appears sticky to attain a desirable workability, the acceptable range of f_V is limited to a range of lower f_V values (below 50%).

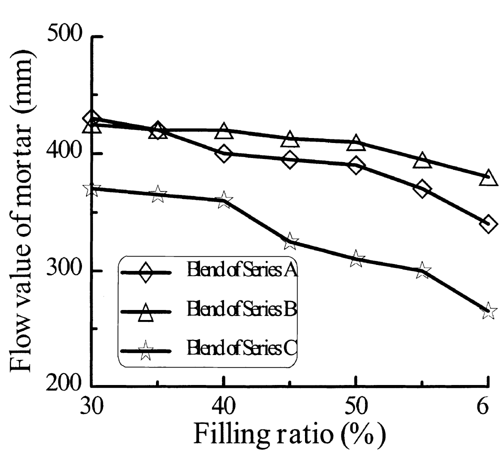


Fig. 7. Effect of filling ratio on the flow value of mortar.

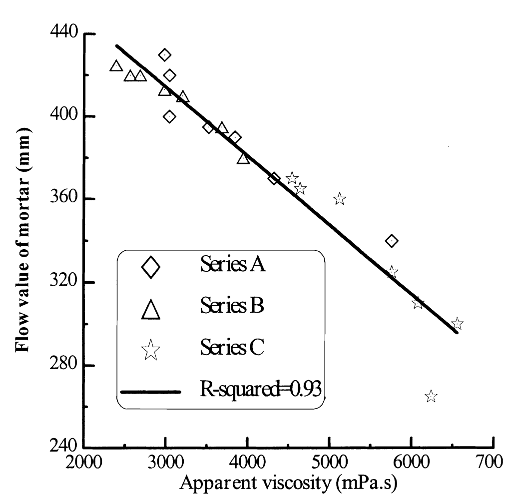


Fig. 8. Relationship between the flow value and the apparent viscosity of mortar ($W/B = 0.28$, shear rate = 1.05 s^{-1}).

Table 6
Test results of fresh concrete[a]

Series A (W/B=0.28, blend of Series A and SP/B=2.5%)																					
f_v	30%			35%			40%			45%			50%			55%			60%		
ϕ_M (%)	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70
workability★	g	s	s	g	g	s	g	g	s	g	g	g	g	g	g	g	g	g	p	g	g
slump (mm) (45 min.)✦	270 (250)	280 (290)	280 (280)		270 (260)		255 (250)	270 (270)	280 (290)	255	265	275	250 (240)	270 (270)	275 (275)	235	270	270	210 (210)	260 (260)	270 (270)
flow (mm) (45 min.)⌖	750 (750)	800 (800)	850 (800)		740 (730)		650 (670)	760 (770)	810 (800)	600	665	700	540 (530)	640 (640)	750 (770)	540	685	700	430 (430)	630 (630)	690 (660)
f_c' (MPa)◆	79		78		80					75	77	74	84	81	80	86	84	87		84	90
Series B (W/B=0.28, blend of Series B and SP/B=2.5%)																					
f_v	30%			35%			40%			45%			50%			55%			60%		
ϕ_M (%)	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70
workability★	s	s	s	s	s	s	g	s	s	g	s	s	g	g	s	g	g	g	g	g	g
slump (mm) (45 min.)✦	240 (240)	265 (270)	270 (270)	245 (240)		245	230 (240)	275 (280)	250 (270)				250 (250)	275 (270)	270 (280)	250			240 (240)	270 (270)	270 (270)
flow (mm) (45 min.)⌖	750 (720)	760 (720)	800 (800)	750 (700)		800	640 (670)	800 (800)	800 (800)				690 (650)	720 (720)	780 (760)	620			520 (500)	650 (700)	730 (720)
f_c' (MPa)	69	66		69										75		78			77	77	83
Series C (W/B=0.28, blend of Series C and SP/B=2.5%)																					
f_v	30%			35%			40%			45%			50%			55%			60%		
ϕ_M (%)	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70	60	65	70
Workability★	g	g	s	g	g	g	g	g	g	p	g	g	p	p	g	p	p	g	p	p	p
slump (mm) (45 min.)✦	260 (260)	270 (270)	280				240 (240)	270 (260)	275		265		220 (210)	240	260	140		260 (240)	140 (110)	200	235
flow (mm) (45 min.)⌖	610 (590)	750 (710)	750				530 (480)	620 (600)	750		575		420 (410)	470	600	400		550 (510)	280 (300)	380	420
f_c' (MPa)	75							81			88							75			

[a] *Notes*: f_V = filling ratio; ϕ_M = mortar content; ★: workability: g = good; s = segregation; p = poor; ✦: slump after 45 min; ⌖: flow after 45 min; ◆: f_c' = compressive strength after 28 days.

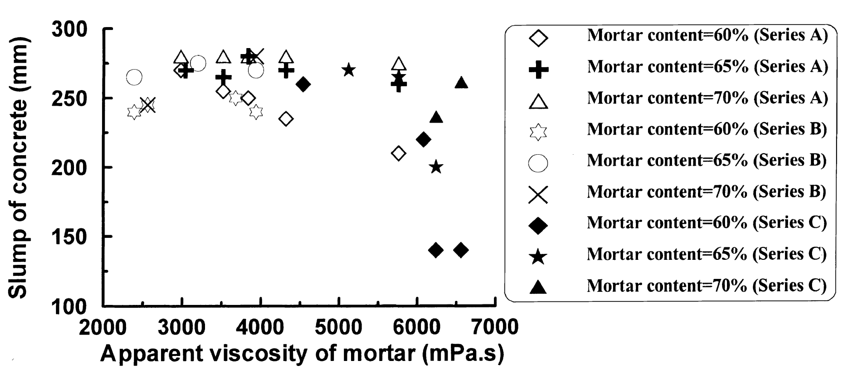


Fig. 9. Relationship between the slump of concrete and the apparent viscosity of corresponding mortar ($W/B = 0.28$, shear rate = 1.05 s^{-1}).

Comparing the result in Fig. 9 with that in Fig. 10, it can be seen that the correlation between the slump-flow value of concrete and the apparent viscosity of corresponding mortar appears more clear than that in Fig. 9, implying that the latter relationship is more representative. Based on the result in Fig. 10, the applicable range of the apparent viscosity of mortar would be less than about 6000 mPa s to attain a concrete slump-flow value beyond 550 mm. In contrast, concrete without segregation would possess an apparent viscosity value more than about 3000 mPa s. Although easily observed when it occurs, segregation is difficult to assess quanti-

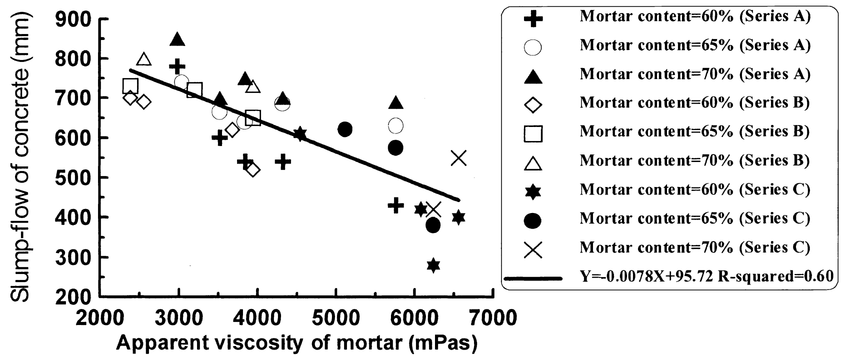


Fig. 10. Relationship between the slump-flow of concrete and the apparent viscosity of corresponding mortar ($W/B = 0.28$, shear rate $= 1.05\ s^{-1}$).

tatively. However, at the end of two-point test, any segregation caused by the stirring of the spindle can be found on the concrete in container. Based on the method proposed by Wallevik and Gjorv [9], upon completion of the two-point test, the speed of the spindle goes back to the maximum speed. The proneness of the concrete to segregation can be regarded as the change in torque during testing at the maximum speed. In addition, the corresponding slump-flow spread is usually beyond 750 mm. In this study, therefore, the slump-flow spread value is adopted as a general criterion for the occurrence of segregation.

Fig. 11 shows that at a constant superplasticizer dosage the slump-flow spread increases when the coarse aggregate content decreases, and when both superplasticizer dosage and coarse aggregate content remain constant, slump-flow spread increases with the decrease of sand content. Combining these two effects, Fig. 12 implies that the slump-flow spread increases with the increase of paste volume. Similarly, the workability of concrete also depends on the mortar content in the concrete. In concrete the mortar content should be the minimum needed to fill up voids among coarse aggregates and to bind them together to form rock-like material as it hardens. However, workable concrete requires a sufficient amount of mortar to fill voids among aggregates and to lubricate the aggregates surface during casting. If there is not enough mortar used the resulting concrete present a poor workability. From Table 6, it also reveals a general tendency that the more the mortar content in concrete is, the larger the slump and slump-flow value will be.

As mentioned above, workability itself is primarily a function of the mortar properties in HPC. To sum up, the fresh concrete conforms to the criterion that too soft a mortar consistency will cause segregation of the concrete, whereas too sticky a mortar consistency will result in poor flowability. In the test program, HPC with a Series A paste possesses fine workability and segregation resistance; those with Series B paste are apt to segregate as f_V is within 30–45%, and those with Series C paste show poor workability as f_V is greater than 50%. Based on the results, marked in the shaded area in Table 6, an acceptable range of mix proportions for high strength HPC with fine workability is shown in Table 7, indicating that the applicable volume of paste is within a range from 39% to 54%, significantly larger than that of a normal concrete.

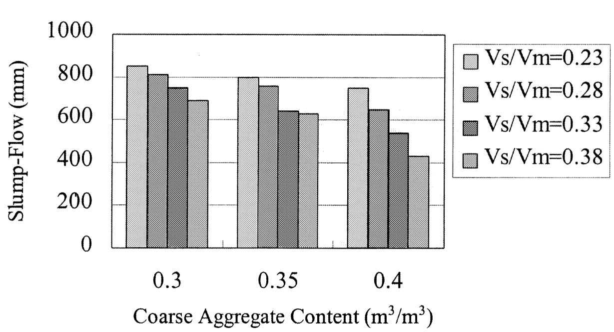


Fig. 11. Relationship between slump-flow and coarse aggregate content ($W/B = 0.28$, blend of Series A and $SP/B = 2.5\%$).

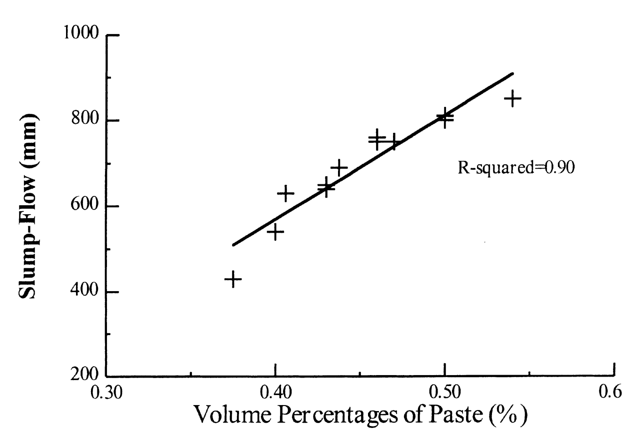


Fig. 12. Relationship between slump-flow and paste volume ($W/B = 0.28$, blend of Series A and $SP/B = 2.5\%$).

Table 7
The appropriate proportion ranges of paste and aggregate in HPC mix

Cement paste			Aggregate
Composition of cement paste	ϕ_P[a] (%)	ϕ_S[b] (%)	ϕ_G[c] (%)
Water-to-binder ratio $W/B = 0.28$, blend of Series A (cement:slag:fly ash = 7:2:1) $SP/B = 2.5\%$	46–39	14–21	407
	48–41	17–24	35
	48–44	22–26	30
Water-to-binder ratio $W/B = 0.28$, blend of Series B (cement:slag:fly ash = 6:3:1) $SP/B = 2.5\%$	43–39	17–21	40
	43–41	22–24	35
	45–44	25–26	30
Water-to-binder ratio $W/B = 0.28$, blend of Series C (cement:slag:fly ash = 7:0.5:2.5) $SP/B = 2.5\%$	46–43	14–17	40
	50–45	15–20	35
	52–45	18–25	30
Water-to-binder ratio $W/B = 0.30$, blend of Series A (cement:slag:fly ash = 7:2:1) $SP/B = 2.0\%$	46–44	14–16	40
	50–45	15–20	35
	54–47	16–23	30
Water-to-binder ratio $W/B = 0.30$, blend of Series B (cement:slag:fly ash = 6:3:1) $SP/B = 2.0\%$	46–40	14–19	40
	50–42	15–23	35
	45–44	25–26	30
Water-to-binder ratio $W/B = 0.30$, blend of Series C (cement:slag:fly ash = 7:0.5:2.5) $SP/B = 2.5\%$	46–41	14–19	40
	50–43	15–22	35
	54–47	16–23	30

[a] ϕ_P denotes the volume percentage of cement paste in HPC mix proportions.
[b] ϕ_S denotes the volume percentage of sand in HPC mix proportions.
[c] ϕ_G denotes the volume percentage of coarse aggregate in HPC mix proportions.

3.4. Examination of the flow behaviour of fresh HPC by rheological method

Table 6 shows that concretes with the same slump values correspond to a variety of slump-flow values; those with approximately equal slump-flow values do not result in agreeable slump values. Furthermore, during the process of a slump-flow test, it happens that some of the concrete samples slump and spread quickly, while performing the other, on the contrary, collapse slowly. Examining solely the results of the slump or slump-flow spread does not reflect the difference. It implies that the consistency of fresh concrete cannot be fully described by a slump or slump-flow test.

In fact, the single-point methods can only reflect the response of the fresh concrete to the particular shear rate. To obtain a more pertinent characterization of the flow behaviour of HPC, it needs to test the flow properties over a certain range of the shear rates while concrete flowing. In the experiments, by using the FHPCM rheometer, the relationship between the torque (T) and the rotational speed of the spindle (N) can be presented in the form of Eq. (4). From the curves of T–N relationship, the g and h values can be obtained by regression. Since these two parameters represent certain fundamental properties of a concrete mix, proper consideration should be given to these two parameters while describing the flow properties of fresh concrete.

According to the results of the rheological measurements, the effect of binder combination on the rheological behaviour of high strength HPC can be drawn in the form of a T–N relationship. Fig. 13 shows that the relationships maintain linear. The HPC with a Series C paste exhibits the highest torque for a fixed N, and corresponds to the largest values of g and h with the

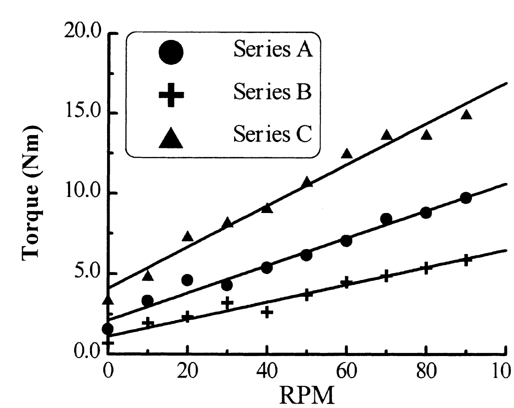


Fig. 13. Effect of binder combination on the torque versus rpm curve of HPC ($f_V = 50\%$, $\phi_M = 60\%$).

same mortar content (ϕ_M), as shown in Fig. 14. The results, that are compatible with those of paste and mortar, implicate that the rheometer is capable to reflect the effect of various constituent materials to the flow properties of fresh HPC.

For high strength HPC with a proper amount of coarse aggregate, fine workability is to be reached by using a mortar with suitable rheological properties. With an alternative way of consideration, as Tattersall presented [10], we explore the resulting values of g and h to determine the acceptable range needed for HPC. According to the rheological measurements, plot the results as a graph of g against h and, for each point, record the suitability or otherwise of the concrete. Fig. 15 shows that the mix ($W/B = 0.28$) with fine workability tends to fall into a clear zone of $1.25 \leqq g \leqq 3.75$ N m and $2.45 \leqq h \leqq 7.35$ N m s. The result manifests the delineated zone gives the combinations of the values of g and h that are the acceptable range for high strength HPC. Obviously, HPC possesses a low g value and a high h value compared to that of ordinary concrete. A lower g value means HPC is apt to flow under its own weight, while a higher h value is required to prevent segregation of aggregates.

Finally, according to Eqs. (7) and (8), the units of g and h can be transferred into fundamental units of the yield shear τ_0 (Pa) and the plastic viscosity μ (Pa s), respectively. The ranges of the two Bingham constants of all the 49 high strength HPC mixes ($W/B = 0.28$) measured by the FHPCM rheometer are as follows: the values of τ_0 vary from 250 to 1400 Pa; the μ from 18 to 107 Pa s. The slump values of these concretes vary from 140 to 280 mm (see Table 6). On the whole, for HPCs with high flowability and adequate stability, the measurements by using the new rheometer give a fine relation between the torque and the rotational speed of spindle. Namely, the Bingham model describes well the flow properties of these HPCs.

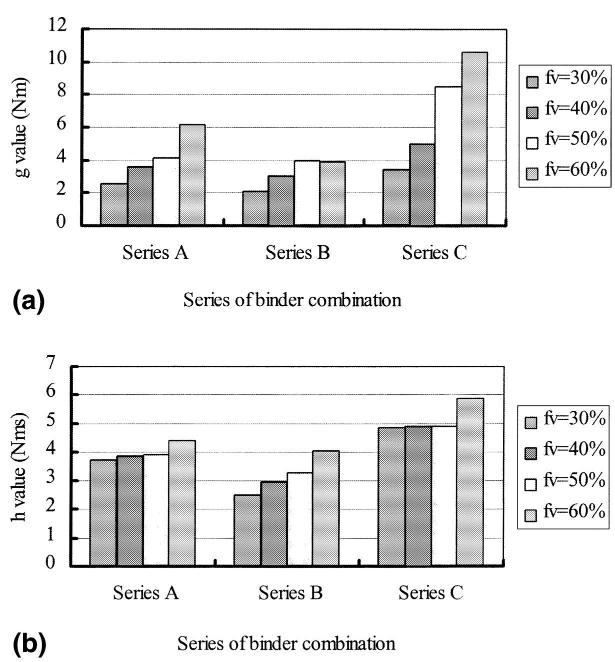


Fig. 14. Effect of binder combination on the g and h of HPC (mortar content = 65%). (a) g versus series of binder combination. (b) h versus series of binder combination.

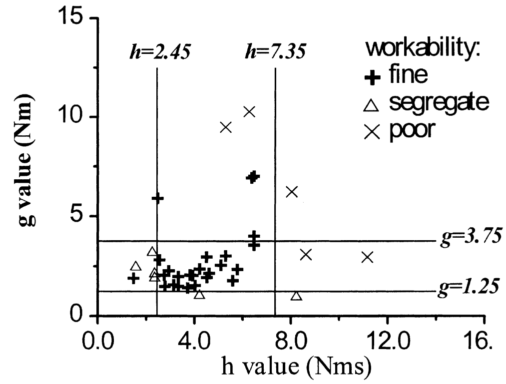


Fig. 15. Suitable range of g and h values for flowable high strength HPC ($W/B = 0.28$).

4. Conclusions

Based on test results, the following conclusions are drawn:

1. The apparent viscosity of paste obtained from rheological measurements can be used as an indicative for the workability of fresh HPC, and the superplasticizer dosage can be determined by investigating the viscosity of paste.
2. The rheological measurement and the flow test can effectively set an appropriate range of filling ratio for different composition of cement paste. The acceptable apparent viscosity of mortar under a shear rate of 1.05 s^{-1} should range from 3000 to 6000 mPa s to assure a mortar with adequate viscosity and flowability, it can be considered as a candidate grouting material for flowable HPC.
3. It is practicable that the flowability-based optimization of paste and mortar yields the required composition for flowable HPC. Accordingly, an acceptable range of mix proportions for HPC with fine workability is proposed, of which the required volume of paste range from 39% to 54% of that of the concrete.
4. Appropriate mix proportions of HPC are derived by carrying out a limited number of rheological measurements on pastes and mortars with appropriate variations in compositions, and slump-flow test on concrete. Since it avoids the need for an elaborated and tremendous task of trial mixes of concretes, this approach is considered applicable and reasonable.

5. The proposed Series A concrete possesses fine workability and segregation resistance; Series B concrete is apt to segregate for f_V within a range from 30% to 45%; Series C concrete shows poor workability as the f_V value exceeds 50%. For HPCs with high deformability without segregation of the materials, the measurements by using the new rheometer indeed result in a good relation between the torque and the rotational speed of spindle.
6. The FHPCM rheometer has been developed for the two Bingham constants for the fluid consistency of fresh HPCs. In evaluating the flow behaviour of fresh HPC, the use of the rheometer provides a more sensitive and reliable result than the slump and slump-flow tests. Furthermore, since it is fully automatic, the test results do not depend on the operator and the uncertainties due to human errors are eliminated.
7. As the rheological test results are represented by Bingham model, an increase of mortar content or a decrease of filling ratio of HPC tends to result in a smaller g value, corresponding to a better flowability.

Acknowledgements

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References

[1] BS1881 Testing Concrete: Part 102. Method for the determination of slump. British Standards Institution, 1983.
[2] BS1881 Testing Concrete: Part 105. Method for the determination of flow. British Standards Institution, 1984.
[3] JSCE-F503. Method of test for the slump flow of concrete. Standards of Japan Society of Civil Engineers, 1990.
[4] Wesche/Von Berg. Rheologische eigenschaften von zementleim und frishbeton. Beton 1973;(Januar):26,27.
[5] Ukraincik . Study on fresh concrete flow curve. Cement and Concrete Research 1980;10:203–12.
[6] Tattersall GH. Relationships between the British Standard test for workability and two-point test. Magazine of Concrete Research 1973;25(84):169–74.
[7] Tattersall GH, Bloomer SJ. Further development of the two-point test for workability and extension of its range. Magazine of Concrete Research 1979;31(109):202–10.
[8] Tattersall GH, Banfill PFG. Rheology of fresh concrete. London: Pitman, 1983:76–304.
[9] Wallevik OH, Gjorv OE. Development of a coaxial cylinders viscometer for fresh concrete. In: Proceedings of the International Conference on Properties of Fresh Concrete. London: Chapman & Hall, 1990:213–24.
[10] Tattersall GH. Workability and quality control of concrete. London: E & FN Spon, 1991:202–42.
[11] Hornung FE, Ulm, Schwenk Zementwerke KG. The use of the Brabender viscocorder to study the consistency of fresh mortar by two-point tests. In: Banfill PFG, editor. Rheology of fresh cement and concrete. The British Society of Rheology, 1991.
[12] Hu C, De Larrard F, Gjorv OE. Rheological testing and modeling of fresh high performance concrete. Materials and Structures 1995;28(175):1–7.
[13] Wallevik OH, Saasen A, Gjorv OE. Effect of filler materials on the rheological properties of fresh concrete. ACI Materials Journal 1995;92(5):524–8.
[14] Mork JH, Gjorv OE. Effect of gypsum-hemihydrate ratio in cement on rheological properties of fresh concrete. ACI Materials Journal 1997;94(2):142–6.
[15] De Larrard F, Hu C, Sedran T, Szitkar C, Joly M, Claux F, Derkx F. A new rheometer for soft-to-fluid fresh concrete. ACI Materials Journal 1997;94(3):234–43.
[16] Ferguson J, Kemblowski Z. Applied fluid rheology. London: Elsevier, 1991:47–134.
[17] DeLarrard F, Szitkar JC, Hu C, Joly M. Design of a rheometer for fluid concrete. In: Bartos PJM, editor. Special concretes: workability and mixing. London: E & FN Spon, 1991:201–208.
[18] Nobuaki O, Makoto H, Shigeyoshi N, Toshiro K. An experimental study on the fluidity of antiwashout underwater concrete. ACI Materials Journal 1996;93(1):20–5.