Cement & Concrete Composites 32 (2010) 450–460

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Development of a modified concrete rheometer to measure the rheological behavior of conventional and self-consolidating concretes

Wen-Chen Jau *, Ching-Ting Yang

Dept. of Civil Engineering, National Chiao-Tung University, Taiwan, ROC

ARTICLE INFO

Article history:
Received 11 May 2009
Received in revised form 6 December 2009
Accepted 4 January 2010
Available online 13 January 2010

Keywords:
Concrete rheometer
Rheological behavior
Yield torque
Viscosity

ABSTRACT

The modified concrete rheometer (MCR) apparatus developed in this study is based on existing concrete rheometers, the main differences being the gap size and measurement method, and thus the interpretation of the results. The gap between the inner cylinder wall and the tip of the vane was set to 6.4 times the diameter of the largest coarse aggregate in order to reduce interaction between the aggregate and the wall and the friction force from the wall. The MCR apparatus was used to measure yield torque directly at different low rotational speeds (above 0.003 rev/s). A study of the yield torque and viscosity of 37 fresh concrete mixtures was also made, with a particular focus on self-compacting concrete or self-consolidating concrete (SCC), and the results were compared with those obtained using other workability tests. The test results showed that the MCR can differentiate between conventional concrete (CC), powder-type SCC and SCC with viscosity-modifying agents (VMA). The rheological behavior of powder-type SCC was found to be influenced by the composition of Class F fly ash and ground granulated blast-furnace slag (GGBFS), and this type of concrete exhibited a wider range of viscosity and yield torque values. Despite the lower powder content and larger water to binder ratio (w/b), the viscosity of VMA-type SCC was shown to be slightly lower than that of powder-type SCC, and the values were clustered together within a certain range; thus, the workability of SCC containing VMA is more easily controlled. In addition, the MCR apparatus can also be applied to CC of differing viscosity and yield torque, thus making this apparatus suitable for determination of the workability of all kinds of fresh concrete.

1. Introduction

The slump test (ASTM C143 [1]) is often used to measure the workability of CC, while the slump flow test (ASTM C1611 [2]) is used for SCC and high-flowing concrete (HFC). Other existing test methods for SCC include the V-funnel flow test, the U-box-filling height [3,4], the J-ring test (ASTM C1621 [5]), and the column test [6]; the current standards in Taiwan are based on the slump flow, V-funnel, and U-box tests.

Previous studies have shown that concrete rheometer tests can be used to analyze the intrinsic properties of fresh concrete, such as viscosity and yield stress [7–9]. Commonly-used concrete rheometers include: (1) coaxial rheometers (BML [10], CEMAGREF-IMG [7]); (2) Laboratoire Central des Ponts et Chaussées (LCPC) rheometers (BTRHEOM [11]); and (3) mixing action rheometers with an impeller (IBB [12–16], ICAR [17–20], a two-point apparatus [21,22]). Notwithstanding the considerably different geometries, the basic principle is to measure the relationship between the torque (T) and rotational speed (N); the slope (h) of the oblique line and the intercept (g) of the torque axis after linear regression can then be obtained, as shown in Eq. (1). According to the theoretical model of the rheometer as described by Tattersall and Banfill [21], the rheology of concrete can be simulated using the Bingham model, as shown in Eq. (2), for which a shear stress (τ) similar to static friction exists prior to the initiation of flow (strain rate). Only when the shear stress reaches a critical value does the shear strain rate ($\dot{\gamma}$) begin to change. Eq. (1) can be converted to represent the relationship between shear stress and shear strain rate, as shown in Fig. 1; therefore, the plastic viscosity and yield stress can then be calculated, as shown in Eq. (2).

$$T = hN + g \quad (1)$$

$$\tau = \tau_y + \eta\dot{\gamma} \quad (2)$$

These two parameters, the yield stress (τ_y) and the plastic viscosity (η), are used to characterize the workability of concrete. In particular, yield stress is closely related to slump and slump flow, while plastic viscosity is more related to the strain rate of slump flow [21,23]; Wallevik [10] pointed out that for various concrete mixture proportions, the yield stress and the plastic viscosity behaviors of fresh concrete differ: yield stress distinctly increases with time, while plastic viscosity is not obviously affected. Thus,

* Corresponding author. Tel.: +886 3 5712121; fax: +886 3 5734111.
E-mail addresses: jau@mail.nctu.edu.tw, rt007585@mail.ruentex.com.tw (W.-C. Jau).

0958-9465/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2010.01.001

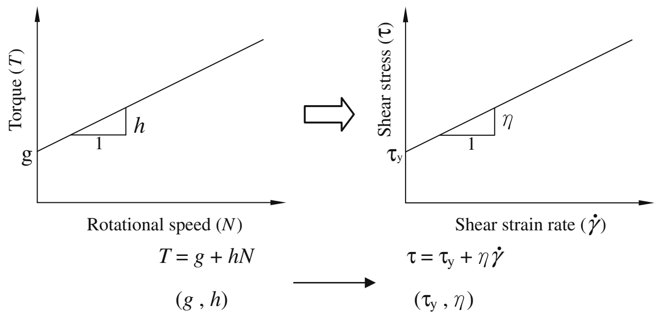

Fig. 1. The Bingham model transform.

the workability of concrete can be measured using a concrete rheometer, as once the yield stress and plastic viscosity have been found, the rheological behavior of fresh concrete can then be determined.

Boger et al. proposed an approach to obtaining the yield stress that differs from the Bingham model [24,25], which involved using a vane rheometer to measure the maximum value of the torque of the plastic material at a very low rotational speed and converting the torque into yield stress using a theoretical model. This approach was demonstrated using a vertical four-bladed vane in a suspended solution system such as bentonite gels to obtain the yield stress [26]. Other studies have applied this method to various commercial greases [27], oil-in-water emulsions [28], and an oil-well cement slurry [29].

Saak [30] used a rotational rheometer to investigate the influence of wall slip on the shear yield stress of cement paste. The maximum shear stress (τ_{max}) can be obtained by measuring the maximum peak value of the torque (T_{max}) under a given rotational speed. The minimum of τ_{max} measured at different rotational speeds is defined as the yield stress, and the peak of the shear stress–time plot is referred to as the dynamic yield stress ($\tau_{y(d)}$), which denotes the onset of viscous flow. Traditionally, the dynamic yield stress is taken as the true yield stress of the material, as it represents the full breakdown of the structural network [30]. Schwartzentruber et al. [31] studied the rheological behavior of fresh cement pastes formulated from SCC, and used the vane method to measure the evolution of torque at an extremely low speed over a constant duration, finding that the maximum value of the shear stress corresponded to the yield stress.

Some scholars [17–20] used the ICAR (International Center of Aggregates Research) concrete rheometer and a testing method known as the stress growth test, which measures the maximum torque of the concrete at a fixed rotational speed (0.025 rev/s) and establishes the relationship between the slump, slump flow and maximum torque of fresh concrete. In this study a wide scatter pattern of the measured torque values was demonstrated, which was attributed to effects of the coarse aggregates. In addition, for a convenient *in situ* test, Roussel [32] developed a vane shear apparatus similar to that used for the field vane shear test in soil mechanics. A scissometer was used to measure the fresh concrete yield stress in order to evaluate the thixotropic behavior of SCC, and the uncertainty of this measurement was estimated to be around 15%.

Ferraris and de Larrard [33] pointed out that the gap between the aggregate and the wall of the rheometer needs to be at least three to five times the size of the largest coarse aggregate in order to avoid interaction. Table 1 summarizes the gap size *versus* max. coarse aggregate size for various popular rheometers.

2. Experimental program

The MCR apparatus is geometrically similar to the popular commercial IBB and ICAR rheometers, the differences in this study compared to previous studies using IBB and ICAR being the size of the gap, shape of the vanes, and method of obtaining the min. yield stress. In order to enable fair comparison, the tests conducted in this study were very similar to those performed in previous researches using IBB [12–16] and ICAR apparatus [17–20], such as the range of rotational speed and calculation of viscosity. Due to the inherent characteristics of the MCR apparatus, there was no intention in this study of comparing the results to those of investigations using rheometers with a very small gap between the vanes and the inner cylinder wall.

2.1. Materials

The cementitious materials used in this study include Portland Type I cement, GGBFS and Class F fly ash, as listed in Table 2. It should be noted that the low-calcium fly ash, ASTM Class F, exhibits slower rates of strength development and does not show early hydration reactions. In addition, the loss of ignition of Class F fly ash was 5.31%, and this combustible material may absorb SP and water, which causes a reduction in workability [34,35,39]. The size distributions of the coarse and fine aggregates are given in Fig. 2. The fine aggregate used in this study was river sand, with a fineness modulus (FM) of 2.8; the coarse aggregate and sand had specific gravities of 2.61 and 2.65, and absorptions of 0.85% and 1.44%, respectively. Two types of high-range water-reducing admixtures (HRWRAs) were used: (1) polynaphthalene sulphonate (PNS) and (2) polycarboxylic acid (PC). The PNS-based HRWRA used for CC had a solids content of about 39.5% with a specific gravity of 1.22; the PC-based HRWRA had a solids content of about 30.2% with a specific gravity of 1.07 and was used for the SCC, HFC and high-viscosity underwater concrete (HVUWC). The commercial

Table 2
Chemical and physical characteristics of cementitious materials.

	Type I Portland cement	GGBFS	Class F fly ash
SiO_2 (%)	20.11	33.52	50.70
Al_2O_3 (%)	5.31	14.42	24.60
Fe_2O_3 (%)	3.68	0.29	4.91
CaO (%)	62.76	42.80	2.33
MgO (%)	2.96	5.91	1.01
Na_2O (%)	0.21	0.31	0.05
K_2O (%)	0.34	0.25	1.74
LOI (%)	0.92	0.30	5.31
Specific gravity	3.15	2.91	2.17
Blaine surface area (m^2/kg)	340	414	360

Table 1
Gaps of concrete rheometers.

	BML C-2000 [7,8,10]	CEMAGREF-IMG [7]	IBB [12–16]	Mk II [21]	TRM [23]	ICAR [17–20]	MCR
Gap (mm)	45	220	50	47	25.6	140	160
Gap/max. coarse aggregate size	1.8	8.8	2.0	1.9	1.0	5.6	6.4

Note: gap: the width between the inner cylinder wall and the tip of the vane.
Max. coarse aggregate size: 25.0 mm (1in.).

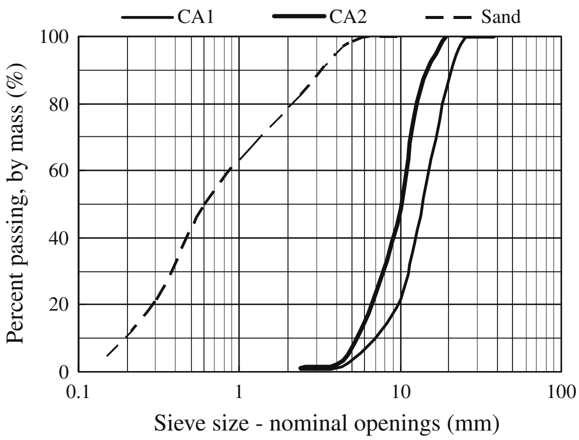

Fig. 2. Grain size distributions of coarse aggregates and sand. [#]CA1: coarse aggregate with a max. size of 25.0 mm (1 in.). [&]CA2: coarse aggregate with a max. size of 19.0 mm (3/4 in.).

VMAs used were as follows: (1) water-soluble powder hydroxypropyl methyl cellulose (HPMC), denoted H; (2) water-soluble starch ether derivatives in powder and emulsion form, denoted S1 and S2, respectively – S2 had a solid content of about 20.3%; and (3) a water-soluble acrylic-based polymer with a solid content of about 7.5%, denoted A.

2.2. Mixture proportions

The mixture proportions used in this study are shown in Table 3. The SCC had the following target values: slump ⩾25 cm; slump flow ⩾50 cm; V-funnel flow time ⩽20 s; U-box-filling height (Bh) ⩾ 30 cm [3,4]. The mixtures denoted SCC-1–11 were powder-type SCC containing GGBFS and Class F fly ash in differing proportions, with a coarse aggregate content of 773 kg/m^3 and a powder content of 500 kg/m^3. For the SCC with VMA, the water to binder ratios were 0.5, 0.45, and 0.35, with different types of VMA added: HPMC for SCC-H-12–14; HPMC and starch ether derivatives (powder) for SCC-H-S1-15–17; starch ether derivatives (powder) for SCC-S1-18–20; starch ether derivatives (emulsion) for SCC-S2-21–23; and acrylic-based polymers for SCC-A-24–25. HVUWC-26–28 included an anti-washout agent for underwater application, with slump ⩾22 cm; CC-29–34 were conventional concretes with water to binder ratios of 0.5 and different dosages of PNS-based HRWRA; and HFC-35–37 were high-flowing concrete with a coarse aggregate content of 838 kg/m^3, higher than that of SCC-1–11, slump ⩾22 cm, and slump flow ⩾50 cm.

2.3. Test apparatus and measurements

The MCR apparatus used in this study to measure the yield torque and viscosity of fresh concrete consisted of a drum of a large diameter of 500 mm with a high capacity of 0.108 m^3, as shown

Table 3
Concrete mixture proportions.

Mixture no.	*w/b*	Cement (kg/m^3)	GGBFS (kg/m^3)	Class F fly ash (kg/m^3)	CA [b](kg/m^3)	Sand (kg/m^3)	HRWRA		VMA ([c]mass of powder (%))			
							PC[a]	PNS[a]	H	S1	S2	A
SCC-1	0.315	500	0	0	773	891	1.1	–	–	–	–	–
SCC-2	0.378	400	0	100	773	830	1.1	–	–	–	–	–
SCC-3	0.384	300	0	200	773	782	1.2	–	–	–	–	–
SCC-4	0.388	200	0	300	773	734	1.3	–	–	–	–	–
SCC-5	0.354	400	100	0	773	895	1.1	–	–	–	–	–
SCC-6	0.360	300	200	0	773	881	1.1	–	–	–	–	–
SCC-7	0.366	200	300	0	773	867	1.1	–	–	–	–	–
SCC-8	0.352	400	70	30	773	878	1.1	–	–	–	–	–
SCC-9	0.350	325	123	53	773	879	1.1	–	–	–	–	–
SCC-10	0.362	250	175	75	773	839	1.2	–	–	–	–	–
SCC-11	0.357	175	228	98	773	832	1.2	–	–	–	–	–
SCC-H-12	0.50	210	140	0	804	983	1.2	–	–	–	–	–
SCC-H-13	0.50	210	140	0	804	983	1.2	–	0.05	–	–	–
SCC-H-14	0.50	210	140	0	804	983	1.2	–	0.10	–	–	–
SCC-H-S1-15	0.50	210	140	0	804	983	1.2	–	0.03	0.05	–	–
SCC-H-S1-16	0.45	247	164	0	804	904	1.2	–	0.03	0.05	–	–
SCC-H-S1-17	0.35	317	211	0	804	801	1.3	–	0.03	0.05	–	–
SCC-S1-18	0.50	210	140	0	804	983	1.2	–	–	0.05	–	–
SCC-S1-19	0.45	247	164	0	804	904	1.2	–	–	0.05	–	–
SCC-S1-20	0.35	317	211	0	804	801	1.3	–	–	0.05	–	–
SCC-S2-21	0.50	210	140	0	804	983	1.3	–	–	–	0.75	–
SCC-S2-22	0.45	247	164	0	804	904	1.3	–	–	–	0.75	–
SCC-S2-23	0.35	317	211	0	804	801	1.2	–	–	–	0.75	–
SCC-A-24	0.50	261	93	19	773	913	1.2	–	–	–	–	0.67
SCC-A-25	0.45	342	122	24	773	777	1.0	–	–	–	–	0.67
HVUWC-26	0.50	408	0	72	773	718	1.0	–	0.70	–	–	–
HVUWC-27	0.45	453	0	80	773	670	1.0	–	0.70	–	–	–
HVUWC-28	0.35	559	0	99	773	583	1.0	–	0.70	–	–	–
CC-29	0.50	280	84	36	1017	762	–	–	–	–	–	–
CC-30	0.50	280	84	36	1017	762	–	0.2	–	–	–	–
CC-31	0.50	280	84	36	1017	762	–	0.4	–	–	–	–
CC-32	0.50	280	84	36	1017	762	–	0.6	–	–	–	–
CC-33	0.50	280	84	36	1017	762	–	0.7	–	–	–	–
CC-34	0.50	280	84	36	1017	762	–	0.8	–	–	–	–
HFC-35	0.40	225	180	45	838	867	1.2	–	–	–	–	–
HFC-36	0.45	200	160	40	838	912	1.2	–	–	–	–	–
HFC-37	0.49	175	140	35	838	985	1.3	–	–	–	–	–

[a] PNS-based HRWRA was used for CC; PC-based HRWRA was used for SCC, HVUWC and HFC.
[b] The grain size of the coarse aggregate for CC was 30% CA1 + 70% CA2; the others were CA2 only.
[c] The powder mass is the mass of the cement, GGBFS and Class F fly ash.

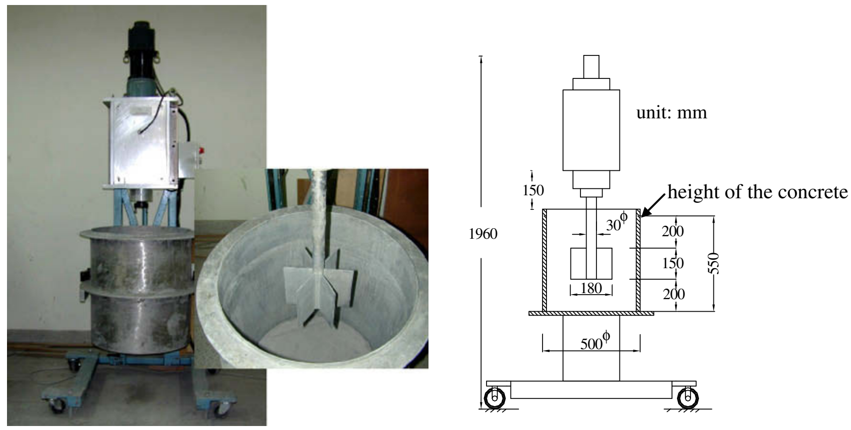

Fig. 3. The MCR apparatus, vane, and principle dimensions.

in Fig. 3; the gap was 160 mm, which is about 6.4 times the maximum aggregate size of 25 mm, chosen in order to avoid the wall effect. The vane had six blades, with a spacing of 60°, whereby the radius ratio (r_1/r_0) of the vane (r_1) and steel drum (r_0) was 0.36. This apparatus was designed to measure torque at low rotational speeds (above 0.003 rev/s): torque and rotational speed were measured and stored in the data acquisition system, which was connected to a computer. The measurable range of the torque and the maximum data collection frequency were 0.01–100.00 N m and 60 Hz, respectively. A built-in program was used to read the data and plot charts.

This apparatus was used to measure the fresh concrete torque at different rotational speeds, which was then converted to yield torque and viscosity. Workability tests such as the slump, slump flow, V-funnel flow time, and box-filling height test were conducted to identify any correlation of yield torque with viscosity. CC, HFC, HVUWC, and in particular, different types of SCC were tested in order to assess the effectiveness of the MCR. As the gap of the MCR apparatus was relatively large, the measured data could not be transformed into yield shear stress and viscosity in fundamental units, owing to the fact that the shear strain rates measured at the drum do not have a linear flow gradient relationship with the shearing surface [33].

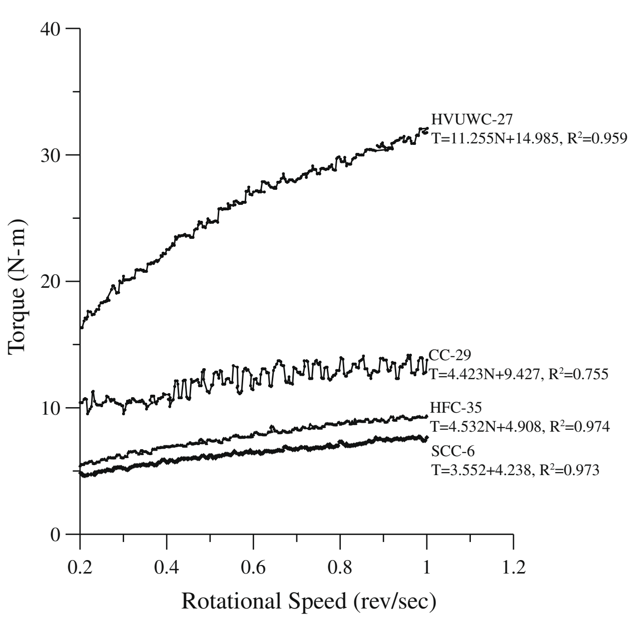

Fig. 4. Typical rheological curves of fresh concrete (using SCC-6, HFC-38, CC-31, and HVUWC-27 as examples).

2.3.1. Plastic viscosity measurement

In this test, the rotational speed was set to change from 0.2 rev/s to 1.0 rev/s within 30 s and the plastic viscosity was calculated as the slope of the linear regression of torque and rotational speed, as shown in Fig. 4. Similar ranges of rotational speed, the unit of which is N m s, have been used by many other researchers, for example, Beaupré et al. [7,8], Khayat et al. [12–16] and Koehler et al. [17–20].

2.3.2. Yield torque measurement

In this study, referring to Saak et al. [30–32], the torque was measured at a rather low rotational speed using a vertical six-bladed vane. Under a given rotational speed, the torque can be obtained by:

$$T = 2\pi r_1^2 H \tau_c + 4\pi \int_0^{r_1} \tau_e r^2 \, dr \qquad (3)$$

where T is the torque (N m), r_1 is the vane radius (90 mm), H is the vane height (150 mm), τ_c is the shear stress (Pa) at the tip of the vane, and τ_e is the shear stress (Pa) along the top and bottom edges of the vane. The maximum torque measured at the fixed speed is as shown in Fig. 5; the minimum torque of T_{max} at different rotational

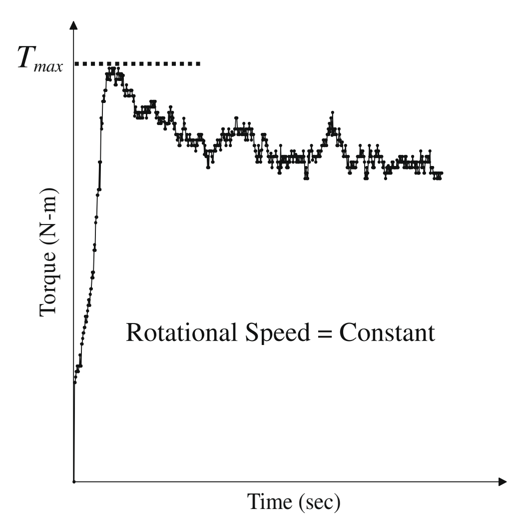

Fig. 5. Illustration of the maximum torque measurement method.

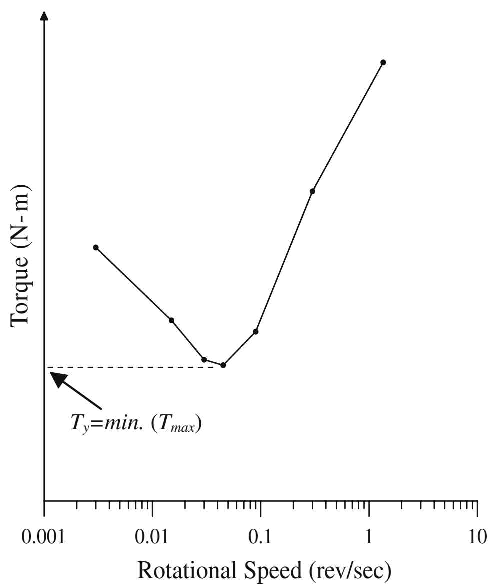

Fig. 6. Illustration of the yield torque measurement method.

speeds was then defined as the yield torque (T_y), as shown in Fig. 6. (The same test method was used by Saak et al. [30], while similar methods were also used in other studies [25,29].) Note that the different rotational speeds were reached within a very short period of time, i.e., 0.1 s.

2.4. Testing procedures

Following the mixing of 0.15 m^3 of fresh concrete, various workability tests were performed, as shown in Table 4. Slump was measured according to ASTM C143 [1]; slump flow (ASTM C1611 [2]) was measured as the average of the maximum and minimum diameters of the spread of the concrete after the standard slump test; and the U-box-filling height and V-funnel flow time according to JSCE [4] were ascertained for each SCC, HVUWC, and HFC, as shown in Figs. 7 and 8. Fresh concrete was also assessed using the MCR, and the yield torque was measured at seven rotational speeds, specifically, 0.003, 0.015, 0.03, 0.045, 0.090, 0.300, and 1.35 rev/s. The torque of the concrete was subsequently measured as the rotational speed of the vane increased from 0.2 to 1.0 rev/s in 30 s.

Concrete cylinder specimens ($\varnothing 15 \times 30$ cm) were made according to ASTM C192 [36], while to obtain SCC specimens, concrete was poured into molds without consolidation. The 28-day compressive strength test was then conducted according to ASTM C39 [37].

3. Test results and discussion

3.1. Comparison of the rheological behavior of the different types of fresh concrete

This study investigated the relationship between torque and rotational speed as measured using the MCR. Linear regression was performed on the data and the R^2 values of the regression for SCC and HFC were found to be above 0.9, as shown in Fig. 4. It was also found that the torque values fluctuated erratically for CC because of its poor workability. The resistance of the coarse aggregate against the rotation of the vane was higher for CC than for SCC and HFC, and the R^2 values of linear regression for CC were below 0.9. The experimental results showed that fresh concrete of better workability and higher uniformity yielded a rheological behavior more suitable for applying linear regression. With regards to the rheological behavior of HVUWC, the torque and the slope (viscosity) were larger than those of the other concretes tested at the same rotational speed due to the higher viscosity required for its anti-washout property.

3.2. Influence of mixture proportions on the workability of powder-type SCC

SCC has been developed and used in Japan since the 1980s, and can be divided into three types: powder-type, VMA-type, and combination-type [3,4], of which powder-type SCC (without VMA) includes Class F fly ash and GGBFS as the cementitious materials and limestone powder as the inorganic filler to replace part of the cement or fine aggregate, and has a larger powder content (480–700 kg/m^3) in order to enable the consistency of the concrete to be controlled. However, powder-type SCC is very sensitive to water variance, which greatly affects the self-compacting property, causing problems in producing stable SCC. The addition of VMA to SCC solves this problem, effectively improving the anti-segregation property and stability of the fresh concrete [38]. Such types of concrete are referred to as VMA-type SCC and combination-type SCC, the powder contents of which are in the range of 300–450 kg/m^3 and 450–600 kg/m^3, respectively [3,4].

In this study, it was found that the higher the replacement ratio of Class F fly ash, the higher the yield torque, as shown in Table 4 and Fig. 9. Therefore, inclusion of an adequate replacement amount of Class F fly ash could improve the workability of powder-type SCC; however a high volume of Class F fly ash (SCC-3, SCC-4) reduces the workability of the concrete, a possible reason for which is that Class F fly ash may absorb water and HRWRA [34,35,39]. In the same table and figure, it is shown that at a 60% replacement ratio of GGBFS, the yield torque is lowest. A higher GGBFS content was found to reduce the yield torque in the different types of concrete examined in this study.

Fig. 10 shows the viscosity data for the powder-type SCC. The amount of Class F fly ash used in this study did not change regularly; on the other hand, the more GGBFS that was used, the higher the viscosity. Nevertheless, the viscosity of the concrete mixed using replacement ratios of 20% and 40% was lower than that of the control concrete.

In SCC-8–11, supplementary cementitious materials (SCM) composed of GGBFS and Class F fly ash (at a mass ratio of 7:3) were used to replace cement. When the replacement ratio of SCM was higher than 35% of the cement, the viscosity began to increase, while the yield torque decreased, as shown in Fig. 11. This is because the higher the replacement ratio, the higher the content of SCM, and as mentioned in previous paragraphs, SCM is composed of 70% GGBFS, and hence the overall rheological behavior is then controlled by GGBFS – i.e., the greater the SCM content, the lower the yield torque and the higher the viscosity.

3.3. Influence of VMA on the workability of SCC and HVUWC

Khayat [40] indicated that commonly-used VMAs in cement-based materials include polysaccharides of microbial or starch sources, cellulose derivatives, and acrylic-based polymers. The results of the tests conducted in this study showed that the viscosity of VMA-type SCC increased with increased dosage of HPMC, along with producing a reduced yield torque, as shown in Fig. 12, thereby improving the self-compactability of the concrete. It can be seen from Fig. 13 that the viscosities of all of the VMA-type SCC were lower than those of the powder-type SCC, with the exception of SCC-HS1-17, SCC-S1-20, SCC-S2-23, and SCC-H-14. The first three of these mixes had a *w/b* of 0.35, and the amount of powder

Table 4
Test results.

Mixture no.	Workability test				Rheological parameters		Mechanical test
	Slump (cm)	Slump flow (cm)	U-box-filling height (cm)	V-funnel flow time (s)	Yield torque, T_y (N m)	Viscosity, *h* (N m s)	28-day compressive strength (MPa)
SCC-1	28	72	30	10	3.83	3.77	65.4
SCC-2	28	72	31	7	1.47	4.36	43.2
SCC-3[a]	*24*	*42*	31	8	4.32	5.42	32.7
SCC-4[a]	*24*	*44*	30	7	8.34	4.60	23.2
SCC-5	28	72	30	4	5.98	3.24	57.8
SCC-6	28	73	31	10	4.51	3.55	53.5
SCC-7	26	66	31	7	0.69	4.41	54.9
SCC-8	27	70	30	5	7.65	2.94	53.5
SCC-9	25	65	30	7	6.57	2.94	50.1
SCC-10	28	73	30	5	3.43	4.62	47.3
SCC-11	27	70	31	11	2.06	7.84	34.0
SCC-H-12[a]	26	61	*19*	16	2.83	1.88	35.2
SCC-H-13	27	66	31	12	2.28	2.38	33.5
SCC-H-14	27	67	31	20	2.11	4.03	31.8
SCC-H-S1-15	27	68	31	6	2.11	1.48	34.9
SCC-H-S1-16	26	63	31	5	1.48	1.42	40.0
SCC-H-S1-17	26	60	31	9	4.41	2.76	63.7
SCC-S1-18[a]	25	58	*21*	10	4.12	1.58	34.6
SCC-S1-19	26	64	31	6	3.43	1.88	48.5
SCC-S1-20	27	68	31	6	1.53	2.94	64.5
SCC-S2-21[a]	26	60	*15*	18	3.13	1.94	32.8
SCC-S2-22	26	65	31	9	2.21	2.59	48.1
SCC-S2-23	27	70	31	6	1.58	4.60	70.5
SCC-A-24	26	53	31	8	3.50	1.82	44.2
SCC-A-25	28	64	31	7	2.65	2.48	47.0
HVUWC-26[a]	27	61	30	*120*	1.15	6.60	23.2
HVUWC-27[a]	26	57	30	*285*	3.40	11.26	33.7
HVUWC-28[a]	*24*	*45*	*19*	*378*	4.97	14.13	40.5
CC-29	5	–	–	–	30.70	4.42	33.8
CC-30	8	–	–	–	27.57	4.53	35.1
CC-31	12	–	–	–	22.95	4.66	36.2
CC-32	15	–	–	–	11.48	4.30	35.7
CC-33	18	–	–	–	9.91	2.71	34.8
CC-34	22	–	–	–	9.81	1.77	36.5
HFC-35[a]	26	65	*26*	8	5.98	4.53	53.0
HFC-36[a]	26	63	*21*	16	6.77	3.77	49.1
HFC-37[a]	25	59	*17*	10	3.15	2.41	42.8

The italicised test values do not meet the target values.
[a] Workability experiment results did not fully meet the following requirements: slump of SCC, ⩾25 cm; slump flow, ⩾50 cm; V-funnel flow time, ⩽20 s; U-box-filling height, ⩾30 cm.

reached 528 kg/m^3. The higher the dosage of powder, the lower the *w/b*, and the necessary addition of VMA therefore caused the high viscosity.

Fig. 13 also shows that most yield torque–viscosity test results of the VMA-type SCC were distributed within a certain area, the box marked by the dashed lines, which is relatively narrow as compared with the distribution range for the powder-type SCC. VMA-type SCC is easy to produce and has a comparatively more stable workability owing to the high moisture variation tolerance of the fine aggregates [41,42].

As shown in Figs. 14 and 15, among the VMA-type concrete with a *w/b* of 0.5 used in this experiment, the yield torque of the SCC with HPMC was lower than that of the starch ether-type or acryl-type SCC, while its viscosity was higher. From Fig. 15, it can also be seen that a decrease in *w/b* causes an increase in the viscosity, due to more powder being used for a lower *w/b* mix.

SCC-H-S1-15–17, shown in Table 3, contained VMA made from a mixture of HPMC and starch ether derivatives. The viscosities of these concretes were similar to those of SCC with starch ether derivatives only (SCC-S1-18–20), as shown in Fig. 15; however, the yield torque varied irregularly, as shown in Fig. 14. For SCC containing an acrylic-based polymer, the viscosity and yield torque variations were similar to those of the SCC with starch ether, and a larger amount of powder in the mixture proportions led to a smaller yield torque and a slight increase in viscosity.

The high viscosity of HVUWC containing a high dosage of HPMC reduced the segregation or washout in water [43,44], and the yield torque was between 1.15 and 4.97 N m, similar to that of VMA-type SCC; however, it had the highest viscosity of 14.13 N ms, which is far larger than the viscosities of the other types of concrete studied, as shown in Table 4. Therefore, although the box-filling height of HVUWC reached 30 cm at *w/b* ratios of 0.5 and 0.45, the V-funnel flow time were 120 s and 285 s, respectively. These flow times are much longer than those of other types of SCC; however, HVUWC still meets the self-consolidating property and can fill the formwork at these high viscosities.

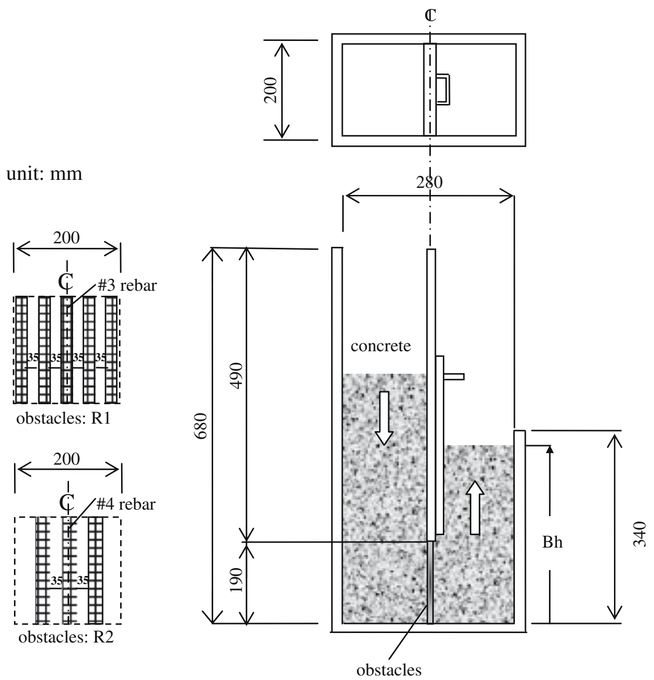

Fig. 7. Apparatus for the U-box-filling height test, used to assess the passibility of SCC through obstacles.

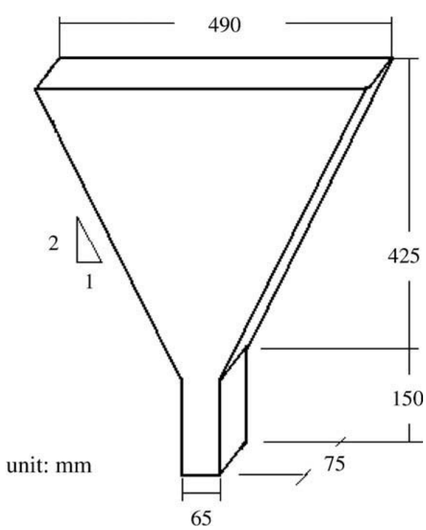

Fig. 8. The V-funnel test apparatus, used to assess the flowability of SCC.

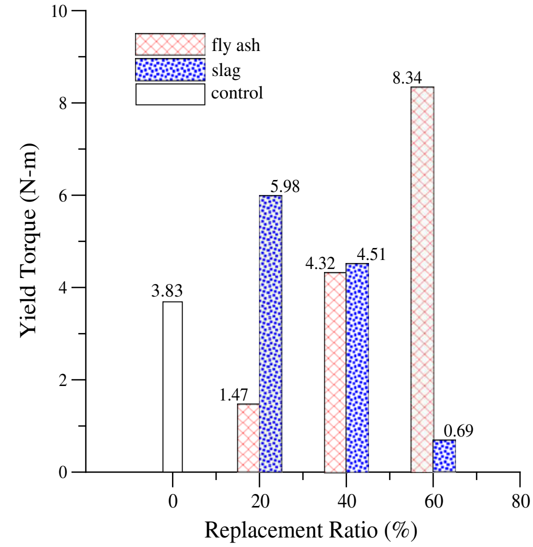

Fig. 9. Effect of the replacement ratio of GGBFS and Class F fly ash on the yield torque of powder-type SCC.

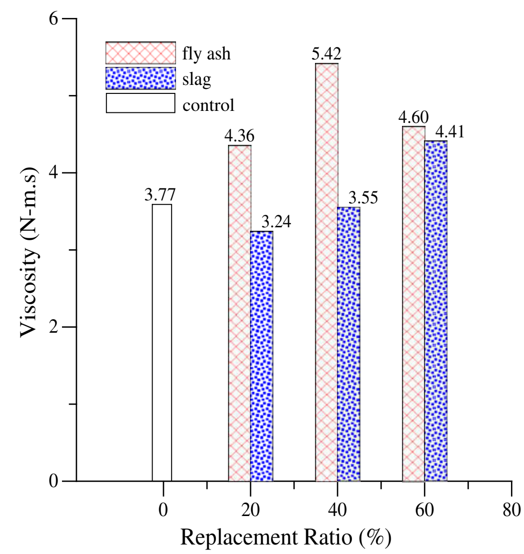

Fig. 10. Effect of the replacement ratio of GGBFS and Class F fly ash on the viscosity variation of powder-type SCC.

3.4. Comparison of the rheological behavior and on-site workability test results

3.4.1. Relationship between rheological behavior and slump

The slump test has long been used as an index of workability; however the flowability, pumpability, self-compactability, and segregation resistance cannot be obtained from the slump test. Therefore, this study used a MCR apparatus to measure the internal physical parameters of the concrete, and analyzed the relationships between yield torque, viscosity, and slump, as shown in Fig. 16. A smaller concrete slump means a larger yield torque and viscosity. The concrete mixture proportions of CC-29–34 were the same except for the dosage of superplasticizer, a higher dosage of which led to a larger slump and increased lubrication between the particles within the concrete. The linear relationship between slump and yield torque can be represented as in Eq. (4), and the slump and viscosity can be represented as in Eq. (5):

$$T_y = -1.750 \times \text{Slump} + 41.168; \quad R^2 = 0.946 \tag{4}$$

$$\eta = -0.004 \times \text{Slump}^3 + 0.118 \times \text{Slump}^2 - 0.992 \times \text{Slump} + 6.984; \quad R^2 = 0.935 \tag{5}$$

However, de Larrard [11] pointed out that, for the same cone slump, the viscosity of concrete can vary by a factor of 1–4. The relationship between viscosity and slump needs further study in order to better understand the effect of viscosity on slump. These equations apply to CC, as the slump test is not suitable for SCC, for which the slump flow test is usually performed.

3.4.2. Relationship between rheological behavior and slump flow

Although different types of SCC can be of similar workability, such as powder-type SCC (SCC-1, 2, 5, 6, 8, 11) and VMA-type SCC (SCC-S2-23), with a slump flow of 70–73 cm, the yield torque

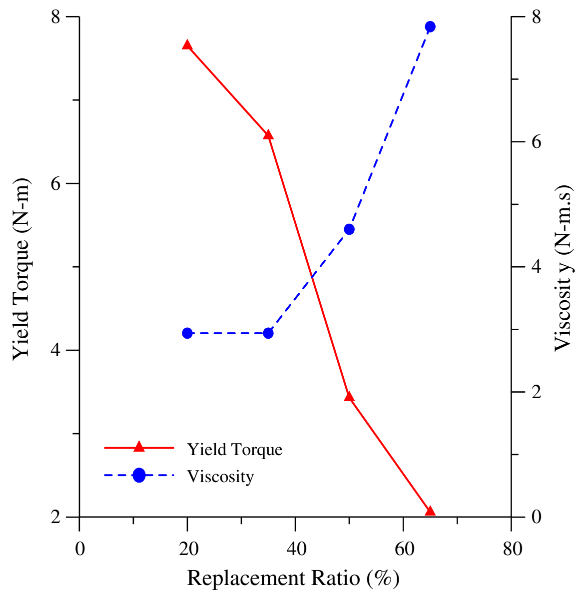

Fig. 11. Effect of the replacement ratio of SCM (GGBFS: Class F fly ash = 7:3) on the yield torque and viscosity of powder-type SCC.

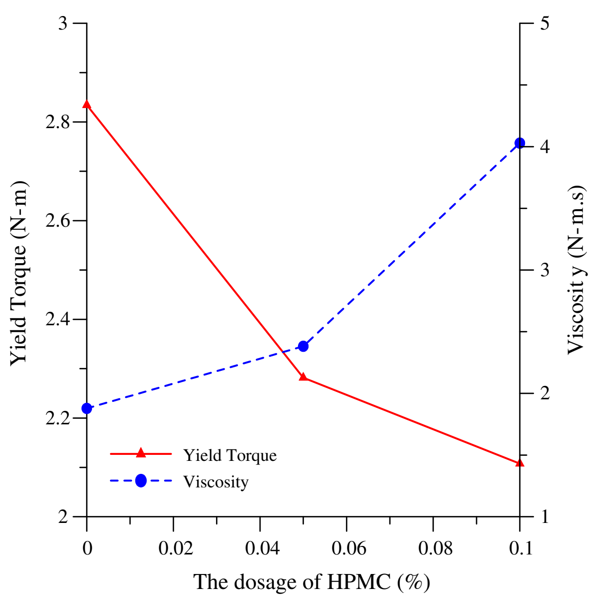

Fig. 12. Influence of HPMC dosage on the variation in yield torque and viscosity of VMA-type SCC.

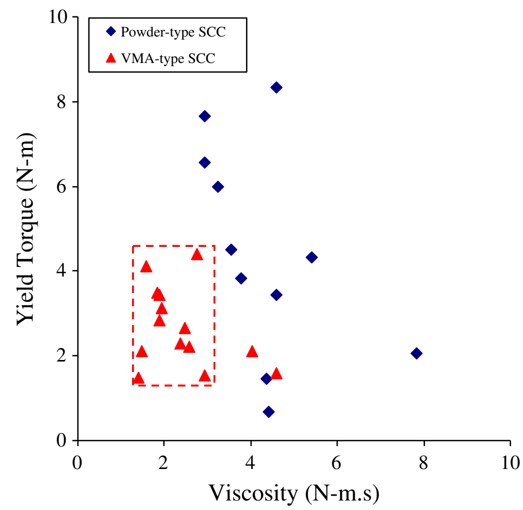

Fig. 13. Relationship between the viscosity and yield torque of powder-type SCC and VMA-type SCC.

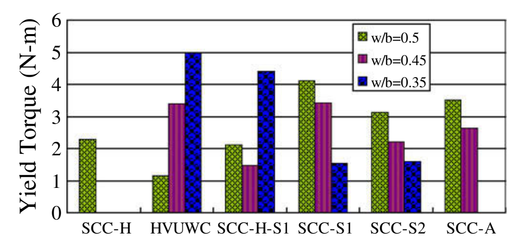

Fig. 14. Effect of *w/b* on yield torque for concrete with VMA.

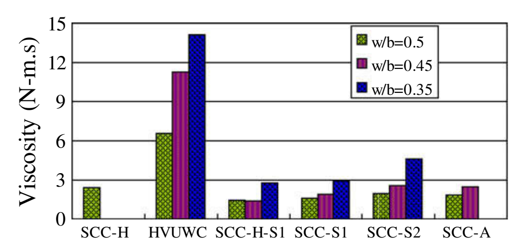

Fig. 15. Effect of *w/b* on viscosity for concrete with VMA.

and viscosity may differ greatly, as shown in Table 4. The slump flow depends on both the yield torque and viscosity and is not influenced by only one single physical property. Ferraris used thirteen concrete mixes targeted to the same slump flow with a variable dosage of HRWRA. These mixes showed a wide range of flow properties; therefore, the slump flow alone is not sufficient information from which to determine whether a flowable concrete is SCC [45]. The rheological behavior of VMA-type SCC showed that the larger the slump flow, the smaller the yield torque, as shown in Fig. 17. The variation in the yield torque of the VMA-type SCC was smaller than that of the powder-type SCC, and the slump flow was found to be about 60 ± 10 cm, indicating that the VMA-type SCC was relatively more stable than the powder-type SCC. In addition, slump flow was found to correlate better with yield torque than with viscosity, as shown in Fig. 17. These findings are in agreement with the results of Sedran [46].

3.4.3. Relationship between rheological behavior and V-funnel flow time

The V-funnel flow time of the powder-type SCC was found to be within 4–11 s, that of the VMA-type SCC was within 5–20 s, and that of the HFC was within 8–16 s, as shown in Table 4. The test results show that the yield torque of the VMA-type SCC increased gradually when the V-funnel flow time increased from 5 to 12 s. No clear relationship between viscosity and yield torque was found for powder-type SCC in this test. Domone [47] showed that there are no obvious relationships between V-funnel flow time, slump flow, and T_{50} (the time at which the slump flow diameter reaches 50 cm). The greater the coarse aggregate content (larger yield torque), the longer the V-funnel flow time. However, in this study, the coarse aggregate contents of the VMA-type SCC and HFC were only slightly higher than that of the powder-type SCC, and therefore the

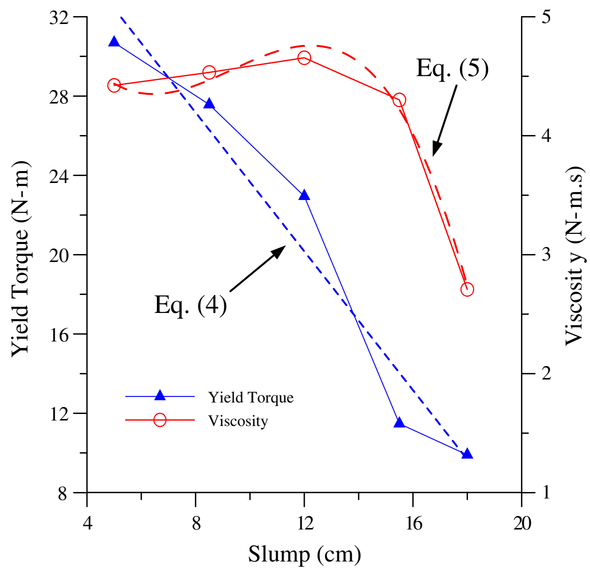

Fig. 16. Relationship between the viscosity, yield torque, and slump of CC.

difference in the V-funnel flow time was not significant. In addition, the high viscosity of the underwater concretes HVUWC-26–28 resulted in a V-funnel flow time greater than 120 s. For a given deformation capacity, the longer the flow time, the higher the viscosity of the concrete [12]; therefore, higher viscosity and yield torque greatly prolonged the V-funnel flow time. Similar results were also reported by Chai [48].

3.4.4. Relationship between rheological behavior and U-box-filling height

According to the reports of Okamura et al. [3,4], the absolute volume of coarse aggregate (with a maximum aggregate size of less than 19 mm) should be within 0.3–0.32 m^3 in order to pass through the gap of the steel bars in the U-box test (R2 grade). If the coarse aggregate content is too high, it will easily become blocked between the bars. The absolute volume of the coarse aggregate in this study was about 0.3 m^3, which reduced the possibility of blockage. In this research, the viscosity and yield torque of both the powder-type and VMA-type SCC were not found to be obviously related to the U-box-filling height. Even the filling heights of HVUWC-26–27, were greater than 30 cm, owing to its low yield torque (but the V-funnel flow time was long). Because of the high absolute volume of the coarse aggregate (0.32 m^3) and the low powder volume of HFC-35–37, these concretes did not pass the U-box filling test. From Table 4, it can be seen that the highest yield torque of concrete with the ability to pass the U-box test was 8.34 N m, while viscosity was not a major factor.

3.5. Influence of the concrete mixture proportions on compressive strength

The 28-day compressive strength data are presented in Table 4. The cement content of the powder-type SCC was 500 kg/m^3, and the strength reduced greatly with increasing Class F fly ash content, with contents of 100, 200, and 300 kg/m^3 (SCC-2, SCC-3 and SCC-4) replacing cement resulting in strengths of 66%, 50% and 35.5% of that of SCC-1, respectively. The same dosage of GGBFS resulted in strengths of 88.4%, 81.8%, and 83.9% that of SCC-1, respectively. Therefore, when GGBFS was used to replace 60% of the cement, the 28-day relative compressive strength was still above 80%, while that of the concrete in which cement was replaced by the same percentage of Class F fly ash was below 40%.

An appropriate dosage of VMA did not significantly affect the 28-day compressive strength, while the compressive strength of the concrete with a high dosage of HPMC (HVUWC-26–28) was reduced as compared with other concretes of the same *w/b*. This result was also observed by Khayat [40,44], i.e., the higher the viscosity, the more air is entrapped in the concrete. For the starch ether emulsion concrete S2, at a dosage of 0.75% of powder by mass, the 28-day compressive strength was not significantly affected, which is similar to the results of Rols et al. [49].

3.6. Application of the MCR test results

Fig. 18 shows the yield torque and viscosity results of the fresh concretes examined in this study. For CC, the wide-ranging values

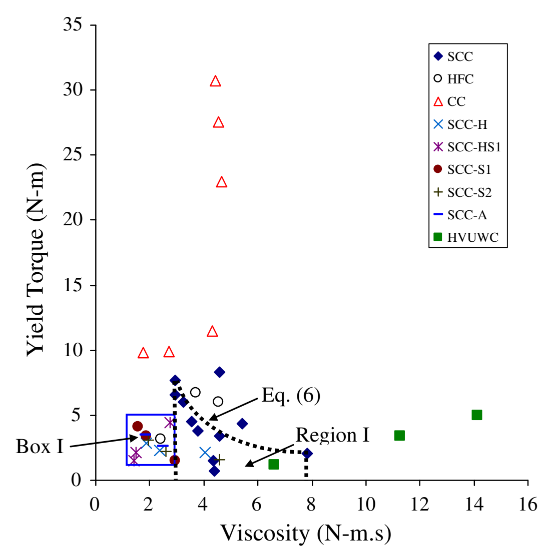

Fig. 18. Illustration of the yield torque and viscosity of fresh concrete.

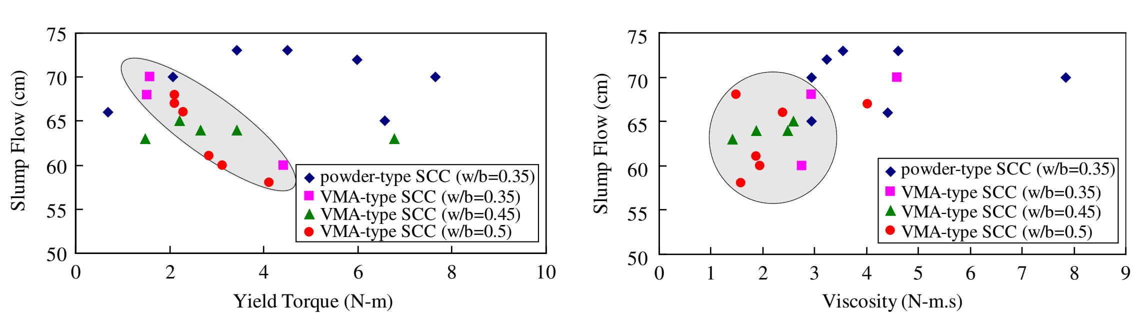

Fig. 17. Relationship between the yield torque, viscosity, and slump flow of SCC.

of yield torque and viscosity fall outside Region I and BOX I, while for SCC, the values can be divided into two different regions: first, for VMA-type SCC, the values fall within BOX I, while those for powder-type SCC fall in Region I, the boundaries of which are demarcated by dashed lines. If the values of T_y and η fall within Region I, the concrete would be considered to be a SCC. The conditions for CC are $9.81 \leqslant T_y \leqslant 30.70$ N m and $1.77 \leqslant \eta \leqslant 4.66$ N m s, and those for BOX I are $1.42 \leqslant T_y \leqslant 4.41$ N m and $1.42 \leqslant \eta \leqslant 2.94$ N m s. The region enclosed by the dashed lines is characterized by Eq. (6):

$$T_y \leqslant 27.172 \times \eta^{-1.2784}, \quad (2.940 \leqslant \eta \leqslant 7.839), \quad R_2 = 0.975 \qquad (6)$$

Therefore, the MCR apparatus is able to measure the yield torque and viscosity of fresh concrete and to distinguish between types of concrete, such as CC, SCC, and most VMA-type and powder-type SCC. In addition, the slump of fresh concrete can be predicted using this apparatus.

4. Conclusion

Based on the test results, the following conclusions were drawn:

1. The MCR apparatus developed in this study is similar to the IBB and ICAR devices, the difference being a different gap size in order to reduce interaction between the aggregate and the wall and the friction force from the wall.
2. The yield torque obtained by testing and the calculated viscosity can be used to distinguish between CC, powder-type SCC, and VMA-type SCC within the range of mixture proportions used in this study.
3. A relationship between slump and yield torque was established for CC, and the measured ranges of yield torque and viscosity for CC were $9.81 \leqslant T_y \leqslant 30.70$ N m and $1.77 \leqslant \eta \leqslant 4.66$ N m s, respectively.
4. For powder-type SCC, the higher the yield torque, the lower the viscosity, and vice versa. Self-consolidating behavior can be expected if the yield torque and viscosity values fall in Region I, as shown in Fig. 18.
5. For VMA-type SCC, the values of yield torque and viscosity must fall within BOX I, and have the following constraints: $1.42 \leqslant T_y \leqslant 4.41$ N m and $1.42 \leqslant \eta \leqslant 2.94$ N m s, respectively.
6. For powder-type SCC, a Class F fly ash replacement ratio of 20% reduced the yield torque; however, replacement ratios of 40% and 60% caused the yield torque to increase substantially, thus reducing the workability. When the GGBFS replacement ratio was increased from 20% to 60%, the yield torque was greatly reduced. When Class F fly ash or GGBFS was used to replace cement in differing mixture proportions, the changes in the viscosity of SCC were not as significant as the changes in yield torque.
7. The yield torque needs to be lower than 8.34 N m in order for the concrete to pass the U-box test (R2 grade), while viscosity was not found to be a major factor influencing the filling height. Both a high viscosity and a high yield torque prolong the V-funnel flow time, and the box-filling height is not directly related to the V-funnel flow time.
8. The viscosity ranges of CC, HFC, and SCC are similar, while the yield torque of CC is large as compared with the other concrete tested. SCC exhibited a lower yield torque; therefore, fresh concrete of a smaller yield torque is of better workability.
9. The viscosity–yield torque range of most VMA-type SCC is more concentrated than that of powder-type SCC, and therefore the stability of the workability is better.
10. An appropriate VMA dosage does not significantly affect the 28-day compressive strength of SCC, while the compressive strength of HVUWC with a high dosage of HPMC is greatly reduced in comparison with other concrete of the same *w/b*.

References

[1] ASTM C143. Standard test method for slump of hydraulic-cement concrete. West Conshohocken (PA): American Society for Testing and Materials; 2008.
[2] ASTM C1611. Standard test method for slump flow of self-consolidating concrete. West Conshohocken (PA): American Society for Testing and Materials; 2005.
[3] Okamura H. Self-compacting high-performance concrete. Concr Int 1997;19(7):50–4.
[4] Omoto T, Ozawa K. Recommendations for self-compacting concrete. JSCE Concr Eng Ser 1999;31.
[5] ASTM C1621. Standard test method for passing ability of self-consolidating concrete by J-ring. West Conshohocken (PA): American Society for Testing and Materials; 2008.
[6] ASTM C1610. Standard test method for static segregation of self-consolidating concrete using column technique. West Conshohocken (PA): American Society for Testing and Materials; 2006.
[7] Banfill P, Beaupré D, Chapdelaine F, de Larrard F, Domone P, Nachbaur L, et al. Comparison of concrete rheometers: international tests at LCPC (Nantes, France). In: Ferraris CF, Brower LE, editors. NISTIR 6819, National Institute of Standards and Technology, USA; 2001.
[8] Beaupré D, Chapdelaine F, Domone P, Koehler E, Shen L, Sonebi M, et al. Comparison of concrete rheometers: international tests at MB. In: Ferraris CF, Brower LE, editors. NISTIR 7154, National Institute of Standards and Technology, USA; 2004.
[9] Ferraris CF. Measurement of the rheological properties of high performance concrete: state of the art report. J Res Nat Inst Stand Technol 1999;104(5):461–78.
[10] Wallevik OH, Saasen A, Gjørv OE. Effect of filler materials on the rheological properties of fresh concrete. ACI Mater J 1995;92(5):524–28.
[11] de Larrard F, Hu C, Sedran T, Szitkar JC, Joly M, Claux F, et al. A new rheometer for soft-to-fluid fresh concrete. ACI Mater J 1997;94(3):234–43.
[12] Khayat KH. Workability, testing, and performance of self-consolidating concrete. ACI Mater J 1999;96(3):346–54.
[13] Beaupré D, Lacombe P, Khayat KH. Laboratory investigation of rheological properties and scaling resistance of air entrained self-consolidating concrete. Mater Struct 1999;32(3):235–40.
[14] Lacombe P, Beaupré D, Pouliot N. Rheology and bonding characteristics of self-leveling concrete as a repair material. Mater Struct 1999;32(8):593–600.
[15] Assaad J, Khayat KH, Mesbah H. Assessment of thixotropy of flowable and self-consolidating concrete. ACI Mater J 2003;100(2):99–107.
[16] Assaad J, Khayat KH. Assessment of thixotropy of self-consolidating concrete and concrete-equivalent-mortar—effect of binder composition and content. ACI Mater J 2004;101(5):400–8.
[17] Koehler EP, Fowler DW. Development of a portable rheometer for fresh Portland cement concrete. ICAR Report 105-3F. Aggregates foundation for technology, research, and education; 2004.
[18] Koehler EP, Fowler DW, Ferraris CF, Amziane SA. New, portable rheometer for fresh self-consolidating concrete. ACI Mater J 2006;SP-233:97-116.
[19] Erdoğan ST, Martys NS, Ferraris CF, Fowler DW. Influence of the shape and roughness of inclusions on the rheological properties of a cementitious suspension. Cem Concr Compos 2008;30(9):763–8.
[20] Amziane S, Ferraris CF, Koehler EP. Measurement of workability of fresh concrete using a mixing truck. J Res Nat Inst Stand Technol 2005;110(1):55–66.
[21] Tattersall GH, Banfill PFG. The rheology of fresh concrete. Boston (USA): Pitman Advanced Publishing; 1983.
[22] Domone PLJ, Xu Y, Banfill PFG. Developments of the two-point workability test for high-performance concrete. Mag Concr Res 1999;51(3):171–9.
[23] Tang CW, Yen T. Optimizing mixture proportion for flowable high-performance concrete via rheology tests. ACI Mater J 2001;98(6):493–502.
[24] Nguyen QD, Boger DV. Direct yield stress measurements with the vane method. J Rheol 1985;29(3):335–47.
[25] Liddell PV, Boger DV. Yield stress measurements with the vane. J Non-Newtonian Fluid Mech 1996;63(2–3):235–61.
[26] Alderman NJ, Meeten GH, Sherwood JD. Vane rheometry of bentonite gels. J Non-Newtonian Fluid Mech 1991;39(3):291–310.
[27] Keentok M, Milthorpe JF, O'Donovan E. On the shearing zone around rotating vanes in plastic liquids: theory and experiment. J Non-Newtonian Fluid Mech 1985;17(1):23–35.
[28] Yoshimura AS, Prud'homme RK, Princen HM, Kiss AD. A comparison of techniques for measuring yield stresses. J Rheol 1987;31(8):699–710.
[29] Haimoni A, Hannant DJ. Developments in the shear vane test to measure the gel strength of oilwell cement slurry. Adv Cem Res 1988:221–9.
[30] Saak AW, Jennings HM, Shah SP. The influence of wall slip on yield stress and viscoelastic measurements of cement paste. Cem Concr Res 2001;31(2):205–12.

[31] Schwartzentruber LD, Roy RL, Cordin J. Rheological behaviour of fresh cement pastes formulated from a self compacting concrete (SCC). Cem Concr Res 2006;36(7):1203–13.
[32] Roussel N, Cussigh F. Distinct-layer casting of SCC: the mechanical consequences of thixotropy. Cem Concr Res 2008;38(5):624–32.
[33] Ferraris CF, de Larrard F, Martys N. Fresh concrete rheology: recent developments. In: Mindess S, Skalny J. editors. Materials science of concrete VI. The American Ceramic Society; 2001. p. 215–41.
[34] Malhottra VM, Mehta PK. Pozzolanic and cementitious materials. In: Malhottra VM, editors. Advances in concrete technology, vol. 1. Gordon and Breach Science Publishers; 1996. p. 45–75.
[35] Joshi RC, Lohtia RP. Fly ash in concrete: production, properties and uses, In: Malhottra VM, editors, vol. 2.Advances in concrete technology. Gordon and Breach Science Publishers; 1997. p. 15–101..
[36] ASTM C192. Standard practice for making and curing concrete test specimens in the laboratory. West Conshohocken (PA): American Society for Testing and Materials; 2007.
[37] ASTM C39. Standard test method for compressive strength of cylindrical concrete specimens. West Conshohocken (PA): American Society for Testing and Materials; 2001.
[38] Assaad J, Khayat KH. Effect of viscosity-enhancing admixtures on formwork pressure and thixotropy of self-consolidating concrete. ACI Mater J 2006;103(4):280–7.
[39] Felekoğlu B, Tosun K, Baradan B, Altun A, Uyulgan B. The effect of fly ash and limestone fillers on the viscosity and compressive strength of self-compacting repair mortars. Cem Concr Res 2006;36(9):1719–26.
[40] Khayat KH. Viscosity-enhancing admixtures for cement-based materials – an overview. Cem Concr Compos 1998;20(2–3):171–88.
[41] Leemann A, Winnefeld F. The effect of viscosity modifying agents on mortar and concrete. Cem Concr Compos 2007;29(5):341–9.
[42] Khayat KH, Guizani Z. Use of viscosity-modifying admixture to enhance stability of fluid concrete. ACI Mater J 1997;94(4):332–40.
[43] Khayat KH. Effects of antiwashout admixtures on fresh concrete properties. ACI Mater J 1995;92(2):164–71.
[44] Khayat KH. Effects of antiwashout admixtures on properties of hardened concrete. ACI Mater J 1996;93(2):134–46.
[45] Ferraris CF, Brower L, Ozyildirim C, Daczko J. Workability of self-compacting concrete. The economical solution for durable bridge and transportation structures. In: International symposium on high performance concrete, proceedings, PCI/FHWA/FIB; 2000. p. 398–407.
[46] Sedran T. Final report of task 3: rheology, rational production and improved working environment through using self-compacting concrete, Brite EuRam project, contract no. BRPR-CT96-0366; 2000. p. 1–20.
[47] Domone PLJ, Chai HW. Design and testing of self-compacting concrete. In: Bartos PJM, Marrs DL, Cleland DJ, editors. Proc. of RILEM int. conf. production methods and workability of concrete. Scotland; 1996. p. 223–36.
[48] Chai HW. Design and testing of self-compacting concrete, Ph.D. Thesis, Department of Civil and Environmental Engineering, University College London, London; 1998.
[49] Rols S, Ambroise J, Péra J. Effects of different viscosity agents on the properties of self-leveling concrete. Cem Concr Res 1999;29(2):261–6.