Workability of Self-Compacting Concrete

by

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ABSTRACT

The slump test is widely used to evaluate the workability of concrete. However, it has serious drawbacks, especially for self-compacting concrete (SCC). Other flow characteristics such as viscosity or filling capacity or time of flow through an orifice are needed to characterize flow in SCC. The goals of this study were multiple: 1) to test flow characteristics of SCC using various devices: two concrete rheometers, several standard tests, and the widely used V-flow and U-flow tests; 2) to determine the correlation between the various tests and especially between the two rheometers; and 3) to attempt to determine the rheological characteristics of SCC. Thirteen mixes were prepared with varying dosages of viscosity modifying admixture (VMA) and high-range water-reducing admixture (HRWR) to achieve a wide range of flow behavior. It was found that the plastic viscosities measured with the two rheometers were correlated at 84 %, and that a SCC mixture is not defined by its high slump and slump spread alone.

INTRODUCTION

Self-compacting concrete (SCC) was first developed in Japan in 1988 to reduce labor in the placement of concrete, by eliminating or reducing the need for vibration to achieve consolidation[1]. Therefore, the main property that defines SCC is high workability in attaining consolidation and specified hardened properties.

Workability is defined either qualitatively as the ease of placement or quantitatively by rheological parameters[2]. The most commonly used test to determine workability in practice is the slump cone test. Either the vertical slump distance or the horizontal spread of the concrete can be measured. The most common rheological parameters, used to qualify workability, are the yield stress and plastic viscosity as defined by the Bingham equation[3]. In some cases, it was found that the Herschel-Bulkley (HB) equation was better suited to describe the flow[4]. This equation leads to the calculation of three parameters, a yield stress and two other parameters that cannot be associated with a physical entity. A linear approximation of the HB curve was introduced by F. de Larrard et al.[4] to define a plastic viscosity, but as this is another approximation, it was decided for this study to use the Bingham equation to calculate yield stress and plastic viscosity. The knowledge of the two parameters, yield stress and viscosity, allows a quantitative description of the workability. The Bingham equation is a linear relationship between the shear rate, $\dot{\gamma}$, and the shear stress, τ. The viscosity, η, is the slope and the intercept is the yield stress, τ_0, as shown in equation (1) below:

$$\tau = \tau_0 + \eta\dot{\gamma} \qquad (1)$$

A highly flowable concrete is not necessarily self compacting, because SCC should not only flow under its own weight but should also fill the entire form and achieve uniform consolidation without segregation. One type of SCC is used in structures with closely spaced reinforcing bars and should be able to flow through and completely fill the form without vibration. This characteristic of SCC is called the filling capacity. Several tests were designed to measure the filling capacity of concrete but none became a standard. The most widely used of these tests is the U-flow test[5]. The U-flow test is used to determine if the concrete mixtures qualified as SCC mixtures. To determine the factors that influence the flow of SCC, it is important to examine the behavior of the concrete in the simulated field tests (U-flow) and to compare with simpler and fundamental tests, such as slump and V-flow.

In this paper, rheological properties of the concrete mixtures were measured using two rheometers, the IBB[i] [6] and the BTRHEOM[i] [7] instruments. The flow of 13 concrete mixtures was determined using standard tests, slump and slump spread, the U-flow and the V-flow tests, which were designed for highly flowable concrete mixtures. The values obtained from these tests were compared and used to define of this type of SCC. A "workability box" [6], described later, was used to frame the parameters of yield stress and viscosity that results in SCC.

[i] Brand names and names of manufacturers are identified in this report to adequately describe the experimental procedure. Such an identification does nor imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material identified is necessarily the best available for the purpose.

TEST METHODS

The standard slump test was performed according to ASTM C143 and the vertical slump of the concrete was measured. Another measurement widely used for flowable concrete but not a standard is the spread of the concrete, after the slump cone was lifted. The diameter of the concrete spread was measured after the concrete had stopped flowing. The time to reach the maximum spread was not recorded.

The IBB rheometer was developed in Canada. It consists of a cylindrical container holding the concrete, with an H-shaped impeller driven through the concrete in a planetary motion. The speed of the impeller rotation was first increased to maximum rotation rate and then the rotation rate was decreased in six stages with each stage having at least two complete center shaft revolutions. The torque (N·m) generated by the resistance of the concrete specimen to the impeller rotation was recorded at each stage as well as the impeller rotation rate (revolutions per second) measured by the shaft tachometer. The torque versus the impeller rotation rate can be approximated by a linear function, whose slope is related to the plastic viscosity and intercept, at zero rotation rate, is related to the yield stress. As the geometry and flow patterns are too complicated in this rheometer, the values obtained are only proportional to the plastic viscosity and yield stress of the concrete. The units used are N·m and N·m·s for yield stress and viscosity, respectively.

The BTRHEOM is a parallel plate rheometer, i.e., the concrete is sheared between two plates. The plate at the bottom is stationary and the plate at the top rotates with variable speed similar to the impeller of the IBB rheometer. The torque generated during rotation is recorded while the rotation rate is first increased and then decreased in stages. This is similar to the IBB procedure but does not use identical rates and times. The rheological parameters can be calculated using the Bingham equation applied to the torque and rotation rate data of the decreasing speed portion of the test. Due to the simple geometry of the shearing area, it is possible to calculate the results in fundamental units, i.e. Pa for yield stress and Pa·s for viscosity.

The most commonly used test for SCC is a U-flow device (Figure 1). This test simulates the flow of concrete through a volume containing reinforcing steel. Other tests exist that operate on the same principle with a different geometry but usually they require a larger amount of concrete than the U-flow. The test is performed by first completely filling in the left chamber with concrete (Figure 1) while the sliding door between the two chambers is closed. The door is then opened and the concrete flows past the rebars into the right chamber. SCC for use in highly congested areas should flow to about the same height in the two chambers. The criterion adopted, in this study, was that if the filling height was more than 70 % of the maximum height possible, the concrete was considered self-compacting. The selection of this percentage is arbitrary and a higher value might be considered more conservative. In the U-flow device used, the maximum height is 285.5 mm, half of 571 mm, the total height. Therefore, a concrete with a filling height of more than 200 mm is considered SCC.

Another test used was the V-flow test. It consists of a funnel with a rectangular cross section. The top dimensions are 495 mm by 75 mm and the bottom opening is 75 mm by 75 mm. The total height is 572 mm with a 150 mm long straight section. The concrete is poured into the funnel with a gate blocking the bottom opening. When the funnel is completely filled, the bottom gate is opened and the time for the concrete to flow out of the funnel is measured. This time is called V-flow time.

A full description of all the tests presented here can be found in reference[2].

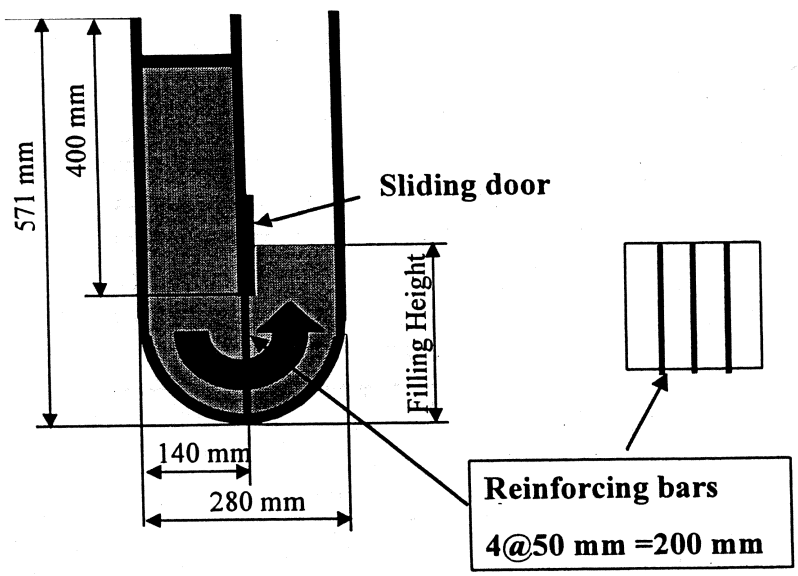

Figure 1. U-flow test[5]

MATERIALS USED

The materials consisted of cement, coarse and fine aggregates and chemical admixtures. No filler or mineral admixtures were used. The cement was a Type I/II with a fineness of 345 m^2/kg. No chemical analysis was conducted on the cement. The aggregates were crushed limestone. The maximum size for the coarse aggregates was 12.5 mm (1/2 in). Two types of chemical admixtures were used: a high range water reducer (HRWR) and viscosity modifying admixture (VMA). The HRWR was a carboxylated copolymer-based mixture. The VMA was a modified cellulose product.
Compositions of the concrete mixtures are shown in Table 1. The HRWR was adjusted to obtain a slump spread of at least 610 mm. The VMA dosage was set at three levels from 0 mL/kg to 859 mL/kg of cement to obtain a wide range of plastic viscosities as measured

with the IBB rheometer. These compositions were selected from a previous larger set of experiments conducted with similar aggregates and cement[8].

Table 1 – Concrete composition and test results. The data in this table are single point measurements, no uncertainty values can be calculated.

Mixture ID	VMA mL/100kg	HRWR mL/100kg	W/C	S/A	Slump mm	Spread mm	U-flow Filling height mm	V-flow s
285	0	1500	0.337	0.431	280	710	115	34.7
286	522	551	0.427	0.501	280	675	**200**	6.9
287	522	503	0.427	0.43	255	635	40	24.6
288	0	1587	0.337	0.501	280	630	110	77.8
289	522	1019	0.427	0.571	290	635	**270**	8.2
290	0	1876	0.337	0.569	280	660	30	34.3
291	859	2277	0.704	0.57	255	620	68	26.9
292	0	1535	0.275	0.43	265	735	64	193.2
293	0	1092	0.275	0.57	280	660	131	74.9
294	522	795	0.349	0.431	280	610	105	36.30
295	522	1223	0.349	0.569	280	630	**273**	13.6
296	859	2647	0.704	0.57	255	610	53	49.9

In the column marked "U-flow" the concretes that are SCC, according to the criteria adopted, are shown in bold characters.
W/C: water-cementitious material ratio
S/A: sand to total aggregate ratio

RESULTS AND DISCUSSION

Table 2 shows the data obtained from the two rheometers. It should be noted that the impeller rotation maximum speed used in the IBB test is shown in the table. In some cases (mixes ID 293), the rotational maximum speed was reduced because the torque generated by the resistance of the concrete was too high to be measured, i.e., the impeller will not rotate at a higher speed.

Comparison of the yield stresses from the two rheometers, IBB and BTRHEOM, indicated no correlation (Table 2). Lack of correlation may be due to the range of yield stresses measured, which was in the vicinity of zero and was sometimes negative. This situation is expected since all the concretes tested were highly flowable and therefore should have very small yield stresses. The negative values are due to the method used to calculate the yield stress. Whether the Bingham or the HB equation is used, yield stress is estimated from an extrapolation of the shear rate versus shear stress curve to zero shear rate. The negative values are attributed to the error in the extrapolation process and have no real physical meaning. It could be inferred that another equation other then Bingham equation should be used.

Table 2: Yield stress and viscosity measured using the BTRHEOM and the IBB rheometers.

Mixture ID	BTHREOM Data		IBB data		
	YS [Pa]	Vis [Pa·s]	Speed used	YS [N·m]	Vis. [N·m·s]
285	-154	166	250	-0.886	8.651
286	**197**	**108**	**250**	**-0.128**	**6.306**
287	355	111	250	-0.031	5.981
288	-97	263	250	0.67	14.642
289	**72**	**141**	**250**	**0.063**	**8.494**
290	-185	241	250	1.516	13.203
291	33	174	250	1.773	6.625
292	-524	398		NA	NA
293	-351	559	80	-3.809	137.311
293	-351	559	100	-0.952	85.29
294	287	231	250	0.990	11.763
295	**103**	**201**	**250**	**1.527**	**10.141**
296	20	174	250	2.088	6.825

Bold = SCC. YS = yield stress, Vis. = viscosity.

The comparison of the viscosity, measured by the two rheometers, shows a good correlation. Figure 2 shows the plot of the viscosity as measured by the two rheometers. For this comparison the concrete mixture ID 293 was not considered because the IBB impeller maximum rotational speed was different from all the other concrete mixtures. The correlation is relatively good ($R^2 = 84$ %) and can be approximated by:

$$\eta_B = 35 + 16\eta_i \qquad (2)$$

where η_B is the viscosity measured with the BTRHEOM and η_i is the viscosity measured with the IBB

This is an acceptable correlation considering the wide range of viscosity covered. This correlation is nevertheless preliminary due to the limited number of data points and the lack of variation in the properties of the materials used, i.e., one type of cement and one type of aggregates. It should be pointed out that only one other attempt to compare two rheometers is known[9]. The results were negative in the previous attempt, i.e., no correlation was found. For this reason, ACI Committee 236A is planning to conduct a series of tests to compare all the existing concrete rheometers. These tests are tentatively scheduled for the fall of 2000.

In the rest of this paper, only the viscosity obtained from the BTRHEOM is used to compare the rheometer results to other tests.

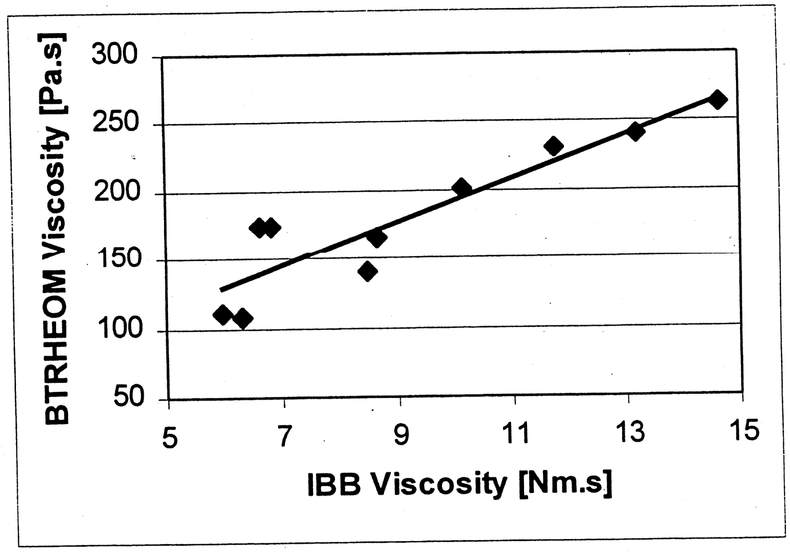

Figure 2: Comparison between the two rheometers: IBB and BTRHEOM

The results obtained for the slump and the slump spread are shown in Table 1. In this test program, the average slump for all mixes was 273 mm ± 13 mm (one standard deviation), a variation of only about ± 5 %. The average spread for all mixes was 655 mm ± 39 mm (one standard deviation). Again, the spread can be considered constant for all the mixes with a variation of 6 %. This is not surprising because the HRWR dosage was adjusted to obtain a slump spread of at least 610 mm. Therefore, on the basis of slump and slump spread, we could conclude that all these concretes have the same workability. However, the results of the U-flow and V-flow and the rheometers clearly show that these concretes do not behave the same in the filling capacity (U-flow height) or in the ease of placement (V-flow time) or the viscosity. The scatter of data in these tests was quite large. The average filling height (Table 1) is 123 mm ± 88 mm (one standard deviation). This corresponds to a variation of 71 %. For the V-flow time (Table 1) the average is 50 s ± 53 s or a variation of 108 %. The plastic viscosity as measured by the rheometers varies by a factor of 2.4 over the range of the mixes for either rheometer. In conclusion, we can affirm that the slump and the slump spread, by themselves, are not the correct tests for measuring the workability of these types of concretes, because they do not predict the concrete behavior during placement. Hayakawa et al. also reached this conclusion[10]. They showed that for the same slump spread a wide range of filling abilities can be obtained. Therefore, no correlation between the V-flow or U-flow test and the slump or slump spread can be obtained.

The U-flow and the V-flow results were examined to determine a better definition of SCC. If the U-flow filling height criterion (>70 % maximum fill height) is used to detect SCC, there are only three concretes that are SCC in this series, namely the concrete with the ID: 286, 289, and 295. The U-flow values above 200 mm are shown in bold in Table 1. Figure 3 shows the comparison between the plastic viscosity and the U-flow and the V-flow tests. For clarity, the V-flow values of the three SCC mixtures are marked with a cross. The three SCC mixtures have, by definition, a U-flow value above 200 mm (black line). For these concrete mixtures, it seems that the V-flow value needs to be lower than 20 s for a concrete to be SCC. From these few data points, we cannot say that this V-flow value is applicable to all concretes. The data does not provide a correlation between the viscosity and the other two tests. Therefore, the viscosity alone cannot uniquely determine if a concrete is SCC or not. It is also important to note that mixture ID # 286 showed a visual indication of segregation. Therefore, it should be emphasized that U-flow alone may not be an universal single test indicator for SCC and that the filling capacity should be used with care.

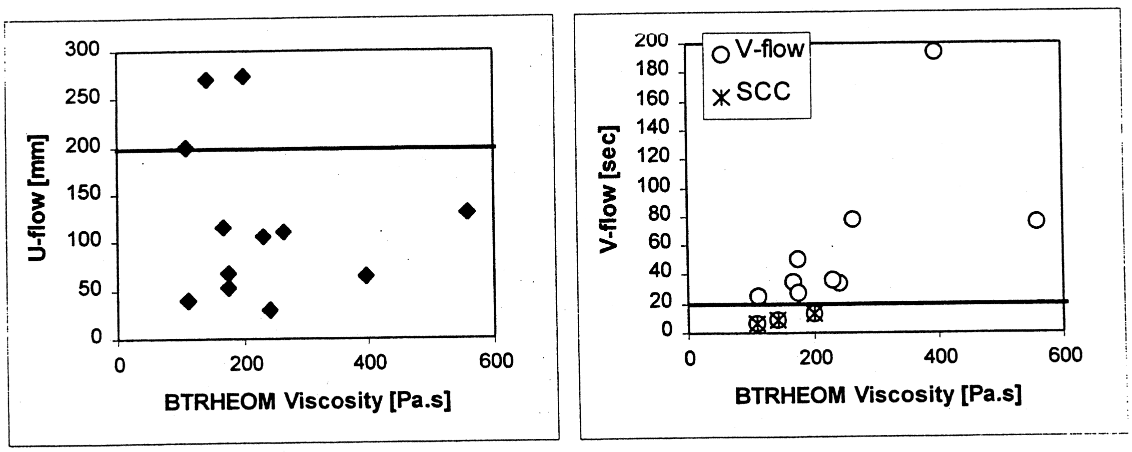

Figure 3: U-flow and V-flow time compared with viscosity measured with the BTRHEOM.

According to Beaupré[6], a better method to evaluate concrete with a specified flow property is to plot the yield stress versus the viscosity. Concrete mixtures, determined to have the desired property, define an area in the plot called a "workability box." Figure 4 shows a plot of the viscosity versus the yield stress as measured with the BTRHEOM for this study. The points, marked with a cross in Figure 4, are SCC. A box can be traced to limit an area around these points that does not include other mixtures. The "workability box" defines the range of viscosity and yield stress needed for a SCC. If these results were trial batches, the drawing of the box would allow the operator to determine whether a mixture is SCC based on the rheometer results. As was mentioned above, the yield stresses measured with the two rheometers do not correlate. Nevertheless, a box can be traced on an equivalent graph plotted using the results from the IBB rheometer. As some of the yield stresses are negative in our study, further trials would be necessary to use the "workability box" from Figure 4. It should be reminded that the yield stresses are negative due to the extrapolation determined by the Bingham equation. This interpretation of the results was given just an indication that to define SCC there is a need for more than one rheological parameter, not as universal definition of SCC.

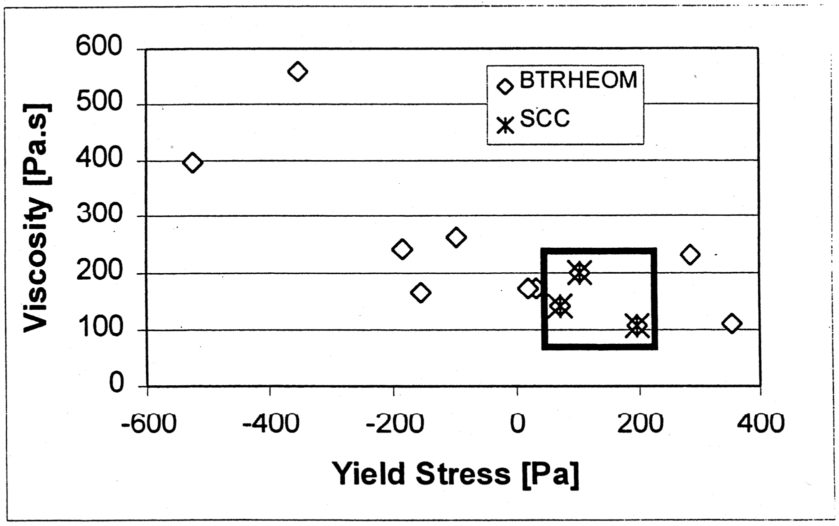

Figure 4: Viscosity vs. Yield stress calculated according to Bingham equation and the workability box

CONCLUSIONS

Thirteen concrete mixes were prepared with a wide range of viscosity. All the mixes were targeted to the same slump and slump spread using a variable dosage of HRWR. These mixes showed a wide range of flow properties when measured using other devices. The following conclusion can be drawn:

- The slump flow is not enough to determine whether a flowable concrete is SCC.
- The value measured with the IBB and the BTRHEOM correlate relatively well on viscosity but not on yield stress on the concrete mixtures tested. Further measurements are needed to determine if the correlation holds with other aggregates and cementitious/filler materials.
- Based on the data presented, the plastic viscosity and the yield stress do not correlate with the V-funnel or the U-flow test.
- Various types of SCC can be defined by a range of yield stress and plastic viscosities as determined graphically with the "workability box" defined by Beaupré. The slump flow is not enough to determine whether a flowable concrete is SCC.

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