The Center for Advanced Cement Based Materials
White Paper

Self-Consolidating Concrete

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Self Consolidating Concrete

A White Paper by Researchers at
The Center of Advanced Cement Based Materials (ACBM)

D.A. Lange, Editor

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Executive Summary

Self Consolidating Concrete is an emerging class of concrete materials that offers great potential for improved ease of placement, increased rate of construction, and reduced cost through reduced time and labor. ACBM organized a research team in the fall of 2004 to coordinate on-going research activities toward three theme questions:

a) How can we improve the robustness of fresh behavior of SCC?
b) What are innovations in testing SCC?
c) How can we measure and model formwork pressure?

This white paper is an effort to bring together the results of independently conducted research, sponsored by a range of agencies and brought together as an activity of ACBM. The three chapters of this white paper were prepared to address the three theme questions. Each chapter provides a literature review, an overview of recent results, and commentary about needs for research in the future.

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Chapter 1. Robustness of SCC

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Abstract

Robustness can be regarded as the ability of the SCC mixture to maintain both the fresh properties and composition pre- and post-casting of one batch or successive batches, due to the composition of the mixture and due to some small changes in the contents of the ingredients of the mixture. Robustness depends on a number of different attributes including the specific composition of the mixture, the mixing history, i.e. the shear energy and shear rate, and the specific application.

SCC might be more susceptible to changes than ordinary concrete because of a combination of detailed requirements, more complex mix design, and inherent low yield stress and viscosity. Variations in properties (and robustness) are attributed therefore to the specific effects of the ingredients on the rheological properties of the mixture, effects of the physical properties (i.e., size and specific density) of the aggregate, and the mixing history. This article reviews all of these effects and indicates how these effects are likely to affect the robustness of the mixture. In addition, the effects of moisture variations and mixing devices on the fresh properties are discussed, and with examples provided on evaluating the robustness with a new segregation probe device.

1. Introduction

Self-consolidating concrete is designed to meet specific applications requiring high deformability, high flowability, and high passing ability. The maximum flowability is governed by the application, and since flowability is controlled by the composition of the mix, observations show that the rheological properties of SCC vary in a wide range, so does its robustness. A recent overview on SCC types, properties, and test methods, are given by Bonen and Shah[1], and Khayat and his coworkers.[2,3]

In a narrow sense, the term 'robustness' might be synonymous to stability, as the latter term refers to the ability of SCC to resist changes, i.e., segregation during transport and placement (dynamic stability) and post placement (static stability). In a broader and more practical sense, the term robustness that is adopted here describes robustness as the ability of a given mixture to maintain its fresh properties and uniformity during processing, casting, and due to some small changes to the composition of the mixture due to some small changes in the mixture's ingredients contents. The term uniformity might be divided into two subcategories; (a) resistance to segregation because of the inherent composition of the mix, and (b) resistance to segregation because of processing that affects the rheological properties.

Indeed, some properties, such as loss of fluidity and compatibility are frequently encountered with regular concretes. However, SCC might be more susceptible than ordinary concrete because: (a) the mix design is more complex as it contains more ingredients that each of them might affect the rheological properties differently, (b) SCC it is likely to be more thixotropic than ordinary concrete, and (c) the requirements from SCC are by far more demanding, thus what might be acceptable for ordinary concrete, might not meet SCC requirements.

2. Effects of Ingredients:

A lack of robustness can be manifested in several ways that affects workability and the other assigned properties of SCC, i.e., flowability, passing ability, and stability. The following review the effects of the ingredients on the rheological properties that affect robustness.

2.1 Effects of ingredients on rheology

Tattersall and Banfill[4] and Banfill[5] showed that the yield stress and plastic viscosity values are exponential functions of the water and superplasticizer contents, and the flow characteristics of the cementitious materials are related to structural buildup during rest and structural breakdown due to remixing. Roy and Asaga[6] concluded that a change from the least severe to the most severe mixing procedure caused both the yield stress and plastic viscosity to decrease by about 60%. Similar results were reported by others.[7,8] More recently, Douglas, et al.[9] showed that the structural buildup and thixotropy are also related to the superplasticizer content, rest time, and mixing energy.

Cyr, et al.[10] have shown that different superplasticizers and mineral admixture affect differently the rheological properties including shear thickening. Accordingly, the shear thickening is increased in the presence of metakaolin, ground quartz and fly ash have no effects on it, whereas silica fume reduces it. Banfill[11] however reported that substitution of up to 60% of the cement by fly ash reduces the yield stress, but has little effects on the plastic viscosity.

Carlsward, et al.[12] have studied the effects of entrapped air, silica fume, limestone, and moisture on the rheological properties. It has been shown that the air content increases the slump flow, reduces the plastic viscosity, but has little effect on the shear stress. Silica fume thickens the mixture, the shear stress is substantially increased, the plastic viscosity is moderately increased, and the slump flow is strongly decreased. By contrast, limestone has little effects on the plastic viscosity and the slump, but increases the shear stress. Similarly, Assaad and Khayat,[13,14] showed that incorporation of pozzolanic materials such as the silica fume, fly ash, and blast furnace slag can increase internal friction of the cement paste and the shear stress.
In addition, the mean interparticle distance play a significant role on the flow characteristics of SCC as it affects the rheological properties and the capacity to flow through obstacles. Higher aggregate content increases the yield stress and viscosity, so does aggregate with high aspect ratio.[15] Similarly Assaad and Khayat[16] showed that an increase in the coarse-to-fine aggregate ratio and an increase of size of aggregate bring about a significant increase in the rate of stiffening.

Bonen and Shah[1] reported on the effects of the superplasticizer content, coarse aggregate-to-cement ratio, and fine aggregate-to-coarse aggregate (c:f) ratio on the flow properties of concrete. It was shown that for any content of superplasticizer-to-binder (SP:b) ratio, the slump flow increases as the aggregate-to-binder (agg:b) ratio decreases (Fig 1). Similarly, the robustness of the flow is proportioned to the agg:b volume and SP:b wt%. In addition, Ye, et al.[17] showed that the fluidity can easily be manipulated by changing the c:f ratio, and the slopes of curves are about the same for the powder-type and VMA-type SCC (Fig 2). Provided the aggregate is spherical, the beneficial role of fine aggregate is related to its ball-bearing effect. Khayat et al. [3] showed that the use of coarse aggregate and sand combinations that enable the increase in packing density can reduce the superplasticizer demand and plastic viscosity of SCC. This was especially the case for concrete with low water-to-binder (w:b) ratio of 0.33. The increase in paste volume is also shown to reduce the plastic viscosity of SCC.

Similar to the fluidity, the viscosity is readily changed by changing the superplasticizer and aggregate contents (Fig. 3). The effects of the latter on viscosity cannot be overlooked as the effects are as important as the role of superplasticizer. The figure also shows that the effect of aggregate on viscosity is exponential.

Clearly, all these ingredients, especially water, superplasticizer, and aggregate, affect the rheological properties differently. Thus, in order to minimize variations that stem from small changes in quantities of these ingredients in successive batches, it is advantageous to add VMAs (viscosity-modifying admixtures) to the mixtures as even small additions of

VMA considerably increase the plastic viscosity and cohesion of the mixture. VMAs are often water-soluble polymers or inorganic substances with very high surface area that bind water upon mixing. A review on the effects of the various VMAs is given elsewhere.[18] Addition of VMA counters the strong adverse effects of small variations in the water and superplasticizer contents, and the contents of the other ingredients. Indeed, Shi, et al.[19] has shown that the flow loss of VMA-free mixtures is higher than in VMA mixtures.

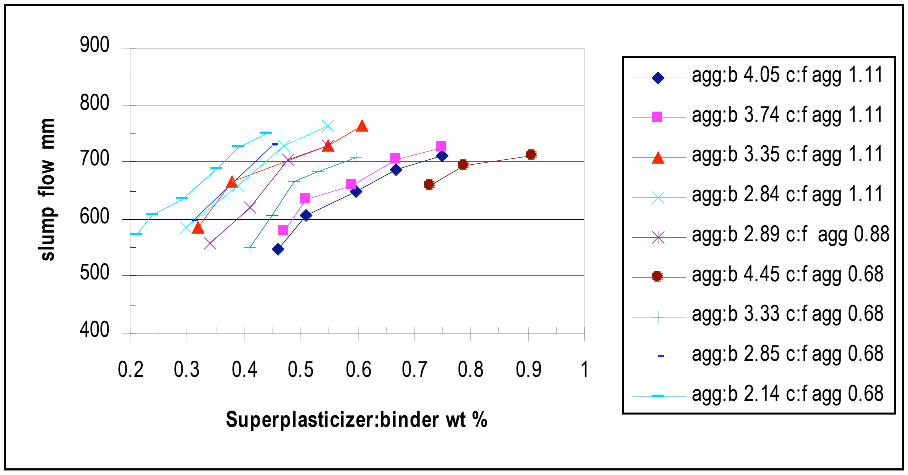


Figure 1: The effects of the superplasticizer:binder ratio (by wt.) on slump flow of concrete at w:b ratio of 0.39 (Bonen and Shah[1])

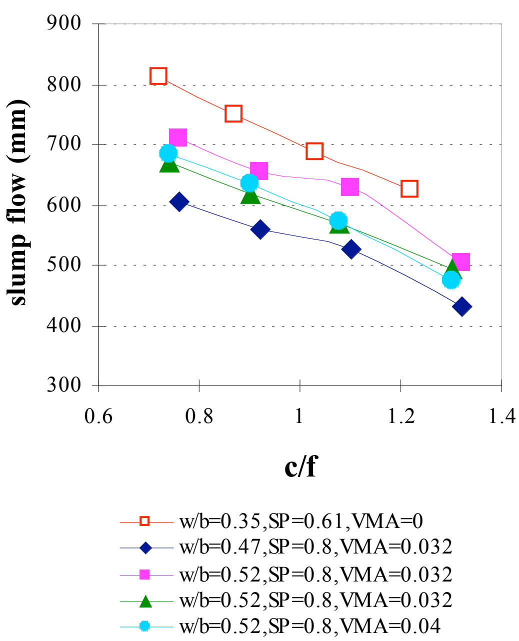


Figure 2 (left): Effect of coarse-fine aggregate ratio on slump flow (Ye, et al.[17])

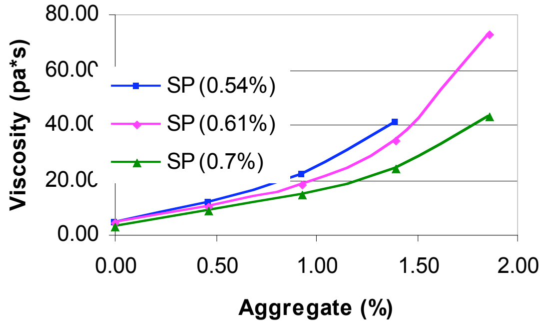


Figure 3: Effects of superplasticizer and aggregate:cement ratio on viscosity

The high flowability and deformability of SCC derives from the characteristically low values of yield strengths and plastic viscosity. As an example, a typical yield stress of SCC is about one order of magnitude smaller than the corresponding yield strength of regular concrete.[20] These low yield stresses and plastic viscosity values inherently compromises the segregation resistance and countermeasures must be taken as discussed below.

2.2 Effects of ingredients on segregation

Aggregate segregation, which is also referred to as sedimentation, is controlled by the viscosity and yield stress of the mixture, the binder density, aggregate size, aggregate density, as well as the content of fines. This implies that the stability of SCC (of low yield stress) can be enhanced by increasing both the viscosity and density of the matrix and by decreasing the maximum size and density of the aggregate. It follows, that higher w:c ratio and/or SP:c ratio increase the susceptibility to segregation and vise-versa, lower w:c ratio and SP:c ratio increase stability and therefore robustness. Similarly, greater fines content increases robustness either because it increases the viscosity or increases the density of the matrix. Silica fume is an example of a viscosity modifier, and slag and limestone are examples of density modifiers.

Aggregate particles in SCC may be regarded as discrete inclusions in a homogeneous matrix. Consequently, the tendency of the aggregate to segregate depends on the properties of both the aggregate and the homogeneous matrix. Large aggregate size and high density decreases stability and vise-versa. However, within common ranges of SCC mixtures and densities of aggregate, Bonen and Shah[21] argued that the most important factor that governs the rate of sedimentation is the aggregate size.

In addition to w:cm ratio and VMA concentration, the stability of SCC depends on the total content of fines in the mixture. Khayat et al. [3] reported that SCC can exhibit greater resistance to surface settlement when the content of total fines in the mixture (smaller than 80 μm) increases for mixtures with similar aggregate packing densities. This was especially the case for SCC made with medium to low content of binder.

It should be noted that the resistance to segregation of the mixture during placing into the forms and after placing might not be the same, because the forces acting on the aggregate under these two conditions are not the same. Once the concrete has been placed in the forms and it is in a static state, the forces acting on the aggregate can be calculated from Stokes' Law. However, during placing, and in particular during horizontal flow, an aggregate particle is subjected to additional forces; the mixture drag and vertical drag that help to keep the particle suspended in the mixture. The mixture drag is proportional to the square of velocity of the mixture and the square of the particle diameter, whereas, the vertical drag is proportioned to the velocity of the mixture and the aggregate shape. Consequently, as the velocity of the mixture is increased, the mixture stability is also increased. Based on this realization that the dynamic stability is less severe than the static stability, Bonen and Shah[21] pointed out that that visual evaluation of segregation during slump flow is an inadequate measure for predicting the static stability.

As noted, the sedimentation velocity of aggregate in a static mode in the formwork is proportional to the radius square of the aggregate, the differences in the specific densities of the aggregate and matrix, and inversely related to the viscosity of the matrix. Because the viscosity of the mixture cannot be too high (otherwise the mixture will not flow), the ability to control the sedimentation rate by increasing the viscosity is limited to certain ranges. Therefore, robustness can be achieved either by reducing the aggregate size or increasing the matrix density or a combination thereof.

Figure 4 shows a plot of equal sedimentation rates of a 12.7 mm spherical aggregate with a density of 2.7 g/cm as a function of the matrix density and viscosity. Because the slopes of the sedimentation rates are highly negative, within the normal ranges of concrete densities, the density of the matrix has a greater effect on the sedimentation rate than the change in viscosity. Second, as the density is increased, the effect of viscosity becomes more prominent.[1]

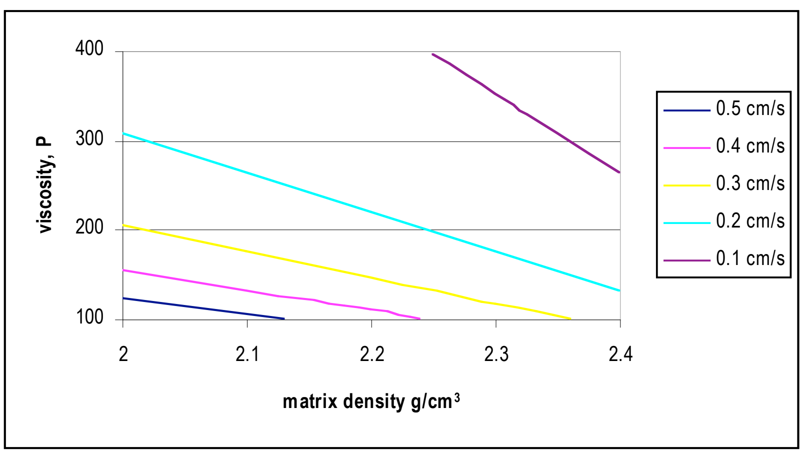


Figure 4: Calculated sedimentation rates of a 12.7 mm spherical aggregate with a density of 2.7 g/cm^3 , CGS units (Bonen and Shah[1]).

Since incorporation of fines affects the density of the matrix, Fig. 4 also indicates that the sedimentation rate can be reduced by increasing the content of the fines with high specific density. Consequently, robustness increases by incorporation of density modifiers, and with regards to fines, the best density modifiers is slag, followed in decreasing order by ground dolomite, ground limestone, and ground quartz. By contrast, neither silica fume nor most types of fly ash can be considered as density modifiers. The density of fly ash varies over a large range, commonly from about 2 to 2.5 g/cm^3 and that of silica fume is about 2.24 g/cm^3. Thereby, in most cases, addition of fly ash and silica fume does not affect the matrix density.[1]

To reiterate, the resistance to segregation should not be based on visual inspection of the slump flow. For example, Ye, et al.[19] showed that high superplasticized SCC mixtures that did not show segregation during slump flow test were prone to high segregation, and addition of VMA was instrumental for controlling it (Fig. 5). Nevertheless, even at relatively high dose of VMA of 0.08%, sedimentation was not completely eliminated. This observation is in agreement with similar results reported by Khayat and Guizani.[22]

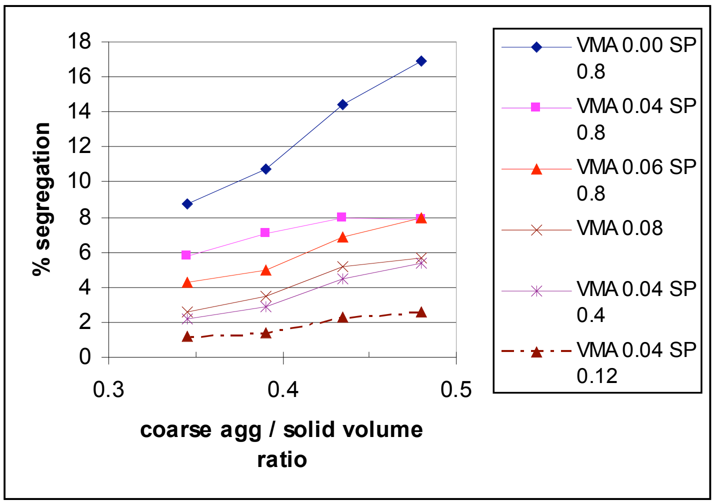


Figure 5: The effects of coarse aggregate, VMA, and superplasticizer on segregation (Ye, et al.[17])

3. Robustness at Limited Compositional Variations

In this section, robustness is discussed vis-à-vis the sensitivity of concrete mixtures to undergo limited variations in concrete properties of successive batches due to some small changes in material characteristics and placement conditions. Under ordinary processing conditions, SCC representing high level of robustness implies that the concrete is less sensitive to changes in the characteristics of primary mixture constituents (sand fineness, aggregate gradation, sand humidity, characteristics of cementitious materials, etc.) on the filling ability, passing ability, and stability.[3]

A lack of robustness can result in significant bleeding and segregation when the water content is greater than the intended limit (for example, due to changes in sand moisture). A more robust SCC enables the concrete supplier to provide better consistency in delivering SCC that is less prone to inaccuracies in batching. This can reduce any intervention needed at the plant or job site to adjust the mixture.[3] Typically, SCC made with low content of VMA and relatively low water content can represent greater robustness than SCC made with low binder content and higher dosage of VMA. In such mixtures, the VMA is used to reduce the variability of the SCC that can arise from changes in material properties and placement conditions. The incorporation of VMA controls bleeding and segregation and increases the robustness of the SCC, while the low water content provides mostly the required level of viscosity[3]. Sakata et al.[23] reported that SCC made with low w:p ratio of 0.33 (powder containing limestone filler), the incorporation of a small concentration of welan gum of 50 g/m^3 can reduce the variability in slump flow of SCC due to changes in cement Blaine (318 to 342 m^2/kg), fineness modulus of sand (2.08 to 3.06), and temperature of fresh concrete (10 to 30°C).

Hwang and Khayat[24] suggested using the minimum water content (MWC) index to determine the robustness of SCC. The MWC is determined for concrete-equivalent mortar as the slope of the increase in flow diameter determined using a mini slump flow cone vs. the increase in w/cm. Concrete-equivalent mortar exhibiting greater MWC can result in lower degree of increase in flow after a given increase in water content, hence more robust. Mixtures made with naphthalene-based superplasticizer are shown to have greater robustness (greater RWD) than similar mixtures with polycarboxylate-based superplasticizer. The type of binder is also shown to affect RWD and robustness.

4. Effect of Aggregate Moisture Content

The natural moisture content of aggregate affects the mixing water content in two ways:

1. If the moisture content of the aggregate is higher than saturated surface dry (SSD), then the amount of (free) mixing water in the mixture is reduced, or
2. If the natural moisture content of the aggregate is lower than SSD, then the amount of mixing water is increased.

Mori et al.[25] examined mixes with 74 different types of aggregate and varying water absorption values. The authors concluded that the slump flow value tends to prominently decrease with an increase in natural moisture content of fine aggregate for mixtures with 0.35 w:c ratio as opposed to 0.5 w:c ratio.

A strong influence on slump flow was observed by Sakai et al.[26] when the amount of water was changed by $\pm$ 5 kg/m^2. These effects were reduced when a viscosity agent was added to these mixtures. Similar observations of slump flow variations were made by Ushijima, et al.[27] They varied the amount of water added to the mixture in such a way so as to simulate a change of aggregate moisture content between -1% to +1.5%. According to their results, the slump flow increased nearly 100 mm when the aggregate surface moisture content was increased about 1%. Highuchi[28] studied the effects of surface moisture of aggregates on concrete properties and the electric power consumed by the mixer. He observed that all the following parameter: viscosity, the power consumption of the mixer, and the O-funnel time increased with an increase in the surface moisture content of sand. The values of power consumption of the mixer were used by Nishizaki et al.[29] to adjust the composition of SCC which varied due to fluctuations in the moisture content of the fine aggregate.

The above findings were recently confirmed by Deshpande[30] who changed the SSD moisture condition of sand and pea gravel two folds from a completely dry state of aggregates to twice the water content of SSD. During the tests, the moisture content was varied in such way that sand and the pea gravel both had the same moisture content, i.e., either both were simultaneously in dry condition or both were in SSD condition. Due to these conditions, the w:cm ratio varied from 0.281 to 0.379.

Figure 6 shows that the slump flow was reduced from about 790 down to about 670 mm, and even larger variations were recorded for the T_{50} test. The latter values varied from as low as 4s for mixtures cast with aggregates in dry condition and as high as 10s for mixtures cast with aggregates in 2 × SSD condition.

The decrease in slump values observed in Fig. 6 is further augmented after some rest time. This phenomenon is attributed to the higher thickening rate of mixtures made at lower w:cm. Fig. 7 shows variations in V-funnel flow time measured either immediately after mixing (curve a) or 20 minutes after mixing (curve b) for mixes containing aggregate with different initial moisture content. It can be seen that when tested immediately after mixing, the V-funnel flow time for mixes with dry aggregate increases from 9s to 19s when tested at 0 and 20 minutes after mixing, respectively. For the same time intervals, the corresponding increase in the V-funnel flow time is only 2-second for mixtures with aggregates in the SSD condition.

5. Effects of Mixing on Robustness

Emborg[31] concluded that the properties of SCC are more sensitive to both, deviation from the designed target and mixing technique. Due to high cementitious content, SCC typically requires longer mixing time compared to normal concrete, and it was noted that this might lead to a reduction in the capacity of the concrete plant, which might cause supply bottlenecks at the site.[32] This longer mixing time is needed for securing complete structural breakdown of the SCC mixtures in order to utilize its superb flow properties.

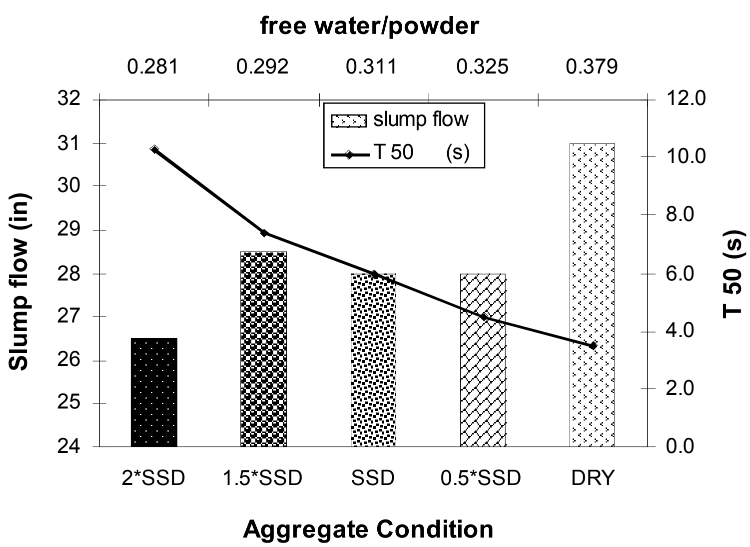


Figure 6: Slump flow and T_{50} values for variations in moisture content of aggregates

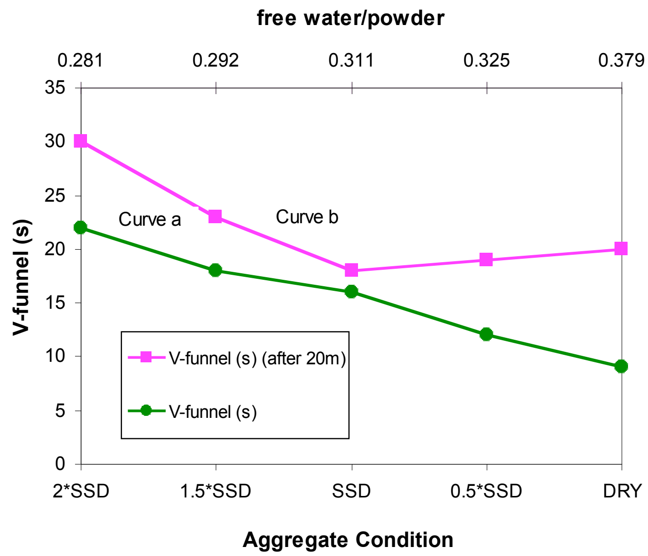


Figure 7: V-funnel flow time for mixtures with aggregate in various moisture conditions

5.1 Effects of mixing equipment

In general, concrete mixers can be classified as either a free fall type (tilting drum) mixers or forced paddle mixers, Emborg[31] and Takada et al.[33] The free fall mixers (also called drum mixers or gravity mixers) are predominantly used at larger plants in northern Europe and Southern Asia.

The forced paddle mixers could be of two types: pan mixers (also called forced pan mixers) and pugmill mixer (also called mortar mixers in the USA). The pan mixers have a vertical axis of rotation and consist of cylindrical, horizontal pan (fixed or rotating) and one or two sets of rotating blades. The pugmill mixers typically consist of a horizontal drum and one or two rotating horizontal shafts with attached blades. Forced pan mixers have higher mixing efficiency than drum or mortar mixers (Deshpande and Olek,[34] and Takada et al.[33]).

Takada et al.[33] performed laboratory investigation of the effect of mixer type on fresh concrete properties of SCC and concluded that for the same composition and mixing sequence, tilting drum mixer increases the V-funnel flow times of SCC as compared to SCC mixed in pan mixer, and to achieve the same slump flow (650±30 mm), smaller amounts of superplasticizer (SP) were needed in the tilting drum mixer. By contrast, SCC produced in pan mixer was found to be prone to changes, which compromised the robustness of the mixtures.

Similar trends were observed by Deshpande, 2006.[30] Mixtures with the same w:p volume ratio were mixed in a mortar mixer and a conventional laboratory pan mixer. It was observed that for the same mixing sequence and mixing time, the mixtures produced using the pan mixer had higher viscosity as compared to the mixtures mixed in the mortar mixer. Mixtures mixed in the mortar mixer required lower dosages of polycarboxylate based superplasticizer to produce rapid-set SCC (RSSCC) with the same slump flow as compared to the dosages required for the mixtures mixed in the pan mixer.

In turn, Emborg[31] noted that the robustness is also a function of the mixer volume and in industrial full scale mixers, the variations in properties are smaller than those produced by laboratory mixers.

5.2 Effect of mixing sequence and mixing time

The effect of mixing sequence and a mixing time on the properties of SCC were studied by Takada et al.[33] using a gravity mixer (G) and a forced paddle mixer (F). It was reported that for the same water-to-powder ratio by volume (V_w/V_p), longer mixing times for 7.5 and 3.5 minutes in gravity mixtures required lower SP dosages and resulted in higher slump flow values and low V-funnel flow times as compared to shorter mixing times of 5.5 and 2.5 minutes. However, in the case of forced pan mixers, in order to obtain the same degree of deformability, mixtures that mixed for 5 minutes required higher dosages of SP than the corresponding mixtures with the same V_w/V_p that mixed for 3.5 minutes.

While such results might not be representative, interpretation of the results suggests that it is not the mixing time, but rather the shear energy and shear rate that count. It is recognized that with a given mixture, completely different flow curves are obtained by varying these two parameters.[4]

The effect of delayed addition of SP on the slump flow and V-funnel time was studied by Domone and Jin.[35] In their study the delay in the time of addition of SP varied from zero to 6 minutes in increments of 1 minute. Fig. 7 shows the mixing sequence in which the powder, sand and 80% of the water were mixed for 2 minutes and then the SP and 20% of the water were incorporated.

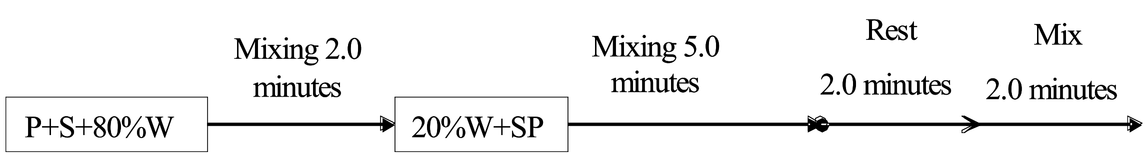


Figure 7: Mixing sequence adopted by Domone and Jin[35]

Three types of superplasticizers were used: naphthalene-based SP, melamine-based SP and polycarboxylic ether-based SP. It was observed that delayed addition increased the fluidity of the SP as measured by both the flow spread and V-funnel flow time. The optimum addition time 'window' was found to be 2 to 4 minutes for the naphthalene- and melamine-based admixtures, but 0 and 0.5 minutes for polycarboxylic-based admixture.

Deshpande and Olek[34] prepared 27 mixtures of RSSCC and found that the time in which the superplasticizer was added affects the rheological properties. The results of this study indicate that early addition of superplasticizer enhances dispersion of cement and increased the flowability of the RSSCC mixture, especially for mixtures mixed in mortar mixer. Addition of silica fume also leads to reduction of the mixing time for mortar mixers. It was also observed that for the same w:p ratio and mixing sequence, the total mixing time in a mortar mixture was shorter that that in the pan mixer.

Chopin and his co-workers[36] studied the effects of mixing time on robustness. The parameters varied in the study included the quantity of powder, use of limestone filler, and various types and contents of silica fume and SP. The authors concluded that although the SCC mixtures generally require longer mixing times than conventional mixtures, their mixing time can be reduced by increasing the fine particle content, (with a constant w:c ratio), increasing the total water amount, and replacing part of the cement by silica fume.

6. Evaluation and Monitoring Static Stability Robustness

In Section 2.2, the effects of the major ingredients on the stability of SCC are discussed. To reiterate, because of the inherent low values of yield stress and viscosity, SCC is especially prone to segregation under static conditions (Figs. 4 and 5). In view of the central role of segregation (that is manifested by sedimentation of aggregate as well as migration of paste and air voids to the top of the element and bleeding, several test methods have been proposed for evaluating the stability of the mixture.

One popular method is based on visual stability index (VSI) of the slump flow of SCC and rating it visually from 0 to 3 in increments of 0.5, where a 0 rating represents no segregation and a rating of 3 represents severe segregation.[37] However, in accordance with Section 2.2, a visual inspection of slump flow is applicable to dynamic stability, but is an inadequate measure to evaluate the static stability of the mixture.

Other common methods are based on column tests in which the mixture is cast into a few cylindrical sections that are mounted one on the top of the other, and at a predetermine time before hardening, the sections are removed and the content of aggregate in each of the sections is determined by wet sieving,[17,38] After hardening, cylinders can be vertically sawed and the distribution of the aggregate along the vertical axis can be determined by visual inspection, point counting, or image analysis. Another approach is to measure the electrical conductivity along a vertical section as a function of time.[39] This method is sensitive to bleeding, rather than settling of aggregate. Additional methods make a correlation between the measured rate of sedimentation of aggregate and the rate of a penetration device. Bui and his coworkers practiced with penetration apparatus that was placed on the leg of L-box two minutes after pouring the concrete into the L-box and measuring the depth of penetration after 45 s. It was claimed that a satisfactory segregation resistance is achieved if the penetration depth of the cylinder head of the apparatus is less than 8 mm.[40] Another version of the above apparatus was based on the penetration depth of a hollow metal cylinder.[41]

More recently, Shen et al.[42] developed a new penetration probe made of a 130 mm diameter ring connected with a 150 mm high rod marked with scale (see also Chapter 2, Section 3.1). The whole probe is made of 1.6 mm diameter steel wire and its total weight is about 18 g. Concrete is cast into a 150 × 300 mm cylinder, and after 2 min of undisturbed rest, the probe is placed on the concrete surface for 1 min. The stability rating is evaluated according to Table 1.[43]

Table 1: Stability rating for segregation probe method[42,43]

Penetration depth (mm)	Rating	Interpretation
< 4	0	Stable
4 ~ < 7	1	Stable
7 ~ 25	2	Unstable
> 25	3	Unstable

The robustness curves of the three base mixes made with graded aggregate, mineral filler, and VMA are compared in Figure 8. The mix design of the mixtures is given in Table 2.

Two parameters need to be examined when comparing the robustness curves: (a) the slope of the w/cm vs. penetration depth curve, and (b) the margin between target w/cm and the w/cm with maximum penetration depth. A flatter slope and larger margin indicate higher robustness. According to the slope and margin, the robustness of the three base mixes is rated in the order VMA > graded aggregate > mineral filler. The higher robustness of the VMA mix is attributed to the increase in viscosity. Graded aggregate also help to enhance robustness, probably because gradation of fine and coarse aggregates can achieve a lattice effect where small aggregates can resist the settlement of middle-sized ones, which in turn resists the settlement of large aggregates.[44]

Table 2: Mix Proportions of SCC for Robustness Test

Mix ID	Mix modification	w/c	Material kg/m^3						Admixture ml/m^3	
			Cement (Type I)	Fly Ash (C)	CA1	CA2	FA	Water	SP *(Grace Adva cast 530)*	VMA *(Master Builders)*
Graded Aggregate	base	0.38	392	93	218	638	833	185	1377	
	GA + 5%	0.38	448	106	201	589	769	211	1236	
	GA -5%	0.38	336	80	234	687	897	158	1413	
Mineral Filler	base	0.33	357	193	810	0	793	179	1413	
	MF+5%	0.33	404	218	741	0	734	202	1389	
	MF-5%	0.33	309	167	869	0	862	155	1483	
VMA	base	0.41	407	0	966	0	824	165	1789	848
	VMA+5%	0.41	474	0	896	0	766	192	1413	777
	VMA -5%	0.41	339	0	1034	0	884	138	1884	824

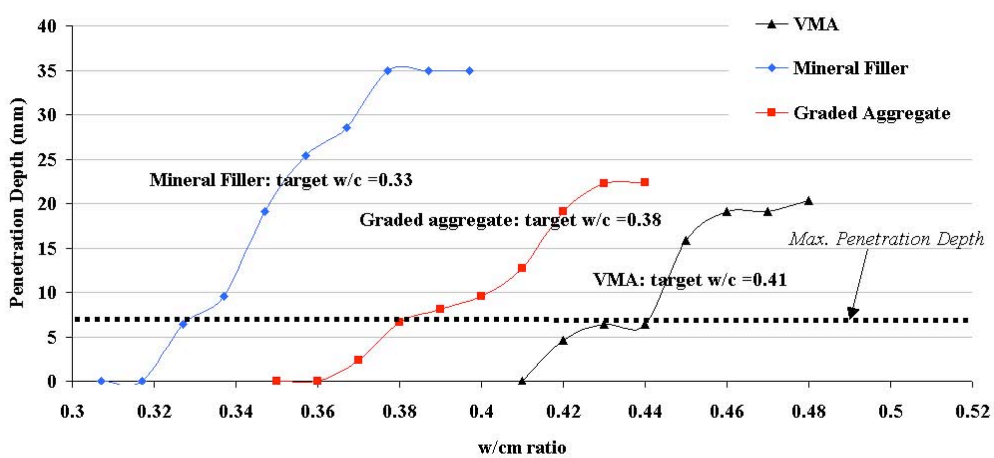
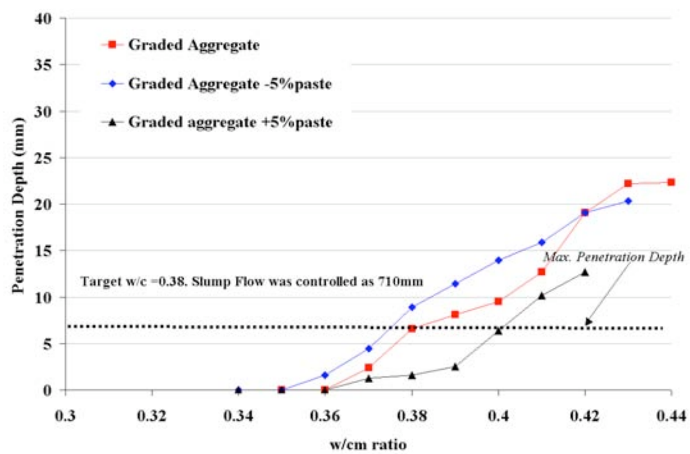


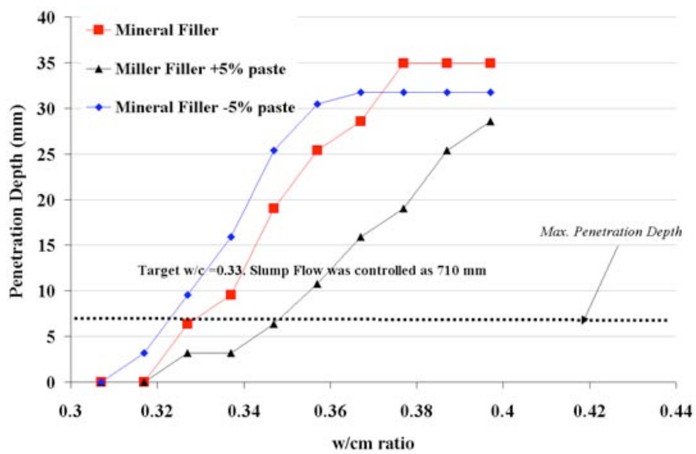
Figure 8: Effects of mix composition on robustness. The robustness increases in the order mineral filler (fly ash), graded aggregate, and VMA.

Fig. 9 shows the effects of a modest variation of the paste content by ±5% on robustness. For all the three types of SCC, the increase in the paste content increases robustness, whilst a decrease of the paste content decreases the robustness. It should be noted, however, that the VMA mixture with 5% less paste could not achieve the same slump flow. Higher paste content improves robustness because it increases the viscosity, density, and yield stress of the matrix.

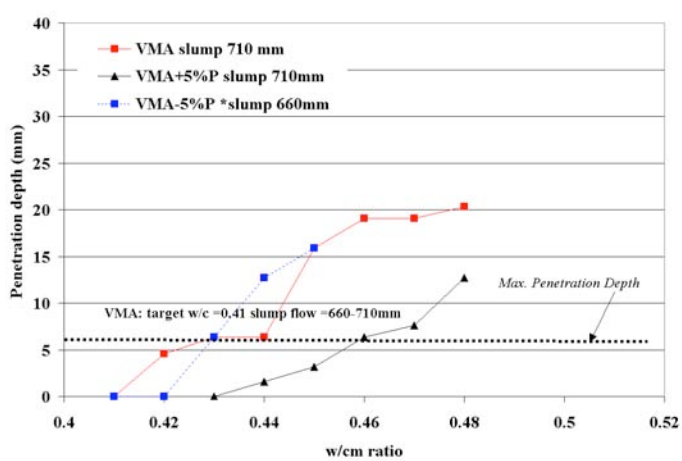
As discussed in Section 2.2, Fig. 10 shows the mixture with slag is more robust than with fly ash.



(a)



(b)



(c)

Figure 9: Effects of modest change in the paste content on the robustness of (a) graded aggregate, (b) mineral filler, and (c) VMA

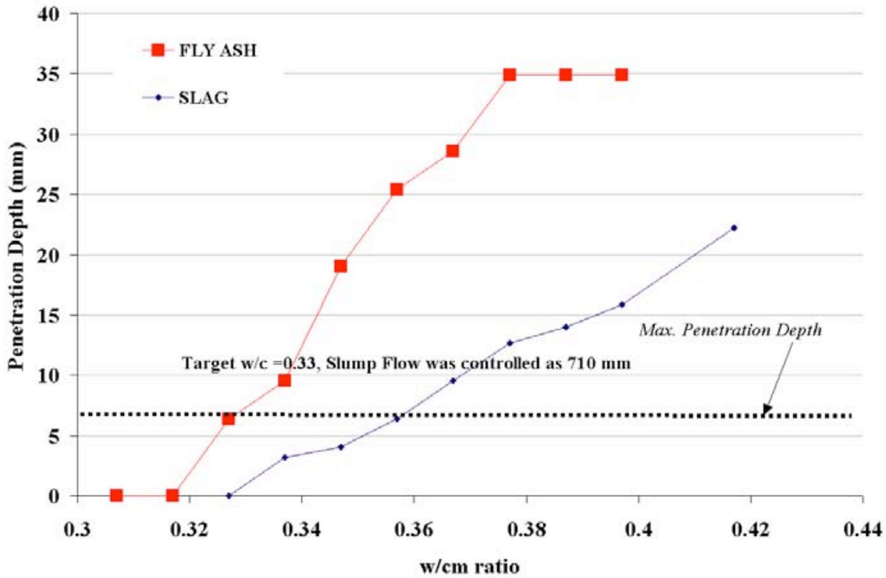


Figure 10: Effects of slag and fly ash mixtures on robustness

7. Concluding remarks

Self-consolidating concrete is an emerging technology that utilizes flowable concrete that eliminates the need for consolidation. Apart from regulation considerations, the growth of the SCC market share depends to a great extent on the robustness of the mixtures.

Robustness depends on a number of different attributes including the mix design, shear energy, shear rate, and application. It implies that a given mixture can be regarded as robust for a lateral flow application, such as garage floor, but might segregate once it cast into tall columns. Similarly, because of thixotropy considerations, a robust mix that is successfully cast into columns might turn out to be a non-robust mix if it has a different mixing history.

From all practical considerations (and in analogy to the flow requirements), it is the opinion of the authors that robustness should be evaluated according to the application. For example, for most lateral flow applications, the VSI method mentioned above is sufficient for rating the robustness of the mix. In more demanding applications, other quantitative methods listed above should be used. Robustness issues can be overcome if a greater attention is paid to the moisture variations in aggregate and carefully metering of all ingredients, especially chemical admixture and water. Higher robustness is achieved by increasing the viscosity of the mixture via materials selection and incorporation of more VMA and/or powder. In regard to the latter, incorporation of supplementary cementitious materials of high specific gravity, such as slag, dolomite, or limestone increases the robustness considerably.

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Chapter 2. Innovations in Testing SCC

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1. Introduction

The use of self-consolidating concrete (SCC) has grown tremendously since its inception in the 1980s. Different from a conventional concrete, SCC is characterized by its high flowability at the fresh state. This helps the SCC to satisfy the performance requirement in the field, such as giving a smooth surface finish, encapsulate the reinforcement without blocking of aggregates, etc. Because of the material performance in its fresh state, the existing testing methods for conventional concrete are no longer suitable for SCC.

Numerous efforts have been explored for new testing methods on SCC in the past decade. There are several organizations that collect the work in this area. The RILEM technical committee, TC 174-SCC (Self-Compacting Concrete), ASTM Subcommittee C09.47 (Self-Consolidating Concrete), ACI Committee 237 (Self-Consolidating Concrete), and TRB Committee AFN10 (Basic Research and Emerging Technologies Related to Concrete) are good examples. Symposiums and workshops[1-4] on this topic were given by these organizations and several test methods on the flowability of SCC have been popularized since then.

Among the existing test methods, slump flow test, using the traditional slump cone, is the most common testing method for flowability (or filling ability) and was standardized in September 2005 as ASTM C 1611. During the test, the final slump flow diameter and T_{50} (time needed for concrete to reach a spread diameter of 20 in. (50 cm)) are recorded. The U-Box, L-Box, and especially J-ring (ASTM C 1621) tests are used for the evaluation of passing ability. These fresh properties are governed by the rheological properties of the material and some studied have been conducted in the lab to investigate the correlation among the measured parameters from above-mentioned methods (e.g. correlating T_{50} and the flow velocity at L-box test to the plastic viscosity)[5,6]. A good test method that can help to quantitatively determine the viscosity and the yield stress of SCC in the field is urgently needed. Segregation resistance is another important issue for SCC. Surface settlement test and the penetration test are two methods to evaluate the resistance to segregation of SCC in the field. However, these methods focus on the static segregation of SCC and the theoretical background for these methods is still unclear. There are no proper test methods for evaluating the dynamic segregation of SCC.

Researchers at the Center for Advanced Cement-Based Materials (ACBM) are targeting development of new test equipment and methods for in-situ evaluation of SCC with an emphasis on viscosity, yield stress, and segregation resistance. The research strategies are: (1) to better understand the fundamental aspect of rheology; (2) to develop new techniques based on simple concepts; and (3) to develop the corresponding equipment that is both lab- and field-friendly. To be different from the existing methods for testing SCC, it is required that these new methods can help to evaluate the properties of SCC not only qualitatively but quantitatively. The research tracks are subdivided into two parts: rheological properties and segregation resistance, which will be described in the following sections of this paper.

2. Falling Ball Viscometer

The basic parameter influencing the performance of the fresh SCC in casting is its rheological properties. Thus, studying the rheology of SCC has become one of the central issues at ACBM. Concrete rheometers with various sensor geometries were designed and used in the past ten years[7-10]. A comparison of different rheometers was conducted at the National Institute of Standards and Technology (NIST)[11]. The study showed that for the same concrete mixtures, different rheometers yielded different results. The reasons could be attributed to various geometries of the sensors and rheometers, testing procedure and the inhomogeneity of the material itself. Another way to investigate the rheological behavior of materials can be made with the application of a falling/pulling ball viscometer. The viscosity calculation is based on the velocity of the moving ball and the equilibrium of forces. The external forces are normally traced with a pulley system[12] or the intensity of a magnetic field[13], neither of which is suitable for field measurement. The objective of this research is to design a falling ball viscometer, which can be used under both the lab and field conditions.

2.1 System Configuration and Calibrations

A falling ball viscometer was designed at ACBM at Northwestern University using a scale with accuracy of 0.001g, an elastic tensile spring, and steel balls of various diameters[14,15] (Fig. 1). When a steel ball is suspended by the spring and is allowed to move in the fluid, then the forces acting on the ball can be resolved into four components. As shown in Fig. 2, these components are gravity (W), tensile force (T), buoyancy (B), and drag force (D). During the measurement, the spring is hooked to a sensor that is located at the bottom of the scale. By suspending the steel ball with the spring, the tensile force in the spring during the downwards movement of the ball can be continuously recorded by reading the numbers shown on the scale. Once the tensile force is known, the displacement of the ball can be computed and this allows for the calculation of the velocity and acceleration of the ball. Hence, the only force left to be determined is the drag force, and it can be solved using the equation of motion shown in Fig. 2. In steady state condition and when Reynolds number (R_n) is less than 0.5, the drag force can be linearly related to the velocity by applying Stoke's Law[16] for a spherical particle as shown in equation 1:

$$D = 6\pi\eta r v; R_n = vr\eta / \rho \qquad (2.1)$$

where, η is the viscosity of the measured liquid; r is the radius of the ball; v is the velocity of the ball; and ρ is the density of the measured liquid. From the equation, it can be noted that the drag force is linearly related to the velocity of the ball and the size of the moving ball.

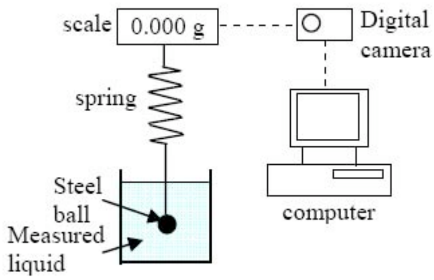


Fig. 1 Configuration of the falling ball viscometer

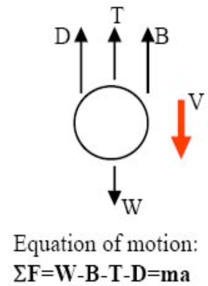


Fig. 2 Free body diagram of the ball

Equation 1 is valid for a spherical particle moving with a constant velocity in a Newtonian fluid. However, with the configuration that introduced, the velocity of a moving ball changes with time. This is attributed to the changing of the tensile force as the spring elongates according to the ball movement. Thus, to make sure the used theory is still valid for the used configuration, a calibration for the designed viscometer is necessary.

Various Newtonian fluids with known viscosities were used for the system calibration. It was found that the viscosity of the measured liquid can be determined through equation 2, where K_e is the slope of the drag force-ball velocity curve that determined experimentally:

$$K_e - 6\pi r\eta = (-0.4738\eta^2 + 62.377\eta)r + (0.0034\eta^2 - 0.3449\eta) \quad (2.2)$$

This calibration is proved to be efficient for Newtonian fluids. It is suggested that the calibration should also be valid for non-Newtonian fluids, if the material behaves according to Bingham model. For a Bingham material, drag force D is linearly related to the velocity of the moving ball, however, the linear line has an intersection with the y axis as shown in Fig. 3, where D_0 can be correlated to the yield stress of the material. The solid line in the figure can be shifted down until it intersects with the origin. This implies that the calibration of the system should also be valid for Bingham fluids. Fresh concrete is normally regarded as a Bingham fluid, thus, the viscometer has a high potential to be applied to concrete. The yield stress acts tangentially to the surface of the steel ball. Thus, the relationship between the initial resistance to motion (subsequently called initial drag force (D_0)) and the yield stress (τ_y) of the measured liquid can be expressed as follows:

$$D_0 = 2\pi r^2 \tau_y \quad (2.3)$$

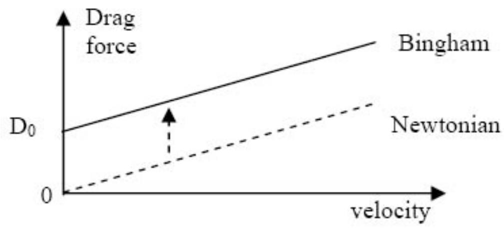


Fig. 3 Validity for Bingham materials

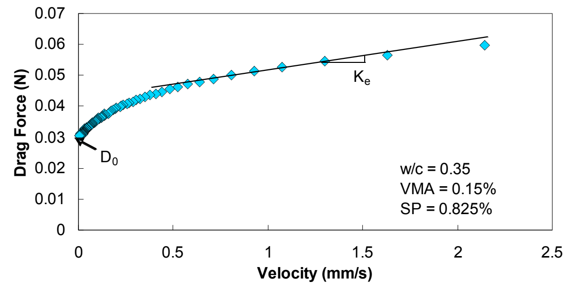


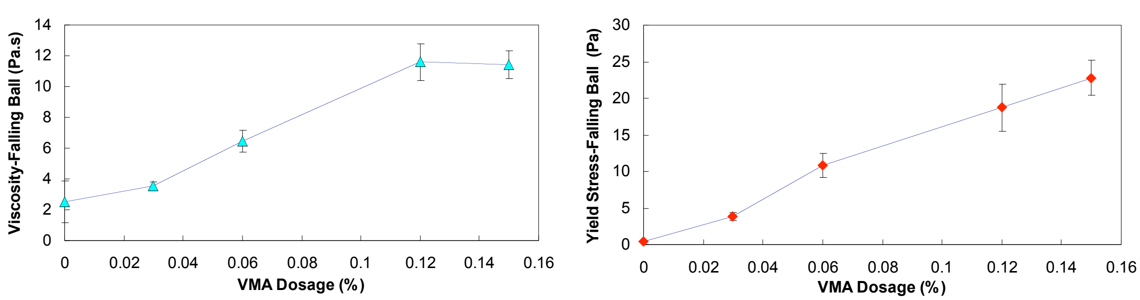
Fig. 4 Falling ball measurement for cement paste with VMA[17]

2.2 Experimental Results

The preliminary study on the feasibility of applying this viscometer to SCC was conducted in two steps. In the first step, the properties of SCC pastes made with the same w/c and different contents of superplasticizer (SP) and viscosity-modifying-admixtures (VMA) contents were studied. In the second step, the research was carried out on SCC mortars made with various sand contents but the same paste matrix.

Paste with Various VMA Dosage

An example of the falling ball viscometer measurement for paste of w/c=0.35 with a VMA dosage of 0.15% (by mass of water) is shown in Fig. 4. An obvious shear-thinning phenomenon can be observed since the drag force is not linearly related to the ball velocity. This hints that the falling ball viscometer is very sensitive to the rheological behavior of the measured liquid. For all the cement pastes made with VMA, the plastic viscosity was calculated by using linear regression of the upper portion of the $D-v$ curve ($v \geq 0.5mm/s$) (Fig. 4). Both the plastic viscosity and the yield stress are plotted as a function of VMA dosage in Fig. 5. As expected, an increase of the viscosity is obtained when the VMA content is increased. It should be noted that the use of this particular polysaccharide-based VMA increased both the yield stress and the plastic viscosity of the cement paste.



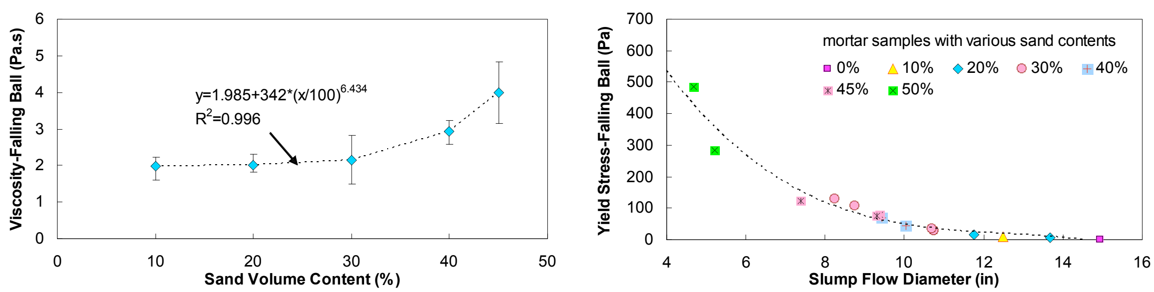
(a) Plastic Viscosity (b) Yield Stress

Fig. 5 Sensitivity of the falling ball viscometer to VMA dosages[17]

Mortars with Various Sand Contents

Mortar samples with various sand contents (10%-50% by the volume of the total mortar mixture) were measured using a steel ball with a 1.25 inch (3.175 cm) diameter. The calculated viscosities from the falling ball viscometer for each mortar are plotted in Fig. 6(a). It can be noted that the viscosity changes slightly when the sand content is less than 30% of the total volume of the mixture. When the sand content is higher than 30%, a significant increase in plastic viscosity with increase of sand content can take place. This result corresponds well to the results obtained by Ferraris et al[18].

It was found that the yield stresses of various batches of mortars can vary over a wide range when the mixture proportioning is kept constant. Qualitatively speaking, the mortar with a bigger flow diameter (mini-slump size: 70 mm and 100 mm for the upper inner and lower inner diameters, and 50 mm for the height) has a lower yield stress. The relationship between the slump flow diameter and yield stress was further studied. Fig. 6(b) plots the yield stress as a function of slump flow diameter for all the mortars measured. A unique relationship between the two studied parameters can be found, which is similar to the results reported by other researchers[19,20]. This strong correlation confirms that the yield stress can be the dominant parameter that governs the slump flow diameter. However, the influences from other parameters, such as mass density, viscosity, surface tension, etc, should not be ignored.



(a) Plastic Viscosity (b) Yield Stress & Slump flow

Fig. 6 Measurements on mortars with various sand contents

2.3 Potential for Field Testing

The scale, the spring, and the steel balls can be easily assembled, disassembled, packed, and carried to any field that requires the in-situ measurement. The lightweight and portability of the equipment make this viscometer a field and lab friendly equipment. It is easy to clean the ball after each measurement, thus the easiness of the maintenance becomes another advantage of this equipment. The cost of the equipment is 15 to 25 times less than any existing concrete viscometer. The designed viscometer has proved to be efficient for both cement pastes and mortars. This enhances the potential of the application of this viscometer to concrete without changing the existing configuration. Directly measurement to concrete will be conducted as the next step.

3. Measuring the Segregation Resistance

Stability and homogeneity of SCC are two key issues that influence the mechanical and durability performance of the material in its hardened state. Thus, concrete is required to have the ability to resist the segregation of aggregate throughout the mixing, transportation and casting process. Due to the high flowability of SCC, it is much more susceptible to stability problem than normal concrete. This hints that it is urgent to have a test method to evaluate segregation in the field.

Material stability has a two-fold meaning. Dynamic stability refers to the resistance of concrete to separation during movement (e.g. mixing, placement into the formwork).

Static stability refers to the resistance of SCC to bleeding and segregation after the SCC is cast until it is hardened. Test methods to measure both the dynamic and static segregation resistance of SCC are needed.

Currently, the most commonly used methods to evaluate segregation resistance are the visual examination method, the column segregation test (ASTM C 1610), and the V-funnel method. In the visual examination method, segregation resistance is evaluated by observing the periphery of the concrete after the slump flow test[21]. A visual stability index ranging from 0 to 3 is used to rate the SCC. The method evaluates segregation qualitatively and it relies on the experience of the examiner. In the column segregation method, the coarse aggregates are sieved from the concrete in the top and bottom section of a column after 15 minutes of casting. The percent of static segregation is then evaluated according to ASTM C 1610 The V-funnel method was firstly developed in Japan[23] and consists of measuring the variation of flow times following different periods of resting after filling the SCC in the V-funnel. Again, this method does not give a quantitative evaluation of segregation. The penetration apparatus (PA) method was first introduced by Bui et al. to qualitatively evaluate the static segregation of SCC[24]. The structure of the apparatus produced by ACBM is shown in Fig. 7. The test can be combined with the L-box test. During the test, the PA is located on the top of the vertical leg of the L-box, and the penetration cylinder is then adjusted to just touch the upper surface of concrete (Fig. 8). After releasing the screw, the cylinder is allowed to penetrate freely into the concrete for 45 seconds. And the final penetration depth can be recorded by reading the scale. It was found that a good segregation resistance of the tested SCC can be indicated by a penetration depth that was less than 7 mm[24].

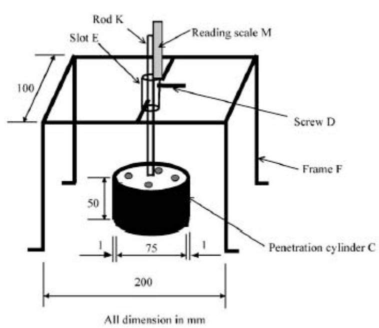


Fig 7. Penetration Apparatus[24]


Fig. 8 Application of the penetration apparatus

Some of the other new testing methods that are under development at ACBM are discussed below.

3.1 Segregation Probe Test

<u>*System Configuration*</u>

The segregation probe, inspired by the Penetration Apparatus method[24], is a fast and effective method to measure the thickness of mortar/paste at the top of fresh SCC. A thicker layer of mortar/paste at the surface corresponds to a lower static stability. The results of the segregation probe method and the measured thickness of the mortar/paste layer in hardened concrete were found to be quite similar.[25]

The segregation probe is a 125mm (5 in.) diameter ring connected with a 150 mm (6 in.) high rod marked with scale (Fig. 9). The whole probe is made of 1.6-mm ($^{1}/_{16}$ in.)

diameter steel wire. The total weight of the probe is about 18 g. Before the test, fresh concrete is cast into a 150 x 300 mm (6 × 12 in.) cylinder with one lift. The concrete is allowed to rest for 2 min. before the test, during which excessive disturbance is avoided. The segregation probe is then placed gently on the concrete surface allowed to settle for 1 min. The penetration depth marked on the rod is used to determine the stability rating according to Table 1.

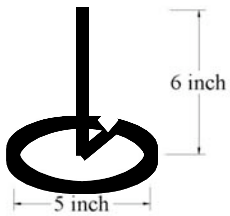


Fig. 9 Segregation Probe[25]

Penetration Depth (mm)	Rating	Corresponding Rating in HVSI of Cut Cylinder
<4	0 Stable	0 stable
4 ~ < 7	1 Stable	1 stable
7 ~ 25	2 Unstable	2 unstable
>25	3 Unstable	3 unstable

Table 1 Stability Rating for Segregation Probe Method[25]

Penetration Mechanism

When the segregation probe is suspended at rest in a suspension it experiences two opposing forces, buoyancy force B_F and gravitational attraction G_F. Due to the higher density of steel compared to the measured liquid, the unbalanced force, (G_F - B_F), will cause the probe to accelerate downward if yield stress of the liquid is not high enough. The resistance offered by the liquid is called the skin friction. Skin friction results in the development of a drag force, F_D, which opposes the motion and increases with increasing particle velocity relative to the liquid (Fig. 10). F_D reduces the acceleration and finally becomes equal to the original driving force (G_F - B_F). Then there are no more unopposed forces acting on the particle and it continues to travel at a constant settling velocity, v_∞.

According to fluid mechanics, this drag force can be expressed by equation 4, where d denotes the diameter of the cylindrical cross section of the probe, v denotes the velocity of the probe, and η represents the viscosity of the liquid. It is widely accepted that concrete flows as a Bingham material. Thus, it is necessary to replace the viscosity in equation 4 by the apparent viscosity as shown in equation 5. In the equation, τ_0 represents the yield stress and $\dot{\gamma}$ is the shear rate, which can be related to the velocity of the probe.

$$F_D = 4(\pi + 1) \cdot d \cdot v \cdot \eta \tag{2.4}$$

$$F_D = 4(\pi + 1) \cdot d \cdot v \cdot (\tau_0 / \dot{\gamma} + \eta)\,;\ \dot{\gamma} = v/d \tag{2.5}$$

Considering the final state of the probe, the equilibrium condition has to be satisfied, which leads to the expression of the final velocity of the probe that shown as follows:

$$v_\infty = \frac{\pi(\pi + 3.4) \cdot d^2 \cdot (\rho_s - \rho_L) \cdot g - 16(\pi + 1) \cdot d \cdot \tau_0}{16(\pi + 1) \cdot \eta} \tag{2.6}$$

where ρ_s and ρ_L are the mass density of the probe and the tested liquid, respectively. It is obvious that the segregation probe will not penetrate the liquid if the yield stress is big enough (equation 7). A typical value of critical yield stress is 28 Pa, which can be calculated by using the density of a cement paste with w/c=0.35. This means the segregation probe penetrates when the yield stress of suspension is less than 28 Pa and keeps still when yield stress exceeds 28 Pa. For SCC, normally the yield stress of its paste matrix is smaller than this critical value, and the yield stress for SCC composite is higher than this value. Thus, the segregation probe should be efficient to evaluate the segregation resistance of SCC.

$$\tau_0 \geq \pi(3.4+\pi)(\rho_s-\rho_L)\cdot g\cdot d/16(\pi+1)$$

(2.7)

Experimental Results

Fig. 11 gives an example in which the segregation probe was used to determine robustness of SCC mixtures to moisture content. The VMA mix has a lower slope of the curve and a larger margin between target w/cm and maximum penetration depth and thus is more robust to moisture content than the other two mixes.

Potential for Field Testing

The segregation probe test is simple and rapid and thus is suitable for quality control and other applications such as robustness measurement. The segregation probe is lightweight, and the test does not rely on the experience of the tester. Due to these reasons, this method is a field-friendly method.

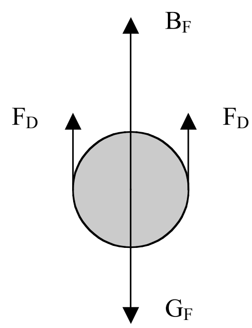


Fig. 10 Forces acting on a cylinder in a liquid

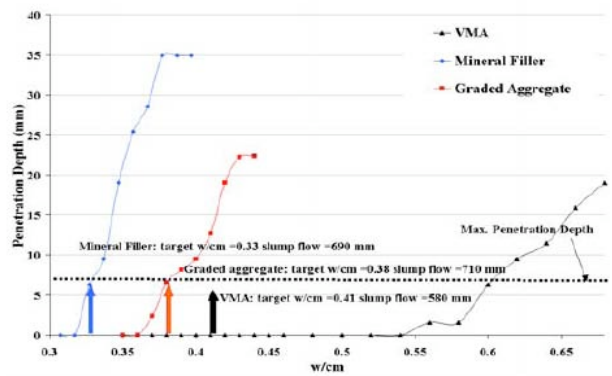


Fig. 11 Using Segregation Probe to Compare Robustness of SCC[25]

3.2 Other Methods in Segregation Measurement

Other test methods that can evaluate the segregation for SCC in a hardened state were also developed at UIUC. In the image analysis method, a concrete cylinder is cut lengthwise into two, and a digital photo is then taken of the cut surface. Image analysis software is used to calculate and compare the percentages of coarse aggregates in different levels of the cut cylinder. Due to the large amount of work needed to prepare and analyze the image, this method is good for the purpose of laboratory study. Another method, called visual stability rating method, was developed for both the field and laboratory testing. In this method, the SCC cylinder is cut lengthwise, and the cut surface is then used to observe the distribution of the coarse aggregates. A Hardened Visual Stability Index (HVSI) is used to assess the stability[25].

For fresh SCC, besides the segregation probe test, eddy current test was also introduced by researchers at UIUC. In this method, a concrete covermeter[25] is used to monitor the position of a metallic aggregate, which is designed to have similar size and density to normal coarse aggregate. This method has a high requirement on the instrument. It measures the position of a single metallic aggregate. However, this method can monitor the settling process in most kinds of suspensions, which may help to understand the segregation mechanism.

A multi-pair electrode conductivity approach was also introduced by Khayat, et. al [6,26] at Université de Sherbrooke, who is a partner of ACBM. The method relies on measuring the differences in electrical conductivity measured at different depths, and as a function of time. The variations in electrical conductivity throughout the sample as a function of time are used to interpret the material homogeneity. Good correlations were established between the stability of concrete determined from physical testing (external bleeding and homogeneity of coarse aggregate distribution along hardened concrete samples) and the bleeding, segregation, and homogeneity indices evaluated from the conductivity approach, as illustrated in Fig.12. The electrical conductivity approach can even be used for quality control on the job site. Variations in electrical conductivity after 20 min of testing can be related to the various indices determined from the conductivity approach, as illustrated in Fig. 13. Thus, the method provides with the reliable measurement on the stability of concrete.

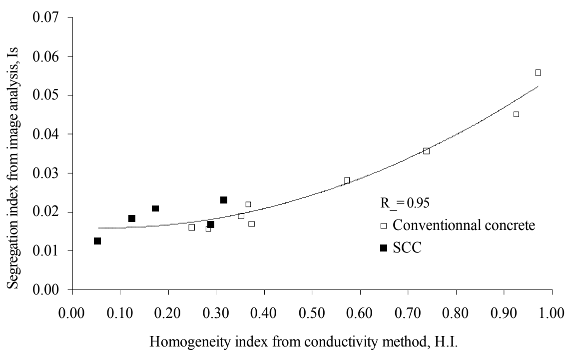


Fig. 12 Relationship between segregation index from image analysis and homogeneity index from electrical conductivity approach[27]

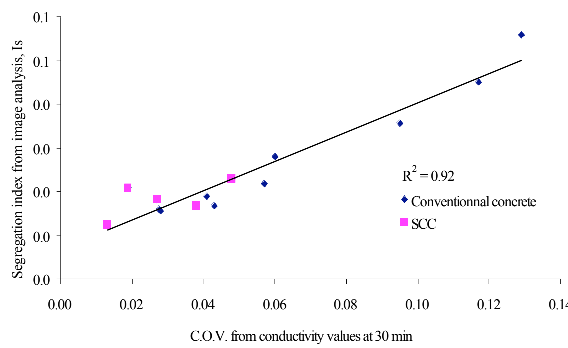


Fig. 13 Variation of segregation index determined from image analysis and coefficient of variation of conductivity values after 20 min of testing (30 min of age)[27]

Khayat et al.[28] developed a pressure filter test to evaluate the ability of SCC to retain its mix water. The test involves the placement of approximately 5 kg of concrete sample in a pressure vessel measuring with compressed air of 700 kPa. The forced bleed water is monitored for 10 minutes to determine the water permeability of the fresh concrete using Darcy's law. The test was shown to be effective in differentiating between the stability of SCC made with different binder contents, w/cm, and VMA concentrations and can be suitable for quality control of SCC in the field.

4. Summary and Future Research

Recent innovations are presented herein to evaluate the rheological properties and static segregation resistance of SCC quantitatively. Both the falling ball viscometer and the segregation probe prove to have high potential for field testing due to the simple theoretical background, the easiness of applying the measurement, the lightweight equipment, and the rapid testing procedure. The precision and reproducibility of the introduced methods need to be further investigated. These testing methods along with the multi-pair electrode conductivity method can be used as quality control methods. They help to improve the understanding of the material behavior. The results of this part of the work can be closely related to other research conducted at ACBM. For example, segregation probe test can be used to study the robustness of SCC, and the yield stress and viscosity measurements can help to understand the formwork pressure produced by SCC. It is necessary to develop a test method to evaluate the dynamic segregation of concrete.

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Chapter 3. Formwork Pressure

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1. Introduction

A major thrust area for research of SCC is in the understanding formwork pressure. Provisions of the current *ACI Manual of Concrete Practice* (i.e. ACI 347R) do not specifically address SCC, but recommend that unless a method based on appropriate experimental data is available, formwork should be designed to withstand the full hydrostatic head of fluid concrete. This guidance generally limits contractors to short walls or extremely strong formwork. Thus, there is great need for better understanding of the pressures that are actually seen in cast-in-place applications in the field. Further study is necessary so that equations can be developed to reliably predict formwork pressures for a range of casting rates, and to calculate allowable casting rates based on formwork strength. As in the case of conventional concrete, there are many factors governing the pressure exerted by SCC, including: the stiffening behavior of undisturbed SCC, the casting rate, the height of the formwork, temperature, vibration, and susceptibility to disturbance of the concrete. An additional difficulty is that there are no standard methods for studying formwork pressure in the field or in the laboratory.

2. Field Observations and Large-Scale Tests

Many laboratory experiments and field tests have shown that SCC pours do not generate full hydrostatic pressure at the bottom of the structure. Tests performed by Vanhove and Djelal (2002) showed a maximum pressure 64% of maximum hydrostatic pressure for a wall placed at 25 m/h from above and a maximum of 68% of maximum hydrostatic pressure for a wall placed at 19.5m/h by pumping from the bottom of the wall. In their study, the maximum pressure was not found at the bottom of the wall but at a height of 1.5m. Maximum hydrostatic pressure was determined using the overall height of the structure. (1)

Testing has also been conducted in field installations. A 28-foot high wall was constructed in the structures lab at the University of Illinois at Urbana-Champaign. The wall was created with SCC material and filled in one continuous pour lasting about seven hours. It was found that only within the top four feet of placed concrete were pressures approaching full hydrostatic pressures recorded. The maximum pressure reached was 5.5 psi, which was only approximately 20% of the maximum hydrostatic pressure at the point of measurement. This wall was filled at a relatively slow rate, maximum of 5.5 ft/hr, due to the large dimensions of the structure (5 ft thick, 80 ft long and 28 ft high). The wall required 415 cubic yards of material. A companion test column was fabricated which involved filling a 10.5-ft tall column. The column was filled at a rate of 60 ft/hr and the highest pressure measured one foot from the bottom. The highest pressure recorded was 80% of hydrostatic pressure. The wall and column were filled using a concrete pump and the material had a target slump flow of 28 in. but varied during the day from 23.5 to 29 in. during the time of the pour and the density of the material was 151 lb/ft^3. (2)

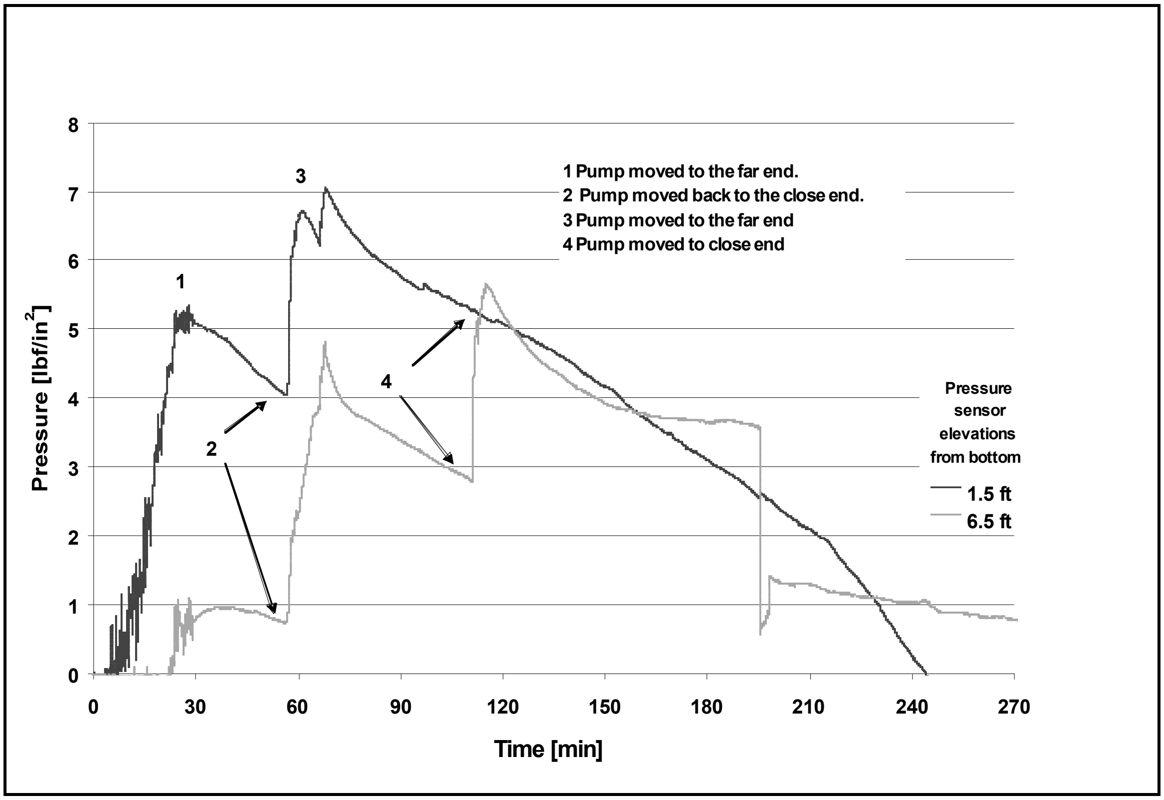

Figure 1: Pressure exerted by SCC on formwork over time

A large reconstruction project in Peoria, Illinois involved the construction of many new retaining walls. The project is being constructed with SCC for the walls. Several of these walls were instrumented with pressure gages to study the development of pressure on the formwork. Figure 1 shows the results of one such wall. One sensor was placed 1.5 ft off the bottom of the wall and the second sensor was placed 6.5 ft off the bottom of the wall. The first hour of pouring was at a rate of 9 ft/hr, the second hour at 4.5 ft/hr and slower for the final hours. The bottom sensor reached a maximum pressure of 7 psi with where as hydrostatic pressure would have been 20 psi. Additionally the highest pressure was reached long before the pour was finished. It is also important to note that at some point in the pour additional concrete in the wall did not cause the pressure to rise, as evident by the maximum pressure occurring just over an hour into the pour which lasted 4 h. (2)

3. Laboratory Tests

There are several means of studying formwork pressure with SCC in the laboratory. One method used by researchers at the University of Sherbrooke and the University of Illinois at Urbana-Champaign (UIUC) uses a PVC tube with sensors mounted to the tube. (2,3) Researchers at both universities use diaphragm sensors that measure total pressure and are in physical contact with the concrete material during the test. These experimental devices are used to study pressure drop over time. The sensors are placed at varying heights and each university uses different height columns. Figure 2 and Figure 3 show results of various mixtures from tests performed at Sherbrooke and UIUC, respectively.

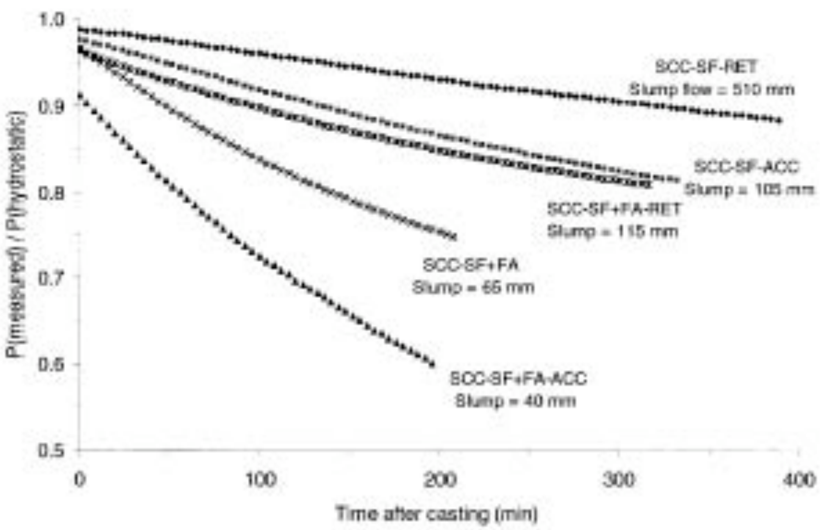

Figure 2: Example of Results from Univ. of Sherbrooke

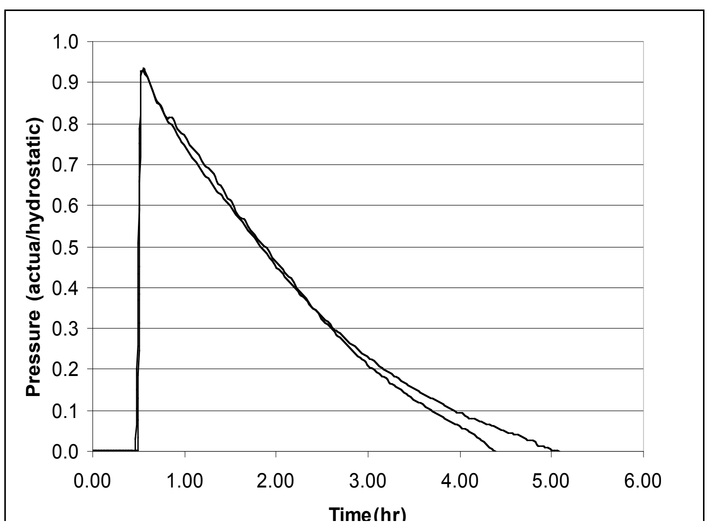

Figure 3: Example of Results from UIUC

An alternative laboratory set up is used by researchers at Northwestern University. Their testing apparatus utilizes a short column of concrete, 300 mm, in a steel mold. Figure 4 is a picture of their test set-up. A loading frame is used to apply a load on the top of the column of concrete to simulate the effect of a much larger column of concrete. This can also apply increasing loads over time to simulate varying casting rates. The cylinder has 2 pressure cells mounted on the sides. One is used to measure total horizontal pressure and the second sensor is used to measure pore water pressure. The general procedure is to fill the cylinder and then apply an ever increasing load until a pre-determined maximum load representing a particular column height. That load is maintained for several hours to simulate the end of filling and the material at rest. (4)

Figure 4: Northwestern University Laboratory Set-Up

It has been found through many laboratory trials that the particular material chosen for the formwork is of great importance in studying formwork pressure. Initial tests at UIUC were performed using cardboard tubes as might be used in the field to pour columns. These proved to be problematic in studying formwork pressure. The cardboard material absorbs moisture from the concrete and swells. This small displacement of the sensor causes the sensor to lose contact with the concrete, and this results in errant measurements of lateral pressure on the form material. A comparison of a plain cardboard tube, one with a plastic liner, and 2 PVC pipe configurations are shown in Figure 5. (5)

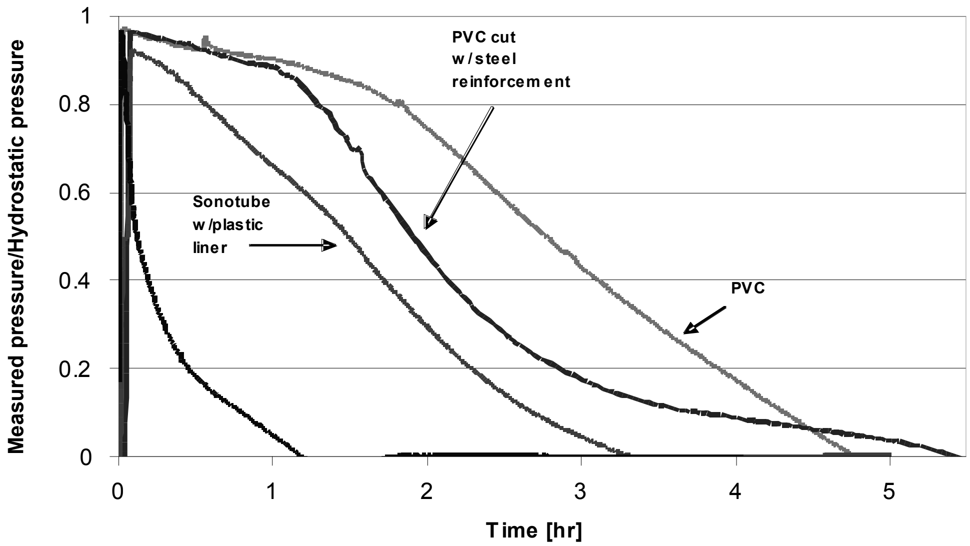

Figure 5: Effect of Formwork Material on Measured Lateral Pressure[2]

4. Mixture Factors that Influence Pressure

Many factors can affect the formwork pressure generated in the process of pouring SCC. This idea is no different than that for normal concrete. Simply, the faster the material is poured, the greater the maximum formwork pressure will be. As a general rule, formwork pressure is related to thixotropic characteristics of an SCC. SCC that is strongly thixotropic—that is, it quickly gels when the material comes to rest—will display a more rapid decay of pressure, and lower overall pressures will be observed during construction.

Other factors affecting formwork pressure include mixture temperature and the presence of set modifying admixtures. As would be expected, mixtures with retarding admixtures will experience a slower pressure drop and a higher maximum pressure whereas mixtures with accelerating admixtures will exhibit faster pressure drop and a lower maximum pressure. Figure 6 shows data collected regarding the influence of mixture temperature on formwork pressure decay. As might be expected, warmer mixtures exhibited faster pressure decay. Accelerating admixtures also lead to more rapid formwork pressure decay.

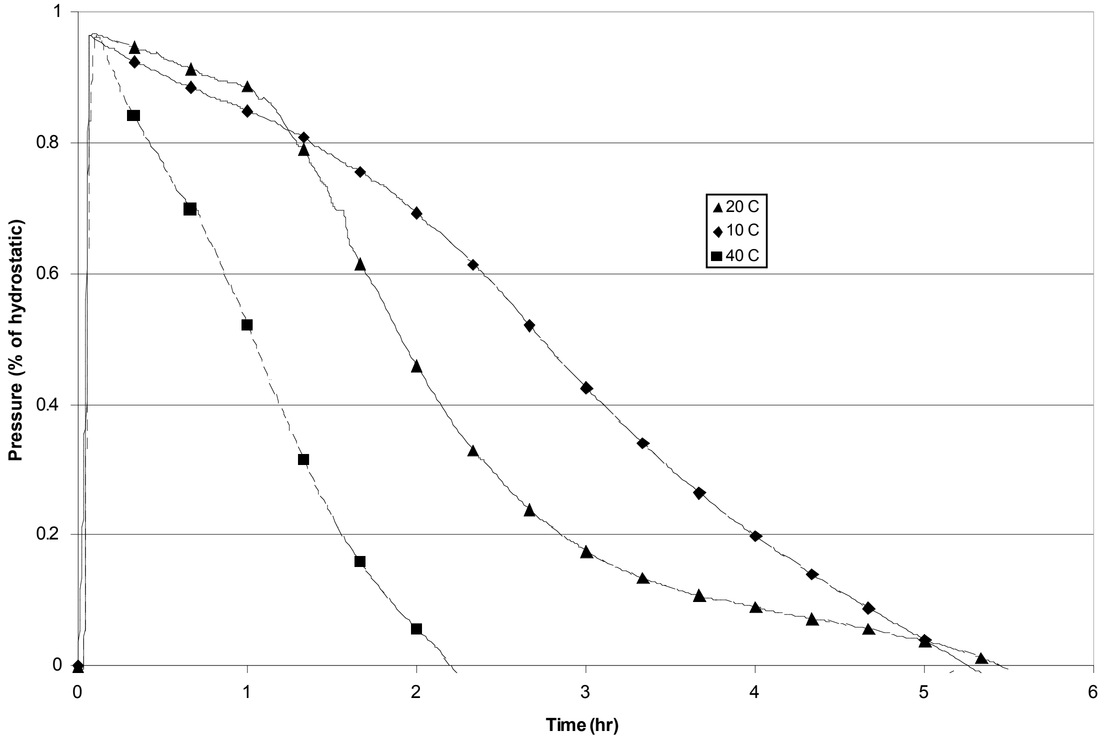

Figure 6: Effect of Mixture Temperature on Pressure Drop[2]

A great deal of research has gone into the influence of thixotropic properties of SCC mixtures on formwork pressure. In general it has been found that mixtures developing cohesion at faster rates will exhibit lower maximum lateral pressures for similar casting rates and as a result can be poured at faster rates for a given strength of formwork. (2)

Aggregate bridging is one mechanism that has been identified to explain the "self-support" of SCC that occurs soon after SCC material is at rest (and well before the point traditionally defined as "set"). It is thought that as the material fills its form the aggregate will line up and touch each other to form a skeleton in the fresh concrete. As the gelation and hydration processes occur, this bridging will get stronger and will lead to a drop in formwork pressure. This mechanism continues to be studied, but there have been results to show the affect of varying coarse aggregate fractions in SCC mixtures. It has been shown that for mixtures of similar proportions of binder but varying coarse aggregate to fine aggregate ratios that the mixtures with greater coarse aggregate contents will exhibit reduced initial pressure and a faster pressure drop. (6)

As stated earlier, thixotropy of mixtures has a significant influence on formwork pressure. Binder proportioning is one factor that affects thixotropy of mixtures. Mixtures containing supplementary cementitious materials (SCM) exhibit greater thixotropy than mixtures with cement as the only binder material and ternary blends tend to show the greatest thixotropy due to increased solid concentration in the mixture. This increased solid concentration is due to the fact that cement replacements are done on a mass basis and SCM tend to have lower densities, resulting in a greater volume of binder material and increased packing density. Accelerators increase thixotropy while retarders reduce thixotropy. VMA has also been shown to increase thixotropy. (7)

5. Modeling of Pressure

Current ACI provisions for formwork pressure (e.g. ACI 347R, Eq. 2-2) were developed many years ago. These empirical expressions related pressure to the rate of placement and the temperature of the material. In recent years there has been an effort to update the equations to account for different kinds of cement and the density of the concrete through the C_c coefficient and the C_w coefficient. These still do not address many of the issues related to SCC where the increased thixotropic nature causes SCC to produce far different pressures than would otherwise be expected using the current equations. (8)

New models are in development to predict maximum pressure values with SCC mixtures. One such model has been proposed using the Janssen model and is a step forward in that it incorporates a measurement of the time-dependent behavior of the material where earlier work ignored time dependent affects. The unique feature of this model is that it measure friction affects and factors the friction between the concrete and formwork walls into the calculation of formwork pressure. The test set up for this experiment uses a vertical load on the top, similar to the system used by the Northwestern University researchers, as well as a metal or wood blade which is pulled through the material. The horizontal pressure is monitored along with the applied vertical load as well as the force necessary to move the blade through the sample of material. Two time-dependent parameters are determined, one for the friction coefficient and one for the horizontal pressure. (9)

An alternative model for formwork pressure has been proposed by Khayat that relates pressure to rheological parameters. This model was developed by measuring lateral pressure on a cylindrical column and a rheological parameter called "break down area." Pressure and breakdown area were compared for three different times. It was found that break down area and lateral pressure as a function of hydrostatic pressure were nearly linearly related. In addition it was found that the three different values for break down area for each mixture were also linearly related. This resulted in a model that used the initial breakdown area, determined during the first 30 minutes after mixing, to predict lateral pressure as a function of hydrostatic pressure and time. (10)

A third model developed at the UIUC (11) relates formwork pressure to the pressure decay recorded in a short test column (3 ft). The test column is rapidly filled, and then the formwork pressure is recorded while the SCC is at rest. The decay curve is fit to a mathematical expression, C(t). This pressure decay curve is used to extrapolate pressure drop for concrete pours at varying rates and varying heights of formwork. The model predicts pressure in a given element where concrete is to be poured based on element height and desired filling rate. Thus, the maximum pressure generated at a particular point in the wall element can be predicted for any arbitrary casting rate. An example is shown in Figure 7 that compares the formwork pressure for three different casting rates (4, 8, and 16 ft/hr). The slowest casting rate limits the pressure to under 5 psi while the rapid casting rate reaches 20 psi. Given that a typical industrial formwork is rated at 1000 pcf (~ 7 psi), construction at the slow rate would proceed with no problems, while construction at the 16 ft/hr could overload the formwork and lead to form failure.

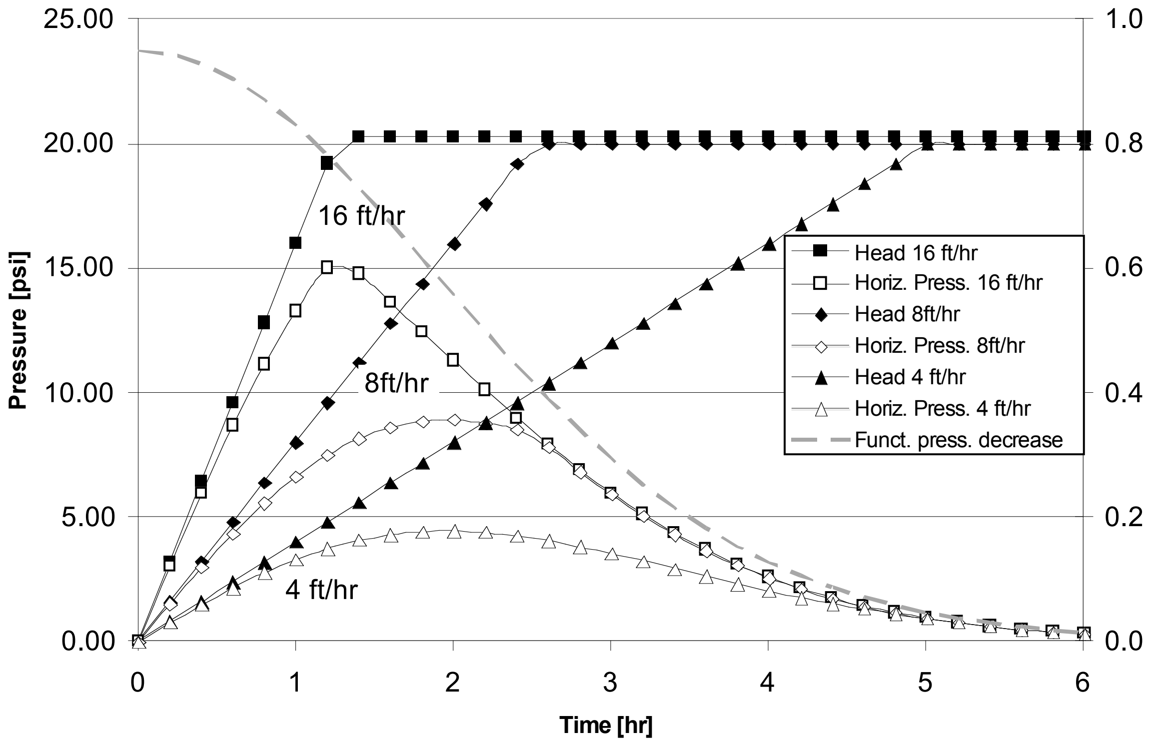

Figure 7: Example results of UIUC formwork pressure model

Summary

SCC exerts greater formwork pressure than normal concrete because it generally takes a greater period of time for its thixotropy to develop "self-supporting" structure in the fresh material. This self-support occurs much earlier than initial set, and is related to fresh concrete rheological behavior.

Formwork pressure can be measured by using pressure sensors mounted in formwork. Laboratory studies using PVC test columns have proven to be convenient and reliable methods for characterizing SCC behavior.

A better understanding of formwork pressure will lead to improved versions of formwork pressure models. Several formwork pressure models have been developed, and one common element is that all of the models require testing the candidate SCC and obtaining the value of a representative parameter to describe rheology, stiffening, or gelation. Such models represent great opportunity to improve prediction of formwork pressures in the field, allowing faster pour rates with greater confidence. These advances will make possible more economical construction with SCC.

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