Development of Self-Consolidating Concrete for Bridge Girders and Evaluation of Its Fresh Properties

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ABSTRACT

Self-consolidating concrete (SCC) has been developed for use in precast prestressed concrete bridge girders in the state of Minnesota. Locally available materials were used with a number of cementitious and filler materials, including ASTM Type III cement, Class C fly ash, and blast furnace slag. SCC was successfully proportioned with both natural river gravels and crushed stone as coarse aggregates. Moreover, for the mix incorporating natural river gravels, air-entrained SCC was successfully developed without using a viscosity enhancing admixture. The effect of a number of parameters on the fresh properties of SCC, including but not limited to temperature, cement, type of coarse aggregates (natural and crushed), were studied.

A number of test methods (e.g., slump flow, L-box, and U-box) have been under development to evaluate the fresh properties of SCC. However, none of these test methods has been integrated into any American standards. A vertical column segregation test has been used to evaluate vertical segregation of SCC mixes. The slump flow test was employed to evaluate the flowability, while self-leveling and passing abilities of the mixes were investigated using a U-box. The L-box test procedure was modified to evaluate, not only flowability and passing ability, but also horizontal segregation resistance of SCC mixes. Although, in general, at least three to four test methods are typically used to evaluate fresh properties, the slump flow test and modified L-box test may be adequate to evaluate the fresh properties of SCC properly.

Key words: high-range water reducer—segregation—self-consolidating concrete

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INTRODUCTION

Self-consolidating concrete (SCC), which was originally developed in Japan due to a shortage of skilled labor and poor compaction of ordinary concrete, is a concrete mix that flows and fills the formwork under its own weight without mechanical vibration (Ramage, Kahn, and Kurtis 2004). In other words, SCC is required to fill the formwork with a void-free structure through congested reinforcement without segregation of its constituent materials.

Although SCC is a relatively recent development, it has demonstrated substantial economic and environmental benefits in terms of faster construction, reduction in manpower, better surface finish, easier and vibration-free placing, reduced noise level, and a safer working environment. Therefore, SCC has recently found a wide use in many countries for different applications and structural configurations (Lachemi et al. 2003). For example, SCC has been successfully pumped using a 250-foot pipeline for construction of a heavily reinforced tunnel in Yokohama City, Japan (Takeuchi, Higuchi, and Nanni 1994). Other areas where SCC is employed involve the filling of formwork with restricted access for consolidation of concrete. For instance, 2,745 yd^3 of ready-mix SCC was successfully used in the construction of 180 columns at the expansion of the Pearson International Airport in Toronto (Lessard, Talbot, and Baker 2002). Because there was insufficient overhead clearance to allow placement and consolidation of conventional concrete, SCC was the only solution (Lessard, Talbot, and Baker 2002).

The main challenge when producing SCC is not only to obtain sufficient flowability and stability, but also sufficient robustness, which is the insensitivity of SCC to small changes in constituent material properties and mix proportions (Hammer et al. 2002). Robustness of SCC is important, especially for precast concrete plants where large quantities of concrete are produced daily. Therefore, the proportioned SCC should be robust enough such that small variations in physical and chemical properties of constituent material will not significantly affect the fresh properties. Moreover, some variables such as free water content can fluctuate during production on a given day. Therefore, fresh properties of a good SCC mixture should not be sensitive to small fluctuations in the mixture proportions (Daczko 2002). Otherwise, whenever there is a small variation in material properties, new mixture designs would need to be developed and tested. This is neither economical nor feasible for precast concrete plants, where continuous production is required.

The required fresh properties of SCC, which are adequate flowability, passing and filling abilities, and segregation resistance, are achieved by effective proportioning of constituent materials and related admixtures. In the design of SCC, high-range water reducing (HRWR) admixtures are essential to achieve required flowability and high concrete strength (minimized water-cementitious material [w/cm] ratio). Stability of SCC is achieved with the selection of compatible constituent materials (i.e., cementitious material and aggregates), constituent material proportion, and viscosity-enhancing admixture (VEA) (Daczko 2002).

Because SCC consolidates without the help of any external force, such as mechanical vibration, it is the fresh properties of SCC that control the quality of the placement. Moreover, when the fresh state of SCC displays signs of segregation and insufficient flowability and deformability, the concrete will not perform as expected (e.g., poor mechanical and aesthetic properties). Therefore, it is essential to evaluate the fresh properties of SCC properly. Based on the existing literature, slump flow, visual stability index (VSI), L-box, U-box, V-funnel, mortar V-funnel, J-ring, filling capacity, and column segregation tests are some of the available testing methods used to evaluate fresh properties. Although a large number of test methods are currently available, none of them is incorporated into any American standards. Moreover, there is no single testing method that is adequate by itself to qualify a mix as SCC. In general, three to four test methods are used in conjunction to evaluate SCC mixes.

This paper outlines the preliminary results of a research project aimed at producing SCC using locally available materials from two precast concrete plants. The sensitivity of developed SCC mixtures to cement source, w/cm ratio, HRWR dosage, and temperature was studied. Observations of how these parameters can impact the mix proportions for precast applications are presented. This paper also discusses various ways that fresh properties of SCC can be evaluated. A modified L-box testing procedure, which may also help evaluate the segregation resistance of SCC, is discussed. The effect of U-box test filling height on the test results is also discussed.

RESEARCH METHODOLOGY

Cementitous Materials

For both plants, two sets of SCC mixtures were tested and evaluated. ASTM Type III cement was the only cementitous material used for the first sets of mixes. However, the plants were using different cement suppliers, and therefore two sources of Type III cement were used in this study. Moreover, the cement used for Plant A was obtained in four different shipments, which were designated as AS1, AS2, AS3, and AS4. For Plant B, the cement was obtained in a single shipment, which was designated as BS1. The chemical and physical properties from the mill reports of the cements from each shipment are given in Table 1, with the exception of AS4, for which no data are available currently. For the second set of SCC mixtures, pozzolanic materials were also used. Class C fly ash was used for Plant A, and blast furnace slag was used as the supplementary cementitious material for Plant B.

Table 1. Chemical and physical properties of cement

	Plant A				Plant B
Particular	**AS1**	**AS2**	**AS3**	**AS4**	**BS1**
Silicon dioxide (SiO_2), %	20.12	20.4	20.7		20.57
Aluminum oxide (Al_2O_3), %	4.81	5.14	5.31		4.82
Iron oxide Fe_2O_3, %	2.06	1.95	1.95		2.14
Calcium oxide (CaO), %	64.32	63.79	64.81		64.04
Magnesium oxide (MgO), %	1.94	2.24	1.67		2.42
Sulfur trioxide (SO_3), %	3.88	3.95	3.61		3.11
Sodium oxide Na_2O, %	0.22	0.25	0.29		0.25
Potassium oxide (K_2O), %	0.48	0.49	0.41		0.49
Mangaan trioxide (Mn_2O_3), %	0.04	0.04	0.03	N/A*	0.04
C_3S, %	62.55	56.04	57.75		60.04
C_2S, %	10.51	16.22	15.79		13.67
C_3A, %	9.26	10.31	10.77		9.16
C_4AF, %	6.27	5.94	5.94		6.52
Equivalent alkali (Na_2O)	0.54	0.57	0.56		0.57
Lime saturation factor	101.5	98.96	98.94		99.02
Al_2O_3/ Fe_2O_3	2.33	2.63	2.72		2.25
Blaine fineness, m^2/kg	N/A	593	563		644

* N/A = not available

Aggregates

For Plant A, two types of natural gravels with nominal maximum particle size of 3/4 inches and 3/8 inches were used as coarse aggregates. The bulk-specific gravity of these aggregates was 2.72, and their absorptions were 1.0% and 1.5%, respectively. Locally available natural sand with 2.71 bulk specific gravity, 3.3 fineness modulus, and 0.9% absorption was used. For Plant B, two types of crushed limestone with nominal maximum particle sizes of 3/4 inches and 1/2 inches were used as coarse aggregates, and natural sand with 3.2 fineness modulus was used as fine aggregate. The specific gravity and absorption values of the coarse aggregates and sand were 2.71 and 2.65, and 1.3 % and 1.2%, respectively.

Admixtures

Different admixtures were used for each plant. For Plant A, two different polycarboxylate-based high-range water-reducing admixtures were used at equal dosages of 9.8 fl oz/cwt. A fixed set-retarding agent (SRA) at a dosage of 0.98 fl oz/cwt was used for all mixtures to reduce the loss of fluidity. Also, a resin type air-entraining admixture (AEA) was employed at a fixed dosage of 0.37 fl oz/cwt. For Plant B, a polycarboxylate-based high-range water-reducing admixture, which was a different admixture than that used by Plant A, but from the same manufacturer, was the only admixture, and it was employed at a fixed dosage of 9.5 fl oz/cwt. All admixtures were provided by the same manufacturer for both plants. No VEA was used.

Mixture Proportion

As summarized in Table 2, except for mix B2-BS1-S, which incorporated slag, the investigated mixtures were prepared with ASTM Type III cement as the only cementitious material. The naming convention for the mixtures was coded according to the following scheme: X-Y-Q, where X represents the plant that provided the coarse and fine aggregates, Y represents the cement provider and shipment number (Table 1), and Q represent the modification from the plants reference mixture (i.e., WR for a change in the amount of HRWR, w for a change in the amount of water, and S for the addition of slag).

Mixtures A-AS1, A-AS2, A-AS3, A-AS4, and A-BS1 had the same mix proportions and same types of materials and dosage of admixtures. However, cement from different shipments was used for each mix to study the effect of cement shipment on SCC flowability. Mixtures B-S1 and B-S1-S were prepared using crushed coarse aggregates, cement, and admixtures obtained from Plant B. Mixture A-AS2-WR1, A-AS2-WRw2, and A-AS2-WRw3 were mixes proportioned with the same materials except w/cm and HRWR dosage. The HRWR dosage and/or w/cm were modified for each mix to have SCC mixes with different slump flow values to study the effect of flowability and filling height on U-box test results. Mixture A-AS2-WRw2 was also used as the reference mixture to study the effect of concrete temperature on SCC flowability. The mixtures A-AS3-w1, A-AS3-w2, A-AS3-WRw3, and A-AS4-WRw were mixtures designed to study the effect of HRWR dosage on flowability. The constituent materials were the same, with additional HWRW and/or water added to the reference mixture as indicated in the mix name. A-AS4-WRw was a similar mix in terms of the type and proportion of the constituent materials, but cement from a different shipment (AS4) was used.

Table 2. Mixture proportions of tested SCC

	Constituent Materials (lbs/yd^3)						Admixtures (oz/cwt)				
Mixture no.				Aggregates			HRWR				
	Water	Cement	Slag	CA I	CA II*	Fine	I	II	III	AEA	SRA
A-AS1	277	800	0	833	819	1289	9.8	9.8	0	0.37	0.98
A-AS2	277	800	0	833	819	1289	9.8	9.8	0	0.37	0.98
A-AS3	277	800	0	833	819	1289	9.8	9.8	0	0.37	0.98
A-AS4	277	800	0	833	819	1289	9.8	9.8	0	0.37	0.98
A-BS1	277	800	0	833	819	1289	9.8	9.8	0	0.37	0.98
B-BS1	275	773	0	861	655	1473	0	0	9.5	0	0
B-BS1-S	274	539	231	857	655	1467	0	0	9.5	0	0
A-AS2-WR1	277	800	0	833	819	1289	10.7	10.7	0	0.37	0.98
A-AS2-WRw2	312	779	0	811	798	1256	10.7	10.7	0	0.37	0.98
A-AS2-WRw3	337	765	0	796	783	1232	11.7	11.7	0	0.37	0.98
A-AS3-w1	266	807	0	840	826	1300	9.8	9.8	0	0.37	0.98
A-AS3-w2	293	791	0	824	809	1274	9.8	9.8	0	0.37	0.98
A-AS3-WRw3	312	779	0	811	798	1256	7.8	7.8	0	0.37	0.98
A-AS4-WRw	293	791	0	824	809	1274	7.8	7.8	0	0.37	0.98
A-AS3	342	761	0	792	779	1226	11.7	11.7	0	0.37	0.98

* Nominal maximum particle size was 3/8 in. for Plant A and 1/2 in. for Plant B

Mix Procedure

All mixtures were prepared in a drum mixer with a 3.5-ft^3 capacity. The mixing sequence consisted of homogenizing fine and coarse aggregates for about one minute before introducing premixed water with AEA. After one minute of mixing, cementitious materials were added, and the mixture was mixed for a further three minutes. After three minutes of mixing, HRWR and SRA were added. Then, the concrete was allowed to rest for three minutes to allow the admixtures to initiate. At the end of the rest, the concrete was remixed for two additional minutes.

TEST METHODS

The various tests were conducted in the following sequence: slump flow and visual assessment, L-box, U-box, and column segregation tests. The time required to carry out those tests was limited to 20 minutes total. The description and testing procedure of the test methods are given in the following sections.

Slump Flow, Visual Stability Index Rating, and T-20 Inch Test Methods

The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstruction (PCI 2003). The slump cone can be used in either the upright or inverted position, because the values of slump flow are nearly the same for both cases (PCI 2003). In this study, the slump cone was used in the upright position throughout the experiments. The slump flow table was made of a 1/2-inch thick plexiglass sheet attached to a stiff wooden base plate. VSI is a rating involving the visual assessment of the slump flow patty to evaluate several parameters as an indication of the stability of SCC (PCI 2003). The mixtures were rated in 0.5 increments by visual examination according to guidelines provided by PCI (PCI 2003). T-20 inch is the time the concrete takes to reach the 20-inch diameter circle drawn on the slump plate, after starting to raise the slump cone. T-20 inch time, which is a secondary indication of flow, can preliminarily be used as an indication of production uniformity of a given SCC mixture (PCI 2003).

U-box Test

This test was developed for evaluating the self-compatibility and filling ability of SCC in heavily reinforced areas (PCI 2003). The apparatus consists of a vessel that is divided by a middle wall into two components, shown in Figure 1. A sliding gate is fit between the two sections, and three No.4 reinforcing bars are installed just to the left of the gate with center-to-center spacing of two inches. The left-hand section of the apparatus is filled in one lift of concrete, and after one minute of rest the sliding gate is opened, allowing concrete to flow into the other compartment. When the concrete flow stops, the height of concrete in each compartment is measured. The results are presented as the ratio of the concrete heights before (h_1) and after (h_2) the gate (i.e., h_2/h_1) (see Figure 1).

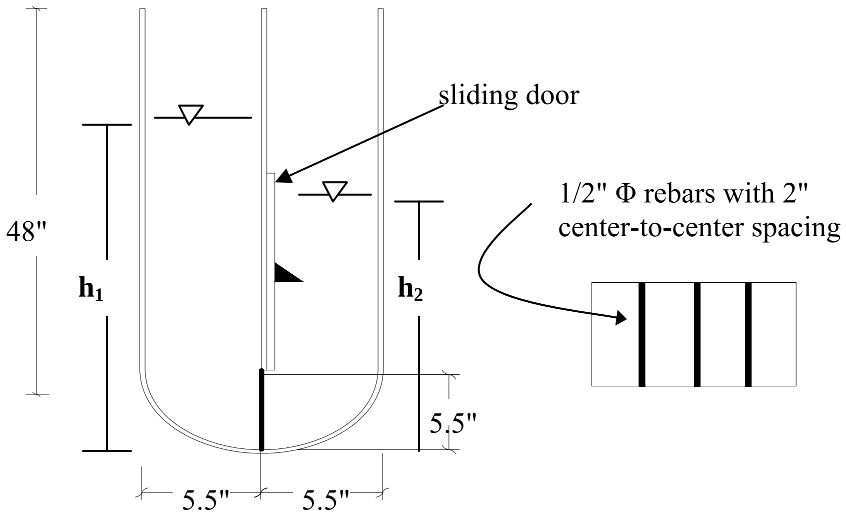

Figure 1. Modified U-box apparatus

The U-box apparatus used in this study was slightly different than that proposed by PCI (2003). The height of the filling component was increased from 24 inches to 48 inches to study the effect of filling height on the results. The U-box apparatus recommended by PCI (2003) has a total height of about 24 inches, and about 0.67 ft^3 of SCC is required to perform the test. Due to the large volume of concrete used, the apparatus is difficult to handle and subsequently clean (Ramage, Kahn, and Kurtis 2004). SCC mixtures A-AS2-WR1, A-AS2-WRw2, and A-AS2-WRw3, which had slump flow values of 19.5, 24.5, and 27.5 inches, respectively, were proportioned to study the effect of flowability and filling height. The U-box test was performed at four different filling heights: 48, 36, 24, and 18 inches. The h_2/h_1 values computed for each mixture and filling height are shown in Figure 2. The sliding door did not operate properly when the test was performed with a filling height of 18 inches for A-AS2-WR1. Except for the h_2/h_1 computed for that case, the results indicate that h_2/h_1 is not very sensitive to U-box filling height for SCC mixtures with poor, moderate, and good flowability. Also, the results show that the test results are less sensitive to U-box filling height as slump flow increases.

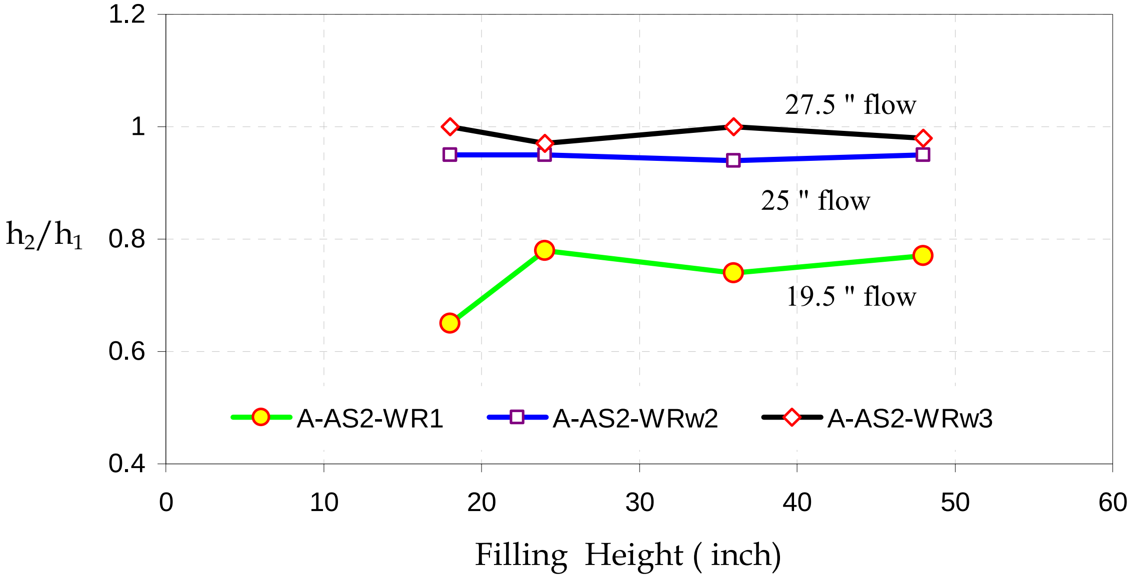

Figure 2. Relationship between U-box filling height and h_2/h_1 value of U-box

Column Segregation Test

This test method is intended to provide the user with a procedure to determine the vertical segregation and stability of SCC. The original apparatus (Brameshuber and Uebachs 2002) consists of 8-inch diameter, 26-inch high PVC Schedule 40 pipe that is separated into four equal sections each measuring 6.5 inches in height. However, this apparatus was modified, and the top 6.5-inch section was further divided into two sections measuring 2 inches and 4.5 inches. The 2-inch section was placed at the top to measure the segregation resistance for the top 2 inches of the column.

The mold was slightly overfilled in one lift. The surface of the concrete was leveled at the top of the mold by means of both lateral and horizontal motion of a thin steel plate (less than 1/16 inches in thickness). The same steel plate and technique was used to separate the column sections after a rest of 10 to 15 minutes. Concrete in each section was placed in containers, and the weight of the concrete was measured for each section. The concrete was then wet-washed through a No. 4 sieve, leaving the coarse aggregate on the sieve, which was subsequently oven-dried and measured for each column section.

The vertical segregation resistance was evaluated by means of a stability weight index (SWI) and stability volume index (SVI), which was defined as the oven-dried weight of coarse aggregate per unit weight of concrete and per unit volume of concrete relative to the base PVC section, respectively (i.e., section S1 in Figure 3).

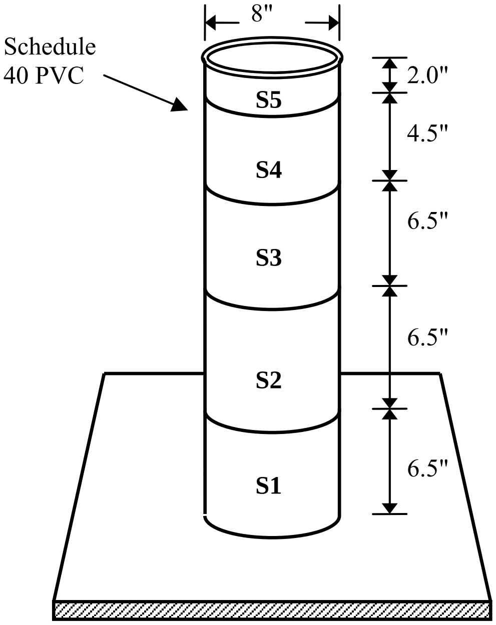

Figure 3. Column segregation test apparatus

L-box Test

This test assesses the flowability of SCC, and the extent to which it is subjected to blocking by reinforcement. The L-box test consists of an L-shaped apparatus (Figure 4). The vertical and horizontal sections are separated by a movable gate, in front of which a reinforcing bar obstacle is placed (Khayat, Assaad, and Daczko 2004). The vertical section is filled with concrete and left to rest for one minute. Then, the gate is lifted and concrete flows under its own weight through the reinforcement into the horizontal section. The concrete heights in the vertical section (h_1) and at the end of horizontal section (h_2) are determined. The h_2/h_1 value, which is the blocking ratio (PCI 2003), is calculated to evaluate the self-leveling characteristic and the degree to which the passage of the mixture through the obstacle is restricted.

The L-box test procedure was modified so that more information regarding the horizontal segregation resistance of the concrete could be obtained. For this purpose, the horizontal section was divided into three sections, each about 8.7 inches in length (see Figure 4). When the flow ceased, the concrete height was measured at a minimum of six points along the flow direction to determine the volume of concrete in each section. After allowing the concrete to sit for 5 to 10 minutes, thin steel plates (less than 1/16 inches in thickness) were used to separate each section. Then, the gate at the end of the horizontal section was opened, and concrete in each section was placed in containers. As soon as the concrete in each section (including the vertical section) was removed, the weight of concrete in each section was measured, and the concrete was wet-washed through a No. 4 sieve, leaving the coarse aggregates on the sieve. After the coarse aggregates were oven-dried, the weight of the coarse aggregates in each section was determined. The horizontal segregation resistance was evaluated by means of SWI and SVI. The SWI and SVI values are calculated relative to the base vertical section (i.e., section LV in Figure 4).

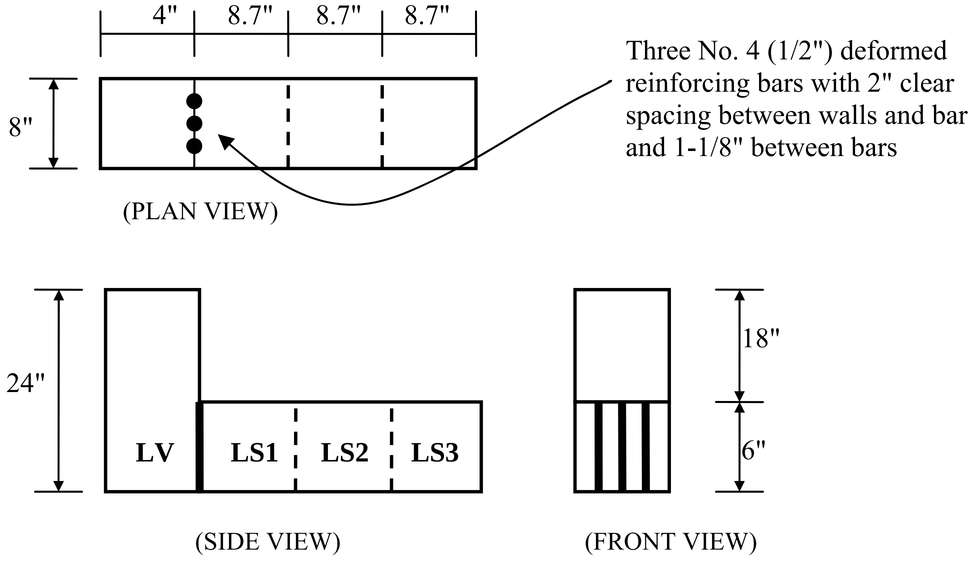

Figure 4. Schematic of L-box apparatus

RESULTS AND DISCUSSION

Flowability and Segregation Results of Base Mixtures

Figure 5 shows SWI values measured for the LV-LS1, LS2, and LS3 compartments of the L-box for mixtures B-BS1, A-AS1, and A-AS3. For an ideal mix, which is defined as a mix without any segregation and blockage tendency, SWI values should be unity and equal for every section of the box. Mixture B-BS1 had a high tendency of blockage and poor filling characteristic measured with the U-box and L-box (h_2/h_1), as shown in Table 3. Mixture A-AS1 had good passing and filling characteristics. Mixtures B-BS1 and A-AS1 had high segregation resistance, which was measured by means of the segregation test. On the other hand, mixture A-AS3 exhibited good passing characteristics (h_2/h_1=1 from L-box), but poor segregation resistance measured with VSI=2.5. Also, very little coarse aggregate was found in the top two inches of the segregation column (Table 3). It is interesting to note that SWI values computed for B-BS1 and A-AS1 mixtures, which had high segregation resistances, were smaller than unity, while SWI values were much larger than unity for A-AS3 mixture, which had a high tendency for segregation. Khayat, Assaad, and Daczko (2004) and Ramage Kahn, and Kurtis (2004) previously established good correlation between L-box and U-box test results. The limited results of the current study are in agreement with their findings.

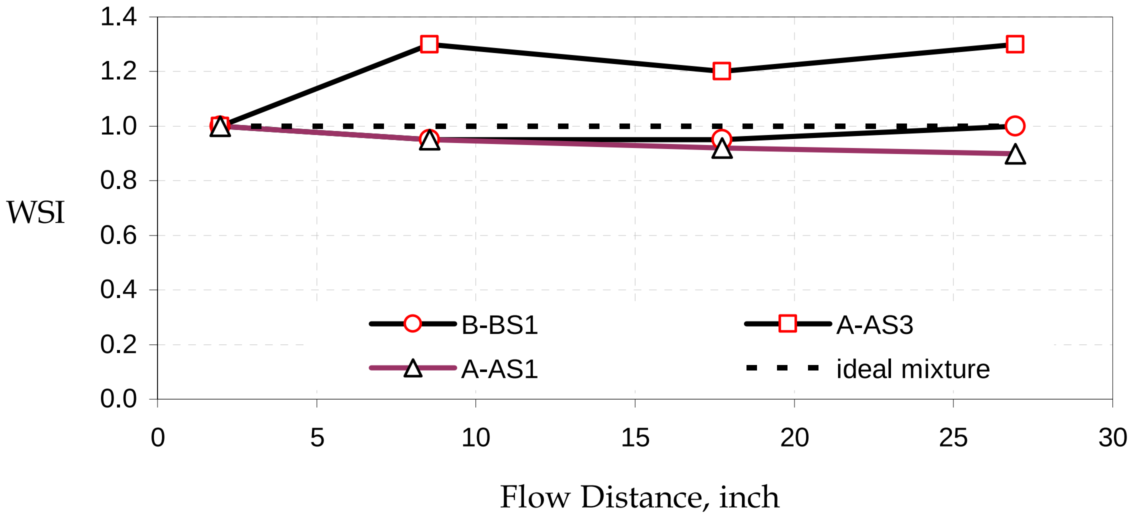

Figure 5. SWI measured with L-box test

Table 3. Fresh concrete properties of tested SCC

	Slump flow test			**L-box**	**U-box**		**WSI (column seg. test)**				
Mix No	Flow (inch)	T_{50} (sec)	SVI	h_2/h_1	h_2/h_1	N*	S1	S2	S3	S4	S5
A-AS1	26	2	1.0	0.70	0.90	>15	1.0	0.98	0.98	0.97	0.96
A-AS2	19.5	N/A	0			>10					
A-AS3	19.5	N/A	0			8					
A-AS4	19.5	N/A	0			3					
A-BS1	27	<1	1.5			4	1.0	0.98	1.03	1.07	1.05
B-BS1	24	7	1.5	0.55	0.50	6					
B-BS1-S	26	6	1.5	0.68	0.70	4					
A-AS2-WR1	19.5	N/A	0		0.77	2					
A-AS2-WRw2	24.5	2	1.0		0.95	2					
A-AS2-WRw3	27.5	1	1.5		0.98	2					
A-AS3-w1	19.5	N/A	0.5			1					
A-AS3-w2	22.0	4	1.0			1					
A-AS3-WRw3	23.5	4	1.0			1					
A-AS4-WRw	26.0	2	1.5			1					
A-AS3	32.5	<1	2.5	1.0	0.98	1	1.00	1.00	0.97	0.65	0.02

* N refers to number of slump flow test, for which average slump flow values were measured

Effect of Cement on Flowability

The effect of change in cement from shipment to shipment on flowability was determined based on the slump flow values measured for A-AS1, A-AS2, A-AS3, A-AS4, and A-BS1. These mixtures had the same aggregates, the same cement type and supplier (except A-BS1), and the same admixtures and dosages (see Table 2). All the cements from the supplier for Plant A, had similar chemical composition, as shown in the mill reports (see Table 1). However, the flow results for the four mixes using the supplier for Plant A showed large differences between the first shipment and the last three shipments. Although an average flowability of 26 inches was measured for A-AS1, the average flowability measured for A-AS2, A-AS3, and A-AS4 was only 19.5 inches. The average flowability measured for A-BS1, for which cement was obtained from the Plant B supplier, was 27 inches, similar to that achieved using the first shipment of cement from the Plant A supplier. Although it is not listed in this paper, two other conventional mixtures, with the same mixture proportion that was used for A-AS1, were prepared with cements AS2 and BS1. For those mixtures, w/cm was 0.51 and no admixtures (i.e., HRWR, SRA, and AEA) were used. The slump values (ASTM C143-00) measured for both mixtures were 6 inches, indicating that the cement source had no effect on conventional concretes made with the same aggregates. Repeatability between SCC batches using the same cement from the same shipment was excellent, varying by less than 1.0 inches. Because there was no significant physical and chemical difference between cement shipments AS1, AS2, AS3, and BS1, and because the same slump values were measured for the mixtures that did not employ admixtures, it is likely that the performance of the admixtures used was significantly controlled by some physical and/or chemical parameters of the cement, which are not clear yet.

Effect of Temperature on Flowability

The effect of temperature on SCC flowability was investigated by batching the A-AS2-WRw2 mixture at three different temperatures. During testing, the average room temperature was about 77±1° F. First, the mixture was prepared under laboratory conditions. In other words, the aggregates were at room temperature, and tap water from the city water supply was used as the mixing water. A slump flow of 24.5 inches, T20 of 2 seconds, and SVI of 1.0 were measured for the reference mixture. The concrete temperature, which was measured just before the slump flow test, was 76° F. For the cold temperature case, the mixture was re-prepared by using cold water as the mixing water. The same water supply was used for mixing water, and the mixing water and aggregates were refrigerated to cool them down. The moisture contents of the aggregates were determined by using aggregate samples that were placed in the aggregate containers in the temperature-controlled environment. Moreover, the mixer was filled with cold water just before batching to get data for low concrete temperatures. The concrete temperature was measured to be 45° F just before the slump flow test. A slump flow of 21 inches, T20 of 5 seconds, and SVI of 1.0 were measured for the mixture at 45° F. A third batch was prepared using hot water as the mixing water. The same water supply was used for hot water, which was heated in an oven. The aggregates were at room temperature (about 77° F). A slump flow of 27 inches, T20 of 1 second, and SVI of 1.0 were measured for the mixture. The measured concrete temperature was 91° F. The test results show that temperature may significantly affect flowability of SCC. Therefore, when there are large temperature fluctuations, fresh properties of SCC mixtures should be reevaluated.

Relationship between HRWR Dosage and Flowability

The relationship determined between slump flow values and HRWR dosage for A-AS3-w1, A-AS3-w2, A-AS3-WRw3, and A-AS4-WRw mixtures is shown in Figure 6. The results show that for each w/cm ratio there is a HRWR saturation dosage, after which increases in HRWR do not improve flowability significantly. The results also indicate that the saturation dosage is not sensitive to small changes in the w/cm ratio for the mixtures studied. The saturation dosages of HRWR determined for A-AS3-w2 and A-AS4-WRw, which had the same w/cm ratio and mixture proportion but cement from different shipments, were about 13.7 and 9.8 fl oz/cwt, respectively. Therefore, test results show that the saturation dosage for HRWR can be affected by properties of cement.

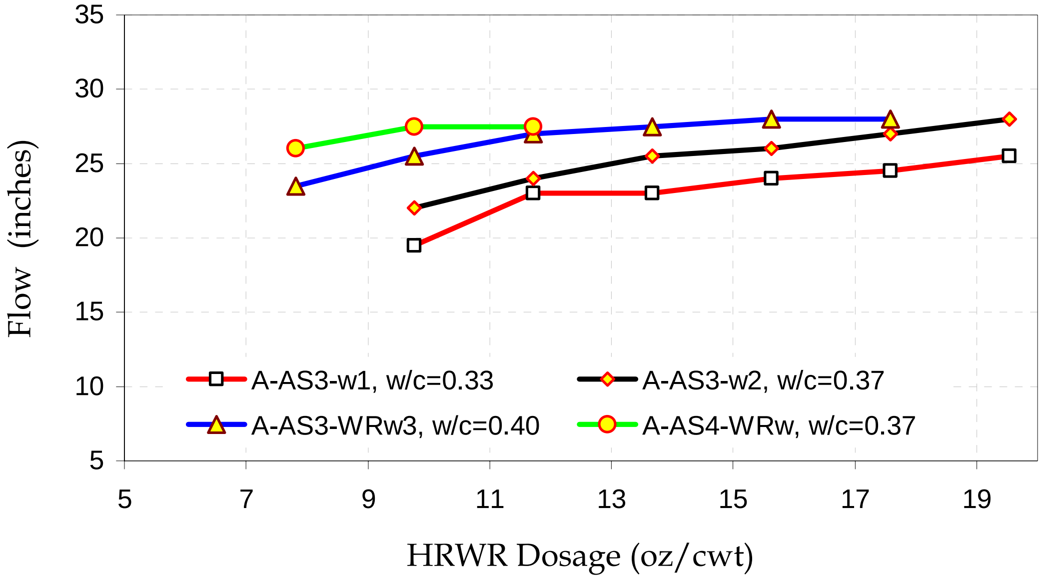

Figure 6. Relationship between HRWR dosage and slump flow

CONCLUSIONS

Based on the results of this study, the following conclusions can be made:

1. SCC with adequate fresh properties has been developed successfully with locally available materials for two precast concrete plants in the state of Minnesota.
2. U-box filling height has negligible effects on the test results (h_2/h_1).
3. The modified L-box testing procedure may be useful as a means of evaluating segregation resistance of SCC.
4. Cement shipments from the same supplier can significant affect flowability of SCC.
5. Fresh properties of SCC mixes are repeatable for the same cement shipment.
6. Flowability of SCC increases as concrete temperature increases.
7. Flowability of SCC does not improve significantly once HRWR saturation dosage is reached. HRWR saturation dosage is a function of at least cement and w/cm ratio.

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