DEVELOPING FRESH CONCRETE SPECIFICATIONS FOR SCC

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ABSTRACT

The proposed paper documents the development of fresh concrete requirements for self-consolidating concrete mixtures (SCC). Current State specifications do not contain any SCC requirements; therefore the focus of this paper (research program) is developing a range of slump flows, T_{20} times, and visual stability indices (VSI) for SCC. To accomplish this task, several mock wall sections measuring 4 ft. x 4 ft. by 6 in. were cast with the SCC mixtures. The mock wall sections also contained reinforcement at 6 in. centers. The SCC was placed in one end of the forms and allowed to fill the forms without consolidation. At one day of age, the formwork was removed and the wall panels were visually inspected. The slabs were then cored to visually inspect consolidation and to examine the variability of compressive strength among the wall. The preliminary results show that a slump flow of at least 24 inches but not greater than 30 in. is required to ensure self consolidating concrete. Additionally, a T_{20} time between 2 seconds and 6 seconds ensures adequate flowability. Finally, the preliminary results support the use of SCC with a VSI of 1.5 or less. Ongoing work is investigating L-box and J-ring requirements for SCC.

Keywords: SCC, Fresh Concrete Specifications, Slump Flow

BACKGROUND

Self-consolidating concrete (SCC) has seen a large increase in use since it was first introduced in the 1980s[1]. This form of high performance concrete is highly flowable in the fresh state while still having a high resistance to segregation. SCC flows and compacts under its own weight and can be placed without the use of internal or external vibration even in highly congested sections. This is the basis of the appeal of using SCC as there is a significant reduction in the required labor for concrete placement. Therefore, SCC has many applications for use in the prestressed/precast concrete industry.

The deformability of SCC is strongly related to the paste flow properties of the mixture[2] and numerous recommendations have been made as to the fresh properties required to achieve a viable SCC mixture. A combination of several tests is necessary to get a good indication of the workability, filling ability, and filling capacity of the concrete. The effect of different values of these properties on the hardened properties of the concrete can be substantial; therefore specifications of fresh properties are necessary for the effective use of SCC.

Slump flow and T_{20} are used as a measure of filling ability while J-Ring and L-box are used as a measure of passing ability. Tests for Segregation resistance include column segregation, visual stability index (VSI), surface settlement, and rate of settlement. NCHRP Report 628 investigated material properties and performance criteria for SCC used for precast, prestressed concrete bridge elements. Recommended combinations of tests for filling capacity in typical applications included slump flow and L-box blocking ratio (h_2/h_1) or slump flow and J-Ring flow. Khayat recommended a slump flow of 23.5 to 29 in., L-box blocking ratio (h_2/h_1) greater than 0.5, J-Ring flow of 21.5 to 26.0 in., and a difference in slump flow and J-Ring flow values lower than 4 in. for use in precast, prestressed applications. For static stability a VSI value between 0 and 1 was recommended.[3]

Different levels of slump flow were examined for SCC. These included high (28 to 30 in.), medium (25 to 28 in.), and low (23.5 to 25 in.). Mixtures with low and medium slump flow had medium levels of passing ability and filling capacity and a high level of stability. Mixtures with high slump flow had high levels of passing ability and filling capacity, but medium to low stability. Also mixtures with high fluidity had lower compressive strengths after 18 hours of steam curing and 56 hours of moist curing when compared to those with lower fluidity. Therefore Khayat recommended SCC mixtures with medium fluidity for use in precast, prestressed concrete girders. When girders were cast with these mixtures, the SCC girders had a smaller number of bugholes than the conventional girders used for comparison.[3]

Similar recommendations of test combinations for indication of flowability, passing ability, and filling capacity were made by Hwang et al. These results came from their tests on 70 SCC mixtures having w/c ratios from 0.35 to 0.42. A slump flow of 24.5 to 28.5 in. was recommended for use in structural applications. J-Ring flows of 23.5 to 27.5 in were recommended as well.[4] Do et al. performed research on developing high strength SCC mixtures for use in bridge girders. A range of slump flows between 25.5 and 29.0 in. was used in this research. Do also recommended a T_{20} of 2 to 5 seconds as he discovered problems with blockage when T_{20} was greater than 5 seconds.[5] In their research on developing economical SCC mixtures, Lachemi et al. targeted slump flows between 19.5 and 27.5 in.[6] El-Chabib et al. used a range of 20 to 30 in. for slump flow and a range of 2 to 7 seconds for T_{20} in their research on SCC.[7] The European Guidelines for SCC suggested a range of values for fresh concrete properties based on the particular application. A range of slump flows from approximately 21.5 to 33.5 in. depending on the application were suggested. For typical applications a range of 26 to 29.5 in. was recommended. Specifications of passing ability and segregation resistance were recommended to be based on the particular concrete application, but specific values were not given.[8]

Other test methods than those typically used for SCC have been suggested. These methods focus on a quantitative measurement of the rheology of the material as this is the basis of the properties that are typically measured. ACBM suggested the use of a falling ball viscometer for measurement of the rheological properties of the fresh concrete. Instead of using a qualitative measurement, such as VSI, for segregation resistance, ACBM suggested the use of a segregation probe test for examining segregation resistance. This method involves measuring the settlement of a metallic ring into a cylinder filled with fresh concrete. This distance is then used as a measure of segregation resistance.[1]

Some previous research has indicated that wall elements cast using SCC have very consistent in-situ properties throughout the depth of the wall. Khayat et al. examined 8 SCC mixtures utilizing various combinations of supplementary cementitious materials and having w/cm ratios between 0.37 and 0.42. Slump flows of these mixtures varied between 25 and 26 in. with one mixture as high as 27.5 in. Wall sections with a length of 37.5 in., a width of 7.9 in., and a height of 59 in. were cast with each mixture. Statistically insignificant differences were found between cores taken at different heights of the wall sections cast with SCC mixtures and the control concrete mixture having a slump of 6.5 in.[9] This behavior is also concurred with by Campion.[10] This indicates that SCC can achieve adequate consolidation and homogeneity when used in wall elements.

EXPERIMENTAL PROGRAM

The goal of the research program was to develop fresh concrete specifications for structures cast with self-consolidating concrete (SCC), specifically for box culverts. However, results from this research easily apply to precast wall panels of similar size and configuration. The experimental program consisted of selecting an SCC mix design and then using this mix proportion to cast 11 mock box culvert wall sections. In future research, cores will be taken throughout the depth of the wall sections and tested in compression. The compressive strength of the concrete will be compared throughout the depth of the section as well as to cylinders cast at the same time as the wall section. The cores will be examined for aggregate segregation as well.

The research began with mixing several test batches. The test batches were used to ensure that the fresh concrete properties of the chosen mix design were within the desired ranges.

Some adjustment of high range water reducer (HRWR) dosage was required to get a feasible SCC mixture. The ability to vary the flow characteristics and other fresh properties was essential to getting a good range of results. The desired range of slump flow and T_{20} were between 25 and 29 in. and 2 and 5 seconds respectively. The SCC mix proportion chosen for use in this experimental program was the result of previous research at the University of Arkansas.[5] This mixture was developed for use in prestressed concrete bridge girders. Since this research only focused on the effects of fresh concrete properties on concrete performance, the exact mix proportion was not critical, only the fresh properties. The mix proportion used in this research is shown in Table 1.

Table 1. SCC Mix Proportion

Material	SCC
Cement (lb/yd^3)	950
Fly Ash (lb/yd^3)	0
Coarse Aggregate (lb/yd^3)	1350
Fine Aggregate (lb/yd^3)	1474
Water (lb/yd^3)	285
w/b	0.3
ADVA 170 (fl oz/cwt)	9-13[a]
ADVA 555 (fl oz/cwt)	0-2.0[a]

Note: 1 lb = 0.454 kg; 1 oz = 29.57 mL
[a]Admixture dosage varied due to temperature and desired flow

The fresh concrete properties that were examined in this research include: Slump Flow, T_{20} time, Visual Stability Index (VSI) and, J-Ring. Slump flow and T_{20} were used as a measure of filling ability, J-Ring as a measure of passing ability and VSI as a measure of segregation resistance.

PROCEDURE

WALL SELECTION AND CONSTRUCTION

The criteria used to select the test specimen size were based upon ease of construction and available mixer capacity. The wall sections employed were constructed by mimicking current AHTD box culvert plans. It was determined that a 4-foot by 4-foot barrel should be adequate for both of the previously mentioned criteria. Specifically, a single barrel edge wall was chosen and three sets of mobile wooden forms were created. When cast, the resulting wall sections measured 4 feet high by four feet wide, with a thickness of 6 inches, and a required volume of concrete of 8 ft^3. Of the three forms, two sets were created with the ability to be linked together, creating an 8 foot length. This new doubled length would create a 16 ft^3 wall section, which is currently beyond the mixing capacity utilized by the research team. While the 8 foot length box culvert wall was not tested, the possibility remains available for future tests. Also included in the plan set were the reinforcing bar size and spacing requirements. The typically used steel reinforcing bars were replaced with wooden dowel rods of equal diameter. Since the wooden dowels had the same cross-section as the required reinforcing bars they created an equivalent blocking effect. The wooden dowel rods proved quite rigid when tied and placed in the arrangement required in the plans. No failure of dowel rods was observed during concrete placement. Once again, the goal of this project is not to determine any flexural or compressive strengths of the entire composite wall section, rather the strength of the wall cores versus their molded counterparts.

MIXING AND POURING

In order to have an adequate amount of concrete to fill the form and perform tests, two mixers of differing capacities were used. The first and primary mixer, a Stone, capable of handling 12.5 ft^3, contained batch sizes of 9.5 ft^3. The second and alternate mixer was also of the Stone brand; with a capacity of 4 ft^3, this mixer was used to batch an additional 2 ft^3. The second mixer was used strictly for contingency purposes. The required material quantities were carefully weighed in advance of each batch and the required quantity of HRWR was added to the mixing water.

For each pour, the wall form was placed on level ground and the mix was introduced via a wheelbarrow at one end only. A small trough was created to help channel and minimize loss of material during placement into the wall form. When poured into the trough, the concrete was allowed to flow on its own and fill the form without any method of vibration being utilized. Shovels were used to help regulate the flow for both fast and slow moving mixes. Once the forms were filled, hooks were placed in top of the walls to allow for transport once the concrete had sufficiently set. The forms were not removed for a minimum of 20 hours after the final placement.

TESTING

Slump flow tests were performed in accordance with ASTM C 1611. The research team preferred the inverted cone method based on previous experience and its ease of use. The cone was filled in one lift; afterwards, the cone was raised and the concrete was allowed to flow until it ceased. Next, the maximum diameter of the displaced concrete was measured, and another measurement was taken perpendicular to the first measurement. Measurements were made to the nearest ¼ in.. The two resulting values were then averaged and recorded to the nearest ½ in. Two slump flow tests were performed for each batch since some previous research has indicated increasing slump flows over the short term[11].

When the slump flow test is performed, the time in which it takes for the sample to reach a 20 inch diameter is known as the T_{20} time. The test method is also from ASTM C 1611. The researchers utilized a board specific for testing SCC. The board essentially provides a template for placement of the inverted slump cone and a clearly marked 20 inch diameter ring. Since two slump flow tests were conducted for each batch, two T_{20} values were also recorded.

The Visual Stability Index or VSI, has its basis in ASTM C 1611 as well. The purpose of this test is to categorize the stability of a mix by observing the concrete once it has been displaced from the slump cone. The sample is indexed from 0 to 3 in increments of 0.5. For the scale, 0 indicates the best possible mix, one that includes no segregation, mortar halo, or bleed water. A value of 3 indicates the worst possible case: a heavily segregated mix which includes a pile of aggregate surrounded by a thin, wide spread of paste with very little aggregate interspersed. The outer edges of this sample will have a ring of paste, known as mortar halo, as well as bleed water which may be seen as a discoloration on or around the edges of the sample and a sheen on the surface.

The J-Ring test is also used in conjunction with the slump flow test. The J-Ring test was performed in accordance with ASTM C 1621. The J-ring contains 16 vertical bars of ⅝ in. diameter and 4 in. height evenly spaced around a 12 in. diameter ring. The ring serves to simulate the ability of the mix to pass through rebar similar to field conditions. For the test to be performed, the ring is placed on the testing surface and the inverted slump cone is placed inside of the ring. The slump cone is filled and lifted in accordance with ASTM C 1621. Once the concrete has stopped flowing, a diameter is measured across the largest part of the displaced concrete mass and a second diameter is measured perpendicular to the first. These measurements are made to the nearest ¼ in. and then the average of the two is taken to the nearest ½ in. In addition to the J-ring flow, the height difference between the inside and outside the ring was measured to the nearest ¼ in.

RESULTS

The fresh concrete properties of each batch along with one day compressive strengths are shown in Table 2. Slump flow tests were performed before and after the J-Ring test for each batch and the first slump flow was recorded as the official value. The overall values of fresh concrete properties gave a good representation of the target range as well as covering values just outside of that range. VSI values were consistently between 0 and 1 with only two of the batches showing significant segregation. One day compressive strengths met the desired value for all batches except for Batch 11, where segregation was readily noticeable.

SLUMP FLOW

Slump flows varied between 15 in. and 37.5 in. This range easily covered the desired range of 25.5 to 29.0 in. as well as values on both the high and low side of the desired range. These limits show that both the extremes of basically high slump concrete (non SCC) and segregated mixtures were examined as well as everything in between. All batches except Batch 11 met the target values for strength at one day. Wall sections cast with Batches 5, 6, 7, and 9 (having slump flows in the desired range) had a good surface finish without significant bugholes. An example can be seen in Figure 1. Walls cast with batches having a slump flow larger than the desired range also showed a good finish. Low slump flows led to significant bug holes and a poor finish as can be seen in Figure 2.

Table 2. Summary of Concrete Properties

Batch	Slump Flow (in.)	T_{20} (sec)	VSI	J-Ring Flow (in.)	J-Ring ΔH (in.)	1 Day f_c
1*	NA	NA	NA	NA	NA	NA
2*	18.5	NA	NA	NA	NA	NA
3*	26.0	NA	0	27.5	NA	NA
4*	27.5	NA	1	27.5	0.50	7670
5	27.0	NA	1	27.5	0.75	6880
6	26.5	10.4	1	27.5	0.50	7500
7	26.5	8.4	1	27.0	0.25	NA
8	22.5	9.8	0	22.0	1.00	6720
9	27.5	6.4	0	30.0	0.25	7420
10	21.0	15.6	0	19.0	1.75	7600
11	37.5	1.6	2.5	41.0	0.00	2330
12	31.0	3.8	2	29.5	0.75	6290
13	24.0	5.0	0	22.5	1.00	6510
14	29.5	4.0	1	27.0	0.50	6230
15*	15.0	NA	NA	NA	NA	NA
16	16.0	NA	NA	NA	NA	6190

*Indicates test batch only.

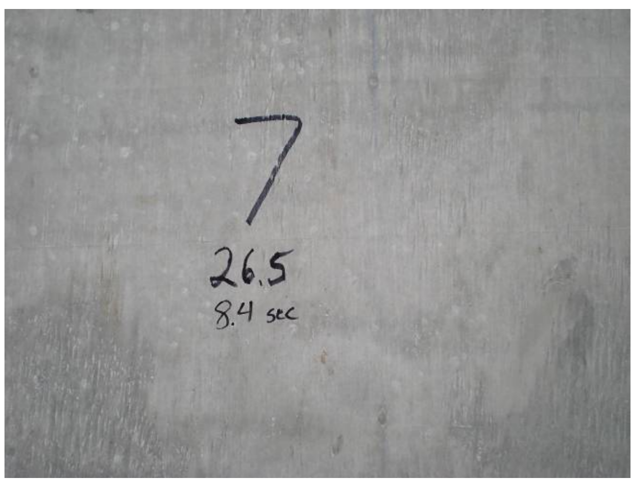

Figure 1. Wall 7 Showing Good Slump Flow

Since previous research at the University of Arkansas had indicated[5] that slump flows tended to increase over the short term, a second slump flow test was performed after each J-Ring test. These tests yielded some interesting results. A comparison of the first set of slump flow tests to the second set are shown in Table 3. Batches 4, 5, 6, 7, 8, 9, and 11 showed an increase in slump flow in the approximately 10 minutes between tests. This increase ranged from 0.5 in to 4 in. The source of the increase in slump flow is unclear, but may be caused by water exiting the aggregate as the concrete sits, or by continued action of the HRWR.

Batches 10, 12, 13, 14, and 16 showed a decrease in slump flow, as would typically be expected. T_{20} times followed the same pattern as slump flows, with lower T_{20} when slump flow increased and higher T_{20} when slump flow decreased.

Figure 2. Wall 16 Showing Poor Slump Flow

Table 3. Comparison of Slump Flow Tests

	First Trial			Second Trial		
Batch	Slump Flow (in.)	T_{20} (sec)	VSI	Slump Flow (in.)	T_{20} (sec)	VSI
1	NA	NA	NA	NA	NA	NA
2	18.5	NA	NA	NA	NA	NA
3	26.0	NA	0	NA	NA	NA
4	27.5	NA	1	31.5	NA	NA
5	27.0	NA	1	29.0	NA	1
6	26.5	10.4	1	28.5	NA	1
7	26.5	8.4	1	30.0	6.4	1
8	22.5	9.8	0	25.0	7.6	1
9	27.5	6.4	0	30.5	4.0	1
10	21.0	15.6	0	19.5	20.0	0
11	37.5	1.6	2.5	38.0	4.4	2.5
12	31.0	3.8	2	31.0	4.0	2
13	24.0	5.0	0	22.0	7.2	0
14	29.5	4.0	1	27.5	4.2	1
15	15.0	NA	NA	NA	NA	NA
16	16.0	NA	NA	15.0	NA	NA

T_{20} TIME

T_{20} times covered a broad range with a minimum of 1.6 seconds and a maximum of 15.6 seconds. Wall sections cast with Batches 12, 13, and 14, exhibiting T_{20} times in the desired range of 2 to 5 seconds, had a good finish with a minimum amount of bugholes. Figure 3 shows the surface finish of the wall cast with Batch 12. Wall 11 had a very low T_{20} but showed some poor surface finish due to segregation. Batches with a high T_{20} but good slump flow yielded a good surface finish as well. However, since T_{20} is a measure of filling ability, consequences of high T_{20} times may not be discovered until cores are examined. The mixture used in this research program tended to have a high viscosity and more batches are necessary to obtain additional data points for low T_{20} times.

Figure 3. Wall 12 Showing Good T_{20}

VSI

All batches had a VSI in the target range of 0 to 1 except for Batches 11 and 12. Batch 11 showed significant segregation (VSI of 2.5) and the wall cast with this batch had a substantial amount of bugholes. Batch 12 showed moderate segregation (VSI of 2), but the wall had a good surface finish. As mentioned previously, the cores will give a much better indication of how this segregation affected concrete performance. The low VSI values for all other batches indicate adequate segregation resistance.

J-RING

Differences between slump flow and J-Ring flows were typically less than 2 in. However, in some cases the J-Ring flow was higher than the slump flow. The increase could also be attributed to the water in the aggregate or HRWR action mentioned in the slump flow section. This result was true for Batches 3, 5, 6, 7, 9, and 11. The difference in height inside and outside the J-Ring was seemingly more consistent in showing the true value of blockage. Height differences varied from 0.25 in. to 1.75 in. From previous research, a height difference of 0.5 in. or less indicated minimal blockage. Batches 4, 6, 7, 9, 11, and 14 exhibited this characteristic. This implies that all other batches had some measure of blockage. Only Batches 10, 15, and 16 had a value higher than 1 in. All three of these batches had low slump flows and batch 15 was not used to cast a wall section. The J-Ring values will be useful when examining the cores from the wall sections to determine how the reinforcement affected consolidation of the concrete.

COMPRESSIVE STRENGTH

All batches for which cylinders were cast met the target one day compressive strength of 6000 psi except for Batch 11, which had significant segregation. Since the target compressive strength was met at one day, core strengths should meet the target compressive strength at time of testing. The variation of compressive strength with slump flow and T_{20} is shown in Figures 4 and 5 with the target range of fresh properties indicated.

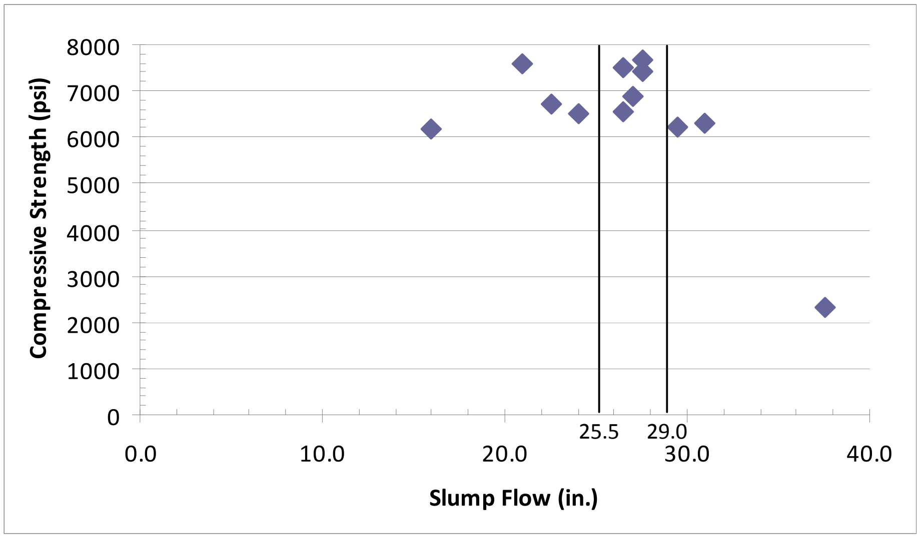

Figure 4. Variation of One Day Strength with Slump Flow

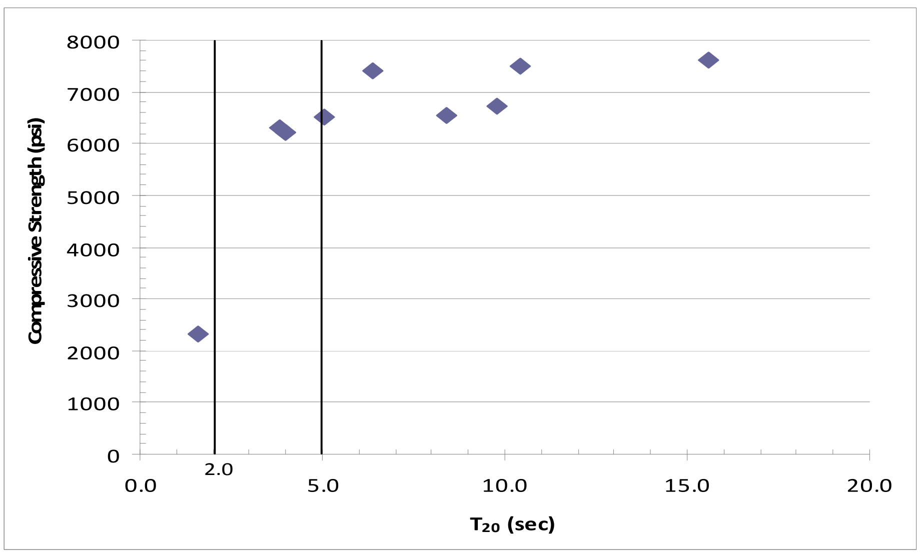

Figure 5. Variation of Compressive Strength with T_{20}

FUTURE RESEARCH

More wall sections will be cast in an attempt to have more data points with both slump flow and T_{20} in the desired range. At the time this paper was written, coring of the wall slabs had not yet occurred. The testing of these cores for both compressive strength and checking for aggregate segregation will give a much better indication of the performance of SCC in this application. Examination of the surface finish of the wall sections gives some information of the filling ability of the concrete but does not give an indication of blockage from the reinforcement. If favorable results are discovered from this portion of the research, taller and longer wall sections may be cast in order to examine the effects of larger size sections.

CONCLUSIONS

- Mixtures with slump flows within the target range of 25 in. to 29.0 in. yielded wall sections with a good surface finish.
- Mixtures with T_{20} times within the target range of 2-5 seconds yielded wall sections with a good surface finish.
- Mixtures with low slump flows and high T_{20} times resulted in wall sections with a very poor surface finish.
- Surface finish of the wall sections was affected by a combination of slump flow and T_{20}.
- All mixtures except one with very significant segregation reached the target compressive strength of 6000 psi at one day.
- More research is necessary to obtain a more substantial indication of the concrete performance.

REFERENCES

1. Lange, D. A. (2007). "Self Consolidating Concrete." *The Center for Advanced Cement Based Materials White Paper*. ACBM.

2. Bui, V. K., Akkaya, Y., Shah, S. P. (2002). "Rheological Model for Self-Consolidating Concrete." *ACI Materials Journal*. Vol. 99. No. 6. 549-559.

3. Khayat, K. H., Mitchell, D. (2009). "Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements". *NCHRP Report 628*. Transportation Research Board.

4. Hwang, S. D., Khayat, K. H., Bonneau, O. (2006). "Performance-Based Specifications of Self-Consolidating Concrete Used in Structural Applications." *ACI Materials Journal*. Vol. 103. No. 2. 121-129.

5. Do, N., Staton, B., Hale, W. (2006). "Development of High Strength Self-Consolidating Mixtures for Use in Prestressed Bridge Girders." PCI National Bridge Conference.

6. Lachemi, M., Hossain, K. M. A., Lambros, V., and Bouzoubaâ, N. (2003). “Development of Cost-Effective Self-Consolidating Concrete Incorporating Fly Ash, Slag Cement, or Viscosity-Modifying Admixtures.” *ACI Materials Journal*. Vol. 100. No. 5. 419-425.

7. El-Chabib, H., Nehdi, M. (2006). “Effect of Mixture Design Parameters on Segregation of Self-Consolidating Concrete.” *ACI Materials Journal*. Vol. 103. No. 5. 374-383.

8. Self-Compacting Concrete European Project Group. (2005). “The European Guidelines for Self-Compacting Concrete: Specification, Production, and Use.” *International Bureau for Precast Concrete (BIBM)*. Retrieved June 2009 from www.efnarc.org.

9. Khayat, K. H., Manai, K., Trudel, A. (1997). “In Situ Mechanical Properties of Wall Elements Cast Using Self-Consolidating Concrete.” *ACI Materials Journal*. Vol. 94. No. 6. 491-500.

10. Campion, M., Jost, P. (2000). “Self-Consolidating Concrete: Expanding the Possibilities of Concrete Design and Placement.” *Concrete International*. Vol. 22. No. 4. 31-34.

11. Sonebi, M., Grünewald, S., and Walraven, J. (2007). “Filling Ability and Passing Ability of Self-Consolidating Concrete.” *ACI Materials Journal*. Vol. 104. No. 2. 162-170.

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