

Development of Self-Consolidating Concrete for Prestressed Bridge Beams

by E.P. Koehler and D.W. Fowler

Synopsis: Sixteen self-consolidating concrete (SCC) mixtures were developed for use in precast, prestressed bridge beams in Texas. The mixtures featured two different sets of aggregates—namely with river gravel or crushed limestone coarse aggregate—and varied in sand-aggregate ratio, paste volume, and paste composition. The 16-hour compressive strengths (release strengths) ranged from 4,500 to 10,500 psi (30 to 70 MPa) depending on the mixture proportions and curing temperature history. The 28-day compressive strengths ranged from 11,000 to nearly 15,000 psi (75 to 100 MPa). The SCC mixtures were developed to achieve the necessary release strengths while balancing the requirements for adequate workability and durability.

This paper discusses the need for higher paste volumes and sand-aggregate ratios to achieve SCC workability requirements and the implications for hardened properties. Semi-adiabatic and isothermal calorimetry measurements performed on concrete and paste specimens, respectively, and compressive strength measurements indicated that although the SCC mixtures exhibited slightly delayed setting times in some cases, they generated heat at a faster rate, generated more total heat, and developed higher 28-day strength for a given release strength. Compared to conventional mixtures with the same release strength, the SCC mixtures exhibited unchanged or slightly reduced shrinkage except when one specific admixture was used.

Keywords: calorimetry; mixture proportioning; prestressed concrete; self-consolidating concrete; shrinkage

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INTRODUCTION

The ability of self-consolidating concrete (SCC) to flow under its own mass, pass through congested reinforcement, and resist segregation can result in substantial benefits for producers and purchasers of precast, prestressed concrete bridge beams. The modifications to mixture proportions required to achieve these workability characteristics may have consequential implications for hardened properties. Potential modifications to mixture proportions include higher paste volume, increased sand-aggregate ratio (S/A), and reduced maximum aggregate size. For prestressed concrete bridge beams, the compressive strength required for the release of tension in strands, typically needed within 16 hours, is crucial so that precasters can re-use their beds with minimal turn-over time. Long-term strength, stiffness, shrinkage, and durability are also important. A Texas Department of Transportation (TxDOT)-sponsored research project was conducted at the University of Texas at Austin (workability and early-age properties) and Texas A&M University (longer-term properties) to evaluate the suitability of SCC for prestressed bridge beams in Texas. This paper discusses the tradeoffs associated with proportioning SCC mixtures to achieve the required workability and hardened properties needed for prestressed concrete bridge beams and presents test results for early-age compressive strength development, heat generation (calorimetry), and shrinkage. Longer-term properties will be reported by the Texas A&M University researchers.

RESEARCH SIGNIFICANCE

To implement SCC in prestressed concrete applications, mixture proportions must be developed that are economical, achieve high early-age compressive strengths, and exhibit adequate workability and long-term hardened properties. Although hardened property requirements do not limit the design of SCC mixtures in some cases, both workability and hardened property requirements controlled the design of the mixtures in the research described herein. This paper illustrates why higher paste volumes and S/As are needed for SCC mixtures in prestressed bridge beams in Texas and discusses the implications.

DEVELOPMENT OF MIXTURE PROPORTIONS

Requirements

SCC mixtures were proportioned for workability and hardened properties. For workability, mixtures were designed for filling ability, passing ability, and segregation resistance¹. The target workability properties are shown in Table 1. For hardened properties, mixtures were designed for 16-hour compressive strength. Because early-age strength development is highly dependent on temperature, mixtures were cured at a range of imposed temperature histories selected to be representative of beams cured in Texas weather conditions throughout the year. These temperature histories, which are shown in Figure 1, vary in the pre-set time (time from casting until temperature increases) and maximum temperature. Each mixture was identified in terms of its nominal 16-hour strength, which was achieved with an 8-hour pre-set time and 120°F (49°C) maximum temperature. Mixtures were developed with nominal 16-hour compressive strengths of 5,000 and 7,000 psi (35 and 48 MPa). The mixtures varied in S/A, paste volume, and paste composition to evaluate the effects of these parameters on hardened properties.

The 2004 TxDOT specifications², which do not address SCC, were also considered. To meet TxDOT specifications, mixtures must contain no more than 700 lb/yd³ (415 kg/m³) of cementitious materials unless otherwise specified or approved. Mixtures must meet one of 8 options (7 prescriptive and 1 performance) intended to mitigate alkali-silica reaction. For this research, the options to replace 20-35% of cement with Class F fly ash and to limit the total alkali content to less than 4 lb/yd³ (2.4 kg/m³) were used. The specifications limit the maximum internal curing temperature to 170°F (77°C) for mixtures where certain specified combinations of supplementary cementitious materials (SCMs) are used and to 150°F (66°C) in other cases. Concrete for prestressed bridge beams in Texas is not typically air-entrained.

Materials

Materials were selected to be representative of those used by precasters in Texas. Two aggregate sets—a crushed limestone coarse aggregate with a natural sand and a river gravel with a separate natural sand—were used (Table 2). The maximum size of both coarse aggregates was $\frac{3}{4}$ inch (19 mm). A Type III cement and Class F fly ash were used (Table 3). Chemical admixtures included a retarder, a viscosity-modifying admixture (VMA), and an experimental admixture that extended workability retention and accelerated strength development. Two polycarboxylate-based high-range water-reducing admixtures (HRWRAs) were used (HRWRA-01 for SCC mixtures and HRWRA-02 for conventional concrete mixtures).

Methodology

Sixteen SCC mixtures were developed to cover the range of mixture proportions likely to be used for prestressed bridge beams in Texas (Figure 2). For each aggregate set, 5 mixtures were developed for a nominal 16-hour compressive strength level of 5,000 psi (35 MPa) and 3 mixtures for a nominal 16-hour compressive strength level of 7,000 psi (48 MPa). For the 5,000 psi mixtures, the S/A varied from 0.40 to 0.50. Three mixtures varied only in S/A (0.40, 0.45, and 0.50) to allow an independent comparison of the effects of S/A. Maintaining a constant paste volume for these three mixtures, however, resulted in paste volumes that were higher than necessary for the mixtures with S/As of 0.45 and 0.50. These higher paste volumes were needed so that all three mixtures would exhibit adequate workability while varying only in S/A. Therefore, separate mixtures were developed with S/As of 0.45 and 0.50 with optimized paste volumes. For the 7,000 psi nominal strength level, three mixtures were developed for each aggregate set varying only in S/A (0.42, 0.46, and 0.50). The SCC mixtures were compared to 4 conventionally placed concrete mixtures (one mixture at each nominal strength level for each aggregate set).

The ICAR SCC mixture proportioning procedure³ was used to develop the final mixture proportions. In this procedure, concrete is represented as a suspension of aggregates in paste, as depicted schematically in Figure 3. This representation provides a consistent, fundamental framework for evaluating mixtures. To proportion mixtures, the combined aggregates, paste volume, and paste composition are selected to achieve the desired workability and hardened properties. These three steps are summarized in Table 4 and described in general terms in the following three paragraphs.

First, the combined aggregates are selected on the basis of maximum size; grading; and shape, angularity, and texture. These factors are selected to minimize the voids content between aggregates and reduce interparticle friction between aggregates while the maximum size and grading are limited for segregation resistance and passing ability. Although a wide range of aggregates can be used in SCC, minimizing the voids content between aggregates and improving the shape and angularity reduces the required paste volume, resulting in greater economy and improved hardened properties³.

Second, the required minimum paste volume is selected separately for filling ability and passing ability. The minimum paste volume is primarily a function of the aggregate characteristics. Without the minimum paste volume, concrete would not exhibit adequate SCC workability regardless of the paste composition. For filling ability, sufficient paste volume must be provided to fill the voids between compacted aggregates and to lubricate aggregates by providing spacing between aggregates (Figure 3). If only sufficient paste volume were provided to fill the voids between aggregates, the substantial interparticle friction between aggregates would prohibit flow. An equation was developed in the ICAR procedure to calculate an estimate of the paste volume for filling ability as a function of the voids in compacted aggregates and the aggregate shape and angularity. Selecting well-shaped and well-graded aggregates reduces the voids in compacted aggregates (increased packing density), which reduces the needed paste volume. Additionally, aggregates that are equidimensional and well rounded reduce interparticle friction, which reduces the paste needed to separate aggregates. For passing ability, increasing the paste volume reduces the volume of aggregates that must pass through congested reinforcement and reduces the interparticle friction between aggregates. The amount of paste volume for passing ability can be reduced by using a smaller maximum aggregate size, reducing the coarseness of the grading, or selected equidimensional, well-rounded aggregates. The minimum paste volume for passing ability can be determined experimentally based on J-Ring blocking by varying the paste volume for a given aggregate blend. The minimum paste volume is selected as the greater of the minimum paste volume for filling ability or passing ability. This amount of paste volume can be increased for robustness with respect to changes in aggregate properties³.

Third, the composition of the paste—namely the blend of powders and the relative amounts of powder, water, and

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air—is selected to achieve proper workability and hardened properties. The paste composition step is where the distinction between powder type- and VMA-type SCC is made⁴. Powder type-SCC consists of high powder contents and low water-powder ratios (typically <0.40) whereas VMA-type SCC consists of lower powder contents, higher w/p (typically >0.45), and VMA. The use of VMA is not restricted to mixtures with these higher w/p. In establishing the paste composition, the powder blend and water-powder ratio are set to achieve the desired concrete rheology. The powder blend and water-cementitious materials ratio are set to achieve the desired long-term hardened properties. When powders with low reactivity at early ages are used—such as Class F fly ash and some mineral fillers—the water-cement ratio is set to achieve the desired early-age hardened properties. Generally, the cement content should be minimized to achieve hardened properties and other powders added to comprise the remainder of the powder volume and to achieve the desired rheology. To maintain constant concrete rheology as the paste volume or aggregates are changed, the paste composition must be adjusted. For all mixtures, the HRWRA is adjusted to achieve the required slump flow, which is related to yield stress³. The near-zero yield stress for SCC is the main workability difference between SCC and conventionally placed concrete. The plastic viscosity—which is approximately correlated to T_{50} and is a function of aggregates, paste volume, and paste composition³—must not be too low (poor stability) or too high (poor placeability).

Nominal 5,000 psi (35 MPa) Mixtures

The ICAR mixture proportioning procedure is demonstrated in the following paragraphs for the nominal 5,000 psi (35 MPa) 16-hour compressive strength mixtures.

Step 1: Aggregates—Each aggregate set was used at S/As of 0.40 to 0.50. The gradings at these S/As were considered suitable for SCC³. The voids contents for all aggregate combinations were determined as shown in Table 5.

Step 2: Paste Volume—The minimum paste volumes for each S/A were determined by experimentally evaluating filling ability and passing ability at various paste volumes in reference to the requirements in Table 1. Due to the congested reinforcement in the prestressed beams, passing ability controlled the selection of minimum paste volume (Table 5). The effect of paste volume on passing ability is illustrated in Figure 4. Decreasing the S/A required more paste volume due to the increased amount of coarse particles. Although the two aggregate sets had similar compacted voids content, the paste volumes required for both filling and passing abilities were higher for the crushed limestone coarse aggregate set due to the greater angularity of the crushed limestone. The minimum paste volumes determined for passing ability were increased by 1% to ensure robustness with respect to changes in aggregate properties.

Step 3: Paste Composition—The paste composition was optimized for each aggregate set and paste volume. A retarder was used in all mixtures to ensure workability retention. The w/c for a nominal 5,000 psi compressive strength, with retarder, was determined to be 0.41 for the river gravel aggregate set and 0.45 for the crushed limestone aggregate set (Figure 5). With the w/c established, the w/p (equal to w/cm in this case) and fly ash rate were adjusted for each paste volume to achieve proper concrete rheology and fill the required paste volume. In all cases, the HRWRA dosage was adjusted to reach the desired slump flow.

The final mixture proportions are shown in Table 6 and Table 7 for the river gravel and crushed limestone aggregate sets, respectively. The main challenge in developing the mixture proportions was the need to achieve the following three objectives simultaneously: passing ability, early-age compressive strength, and maximum cementitious materials content. The passing ability requirements dictated a minimum paste volume so that SCC would flow through the congested reinforcement typical of prestressed concrete bridge beams. The minimum strength requirements dictated low w/c and—in order for sufficient paste volume and rheology—low w/p and high powder contents. Although fly ash could have been eliminated, resulting in higher w/p and lower powder content, the cement content would still have been too high. Consequentially, it was not possible to keep the cementitious materials content less than 700 lb/yd³ (415 kg/m³). Had the cementitious materials content been kept below this limit, the paste volume would have been too low for workability, the w/c too high for early-age compressive strength, or both. Ensuring passing ability and 16-hour compressive strength was determined to be more important than limiting total cementitious materials content. Despite the high cementitious materials content, the use of fly ash increased economy, reduced heat generation, and enhanced durability.

Nominal 7,000 psi (48 MPa) Mixtures

For mixtures at a nominal 7,000 psi (48 MPa) 16-hour compressive strength level, the challenge of achieving passing ability, early-age compressive strength, and maximum cementitious materials content simultaneously was magnified. For example, with the river gravel aggregate set, the maximum w/c was determined to be 0.31 to achieve the nominal strength of 7,000 psi (with use of retarder for workability retention). Table 8 shows several options that were considered for an S/A of 0.42. In the first option, the cement content was limited to 700 lb/yd³ (415 kg/m³); however, the w/c was too high. In the second option, the w/c was reduced to 0.31; however, the cement content was too high. In the third option, 20% fly ash was used to reduce the cement content and the w/p was reduced to ensure the proper w/c; however, the water content was too low for workability, resulting in extremely viscous concrete.

Because none of these three mixtures was viable, a new experimental admixture was considered. This experimental admixture extends workability retention and accelerates strength gain. The extended workability retention allowed the retarder to be removed. The lack of retarder, combined with the accelerated strength gain associated with the experimental admixture, allowed the w/c to be increased, as shown in Table 8. A low dosage of VMA was used in the mixtures with S/As of 0.42 to ensure stability. The experimental admixture was used in all mixtures designed for a nominal 16-hour compressive strength level of 7,000 psi (48 MPa), as listed in Table 6 and Table 7.

Discussion

SCC is defined in terms of its workability. Changes in hardened properties associated with SCC are primarily attributable to specific changes in mixture proportions required to achieve workability characteristics, not to the workability characteristics themselves³. Therefore, hardened properties should be evaluated on a case-by-case basis in terms of specific changes to mixture proportions instead of associating certain hardened properties with SCC in general. In addition, the improved consolidation and lack of vibration associated with SCC may result in improved hardened properties³. For the mixtures described in this paper, the major changes in mixture proportions were increased paste volume, increased S/A, and use of fly ash. The maximum aggregate size was unchanged.

Paste volume—SCC must have higher paste volume than conventionally placed concrete to ensure filling ability and passing ability. For prestressed concrete bridge beams and other highly congested members, the selection of minimum paste volume is typically controlled by passing ability. Depending on the aggregate, paste volumes of 28–40% are typical for SCC³. Higher paste volume does not necessarily require higher cement or cementitious materials content. Higher paste volume has been associated with increased shrinkage^{1,3,5,6,7}, reduced modulus of elasticity^{1,3,8}, and increased cost. Although increasing the paste volume may reduce modulus of elasticity, changing the stiffness of the aggregates can have a greater effect³. The paste volume required for passing ability is primarily a function of the aggregate characteristics and can be reduced by reducing the maximum size, reducing the coarseness of the combined grading, and improving the shape and angularity of both the fine and coarse aggregates³. These changes can also affect hardened properties themselves and should be evaluated accordingly. To a lesser extent, passing ability can be increased by reducing the paste yield stress and plastic viscosity³.

S/A—The S/A relates to aggregate grading, whereas workability depends on aggregate grading and shape and angularity characteristics. Increasing the S/A can improve passing ability and segregation resistance while decreasing the S/A can—to a certain point—result in improved filling ability³. When changing the S/A, it is important to consider the individual properties of the sand and coarse aggregates. For instance, reducing the coarseness of a grading (higher S/A) is known to reduce modulus of elasticity^{1,8}. If the coarse aggregate is of much lower stiffness than the sand, however, an increase in S/A may result in increased modulus of elasticity³. There are typically optimal S/As associated with packing density and filling ability³. The actual optimal S/A for a given aggregate set depends on the grading, shape, and angularity of the individual fine and coarse aggregates³.

Maximum aggregate size—The maximum aggregate size in SCC is limited by passing ability and segregation resistance. Increasing the maximum size improves filling ability to the extent it improves the combined aggregate grading³. The maximum aggregate size is limited by clear spacings, such as between reinforcement. However, further reducing the maximum aggregate size can reduce the paste volume needed for passing ability. In general, the largest maximum aggregate size should be used subject to limits on passing ability and segregation resistance. Increasing the maximum aggregate size is known to increase modulus of elasticity⁸ and reduce compressive strength⁹.

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Fly ash—SCC often incorporates fly ash and other SCMs to achieve adequate paste volume and w/p for workability. Fly ash also reduces cost, reduces heat generation, and improves durability³. In the SCC mixtures described in this paper, the cement contents were approximately the same or slightly increased relative to the comparable conventional control mixtures; however, the water contents and fly ash contents were increased to achieve adequate paste volume and w/p for workability.

Calorimetry and Early-Age Compressive Strength

Isothermal and semi-adiabatic calorimeter measurements were used to evaluate the heat generation of paste and concrete mixtures, respectively. Isothermal calorimeter measurements were made with an 8-channel isothermal heat conduction calorimeter with 20 ml maximum specimen size (Thermometric 3114 TAM Air). Pastes were mixed in a blender and placed in the calorimeter, which was maintained at constant temperatures ranging from 41 to 140°F (5 to 60°C)¹⁰. The semi-adiabatic calorimeter consisted of a 6x12-inch (152x305-mm) cylindrical concrete specimen positioned inside an insulated, 55-gallon (208-liter) steel drum. Measurements were made of the concrete temperature, heat loss through the calorimeter walls, and ambient temperature surrounding the calorimeter. These measurements were used to calculate the adiabatic temperature rise¹¹. The concrete mixtures tested had fresh temperatures of 75 to 81°F (24 to 27°C) and were measured in the semi-adiabatic calorimeter for 7 days.

Figure 6 shows isothermal calorimetry results for 5 pastes tested at 73.4°F (23°C). The addition of fly ash delayed the start of heat evolution and reduced the peak rate of heat evolution. This reduction was expected due to the lack of reactivity of low calcium fly ashes at early ages. HRWRA delayed the start of heat evolution but increased the maximum rate of heat evolution. This behavior was expected because HRWRAs delay initial setting but result in improved dispersion and more efficient hydration^{12,13}. When combined, fly ash and HRWRA resulted in delayed start of heat evolution and increased peak rate of heat evolution. The addition of retarder to the paste with fly ash and HRWRA further delayed the start of heat evolution and slightly reduced the peak rate of heat evolution. In terms of total heat evolved, the mixtures with fly ash evolved less heat per mass of cementitious materials at all ages measured. However, when compared per mass of cement only, as shown in Figure 7, the mixtures with fly ash evolved heat at a faster rate per cement mass after a certain time (6-8 hours) and generated more total heat per cement mass, reflecting the eventual contribution of fly ash to hydration. As mentioned earlier, the SCC mixtures had similar or only slightly higher total cement contents as the comparable conventional mixtures.

Isothermal calorimetry was used to determine activation energy, which reflects the sensitivity of hydration to temperature. Eight pastes, varying in fly ash rate and admixture type and dosage, were tested to represent the range of paste compositions in the concrete mixtures. As shown in Table 9, the activation energies of the pastes representing the SCC mixtures varied from 34 to 37 kJ/mol, which were similar to the 35 kJ/mol determined for the two pastes representing conventionally placed concrete mixtures. The activation energy of the paste with the experimental admixture, however, was significantly reduced to 24.6 kJ/mol. Therefore, the amount of heat generated in mixtures with the experimental admixture is expected to vary less with temperature changes.

Semi-adiabatic calorimeter results for 5 concrete mixtures are compared in Figure 8. For the 5,000 psi strength level, the SCC mixtures from both aggregate sets generated greater adiabatic temperature rise than the comparable conventional mixtures, which was likely due to the reduced w/c and improved dispersion and hydration from the HRWRA. The 7,000 psi mixture generated less heat than the 5,000 psi mixtures prior to 24 hours. Setting time and total adiabatic temperature rise after 40 hours are shown for all mixtures in Table 6 and Table 7. The data show that, for a given aggregate set, the setting times of the SCC mixtures at the nominal 5,000 psi strength level were delayed; however, these mixtures generated heat at a faster rate, generated more total heat, and developed higher 28-day compressive strengths. The same trends were true for the 7,000 psi mixtures; however, the setting times were not delayed.

The amount of heat generated is important because the curing temperature history significantly affects 16-hour compressive strength, as indicated in Figure 9 for two SCC mixtures. In addition, total heat generated should be minimized to prevent thermal cracking and delayed ettringite formation. Depending on the weather conditions and curing practices, the 16-hour compressive strength could vary from 4,500 to 8,100 psi (31 to 56 MPa) for mixture RG-5-50a and from 4,900 to 9,000 psi (34 to 62 MPa) for mixture RG-7-50. Figure 10 shows the compressive strength of 4 mixtures as a function of equivalent age. Similar strength versus maturity curves were developed for each mixture. These curves, along with knowledge of the amount of heat generated by the concrete mixtures, can be

used to select curing conditions and mixture proportions based on expected ambient weather conditions in order to achieve the desired release strength.

Shrinkage

Shrinkage was measured in accordance with ASTM C 157 with 3x3x11.25-inch (76x76x286-mm) specimens with 10-inch (255-mm) gage length. After casting, specimens were stored at 73°F (23°C) and 100% relative humidity for the first 16 hours. The specimens were then demolded, measured for initial length, and stored at 73°F (23°C) and 50% relative humidity for the remainder of the test. Drying was started at 16 hours to reflect field conditions. Autogenous shrinkage, which may be of concern given the low water-cement ratios, was not independently measured.

For the 5000 psi nominal strength level, shrinkage was unchanged for the river gravel mixtures (Figure 11) and slightly decreased for the crushed limestone mixtures (Figure 12) when compared to the conventional mixtures. At the 7,000 psi nominal strength level; however, the shrinkage increased for both aggregate sets compared to the conventional mixtures. This increase in shrinkage, which varied from 14 to 26%, was attributable to the experimental admixture as shown in Figure 11. Decreasing the S/A ratio reduced shrinkage in the crushed limestone aggregate set slightly but had no effect on the river gravel aggregate set. Decreasing the paste volume in mixtures RG-5-50a and LS-5-50a had no effect on shrinkage. Despite the lower paste volumes in RG-5-50a and LS-5-50a, the total water contents per unit volume were approximately the same as in the SCC mixtures with higher paste volume (RG-5-50a vs. RG-5-50; LS-5-50a vs. LS-5-50). For a given strength level and S/A, the mixtures with the crushed limestone aggregate set exhibited 10-30% higher shrinkage than the mixtures with the river gravel aggregate set, which was likely due to the reduced stiffness of the crushed limestone aggregates and possibly due to the higher paste volumes in the crushed limestone aggregate mixtures.

CONCLUSIONS

SCC mixture proportions were developed to meet both workability and hardened property requirements for prestressed bridge beams. The mixtures varied in aggregate source, S/A, paste volume, and paste composition. Selecting SCC mixture proportions is an optimization process that requires consideration of the specific effects of each change in mixture proportions on workability and hardened properties. Requirements for workability and hardened properties imposed conflicting limits on mixture proportions. To provide a minimum paste volume for workability and a maximum w/c for 16-hour compressive strength, the total cementitious materials content was above the original maximum target of 700 lb/yd³ (415 kg/m³). The 16-hour compressive strength varied significantly with the curing temperature history; therefore, strength-maturity relationships were developed that can be used to select mixture proportions and curing practices based on required 16-hour compressive strength and expected weather conditions. Calorimetry and early-age compressive strength measurements indicated that although the setting times of the SCC mixtures were delayed at the nominal 5,000 psi (35 MPa) compressive strength level, the SCC mixtures generated heat at a faster rate, generated more total heat, and developed higher 28-day compressive strengths. For the nominal 5,000 psi compressive strength level, shrinkage was unchanged for the river gravel aggregate set and slightly reduced for the crushed limestone aggregate set relative to the comparable conventional concrete mixtures. For the nominal 7,000 psi (48 MPa) compressive strength level, the shrinkage was increased 14-26% relative to the conventional concrete mixtures, which was due to the effect of the experimental admixture.

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Table 1: Target Workability Properties

Property	Test Method	Target Properties
Filling Ability	Slump Flow (ASTM C 1611, inverted cone)	Achieve a slump flow of 28-30 inches (710-760 mm) with $VSI \leq 1.0$ and $3 s < T_{50} < 7 s$; maintain a 23-inch (580-mm) slump flow 20 minutes after mixing.
Passing Ability	J-Ring (ASTM C 1621)	For an AASHTO Type IV beam, strands ~1.5-inch (40 mm) clear spacing. J-Ring $\Delta H < 0.50$ inches (13 mm)*
Segregation Resistance	Column Segregation (ASTM C 1610)	Exhibit minimal segregation and top bar effect. Static segregation $\leq 15\%$.
*In the J-Ring test, the difference in concrete height between the inside and outside of ring has been found to be a better indication of passing ability than the difference in slump flow with and without J-Ring.		

Table 2: Aggregate Characteristics

	River Gravel Set		Crushed Limestone Set	
	River Gravel	Natural Sand A	Crushed Limestone	Natural Sand B
Specific Gravity	2.59	2.58	2.59	2.60
Absorption Capacity, %	0.78	0.54	1.43	0.56
Compacted Voids Content, %	34.2	33.6	41.4	32.4
Gradation (% Passing)	1" (25 mm)	100.0	100.0	
	¾" (19 mm)	94.8	95.1	
	½" (13 mm)	64.3	70.5	
	⅜" (9.5 mm)	40.4	38.2	
	#4	7.8	0.2	98.5
	#8	2.2		86.9
	#16	1.5		75.1
	#30	1.2		53.4
	#50			20.9
	#100			6.8
	#200	1.2		1.8

Table 3: Cement and Fly Ash Characteristics

Cement (Type III)		Fly Ash (Class F)	
C ₃ S, %	56.6	Silicon Dioxide (SiO ₂), %	52.5
C ₂ S, %	16.3	Aluminum Oxide (Al ₂ O ₃), %	21.8
C ₃ A, %	7.2	Iron Oxide (Fe ₂ O ₃), %	4.9
C ₄ AF, %	10.3	Calcium Oxide (CaO), %	13.9
Total Alkalies (as Na ₂ O _{eq}), %	0.50	Magnesium Oxide (MgO), %	2.0
Sulfur Trioxide (SO ₃), %	3.5	Sulfur Trioxide (SO ₃), %	0.8
Blaine Fineness, m ² /kg	539	Available Alkalies (as Na ₂ O _{eq}), %	0.24
Specific Gravity	3.15	Specific Gravity	2.33
Loss on Ignition, %	2.1	Loss on Ignition, %	1.05

Table 4: Summary of ICAR SCC Mixture Proportioning Method³

Factor	Objective	Sub-Factors	Target
Aggregates	Minimize voids content (increase packing density) and reduce interparticle friction; limit grading as needed for passing ability and segregation resistance	Maximum Size	Reduce as needed for passing ability or segregation resistance
		Grading	None universally optimal, best depends on aggregate and application
		Shape, Angularity, Texture	Reduce interparticle friction
Paste Volume	Ensure filling and passing ability by filling voids in compacted aggregates and separating aggregates (lubrication); provide additional paste for robustness	Filling Ability	Fill voids and lubricate aggregates
		Passing Ability	Reduce aggregate volume and interparticle friction
		Robustness	Minimize effects of changes in materials and proportions
Paste Composition	Ensure adequate concrete rheology (yield stress, plastic viscosity, thixotropy) and hardened properties (strength, stiffness, durability), optimize economy	Water	w/p for rheology, w/c for early-age hardened properties, w/cm for long-term hardened properties
		Powder	Total volume of powder and relative amounts of cement, SCMs, and mineral fillers for economy, strength, and durability
		Air	As needed for durability
Adjust HRWRA to reach desired slump flow (yield stress for self-flow). Use VMA if necessary.			

Table 5: Minimum Paste Volume Requirements

S/A	River Gravel			Crushed Limestone		
	Voids Content (%)	Req'd Paste Volume (%)		Voids Content (%)	Req'd Paste Volume (%)	
		Filling Ability	Passing Ability		Filling Ability	Passing Ability
0.40	23.9	32	36	23.9	38	41
0.45	23.6	30	34	23.3	36	38
0.50	23.2	28	32	22.7	35	36

Larger minimum paste volume for filling ability or passing ability selected

Table 6: Final Proportions for River Gravel/Natural Sand Aggregate Set

	Conventional		f _c '=5,000 psi (35 MPa)					f _c '=7,000 psi (48 MPa)		
	RG-5-C	RG-7-C	RG-5-50	RG-5-45	RG-5-40	RG-5-50a	RG-5-45a	RG-7-50	RG-7-46	RG-7-42
Mixture Proportions										
Cement, lb/yd ³ (kg/m ³)	625 (371)	700 (415)	633 (376)	633 (376)	633 (376)	624 (370)	646 (383)	720 (427)	720 (427)	720 (427)
Fly Ash, lb/yd ³ (kg/m ³)			298 (177)	298 (177)	298 (177)	156 (93)	239 (142)	180 (107)	180 (107)	180 (107)
Coarse Aggregate, lb/yd ³ (kg/m ³)	1937 (1149)	1938 (1150)	1372 (814)	1509 (895)	1646 (977)	1459 (885)	1532 (909)	1401 (831)	1513 (897)	1625 (964)
Fine Aggregate, lb/yd ³ (kg/m ³)	1234 (732)	1235 (732)	1366 (811)	1230 (730)	1093 (649)	1453 (862)	1249 (741)	1395 (828)	1284 (761)	1172 (695)
Water, lb/yd ³ (kg/m ³)	225 (133)	200 (118)	261 (155)	261 (155)	261 (155)	257 (153)	265 (157)	243 (144)	243 (144)	243 (144)
HRWRA-01, oz/yd ³ (L/m ³)			91 (3.5)	83 (3.2)	78 (3)	83 (3.2)	89 (3.4)	118 (4.6)	119 (4.6)	115 (4.5)
HRWRA-02, oz/yd ³ (L/m ³)	68 (2.6)	117 (4.5)								
Retarder, oz/yd ³ (L/m ³)			25 (1)	25 (1)	25 (1)	25 (1)	26 (1)			
Experimental Admixture, oz/yd ³ (L/m ³)								578 (22.4)	578 (22.4)	578 (22.4)
VMA, oz/yd ³ (L/m ³)										4 (0.2)
Mixture Indices										
S/A	0.39	0.39	0.5	0.45	0.4	0.5	0.45	0.5	0.46	0.42
Coarse Agg. Vol., %	44.4	44.4	31.4	34.6	37.7	33.4	35.1	32.1	34.7	37.2
Paste Volume, %	27.2	27.2	37.1	37.1	37.1	33.1	36.1	35.8	35.8	35.8
w/cm	0.36	0.285	0.28	0.28	0.28	0.33	0.3	0.27	0.27	0.27
w/c	0.36	0.285	0.412	0.412	0.412	0.413	0.411	0.338	0.338	0.338
Fly Ash, % Mass	0	0	32	32	32	20	27	20	20	20
Typical Fresh Properties										
Yield Stress, Pa	294	195	6	44	16	11		0	0	0
Plastic Viscosity, Pa.s	42	263	34	37	24	23		56	66	51
Slump, in. (mm)	7.5 (190)	7.25 (185)								
Slump Flow, in. (mm)			30 (760)	28 (710)	30 (760)	28 (710)		28 (710)	28 (710)	27 (690)
T ₅₀ , s			3.8	4.2	3.8	4.9		8	7.4	7.4
VSI			0	0	0.5	0		0	0	0
J-Ring ΔH, in. (mm)			0.13 (3)	0.34 (9)	0.19 (5)	0		0.25 (6)	0.25 (6)	0.44 (11)
Col. Segregation, % Static Seg.			5	0	3	13		7	0	7
Initial Set, Hr:Min	3:55	6:15	4:50	4:25	4:15	4:40		5:50	4:50	4:15
Final Set, Hr:Min	5:10	8:50	6:10	5:35	5:35	5:50		7:00	5:50	5:15
Adiabatic Temp. Rise @ 40 hours, °C	53.2	54.8	63.4	62.5	61.6	58.7		61.0	62.3	59.8
Typical Hardened Properties										
16-hr (8hr pre-set, 120F max) f _{ci} , psi (MPa)	5784 (39.9)	6871 (47.4)	5622 (38.8)	6021 (41.5)	5501 (37.9)	5521 (38.1)		7108 (49)	6986 (48.2)	7296 (50.3)
16-hr (4-hr pre-set, 170F max) f _{ci} , psi (MPa)	7099 (48.9)	8456 (58.3)	8705 (60)		8254 (56.9)	8094 (55.8)		8767 (60.4)		9020 (62.2)
28-day f _c , psi (MPa)	10854 (74.8)	12706 (87.6)	11733 (80.9)	12062 (83.2)	11774 (81.2)	11223 (77.4)		13023 (89.8)	13970 (96.3)	14042 (96.8)
112-day Shrinkage, μ-strain	-397	-423	-387	-397	-397	-393		-505	-480	-507

Mixture Designation

RG-5-50a

↑ "a" for paste volume alternate for given S/A
 S/A (%) or "C" for conventional concrete
 nominal 16-hr strength (ksi)
 coarse aggregate (RG or LS)

Table 7: Final Proportions for Crushed Limestone/Natural Sand Aggregate Set

	Conventional		f _c =5,000 psi (35 MPa)					f _c =7,000 psi (48 MPa)		
	LS-5-C	LS-7-C	LS-5-50	LS-5-45	LS-5-40	LS-5-50a	LS-5-45a	LS-7-50	LS-7-46	LS-7-42
Mixture Proportions										
Cement, lb/yd ³ (kg/m ³)	600 (356)	680 (403)	640 (379)	640 (379)	640 (379)	604 (358)	604 (358)	720 (427)	720 (427)	720 (427)
Fly Ash, lb/yd ³ (kg/m ³)			426 (253)	426 (253)	426 (253)	297 (176)	370 (220)	180 (107)	180 (107)	180 (107)
Coarse Aggregate, lb/yd ³ (kg/m ³)	1752 (1039)	1754 (1040)	1263 (749)	1389 (824)	1515 (899)	1372 (814)	1461 (867)	1383 (821)	1494 (886)	1605 (952)
Fine Aggregate, lb/yd ³ (kg/m ³)	1382 (820)	1383 (821)	1267 (752)	1141 (677)	1014 (602)	1377 (817)	1200 (712)	1389 (824)	1278 (758)	1167 (692)
Water, lb/yd ³ (kg/m ³)	252 (150)	224 (133)	288 (171)	288 (171)	288 (171)	270 (160)	273 (162)	257 (152)	257 (152)	257 (152)
HRWRA-01, oz/yd ³ (L/m ³)			84 (3.2)	70 (2.7)	65 (2.5)	75 (2.9)	64 (2.5)	110 (4.3)	88 (3.4)	88 (3.4)
HRWRA-02, oz/yd ³ (L/m ³)	44 (1.7)	78 (3)								
Retarder, oz/yd ³ (L/m ³)			26 (1)	26 (1)	26 (1)	24 (0.9)	24 (0.9)			
Experimental Admixture, oz/yd ³ (L/m ³)								578 (22.4)	578 (22.4)	578 (22.4)
VMA, oz/yd ³ (L/m ³)										3 (0.1)
Mixture Indices										
S/A	0.44	0.44	0.5	0.45	0.4	0.5	0.45	0.5	0.46	0.42
Coarse Agg. Vol., %	40.1	40.2	28.9	31.8	34.7	31.4	33.5	31.7	34.2	36.8
Paste Volume, %	28.3	28.2	42.1	42.1	42.1	37.1	39.1	36.6	36.6	36.6
w/cm	0.42	0.33	0.27	0.27	0.27	0.3	0.28	0.285	0.285	0.285
w/c	0.42	0.33	0.450	0.450	0.450	0.448	0.452	0.356	0.356	0.356
Fly Ash, % Mass	0	0	40	40	40	33	38	20	20	20
Typical Fresh Properties										
Yield Stress, Pa	177	121	2	15	18	6		0	0	0
Plastic Viscosity, Pa.s	47	133	34	33	27	23		30	32	25
Slump, in. (mm)	8.25 (210)	7.0 (180)								
Slump Flow, in. (mm)			29 (740)	29 (740)	28 (710)	30 (760)		29 (740)	29 (740)	30 (760)
T ₅₀ , s			6	4.4	5.1	4.9		6.3	5.5	4
VSI			0	0.5	0.5	1		0	0	1
J-Ring ΔH, in. (mm)			0.25 (6)	0.28 (7)	0.28 (7)	0 (0)		0.16 (4)	0.44 (11)	0.31 (8)
Col. Segregation, % Static Seg.			1	8	13	20		8	0	4
Initial Set, Hr:Min	3:30	5:10	4:05	4:05	4:00	4:00		5:10	5:10	5:20
Final Set, Hr:Min	4:50	6:30	5:20	5:35	5:30	5:10		6:05	6:05	6:15
Adiabatic Temp. Rise @ 40 hours, °C	49.6	54.0	67.1	66.2	66.3	62.2		61.0	60.9	61.7
Typical Hardened Properties										
16-hr (8hr pre-set, 120F max) f _{cu} , psi (MPa)	5260 (36.3)	7165 (49.4)	6112 (42.1)	5850 (40.3)	5641 (38.9)	5603 (38.6)		7422 (51.2)	7187 (49.6)	7657 (52.8)
16-hr (4-hr pre-set, 170F max) f _{cu} , psi (MPa)	6969 (48)	9073 (62.6)	10435 (71.9)		9579 (66)	8706 (60)		9213 (63.5)		9090 (62.7)
28-day f _{cu} , psi (MPa)	11135 (76.8)	13146 (90.6)	13713 (94.5)		13066 (90.1)	13075 (90.1)		14802 (102.1)		14931 (102.9)
112-day Shrinkage, μ-strain	-537	-467	-510	-503	-477	-503		-587	-583	-553

Table 8: Mixture Proportioning Options for 7,000 psi Nominal Strength

Option	Paste Volume %	w/p w/cm	w/c	Fly Ash %	Cement lb/yd ³	Cementitious lb/yd ³	Exp. Admix. oz/yd ³	VMA
1) 700 lb cement	36.0	0.498	0.498	0	700.0	700.0	--	--
2) w/c=0.31, no fly ash	36.0	0.31	0.31	0	910.3	910.3	--	--
3) add fly ash, reduce w/cm	36.0	0.248	0.31	20	777.3	971.7	--	--
4) experimental admixture	35.8	0.27	0.338	20	720.0	900.0	578	4

Notes: S/A = 0.42, minimum paste volume 36% for passing ability, w/c=0.31 for strength with retarder; retarder included in mixes 1-3 for workability retention

Table 9: Activation Energy from Isothermal Calorimetry

ID	w/cm	Fly Ash	HRWRA-01	HRWRA-02	Retarder	Exp. Admixture	Activation Energy
		%	% cm mass	% cm mass	% c mass	% c mass	kJ/mol
1	0.27	20	0.33%			2.43%	24.6
2	0.27	20	0.33%				34.0
3	0.28	32	0.25%		0.04%		36.3
4	0.28	32	0.25%				37.2
5	0.27	40	0.19%		0.04%		35.7
6	0.33	20	0.29%		0.04%		34.7
7	0.285	0		0.49%			35.2
8	0.42	0		0.20%			35.3

Notes:

- 1.) Mixtures 1-6 represent SCC mixtures, 7-8 conventional placed concrete mixtures
- 2.) Admixture dosages expressed as % admixture solids mass per cementitious materials mass (HRWRAs) or per cement mass (retarder and experimental admixture)
- 3.) Activation energy determined with isothermal calorimetry **Error! Reference source not found.**

- a. Generated heat ($H(t)$) measured in specimens tested at 5, 15, 23, 38, 60°C
- b. Ultimate heat of hydration (H_u) calculated for each mixture as function of mass fractions (p_i):

$$H_u = (500 \cdot p_{C_3S} + 260 \cdot p_{C_2S} + 866 \cdot p_{C_3A} + 420 \cdot p_{C_4AF} + 624 \cdot p_{SO_3} + 1186 \cdot p_{FreeCa} + 850 \cdot p_{MgO}) \cdot p_{cement} + (1800 \cdot p_{CaO}) \cdot p_{flyash}$$

- c. Degree of hydration ($\alpha(t)$) calculated:

$$\alpha(t) = \frac{H(t)}{H_u}$$

- d. Degree of hydration fit to three-parameter model (α_u , β , τ are empirical constants; α_u and β assumed to be independent of temperature):

$$\alpha(t) = \alpha_u \cdot e^{-\left[\frac{\tau}{t}\right]^\beta}$$

- e. Slope of $\ln(\tau)$ versus $1/T_c$ used to calculate activation energy (E_a) with following equation (where T is temperature in Kelvin, R is ideal gas constant):

$$E_a = - \frac{\ln\left(\frac{\tau_{ref}}{\tau_c}\right)}{\left(\frac{1}{T_{ref}} - \frac{1}{T_c}\right)} \cdot R$$

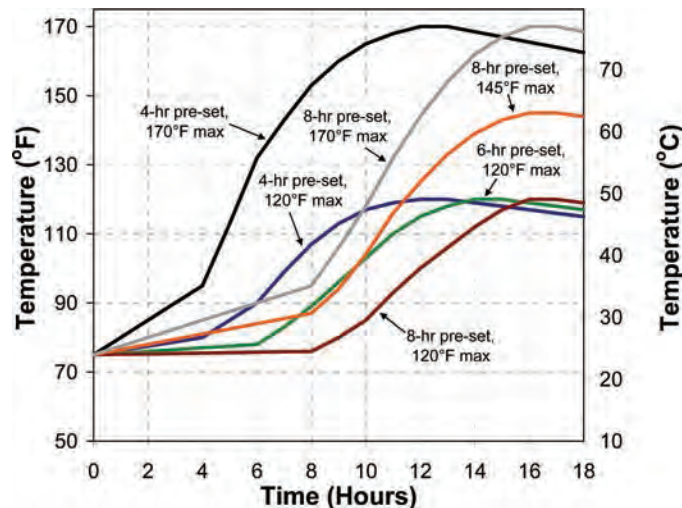


Fig. 1—Curing temperature histories imposed for all mixtures.

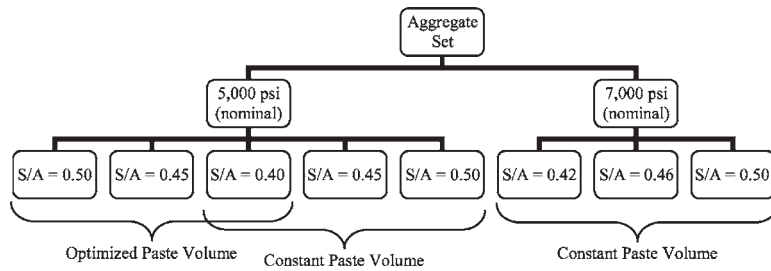


Fig. 2—SCC mixtures developed for each aggregate set.

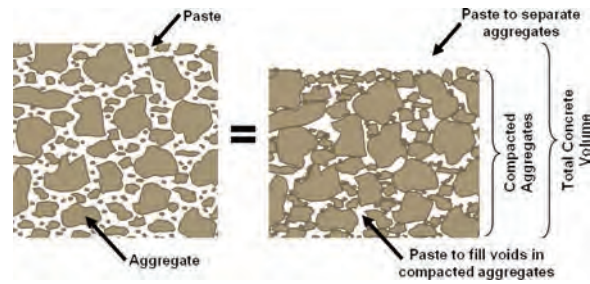


Fig. 3—Representation of concrete as suspension of aggregates in paste.

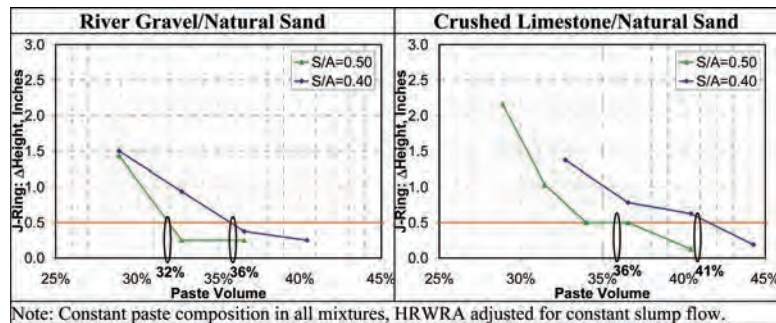


Fig. 4—Selection of minimum paste volume for passing ability.

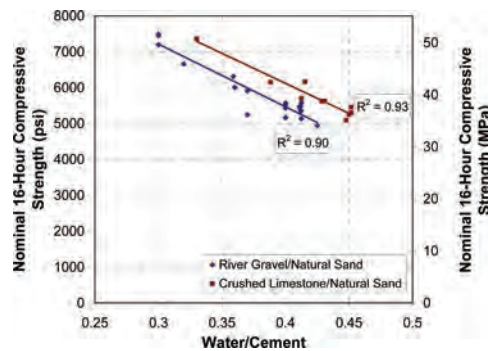


Fig. 5—Establishment of required water-cement ratio for nominal 16-hour compressive strength (retarder in all mixtures).

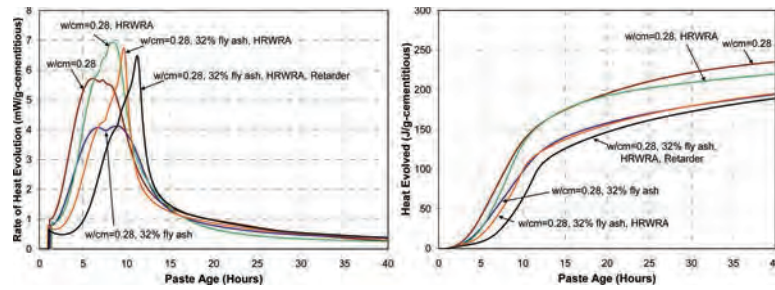


Fig. 6—Isothermal calorimetry results (23 °C, per cementitious materials mass).

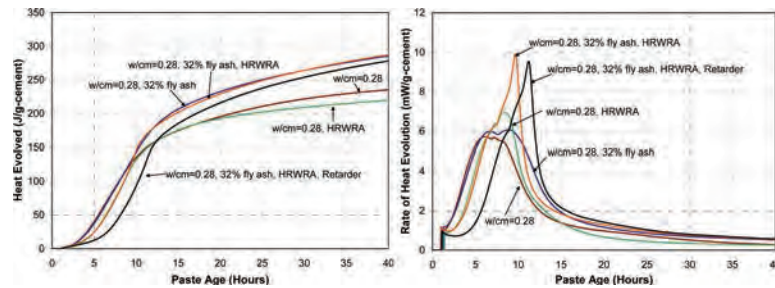


Fig. 7—Isothermal calorimetry results (23 °C, per cement mass).

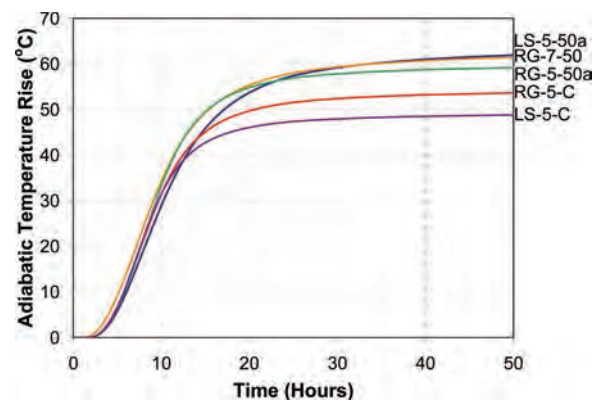


Fig. 8—Semi-adiabatic calorimetry results.

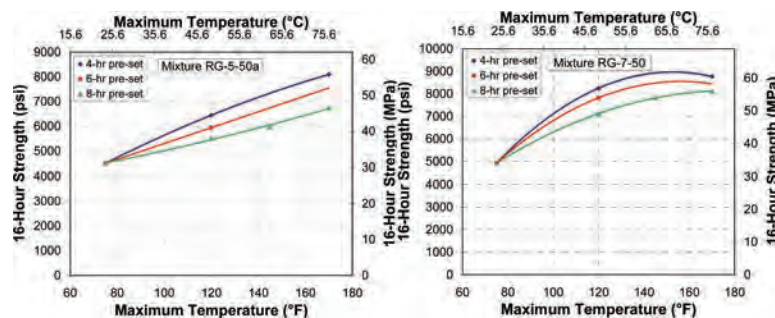


Fig. 9—Effects of temperature history on compressive strength.

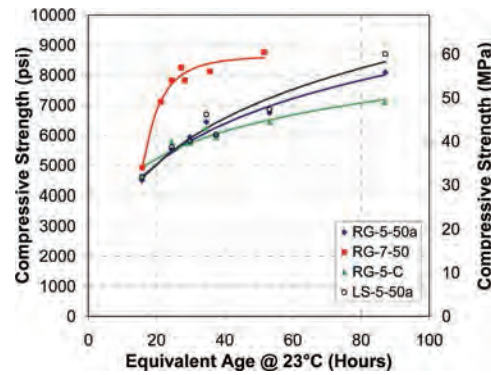


Fig. 10—Maturity relationships for 16-hour compressive strength.

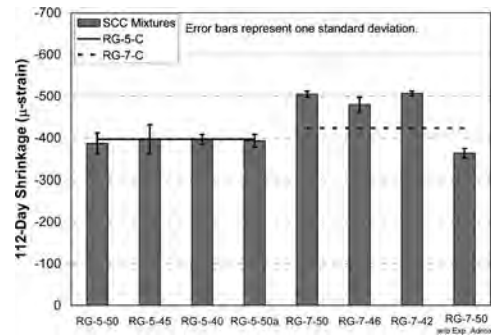


Fig. 11—Shrinkage of river gravel/natural sand aggregate set.

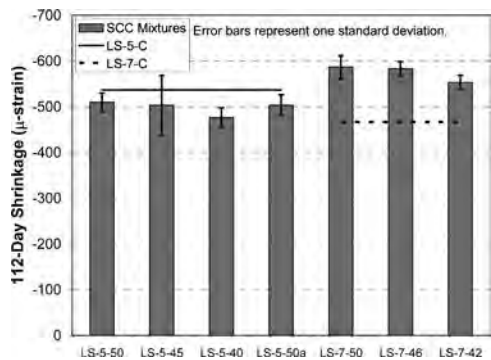


Fig. 12—Shrinkage of crushed limestone/natural sand aggregate set.

Applicability of Standard Equations for Predicting Mechanical Properties of SCC

by H.N. Atahan, D. Trejo, and M.D. Hueste

Synopsis: Self-consolidating concrete (SCC) is being implemented throughout the US. Some advantages of SCC include its ease of placement, reduced labor requirements for placing the material, reduced noise when placing, and its improved finish quality. Clearly there are benefits of using this material. However, the AASHTO LRFD specifications were developed based on material characteristics of conventional, normal strength concretes. Because of this, engineers and designers are reluctant to specify and use SCC for bridge applications, possibly making the potential benefits of this material underutilized. This research investigated compressive strength development, modulus of elasticity (MOE), modulus of rupture (MOR), and splitting tensile strength (STS) of SCC mixtures specifically designed for precast, prestressed, concrete bridge girders. The experimental program included two target 16-hour compressive strength levels and two coarse aggregate types (river gravel and crushed limestone) with varying volume fractions. The measured mechanical properties for the SCC mixtures were compared with the results of conventional concrete (CC) mixtures of similar release strengths, as well as the estimated values from the 2006 AASHTO LRFD prediction equations. Results indicate that the AASHTO equations either predict the mechanical properties of SCC fairly well or underestimate the properties of SCC.

Keywords: AASHTO LRFD specifications; modulus of elasticity; modulus of rupture; prediction equations; self-consolidating concrete; splitting tensile strength

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INTRODUCTION

The use of conventional high strength concrete for the precast prestressed concrete structural applications is routine in the concrete industry. However, this type of concrete often requires considerable labor when placing and finishing. Significant research is now underway with the objective of implementing self-consolidating concrete (SCC) for such applications throughout the world. Reduced labor requirements for placing the material, reduced noise during placement, and improved finish quality are some of the advantages of using SCC. However, some of the fundamental differences between SCC and conventional concrete (CC) mixtures make engineers reluctant to use this material. A good SCC should not segregate, should be highly flowable, and should have a good passing ability. To achieve these characteristics SCC mixtures need more paste volume than is needed for CC mixtures. Increasing the paste content results in a reduction in aggregate volume. Aggregate, specifically the coarse aggregate, can have a significant influence on the material characteristics. These material characteristics can influence the structural performance. It is unknown whether common code equations developed to predict the mechanical properties of CC are applicable to SCC. As such, research is needed to determine whether existing design equations for predicting the modulus of elasticity (MOE), modulus of rupture (MOR), and splitting tensile strength (STS) are applicable for SCC mixtures.

The MOE, MOR and STS of concretes are important engineering properties needed for the design of concrete structural elements. Accurate prediction of these properties is important and serious problems could arise if these properties are not reliably estimated during design. In this paper the research results will focus on the application of SCC for precast, prestressed structural applications. Underestimation of these characteristics can result in larger camber, increased cracking, and decreased long-term performance.

The American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD)¹ specifications provide empirical equations to predict the mechanical properties of concrete when designing structural members. However, these relationships have been developed based on the data obtained from tests conducted on CC mixtures and are valid for compressive strength values up to 15,000 psi (103 MPa). There is a clear need to identify if the design formulas being used for predicting the mechanical properties of elements containing CC are applicable to elements containing SCC mixtures. If it is determined that existing prediction equations are not applicable, new equations should be proposed. As such, this research investigated the development of compressive strength gain, the MOE, MOR and the STS of SCC mixtures and evaluated whether existing design equations for mechanical properties are applicable for members containing SCC. The influence of mixture proportion and aggregate type was also evaluated.

AASHTO LRFD PREDICTION EQUATIONS

Modulus of elasticity

The AASHTO LRFD¹ equation for predicting the MOE for concretes with unit weights between 90 and 155 lbs/ft³ (1,440 and 2,480 kg/m³) and specified compressive strengths up to 15,000 psi (103 MPa) is as follows:

$$E_c = 33 \cdot K_I \cdot w_c^{1.5} \cdot \sqrt{f'_c} \quad (\text{psi and lbs/ft}^3 \text{ units}) \quad (1a)$$

$$E_c = 0.043 \cdot K_I \cdot w_c^{1.5} \cdot \sqrt{f'_c} \quad (\text{MPa and kg/m}^3 \text{ units}) \quad (1b)$$

where E_c , K_I , w_c and f'_c represent the MOE, correction factor for the aggregate source, unit weight of concrete, and compressive strength, respectively. Because the MOE of concrete is affected by the type of aggregate utilized, AASHTO recommends using a correction factor, K_I , to better predict the MOE value. However, no specific K_I values are recommended by AASHTO for different aggregate types. AASHTO also states that unless a value has been determined by physical tests, it should be taken as 1.0. It should also be noted that this prediction equation includes the unit weight of concrete as well. It is a well known that the unit weight of concrete is closely related to the type of coarse aggregate used. The higher the density of the aggregate, the higher the unit weight of concrete. Thus, even if there were no test results available to calculate the K_I value, the close estimation of unit weight would also result in a better prediction of the MOE.

Modulus of rupture and splitting tensile strength

The AASHTO LRFD¹ specifications recommend empirical equations for predicting the MOR of a concrete member when calculating the cracking load. The allowable tensile stress is estimated based on the flexural tensile strength of the concrete measured using the MOR. The AASHTO LRFD¹ maximum allowable tensile stress limit in fully prestressed concrete components (other than segmentally constructed bridges) at the service limit state is $6.0\sqrt{f'_c(\text{psi})}$. For predicting the flexural tensile strength of concrete, AASHTO provides prediction formulas for the lower and upper bounds, and states that it is appropriate to use the lower bound when considering the service load cracking. The lower bound for predicting the MOR of concrete is recommended as follows:

$$7.6\sqrt{f'_c(\text{psi})} \quad (0.63 \cdot \sqrt{f'_c(\text{MPa})}) \quad (2)$$

where f'_c is the compressive strength of concrete up to 15,000 psi (103 MPa). When calculating the cracking moment of a member to determine the minimum reinforcement requirement, AASHTO states that the appropriate upper bound MOR value should be taken as:

$$11.7\sqrt{f'_c(\text{psi})} \quad (0.97 \cdot \sqrt{f'_c(\text{MPa})}) \quad (3)$$

The purpose of the minimum reinforcement is to ensure that the nominal moment capacity of the member is at least 20 percent greater than the cracking moment. Because the actual MOR value could be as much as 50 percent greater than the lower bound value, using the flexural strength of a member equal to the lower bound value could reduce the factor of safety¹.

In addition to the flexural strength, the tensile strength is also an important material property in determining the web-shear cracking of prestressed concrete members. The cracks can initiate in the web and propagate both upward and downward to form a complete diagonal tensile crack². In estimating the direct tensile strength of concrete, AASHTO recommends using either pullout test in accordance with ASTM C900³ or the splitting tensile strength method in accordance with AASHTO T 198⁴. The AASHTO equation for determining the tensile strength of concrete is as follows:

$$STS = 7.3\sqrt{f'_c(\text{psi})} \quad (STS = 0.59 \cdot \sqrt{f'_c(\text{MPa})}) \quad (4)$$

No upper and lower limits or maximum f'_c are recommended for the STS.

EXPERIMENTAL PROGRAM

Materials and mixture proportions

Two types of coarse aggregates (river gravel and crushed limestone) and two types of natural sand commonly available in Texas and satisfying the limits of ASTM C-33⁵ were used for both the SCC and CC mixture designs. Physical properties of the aggregates are summarized in Table 1. A locally available Type III (low alkali, high early strength) cement and class F fly ash were used. The chemical and physical characteristics of the cement and the fly ash are given in Table 2.

Mixture proportions of the SCC mixtures were obtained from another research group participating in the overall research program⁶ and are shown in Table 3. In this table (and Table 4), the initial letters of mixture names identify whether the concrete is an SCC (identified with an S) or CC (identified as CC). The following number identifies the targeted 16-hour strength (5 for 5 ksi and 7 for 7 ksi). The letter following the strength indicator identifies the aggregate type in the mixture where “G” represents river gravel and “L” represents limestone. Thus a mixture identified as “S5G” represents a SCC mixture with a 16-hour target strength of 5000 psi (35 MPa) containing river gravel coarse aggregate. To achieve sufficient workability, a commercially available polycarboxylate-based high-range water reducer (HRWR) was used in the SCC mixtures. A retarder and an accelerator were also utilized in some of the mixtures depending on their 16-hour release strengths. To maintain the stability of the SCC in its fresh state a commercially available viscosity-modifying admixture (VMA) was used for one of the mixtures containing crushed limestone. The total paste volume and the coarse aggregate to total aggregate ratios along with the chemical admixtures were optimized to satisfy the desired workability characteristics and targeted compressive strengths of the SCC. Concretes with 5000 psi (35 MPa) and 7000 psi (48 MPa) 16-hour compressive strength levels for each aggregate type were targeted.

In the design of the CC mixtures, a second type of polycarboxylate-based HRWR, which is more suitable for concrete mixtures containing lower amounts of fine materials, was used. No accelerator, retarder, or fly ash was introduced into the CC mixtures. The coarse aggregate volumes were selected based on the mixture proportions that are commonly being used by the precasters in Texas⁷. The total cement amount was limited at 700 lbs/yd³ (415 kg/m³) for these mixtures. Mixture proportions for the CC mixtures are shown in Table 4.

Mixing procedure and sample sizes

A four cubic foot maximum capacity drum mixer was used for mixing the SCC and CC mixtures. For the compression, MOE, and STS tests, 4x8 inch (100 x 200 mm) cylinder molds were used. For the MOR tests, 4x4x16 inch (100x100x400 mm) prism samples were used for all testing days. It should be noted that AASHTO T-23⁸ requires that, unless required by the project specifications, field-made flexural strength test specimens shall not have a width or depth of less than 6 inches (150mm). Due to mixture capacity limitations, beams with dimensions of 4x4x16 inch (100x100x400 mm) were evaluated in this research. The size effect factor was determined by casting 6x6x20 inch (150x150x500 mm) specimens and comparing these results with the results from 4x4x16 inch (100x100x400 mm) samples. Three beam specimens were cast from the same mixture and cured under the same conditions for each size prism and tested at 28 days. No internal or external consolidation was applied to the SCC mixtures. The CC mixtures were consolidated using a laboratory size vibration table. Testing molds were released 15½ hours after introducing water to the concrete mixture. The 16-hour test samples were transferred to the laboratory while the remaining samples were transferred to a standard curing room in accordance with AASHTO T-126⁹ and kept there until testing.

Testing procedure

The slump flow, the time for the concrete to spread to a diameter of 500 mm (T_{50}), the visual stability index (VSI), the unit weight, and the air content were evaluated for the SCC mixtures. The VSI was determined to the nearest 0.5 precision¹⁰. For the CC mixtures, the slump, the unit weight, and air content were assessed. Results from the fresh concrete testing for the SCC and CC are also summarized in Table 3 and 4, respectively. Detailed fresh characteristics of SCC mixtures can be found in reference 6.

A 500 kip (2224 kN) servo controlled hydraulically operated compressive test machine programmed to run in a load controlled mode was used for all compressive strength, MOE, and STS tests. Compressive strength tests were performed in accordance with AASHTO T-22¹¹ at the ages of 16 hours and 3, 7, 28, 56 and 91 days. MOE tests were tested in accordance with ASTM C469¹² at the ages of 16 hours and 7, 28, 56 and 91 days. The compressive strengths of MOE samples were determined using the same samples immediately after releasing the load for the MOE testing. STS tests were done in accordance with AASHTO T-198⁴. For the MOR tests, a 20 kip (90 kN) capacity test machine was used. Tests were performed in accordance with AASHTO T-97¹³. Both STS and MOR tests were performed at the ages of 16 hours and 7, 28, and 56 days. For all tests, a minimum number of 3 samples were evaluated at each testing date. Because the compressive strength data and the MOR and STS values were not measured from the same samples, the average compressive strength and MOR and STS values for each testing date were used in the analysis.

RESULTS AND DISCUSSION

To properly implement the use of SCC for precast, prestressed applications, design engineers need to know if existing AASHTO design equations are applicable for beams containing SCC. Limited work has been performed to assess the applicability of the AASHTO code equations for beams containing SCC. The following discussion presents results and provides an analysis on whether current AASHTO code equations can be used for precast, prestressed beams containing SCC. It should be noted that this research focused on concrete mixtures with high-early strength requirements typical of that required for precast, prestressed concrete plants. It is also important to note that the 16-hour strength is one of the most critical parameters for these plants to be cost-effective and high-early strength mixtures generally exceed the required ultimate compressive strengths¹⁴.

Compressive strength

Compressive strength as a function of time for the concretes containing river gravel and limestone are shown in Figure 1a and 1b, respectively. For the 5000 psi (35 MPa) release strength SCC mixtures containing river gravel, the compressive strengths changed between 5000 psi (35 MPa) and 14,000 psi (93 MPa) between the ages 16 hours and 91 days. This range was 7000 psi (48 MPa) to 17,000 psi (117 MPa) for the SCC with target release strengths of 7000 psi (48 MPa). For the crushed limestone mixtures the compressive strengths changed from 6,000 psi (40 MPa) to 15,000 psi (105 MPa) and from 7,200 psi (50 MPa) to 17,000 psi (117 MPa) for the 5000 psi (35 MPa) and 7000-psi (48 MPa) targeted release strength mixtures, respectively. In general, the 28-day strengths were between approximately 11,000 psi (76 MPa) and 16,000 psi (110 MPa) depending on the mixture proportion.

For the CC mixtures, the same 16-hour strengths were targeted. The curves representing the CC mixtures for each aggregate type and release strength group are shown in Figures 1a and b. Although the SCC and CC mixtures result in similar compressive strengths at 16 hours, the strength developments during later ages are significantly different. For example, the 28-day compressive strengths of the SCC mixtures containing river gravel were approximately 28 and 24 percent higher than that of the CC mixtures having the same aggregate for the 5000 psi (35 MPa) and 7000 psi (48 MPa) targeted release strength levels, respectively. These increases were 30 and 17 percent for the 5000 psi (35 MPa) and 7000 psi (48 MPa) SCC mixtures containing crushed limestone, respectively.

Because the 16-hour strength is a critical parameter that must be achieved in the precast plants, the same release strengths were targeted for SCC and CC mixtures. Because the mixture proportioning process for SCC and CC mixtures are quite different, making systematic comparisons is not possible. However, the differences in the compressive strengths of the SCC and CC mixtures are likely attributed to the use of the fly ash and polycarboxylate based HRWR admixtures, which likely provided better dispersion of cement and fly ash particles in SCC mixtures. This likely resulted in better hydration of these particles. The filler and pozzolanic effects of the fly ash also likely contributed to the higher compressive strength of SCC mixtures especially at later ages. Another notable point is that the CC mixtures contain considerably higher coarse aggregate amounts compared to the SCC mixtures. More stress concentrations are likely to occur as the coarse aggregate volume increases¹⁵.

Modulus of elasticity

Approximately 200 samples were included in the analysis of the MOE from the SCC mixtures. These data indicate that the best correlation between the compressive strength and the MOE is obtained using a power function of the compressive strength. Because the unit weights of the concretes were determined to have a statistically significant

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effect on the MOE of these concretes, this term was also included in the prediction model, $(w_c/150)^m$, where w_c is the unit weight of concrete and m is an exponential factor. For the materials and mixtures used in this research, the following MOE prediction models were derived:

$$MOE = 267,100 \cdot (f'_c)^{0.343} \cdot (w_c/150)^{3.3} \quad (\text{psi and lbs/ft}^3 \text{ units}) \quad (5a)$$

$$MOE = 10,150 \cdot (f'_c)^{0.343} \cdot (w_c/2400)^{3.3} \quad (\text{MPa and kg/m}^3 \text{ units}) \quad (5b)$$

where f'_c and w_c represents the compressive strength and unit weight of the concrete. The coefficient of determination (R^2) for this model is 0.84. It should be noted that this prediction formula is valid between the strength ranges of 5000 psi (35 MPa) and 17,000 psi (117 MPa). Figure 2 shows the experimental data and 95 percent prediction confidence intervals of this model. When calculating the 95 percent prediction confidence intervals, the average unit weight of the SCC mixtures (149 lbs/ft³ (2,385 kg/m³)) was used. The prediction curve recommended by AASHTO LRFD¹, assuming K_I and the unit weight of concrete as 1.00 and 149 lbs/ft³ (2,385 kg/m³), respectively, is also included in this figure. It can be seen that the AASHTO prediction formula predicts the MOE of the SCC mixtures reasonably well. However, it should be noted that because the results from both coarse aggregate types were combined, the variation in the data is increased. The increase in the variation resulted in a wider prediction confidence interval band that decreases the precision of prediction equation. For a more accurate prediction of MOE of SCC mixtures, the K_I value in AASHTO LRFD equation can be modified to 1.05 (with the unit weight of 150 lbs/ft³ (2,400 kg/m³)) and 0.95 (with the unit weight of 148 lbs/ft³ (2,370 kg/m³)) for SCC mixtures containing river gravel and limestone, respectively. The effect of coarse aggregate type on MOE of SCC mixtures is shown in Figure 3.

The CC mixture data obtained from the research are also included in Figure 3. As seen in this figure, the effect of the differences in mixture characteristics between SCC and CC on the MOE is notable. Because the CC mixtures contain substantially higher coarse aggregate volumes compared to SCC mixtures, they exhibit significantly higher MOE values for both coarse aggregate types. However, when the river gravel was utilized as coarse aggregate, the difference between the MOE of SCC and CC mixtures was more significant compared to limestone mixtures. The absorption capacities of the crushed limestone and river gravel used in this research are 1.43 and 0.78 percent, respectively, indicating that the limestone has a higher porosity than the river gravel. It is thought that the stiffness of the mortar phase and the limestone is likely closer than the stiffness between the mortar phase and the river gravel. As such, although there is a significant difference in coarse aggregate volumes of the SCC and CC mixtures containing limestone, its effect on MOE is likely reduced.

Modulus of rupture

Linear regression analysis was used to predict the MOR of the SCC mixtures using the compressive strength as a variable. However, prior to performing this analysis these data had to be converted because beam size has a significant influence on the MOR value. As already noted, limitations on the mixer size used in this research resulted in casting smaller prisms than that specified in AASHTO T-23⁸. To determine the correlation factor between 4x4x16 inch (100x100x400 mm) and 6x6x20 inch (150x150x500 mm) specimens, a separate study was performed. Samples from this study were evaluated for MOR at 28 days. Figure 4 shows the relationship between the MOR results of different size beams as well as the regression equation. Fifty-four beams, three for each of 18 data points (14 SCC and 4 CC mixtures), were tested. From Figure 4 it can be seen that the relation is linear and the correlation of determination (R^2) is 0.82.

In calculating the MOR of a beam a linear stress distribution throughout the cross-section is presumed. However, in reality, at a certain distance from the tensile face of the beam (i.e., boundary layer) the stress is reduced due to distributed pre-cracking resulting from the materials having a heterogeneous microstructure¹⁶. According to Bazant and Li¹⁶, the boundary layer, l_f , can be approximated as a material property related to the maximum aggregate size. Making this assumption and using the theory of quasi-brittle fracture Bazant and Li¹⁶ derived the following equation:

$$(f_r / f'_t) = 1 + \frac{2}{h} \cdot l_f \quad (6)$$

where f_r , f_t' , and h are the MOR, direct tensile strength of the concrete, and beam depth. Both coarse aggregates used in this research have the same maximum size. Accordingly, all the beam samples are presumed to have the same value for the boundary layer. Based on this simplified equation, as the beam size increases the MOR decreases. It can be seen that the data obtained for comparing beam size also shows this same relationship. In this paper it is assumed that this relation is valid for compressive strength ranges from 5000 psi (35 MPa) to 17,000 psi (117 MPa) even though testing was performed on samples exhibiting compressive strength values only from 9500 psi (66 MPa) to 15,500 psi (107 MPa).

This research found that the relationship between the MOR and the compressive strength is not linear (as is the case with standard prediction equations). As such, a logarithmic transformation was used to transform the response variable (i.e., the MOR). The MOR prediction model for all data was determined to be as follows:

$$MOR = 375 \cdot 10^{3.7 \cdot 10^{-5} \cdot f_c'} \quad (\text{psi units}) \quad (7a)$$

$$MOR = 2.59 \cdot 10^{5.3 \cdot 10^{-3} \cdot f_c'} \quad (\text{MPa units}) \quad (7b)$$

where f_c' is the compressive strength of the SCC mixtures. The coefficient of determination for this model is $R^2=0.92$. The prediction formula is valid for compressive strength ranges from 5000 psi (35 MPa) to 17,000 psi (117 MPa). The relationship between the compressive strength and the MOR of the SCC mixtures is shown in Figure 5. Using this model and its 95 percent prediction confidence intervals, the AASHTO LRFD prediction equation was compared with the SCC data. The MOR data obtained from the CC mixtures were also included in this figure along with the data reported by Hueste et al.⁷ It should be noted that all results from the Hueste et al.⁷ data were obtained using 6x6x20 inch (150x150x500 mm) beams. The MOR values obtained from the SCC mixtures exhibited slightly lower results when compared with the CC mixtures.

Two prediction formulas are recommended by the AASHTO LRFD¹ specification for the upper and lower bound MOR values. However, within the limits of the materials and mixtures used in this study, the best-fit curve generated using $11.7 \cdot \sqrt{f_c'(psi)}$ is considerably higher than the upper bound of the 95 percent prediction confidence interval band up to a compressive strength value of approximately 13,000 psi (90 MPa). In the same manner the recommended lower bound ($7.6 \cdot \sqrt{f_c'(psi)}$) also does not seem to be representative of the SCC data. Although the MOR is reasonably well predicted for compressive strength values between 5000 (35 MPa) and 10,000 psi (69 MPa) using the AASHTO equations, these equations underestimate the actual MOR for SCC values above this range.

Splitting tensile strength

Simple linear regression analysis was performed using the data collected in this study to predict the STS of SCC mixtures using the compressive strength values. The MOR prediction model from this research is as follows:

$$STS = 490 \cdot 10^{2.1 \cdot 10^{-5} \cdot f_c'} \quad (\text{psi units}) \quad (8a)$$

$$STS = 3.39 \cdot 10^{3.0 \cdot 10^{-3} \cdot f_c'} \quad (\text{MPa units}) \quad (8b)$$

The coefficient of determination of this model is $R^2=0.59$. The prediction formula is valid between the compressive strength ranges of 5000 psi (35 MPa) to 17,000 psi (117 MPa). Using this model and its 95 percent prediction confidence intervals, the AASHTO prediction equation, $7.3 \cdot \sqrt{f_c'(psi)}$, was compared with the SCC data.

The relationship between the compressive strength and the STS for SCC mixtures along with the AASHTO prediction equation can be seen in Figure 6. This equation predicts the STS of SCC mixtures relatively well, however, the AASHTO model tends to be a bit conservative. The data points from high-strength CC mixtures reported by Hueste et al.⁷ were also included in this figure. It can be seen from this figure that the STS of the SCC mixtures tends to be slightly higher than the STS of the CC mixtures. It is believed that this is attributed to the improved microstructural characteristics of the SCC mixtures. Utilization of new generation, HRWR admixtures likely results in better dispersion of the cement and fly ash particles making the structure more homogeneous. As a

result of this refinement, both the strength of the paste and the bond characteristics between the coarse aggregate and paste are likely improved. Similar results have been reported in the literature¹⁷.

CONCLUSIONS

Based on materials used in this research and the test results from the SCC and CC mixtures specifically designed for precast prestressed structural applications ranging from 5000 psi (35 MPa) to 17,000 psi (117 MPa) and having densities in the range from 146 to 154 lbs/ft³ (2,340 to 2,465 kg/m³), the following conclusions can be drawn.

1. Although the SCC and CC mixtures resulted in similar compressive strengths at 16 hours, the strength developments of these concretes during later ages were significantly different. For the same targeted release strength, SCC mixtures exhibit significantly higher compressive strengths compared to CC mixtures.
2. Because the CC mixtures contain substantially higher coarse aggregate volumes compared to SCC mixtures, they exhibited significantly higher MOE results for both coarse aggregate types. The difference was more significant when river gravel was utilized compared to limestone aggregate.
3. The coarse aggregate type is a significant factor in determining the MOE of both SCC and CC mixtures.
4. The MOE prediction equation recommended by AASHTO LRFD, assuming the correction factor, K_1 , and unit weight of concrete is 1.00 and 149 lbs/ft³ (2,385 kg/m³), respectively, estimated the MOE of SCC mixtures reasonably well.
5. The MOR values obtained from SCC mixtures exhibited slightly lower results compared to CC mixtures.
6. The AASHTO LRFD equation for predicting the lower bound MOR values predicted the actual values for SCC mixtures with compressive strengths between 5000 psi (35 MPa) and 10,000 psi (69 MPa) reasonable well. However, for higher compressive strengths it underestimated the MOR values. A modification for the lower bound may be appropriate.
7. The AASHTO LRFD equation recommended for the upper bound of MOR is considerably above the 95 percent prediction confidence interval band up to compressive strength values of approximately 13,000 psi (90 MPa), and a modification may be appropriate.
8. The STS of SCC mixtures tends to be slightly higher than the STS of CC mixtures.
9. The AASHTO LRFD equation predicted the STS of SCC mixtures relatively well and is likely conservative.

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Table 1 Physical properties of fine and coarse aggregates

Physical properties	Aggregate Type			
	River gravel	Sand #1	Crushed limestone	Sand #2
Specific gravity	2.61	2.58	2.59	2.60
Absorption capacity, %	0.78	0.54	1.43	0.56
Fineness modulus	6.52	2.72	6.58	2.89

Table 2 Chemical and physical properties of cement and fly ash

Chemical composition	Cement	Fly Ash	Physical Property	Cement	Fly Ash
SiO ₂ , %	20.6	52.5	Fineness, ft ² /lbs (m ² /kg)	2,630 (539)	-
Al ₂ O ₃ , %	4.9	21.8	Setting Time:		
Fe ₂ O ₃ , %	3.4	4.9	Initial, min	110	-
CaO, %	64.1	13.9	Final, min	210	-
MgO, %	0.8	2.00	Compressive Strength		
SO ₃ , %	3.5	0.79	1 day, psi (MPa)	3,495 (24.1)	-
Total Alkalies, % (*)	0.50	0.81	3 day, psi (MPa)	4,730 (32.6)	-
Free Lime, %	1.5	-	7 day, psi (MPa)	5,670 (39.1)	-
C ₃ S, %	56.6	-	28 day, psi (MPa)	6,785 (46.8)	-
C ₂ S, %	16.3	-	Specific Gravity	3.15	2.33
C ₃ A, %	7.2	-	Strength Act. Index, %		
C ₄ AF, %	10.3	-	7 day	-	73.6
LOI, % (**)	2.1	1.05	28 day	-	82.0

*Na₂O + 0.658K₂O

**Loss on ignition

Table 3 Mixture proportions and fresh characteristics of SCC mixtures

Coarse Aggregate	River gravel								Limestone					
Release strength	5000 psi (34.5 MPa)					7000 psi (48.3 MPa)			5000 psi (34.5 MPa)			7000 psi (48.3 MPa)		
Mixture Name	S5G 1	S5G 2	S5G 3a	S5G 3b	S5G 3c	S7G 4	S7G 5	S7G 6	S5L 3a	S5L 3b	S5L 3c	S7L 4	S7L 5	S7L 6
Mixture proportions														
Cement, lb/yd ³ (kg/m ³)	624 (370)	646 (383)	633 (376)			720 (427)			640 (380)			720 (427)		
Fly Ash, lb/yd ³ (kg/m ³)	156 (93)	239 (142)	298 (177)			180 (107)			426 (253)			180 (107)		
Water, lb/yd ³ (kg/m ³)	252 (150)	260 (154)	255 (152)			208 (123)			288 (171)			225 (133)		
Coarse lb/yd ³ (kg/m ³)	1,461 (867)	1,535 (911)	1,374 (815)	1,511 (897)	1,649 (978)	1,414 (839)	1,527 (906)	1,641 (973)	1,259 (747)	1,385 (822)	1,511 (896)	1,394 (827)	1,505 (893)	1,617 (959)
Sand lb/yd ³ (kg/m ³)	1,456 (864)	1,251 (742)	1,368 (812)	1,232 (731)	1,095 (650)	1,408 (836)	1,296 (769)	1,184 (702)	1,264 (750)	1,138 (675)	1,011 (600)	1,399 (830)	1,287 (764)	1,175 (697)
HRWR, oz/ft ³ (kg/m ³)	74 (3.1)	81 (3.4)	92 (3.8)	80 (3.3)	82 (3.4)	140 (5.8)	117 (4.8)	108 (4.5)	60 (2.4)	58 (2.4)	58 (2.4)	108 (5.8)	117 (4.8)	108 (4.5)
Retarder, oz/ft ³ (kg/m ³)	27 (1.1)	27 (1.1)	25 (1.0)	25 (1.0)	25 (1.0)	-	-	-	26 (1.1)	26 (1.1)	26 (1.1)	-	-	-
Accelerator, oz/ft ³ (kg/m ³)	-	-	-	-	-	578 (29.8)			-	-	-	578 (29.8)		
VMA, oz/ft ³ (kg/m ³)	-	-	-	-	-	-	-	-	-	-	-	-	-	4 (0.2)
Fresh characteristics														
Slump flow, Inches (mm)	27.5 (700)	27.5 (700)	27.5 (700)	28.5 (725)	28.0 (710)	28.0 (710)	28.0 (710)	28.0 (710)	29.0 (735)	28.5 (725)	28.5 (725)	29.0 (735)	29.5 (750)	29.0 (735)
Air, %	1.4	1.5	1.4	1.6	1.4	1.1	0.8	0.8	1.1	1.0	0.9	1.3	1.2	1.1
Unit weight, lbs/ft ³ kg/m ³	148.6 (2,377)	148.3 (2,373)	148.2 (2,371)	148.1 (2,371)	148.1 (2,371)	151.0 (2,415)	151.6 (2,425)	151.6 (2,425)	146.7 (2,345)	146.7 (2,347)	147.0 (2,351)	149.6 (2,395)	150.0 (2,400)	150.0 (2,400)
T ₉₀ , sec.	2.3	2.4	2.7	2.3	2.0	7.1	7.0	6.9	2.7	2.9	3.2	4.8	4.5	6.9
VSI	0.5	0.5	0.5	1.0	1.0	0.5	0.5	0.5	1.0	0.5	1.0	1.0	1.0	1.0

Table 4 Mixture proportions and fresh characteristics of CC mixtures

Coarse aggregate:	River Gravel		Limestone	
Targeted Strength @ 16 hrs	5000psi (34.5MPa)	7000 psi (48.3 MPa)	5000 psi (34.5 MPa)	7000 psi (48.3 MPa)
Mixture Name	CC5-G	CC7-G	CC5-L	CC7-L
Mixture proportions				
Cement, lbs/yd ³ (kg/m ³)	625 (371)	700 (415)	600 (356)	680 (403)
Water, lbs/yd ³ (kg/m ³)	225 (134)	200 (119)	252 (149)	224 (133)
Coarse aggregate, lbs/yd ³ (kg/m ³)	1,935 (1,148)	1,935 (1,148)	1,750 (1,039)	1,752 (1,039)
Sand, lbs/yd ³ (kg/m ³)	1,232 (731)	1,232 (731)	1,380 (820)	1,382 (820)
HRWR, oz/yd ³ (kg/m ³)	56 (2.6)	91 (4.3)	37 (1.5)	68 (2.8)
Fresh characteristics				
Slump, inches (mm)	7.5 (190)	6.5 (165)	8.0 (200)	8.0 (200)
Air, %	1.2	1.1	1.3	1.5
Unit weight, lbs/ft ³ kg/m ³	151.9 (2,430)	154.1 (2,465)	150.0 (2,400)	151.9 (2,430)

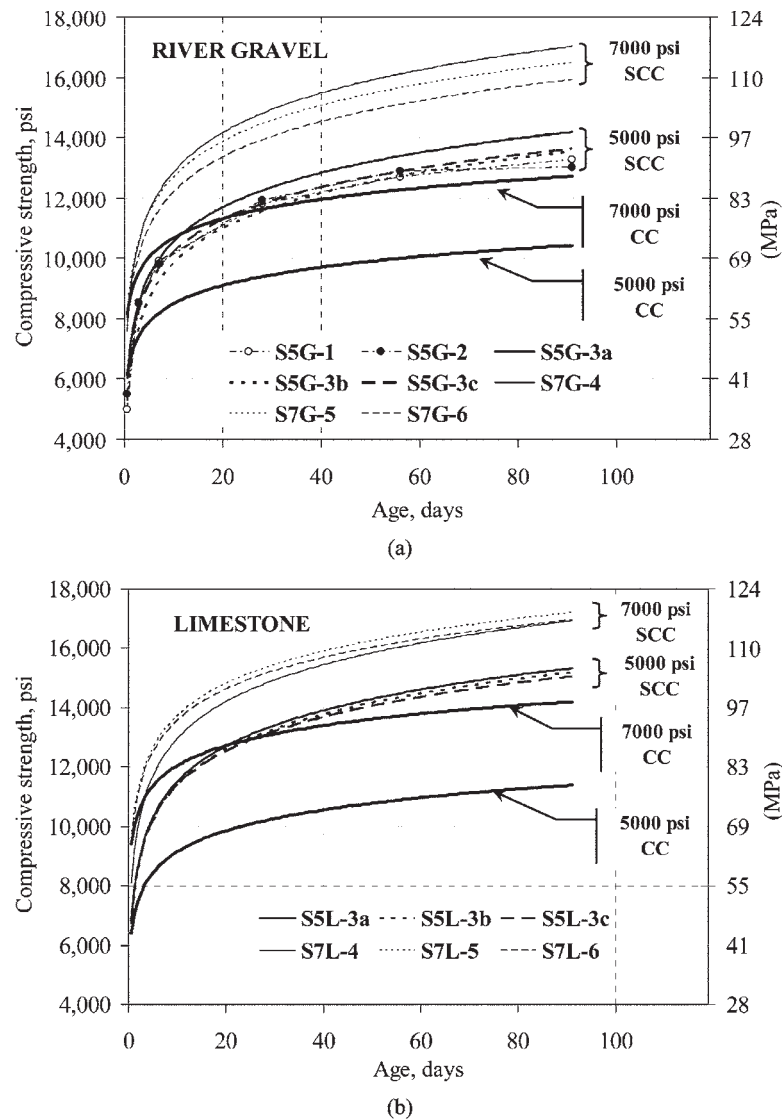


Fig. 1—Compressive strengths of SCC and CC mixtures: (a) river gravel; and (b) limestone.

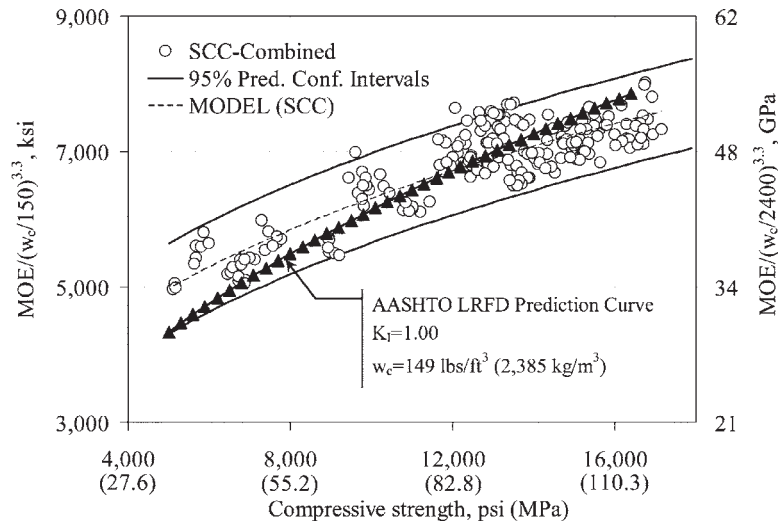


Fig. 2—AASHTO LRFD prediction curve for MOE and its comparison with SCC model.

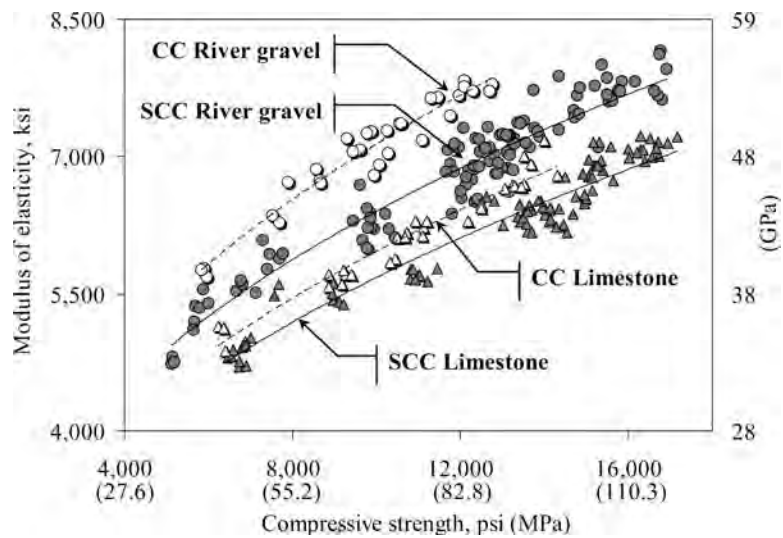


Fig. 3—Effect of coarse aggregate type on MOE of SCC and CC mixtures.

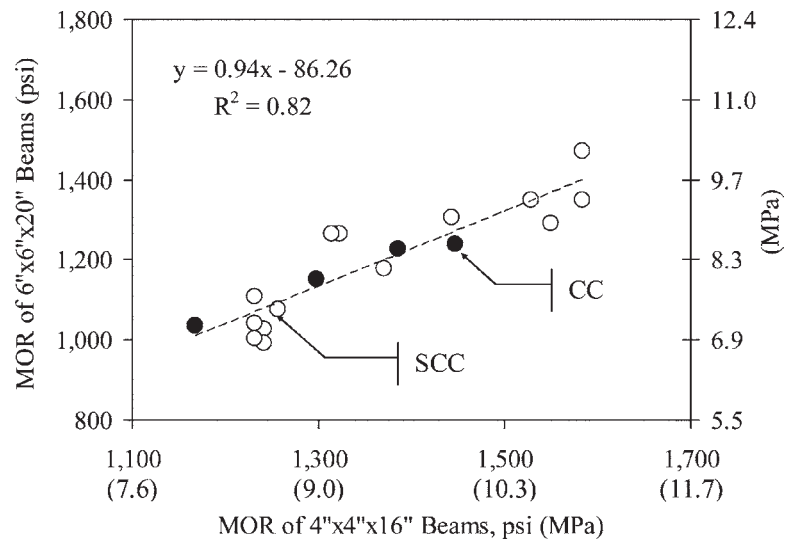


Fig. 4—Relationship between the MOR results of different size beams.

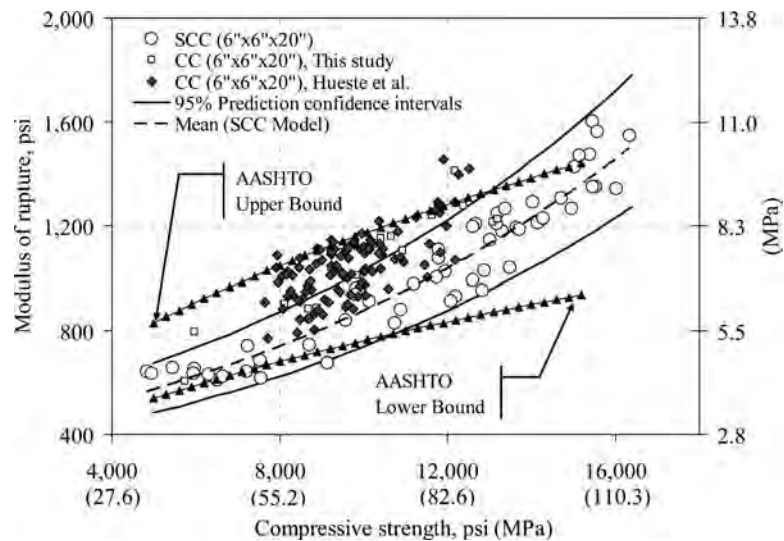


Fig. 5—MOR prediction model for SCC and its comparison with AASHTO equations and CC data.

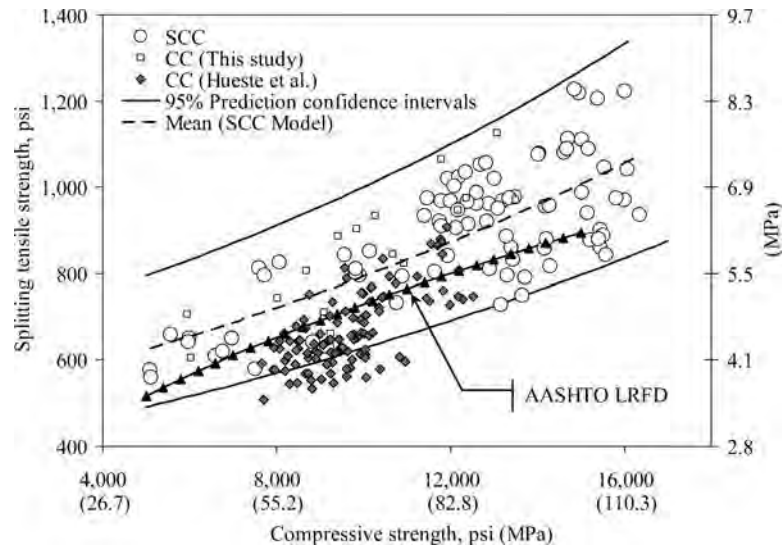


Fig. 6—STS prediction model for SCC and its comparison with AASHTO equation and CC data.

Effect of Admixture Combination on Top-Bar Effect of Highly Flowable and Self-Consolidating Concrete Mixtures

by K.H. Khayat, E.K. Attiogbe, and H.T. See

Synopsis: This paper summarizes a testing program undertaken to evaluate the uniformity of bond strength between concrete and reinforcing bars positioned at various depths of experimental wall elements. In total, four self-consolidating concrete (SCC) mixtures and three conventional flowable mixtures were prepared with different combinations of viscosity-modifying admixtures and high-range water reducers. The concrete mixtures were used to cast experimental wall elements measuring 1.54 m in height, 1.1 m in length, and 0.2 m in width. Two of the walls were steam-cured, while the remaining four elements were air-cured. Each wall had 16 reinforcing bars, four per row positioned at four levels, that were subjected to pullout tests at 1 and 28 days of age.

The concrete mixtures were prepared with Type III cement, 20% Class F fly ash substitution, and a low w/cm of 0.37, which is typical of structural precast concrete construction. The targeted 1-day compressive strength was 40 MPa. Uniform distribution of in-situ compressive strength and adequate bond to the reinforcing bars were obtained with relatively small variations along the experimental wall elements. The 1- and 28-day top-bar effect ratios varied between 1 and 1.4 for the majority of the test results. These values were lower for the air-cured mixtures compared to the steam-cured mixtures. The top-bar effect is shown to be sensitive to the type of VMA used in the SCC.

Keywords: bond; reinforcing bars; self-consolidating concrete; top-bar effect; viscosity-modifying admixture

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INTRODUCTION

Casting concrete with high flowability can increase the risk of bleeding, segregation, and surface settlement. This can in turn weaken the aggregate-cement paste interface, which can reduce mechanical properties. Bleeding can increase the porosity of the interface under horizontally positioned reinforcing bars (Zilveti et al. 1985). The surface settlement of fresh concrete can further reduce bond strength (Menzel 1952; Welch and Patten 1962; Khayat 1998). Ensuring adequate stability is especially critical in deep structural elements. As in the case of conventional concrete, highly flowable concrete can be proportioned to exhibit adequate stability, limited top-bar effect, and uniform in-place distribution of mechanical properties (Khayat et al. 1997; Sonebi et al. 2001).

The main objective of this study is to evaluate the uniformity of bond strength between concrete and horizontally positioned reinforcing bars along experimental wall elements cast with highly flowable and self-consolidating concrete (SCC) mixtures. The study reported here is a follow-up of a similar investigation carried out by the authors (Khayat et al. 2003) to investigate the effect of SCC mixture composition on bond characteristics of prestressing strands. In both investigations, the performance of concrete mixtures made with different types of high-range water reducers (HRWRs) and viscosity-modifying admixtures (VMAs) was investigated. Similarly, the effect of curing on the development of mechanical properties and bond was evaluated.

CONCRETE MIXTURES AND MATERIAL PROPERTIES

Two highly flowable concrete mixtures with slump consistency of 210-230 mm were prepared with HRWR-1 for the reference air- and steam-cured mixtures. Four SCC mixtures with corresponding slump flow values of 650-700 mm, respectively, were tested. As shown in Table 1, Mixtures 1 and 2 incorporated a polycarboxylate-type HRWR (HRWR-1) and no VMA. HRWR-1 is designed to provide normal-set characteristics to concrete mixtures. Mixture 3 was prepared with HRWR-1 and a cellulose-based VMA (VMA-1). Mixtures 4, 5, and 6 were proportioned with a newer type of polycarboxylate HRWR (HRWR-2) that provides high-early strength with minimal or no steam curing. Mixture 4 was prepared with VMA-1, Mixture 5 with a synthetic-based VMA (VMA-2), and Mixture 6 without any VMA. The specimens cast with Mixtures 2 and 3 were steam-cured, whereas the remaining mixtures were left in the formwork for one day before demoulding and air-curing in the laboratory until the age of 28 days.

As indicated in Table 2, the concrete mixtures were proportioned with 475 kg/m³ of cementitious materials containing Type III cement and 20% substitution with Class F fly ash. A low *w/cm* of 0.37 was used, which is typical of structural precast concrete construction. Riverbed siliceous sand and crushed dolomitic limestone aggregate of 14 mm top size were used and had specific gravities of 2.69 and 2.74, respectively, and absorption values of 0.4% and 1.2%, respectively. Deformed reinforcing bars of 20-mm nominal diameter and approximately 400-MPa yield strength were used to evaluate the pullout bond between the steel and concrete.

CASTING OF EXPERIMENTAL WALL ELEMENTS

Experimental wall elements measuring 2.15 m in length, 1.54 m in height, and 0.2 m in width were constructed (Fig. 1) using plywood. The formwork was divided vertically in the middle for casting two elements at a time. Each wall had 16 reinforcing bars, grouped four per row and positioned at four levels. The spacing between adjacent bars was 200 mm.

A rigid plastic sheathing was tightly attached to the outer end of each bar near the loaded end to prevent bond to concrete near the reaction point and reduce confining stresses along the bonded region. The remaining exposed length of the bar (50 mm) was cleaned to ensure adequate bond.

Concrete batches of 375 L were prepared for casting of the wall elements. The concrete was placed in three lifts and consolidated using an internal poker vibrator in the case of the flowable concrete, and in two lifts without any mechanical consolidation for the SCC. The air-cured elements were left in the formwork for 22 hours in the laboratory along with reference cylinders, after which they were allowed to air-cure until the time of testing. The ambient temperature during that period varied between 21 and 25°C and the relative humidity between 50% and 70%. In the case of steam curing, the wall along with the formwork was maintained in a special temperature-controlled environment of 100% relative humidity. The targeted steam-curing schedule was as follows: (i) ambient temperature for 2 hours after casting, (ii) temperature raised over 3 hours to 60°C, (iii) temperature maintained at 60°C for 6 hours, and (iv) temperature decreased over 5 hours to ambient temperature (21–23°C).

TEST METHODS

The slump consistency, unit weight, and air contents were determined. The caisson filling capacity test (Yurugi et al. 1993) was used to evaluate the restricted deformability of the concrete (Fig. 2). The test consists of casting concrete in a transparent box measuring 300 x 500 x 300 mm and fitted with closely spaced bars. The concrete is introduced from a hopper at a constant rate until the concrete reaches a height of 220 mm in the non-reinforced section of the box. The concrete flows under its own weight among the copper tubes until the flow is stabilized. The filling capacity is calculated as the ratio of the area covered by the propagated concrete to the maximum potential area. The static stability was evaluated by determining the surface settlement of the concrete cast in a PVC column measuring 200 mm in diameter and 700 mm in height (Fig. 2). The settlement is monitored using a dial gage fixed on top of a thin plate placed at the upper surface of the concrete (Manai, 1995).

The resistance of SCC to segregation was also evaluated using the column segregation test (Assaad et al. 2004) which became the basis for ASTM C 1610. The test consists of casting concrete in a column measuring 640 mm in height and then determining the variations in relative concentration of coarse aggregate at four sections along the column. A 200-mm diameter PVC tube divided into four sections is used. A leak-free joint is provided between the sections that can be easily uncoupled enabling the flow out of concrete onto a special tray. The concrete is weighed and washed out on a 4.75 mm sieve to retain coarse aggregate. The coefficient of variation of the distribution of coarse aggregate is used to calculate a segregation index.

Several cylinders measuring 100 mm in diameter and 200 mm in height were prepared to determine mechanical properties at 1 and 28 days. These reference cylinders were subjected to the same curing conditions as the corresponding wall sections. A hydraulic jack with a 135-KN capacity was used for the pullout test. The pullout load was applied gradually and recorded using a load cell. The net slip of the bar was measured using an L.V.D.T. connected to the unloaded end of the bar.

Following the pullout testing at 28 days, 16 cores measuring 95 mm in diameter and 200 mm in length were extracted at four levels corresponding to those of the anchored bars. The compressive strength and elastic modulus (ASTM C 469) of cores were compared to those obtained from reference cylinders. The 28-day bond strengths of reinforcing bars positioned near the bottom of the wall elements to bond strength of bars at different heights were normalized by the square root of *in-place* compressive strength values.

TEST RESULTS AND DISCUSSION

The fresh and mechanical properties of the tested mixtures are summarized in Table 3. The four SCC mixtures proportioned with Type III cement, 20% fly ash, and *w/cm* of 0.37 had high levels of filling capacity of 85% ± 5% and high static stability with maximum surface settlement limited to 0.10%. Static stability of SCC determined with the segregation column showed that Mixtures 3 and 4 made with VMA-1 were highly stable compared to the non-VMA SCC (Mixture 6), with segregation coefficients of 4.6% and 3.8% versus 9.3%.

The six tested mixtures exhibited considerable loss of consistency given the type of cement used and the relatively low water content. Mixture 4 containing the HRWR-2 and VMA-1 had the highest degree of fluidity loss. The slump flow values at the beginning and end of casting (7 minutes later) were 700 and 640 mm for one section of the wall and 715 to 620 mm over 8 minutes for the second section of the wall. Other mixtures exhibited approximate slump flow loss of 30 to 50 mm within 10 minutes. Mixture 6 made with the HRWR-2 and no VMA had the lowest

demand of HRWR compared to Mixtures 4 and 5 containing the same HRWR and VMA-1 and VMA-2, respectively. The HRWR demand was slightly lower for Mixture 4 containing VMA-1 and HRWR-2 than that of Mixture 3 made with the same VMA and HRWR-1.

Peak temperatures in wall elements subjected to air-drying were 55 to 60°C compared to approximately 74°C for steam-cured concrete. The spread between the peak hardened temperatures and that of the fresh concrete for air-dried and steam-cured wall elements were approximately 35 and 50°C, respectively.

Typical variations in temperature of air-cured and steam-cured concretes corresponding to Mixtures 6 and 3, respectively, are plotted in Fig. 3. The onset of sharp increase in temperature was limited to 5 ± 1 hour. The onset and extent of heat rise were lower in the case of Mixture 4 prepared with HRWR-2 and VMA-1 than those of Mixtures 1 and 6, yet there was no adverse effect on the 1-day compressive strength of the former mixture (Table 3).

For the air-cured concrete Mixtures 1, 4, and 6, the onset of sharp increase in temperature corresponded to approximately 4, 6, and 4 hours, respectively, and the peak temperatures were 60, 54, and 60°C, respectively. The spreads between the peak and casting temperatures for these walls were approximately 36, 31, and 34°C, respectively.

In the case of steam-cured concretes, peak temperatures in walls cast with the highly flowable concrete and SCC (Mixtures 2 and 3) were 76 and 72°C, respectively. The spread between peak and casting temperatures were 50 and 49°C, respectively.

Mechanical properties

As shown in Table 3 that summarizes the mechanical properties obtained from the testing of reference samples, the coefficient of variation (C.O.V.) of compressive strength results varied between 0.8% and 2.9% at 1 day and 1% and 3.5% at 28 days, indicating excellent reproducibility of the tests. Comparable 1-day compressive strengths of 41.0 ± 0.6 MPa were obtained for SCC mixtures regardless of the curing condition and admixture combination.

In the case of highly flowable concrete, the steam-cured Mixture 2 had greater 1-day strength than that of the air-dried concrete (Mixture 1) (42 vs. 37 MPa). On the other hand, greater compressive strength was obtained after 28 days for Mixture 1 compared to Mixture 2 (52 vs. 56 MPa). The air-cured SCC mixtures developed higher 1-day compressive strength than the air-cured highly flowable concrete. Mean compressive strengths of Mixtures 4, 5, and 6 varied between 40 and 42 MPa compared to 37 MPa for Mixture 1. No significant differences were noted in the modulus of elasticity results.

After 28 days of age, Mixtures 4, 5, and 6 developed compressive strengths ranging between 56 and 59 MPa compared to 56 MPa for Mixture 1. The elastic modulus of the former mixtures was 34 GPa compared to 38 GPa obtained for Mixture 1. In the case of the SCC, Mixture 3 that was steam-cured containing HRWR-1 and VMA-1 developed substantially lower 28-day compressive strength and elastic modulus values than those obtained for the air-cured SCC containing HRWR-2 (Mixture 4), with a 28-day compressive strength of approximately 51 vs. 56 MPa and elastic modulus of 32 vs. 34 GPa. The substitution of the HRWR-1 by HRWR-2 yielded similar compressive strength at one day (40 vs. 42 MPa) but greater 28-day strength. The substitution of the VMA-1 by VMA-2 (Mixtures 4 and 5) had no effect on strength development.

The 28-day in-place compressive strength, modulus of elasticity, and Poisson's ratio of core samples at various heights are summarized in Table 4. Mixture 1 had the lowest in-place compressive strength whereas Mixture 4 had the highest overall strength. While the reference cylinders showed a greater 28-day compressive strength for the air-cured Mixture 1 compared with the steam-cured Mixture 2 (Table 3), the 28-day in-place strength for Mixture 1 was lower than that for Mixture 2 (Table 4). This is not surprising given that cylinder strength and in-place strength are not always in agreement.

The distribution of in-place compressive strength values of core samples at various heights is shown in Table 4 and plotted in Fig. 4; the values are plotted against those obtained for the reference cylinders. In general, the distribution of compressive strength was $100\% \pm 6\%$ of strength results at the bottom, which translates into approximately ± 3 MPa. For the majority of the mixtures, greater in-place compressive strengths were obtained at mid-height with a reversal of strength towards the top.

The in-place compressive strength at 28 days was substantially higher for Mixture 4 compared to Mixture 3. For the highly flowable concrete (Mixture 1), the 28-day in-place compressive strength was approximately 85% of control cylinders. This is typical for core samples tested in compression in a perpendicular direction to the casting position.

On the other hand, for the steam-cured highly flowable concrete (Mixture 2), the in-place strength was generally greater than the strength of the reference cylinders. For the steam-cured SCC (Mixture 3), the 28-day in-place strength ranged between 95% and 106% of the reference cylinders. For the air-cured SCC, Mixture 4 had a greater relative compressive strength, ranging between 101% and 104%, compared to 86% to 96% in the case of Mixtures 5 and 6. Therefore, compared to Mixture 1, the SCC mixtures developed greater in-place compressive strength, thus demonstrating the self-compactibility of the concrete.

Bond strength

An example of the pullout load and free-end slip results obtained at various heights along the wall element cast with the highly flowable, air-cured concrete is shown in Fig. 5. The figure plots the mean results obtained from the pullout of two reinforcing bars at four levels along the wall that are positioned at distances of 12, 55, 98, and 142 cm from the bottom. The top-bar effect refers to the ratio of bond strength of the bottom reinforcing bar to that of the top bar. The variations of the top-bar effect along the height of the various elements that were determined at 1 and 28 days of age are plotted in Fig. 6 and 7, respectively. The latter plot presents the normalized top-bar effect where the ratio of the bond strength is divided by the square root of compressive strength determined from core samples at heights corresponding to the tested reinforcing bars after 28 days. In general, all tested mixtures developed adequate bond with relatively small variations in bond strength along the 150-cm-high experimental wall elements. The top-bar effect varied between 1.00 and 1.65, with the majority of the cases limited to 1.40.

The top-bar ratios obtained for the reinforcing bars at 28 days are compared in Fig. 8 to design recommendations offered by Jirsa and Breen (1981). Such recommendations were given for the variation of the top-bar factor with depth of concrete below spliced or anchored reinforcing bars for mixtures of various slump consistency levels. The results show that the two tested highly flowable concrete mixtures lie well within the design recommendations offered for concrete with slump consistency of 50 and 100 mm. For the majority of cases, the four SCC concrete mixtures can develop top-bar factors similar to those of concrete with slump of 100 to 150 mm cast with internal vibration. These comparisons illustrate the highly stable nature of the optimized SCC mixtures tested in this investigation.

Steam-curing vs. air-drying – In general, the top-bar effect was lower for the air-cured highly flowable concrete (Mixtures 1 and 1R) compared to the steam-cured concrete (Mixture 2). For the flowable concrete, similar bond strengths with reinforcing bars were obtained for Mixture 1R (air-cured) and Mixture 2 (steam-cured) at 1 day, with the latter exhibiting greater strength at mid-height. The top-bar effect ratio at 1 day was lower for the steam-cured concrete compared to air-cured concrete (Fig. 6). The maximum top-bar effect ratio for the reinforcing bars in the case of Mixture 2 was 1.28 compared to 1.33 for the wall cast with the air-cured Mixture 1R. After 28 days of age, the normalized top-bar effect ratio for the steam-cured Mixture 2 was higher than that for the air-cured Mixture 1R (Fig. 7). The maximum normalized top-bar effect ratios for Mixtures 1R and 2 were 1.25 and 1.40, respectively.

In comparing the bond strength of steam-cured flowable concrete to steam-cured SCC (Mixture 2 vs. 3), it can be noted that at 1 day of age, the former concrete had greater bond strength than the SCC at mid-heights and similar values at the top and bottom reinforcements. The vibrated concrete had more homogenous distribution of bond strength along the height than the SCC. The maximum top-bar effect values for reinforcing bars in the vibrated flowable concrete and SCC mixtures at 1 day were 1.28 and 1.45, respectively (Fig. 6). At 28 days, the normalized top-bar effect was similar for both mixtures, except at mid-height where the flowable mixture exhibited a lower top-bar effect ratio. The maximum top-bar effect ratios for reinforcing bars in Mixtures 2 and 3 were 1.40 and 1.59, respectively (Fig. 7).

For bond to reinforcing bars after 1 day of age, the steam-cured SCC (Mixture 3) had similar overall bond strength to the air-cured SCC mixtures. Mixtures 4 and 6 had lower top-bar effect ratios than Mixtures 3 and 5 with Mixture 3 exhibiting better performance than Mixture 5. The maximum top-bar effect ratios for reinforcing bars after 1 day in Mixtures 3, 4, 5, and 6 were 1.45, 1.26, 1.64, and 1.16, respectively (Fig. 6). After 28 days, all four mixtures developed similar bond strengths to reinforcing steel, except at mid-height where the steam-cured concrete (Mixture 3) exhibited lower bond strength. The normalized top-bar ratios show that the three air-cured SCC exhibited better performance than the steam-cured SCC. Mixture 4 had by far the best overall performance with a maximum normalized top-bar effect ratio of 1.23 at 142 cm from the bottom of the cast wall element. This value was followed by Mixtures 6, 5, and 3 with maximum top-bar effect ratios of 1.30, 1.33, and 1.59, respectively (Fig. 7).

Effect of VMA – As shown in Fig. 4, Mixture 4 had a greater in-place strength relative to the strength of the reference cylinder than those for Mixtures 5 and 6. This indicates the improved consolidation obtained with

VMA-1 which was used in Mixture 1. The normalized top-bar effect ratio was the lowest in the case of Mixture 4, followed by Mixture 6 and Mixture 5. The maximum values of the normalized top-bar effect ratios for Mixtures 4, 5, and 6 were 1.23, 1.33, and 1.30, respectively. The slightly better top-bar value for Mixture 4 reflects the improved consolidation and better stability obtained with VMA-1.

Comparison of different mixtures – Despite the lack of VMA, Mixture 6 proportioned with the HRWR-2 had a limited overall top-bar effect along the wall height after 1 day. The maximum top-bar ratio was 1.16 for the reinforcing bars. Mixture 4 made with VMA-1 and HRWR-1 exhibited the lowest overall top-bar effect after 28 days with a maximum normalized ratio of 1.23 (Fig. 7). Mixture 2 corresponding to the steam-cured vibrated flowable concrete exhibited a low overall top-bar effect ratio at 1 day of 1.28; however, the normalized top-bar effect after 28 days was among the highest, reaching 1.40. At 1 day of age, Mixture 5 containing the VMA-2 and HRWR-2 had the highest top-bar effect ratio (maximum value of 1.64). At 28 days, the highest normalized top-bar effect was obtained with the steam-cured SCC (Mixture 3) with a maximum value of 1.59.

CONCLUSIONS

Based on the above results, the following conclusions can be made:

1. The overall results indicate that proper selection and combination of HRWR and VMA have beneficial effects on bond between SCC and reinforcing bars.
2. The investigated SCC mixtures had similar 1-day compressive strength of 41 ± 1 MPa regardless of the curing type. The steam-cured SCC (Mixture 3) developed lower 28-day compressive strength and elastic modulus values than those obtained with the air-cured SCC (Mixture 4) both in the case of cylinder and core samples.
3. For the flowable air-cured concrete, the in-place compressive strength was approximately 85% of control cylinders. Compared to in-place compressive strength at the bottom of the wall elements, all six mixtures had rather uniform distribution of in-place strength at 28 days corresponding to $100\% \pm 6\%$ of the bottom strength, or ± 3 MPa. The air-cured SCC developed greater in-place compressive strength than the air-cured flowable concrete.
4. In general, all tested mixtures developed adequate bond to the reinforcement with relatively small variations in bond strength along the 150-cm-high experimental wall elements. The top-bar effect ratios of reinforcing bars were mostly limited to 1.4 because of the highly stable nature of the concrete.
5. For both the highly flowable concrete with slump of about 230 mm and the SCC mixtures, the top-bar effect of the air-cured mixtures was lower than that of the steam-cured mixtures.
6. The substitution of the VMA-1 (Mixture 4) by VMA-2 (Mixture 5) or the non-use of VMA (Mixture 6) had no effect on strength development. However, Mixture 4 developed slightly greater in-place compressive strength at 28 days, indicating the improved consolidation and mixture stability obtained with VMA-1.
7. The top-bar effect is shown to be sensitive to the type of VMA used in the SCC. In general, mixtures produced with the cellulose-based VMA (VMA-1) had considerably lower top-bar effect than those produced with the synthetic-based VMA (VMA-2); both mixtures were proportioned with the same HRWR.
8. The normalized top-bar ratio at 28 days was lower for Mixture 4 prepared with HRWR-1 than for Mixture 3 made with HRWR-2 and the same VMA (VMA-1). The normalized top-bar ratios of Mixtures 3 and 4 were generally the worst and best, respectively, among the six tested mixtures (maximum normalized top-bar effect ratios at 28 days of 1.23 for Mixture 4 and 1.59 for Mixture 3).

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Table 1 – Detail of concrete mixtures

Mixture type	Mix	HRWR (mL/100 kg CM)	VMA (mL/100 kg CM)	Curing
Conventional flowable concrete (200-220 mm slump)	1 1R	HRWR-1	No	Air
	2	HRWR-1	No	Steam
SCC (Sand to total aggregate ratio = 0.55)	3	HRWR-1	VMA-1	Steam
	4	HRWR-2	VMA-1	Air
	5	HRWR-2	VMA-2	Air
	6	HRWR-2	No	Air

Table 2 – Mixture proportions of conventional flowable concrete and SCC mixtures

Mixture	Conventional flowable concrete		SCC			
	1R - Air	2 - Steam	3 - Steam	4 - Air	5 - Air	6 - Air
Type III cement (kg/m ³)	377	371	363	380	382	386
Class F fly ash (kg/m ³)	94	93	91	94	94.5	96
w/cm	0.37	0.37	0.37	0.37	0.38	0.37
5-14 mm agg. (kg/m ³)	972	957	743	776	780	789
Sand (kg/m ³)	754	742	909	949	966	966
HRWR-1 (l/m ³)	1581	2167	3078	-	-	-
HRWR-2 (l/m ³)	-	-	-	2825	3371	2695
VMA-1 (l/m ³)	-	-	2066	2157	-	-
VMA-2 (l/m ³)	-	-	-	-	1865	-

Table 3 – Fresh and mechanical properties of the tested concrete mixtures

Mixture	Conventional flowable concrete		SCC			
	1R	2*	3*	4	5	6
Unit weight (kg/m ³)	2370	2340	2270	2370	2410	2410
Fresh air content (%)	1.9	3.3	4.8	2.3	1.5	1.6
Concrete temperature (°C)	24	26.5	23	22	24	25.8
Ambient temperature (°C)	23	24.5	22	23	23.5	24
Slump / slump flow (mm) - beginning of casting	230	230	675	700	700	720
Slump / slump flow (mm) – end of casting	225	230	625	640	665	710
Peak temperature (°C)	60	76	72	54	-	60
Max. surface settlement (%)	-	-	0.103	0.100	-	0.102
Column segregation (%)	-	-	4.6	3.8	-	9.3
Filling capacity (%)	-	-	82	88	89	75
Compressive strength (MPa)						
Reference cylinders 1 day	37	42	40	42	41	40
C.O.V.**	0.9	0.8	2.9	1.4	1.4	3.2
28 days	56	52	51	56	59	59
C.O.V.**	1.0	3.4	1.9	2.4	3.5	3.5
Elastic modulus (GPa) 1 day	31	31	29	31	-	-
28 days	38	35	32	34	35	35
Poisson's ratio 1 day	-	-	0.21	0.21	0.23	-
28 days	0.21	0.22	0.21	0.21	0.23	0.21

* steam-cured

** C.O.V. : coefficient of variation (%)

Table 4 – In-place mechanical properties at 28 days of age

Mixture	Dist. from bottom (cm)	Comp. strength		MOE (GPa)	Poisson's ratio	Core/cylinder f_c (%)
		Mean (MPa)	C.O.V. (%)			
1R Flowable air-cured concrete	12	47	--	33	0.21	84
	55	47	2.72	--	--	84
	98	49	2.94	--	--	88
	142	45	--	32	0.23	80
2 Flowable steam-cured concrete	12	53	--	32	0.24	103
	55	55	1.45	--	--	107
	98	56	3.84	--	--	109
	142	50	--	33	0.23	97
3 SCC steam-cured	12	51	--	32	0.22	100
	55	53	0.65	--	--	104
	98	54	2.03	--	--	106
	142	49	--	30	--	95
4 SCC air-cured	12	59	--	34	--	103
	55	55	4.78	--	--	101
	98	55	1.09	--	--	101
	142	57	--	31	0.20	104
5 SCC air-cured	12	54	--	34	0.20	92
	55	56	3.45	--	--	96
	98	55	2.33	--	--	94
	142	52	--	33	0.24	89
6 SCC air-cured	12	53	--	32	0.18	91
	55	54	2.41	--	--	92
	98	55	1.45	--	--	93
	142	51	--	30	0.19	86

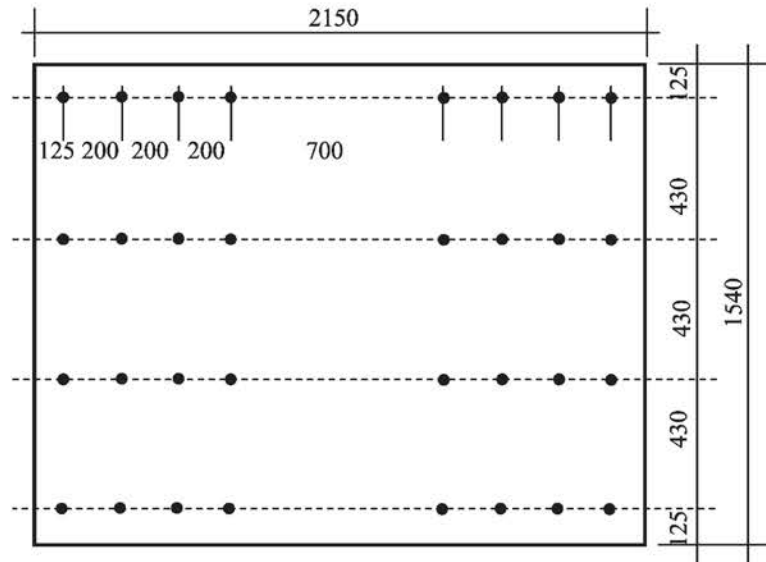


Fig. 1—Schematic of wall elements (dimensions in mm).

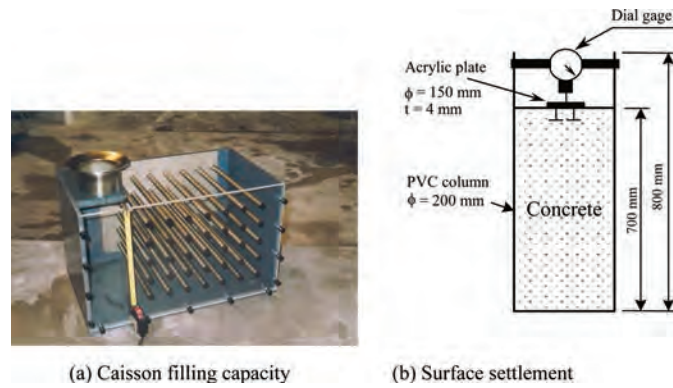


Fig. 2—Test methods to evaluate stability of plastic concrete.

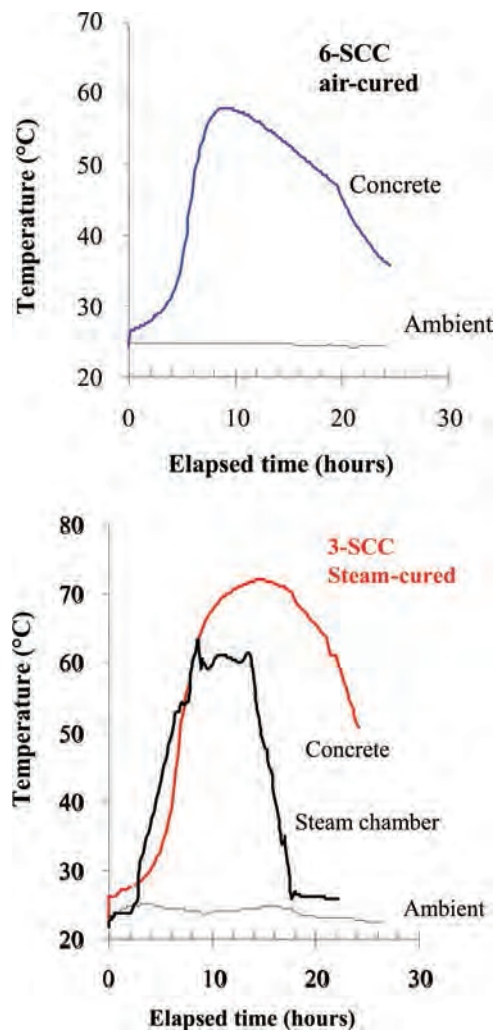


Fig. 3—Typical examples of temperature changes of air-cured and steam-cured SCC (Mixtures 6 and 3).

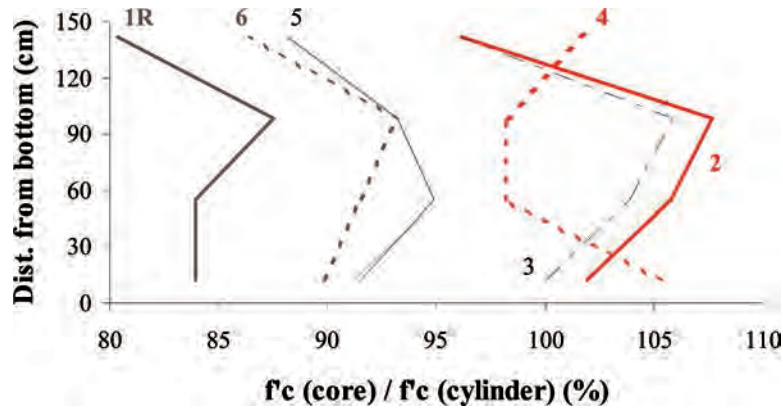


Fig. 4—Distribution of the ratio of in-place compressive strength at 28 days to strength determined from reference cylinders for the different mixtures.

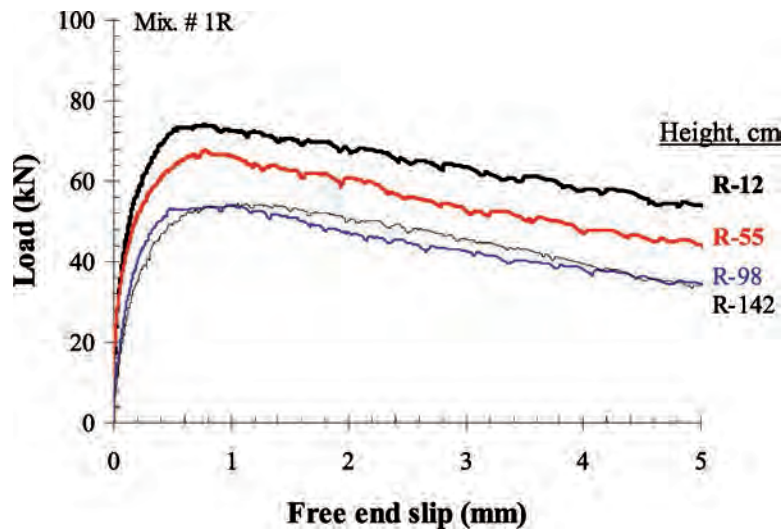


Fig. 5—1-day pullout load versus free-end slip results at different heights along wall cast with Mixture 1R.

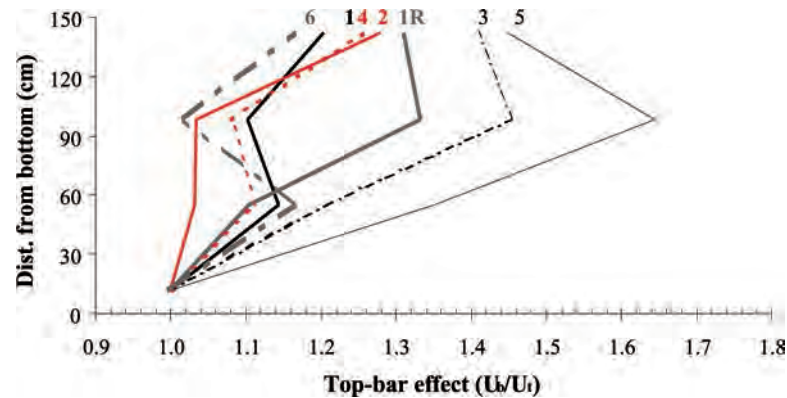


Fig. 6—Variations in top-bar ratio with height for reinforcing bars at 1 day in the different mixtures.

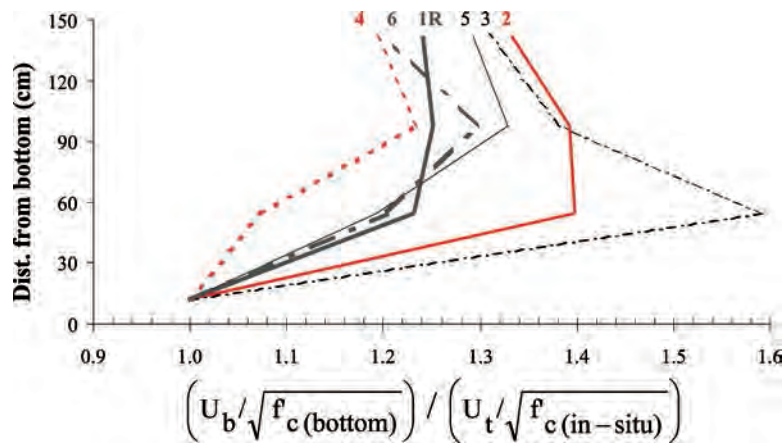


Fig. 7—Variations in normalized top-bar ratio with height for reinforcing bars at 28 days in the different mixtures.

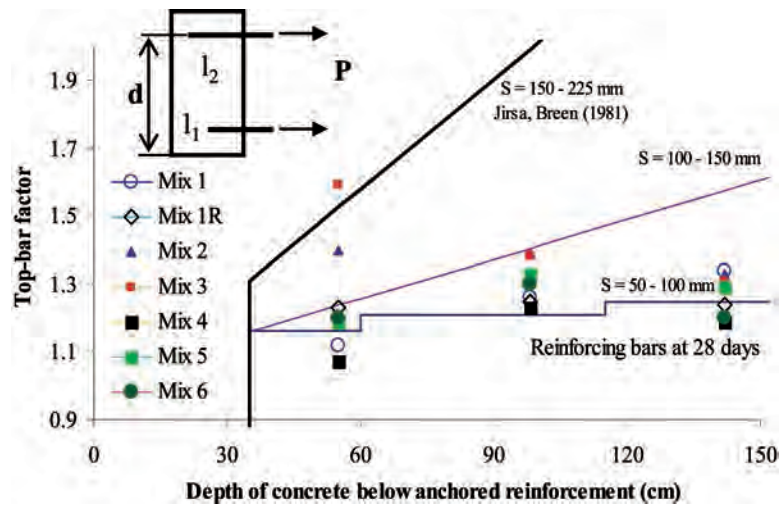


Fig. 8—Comparison of top-bar ratio of reinforcing bars at 28 days with the recommendations of Jirsa and Breen (1981).

Improving Precast Operations in Sweden Through the Application of Self-Consolidating Concrete

by R.C. Lewis and J. Larsson

Synopsis: The precast industry has always been looking for ways to improve production. Be that ease of casting or finishing, faster turnaround or better economics due to less damage or reduced concrete costs. The advent of self consolidating concrete (SCC) has enabled some of these aspects to be realised. The development of SCC and new mixture design procedures has improved certain facets of the precast industry. However, the excessive use of fillers or very high cement contents has had equal drawbacks for the use of SCC in this environment. With the advances in software allowing very precise particle packing analyses to be made of the materials, new mix designs with lower total binder contents – and little or no fillers – are possible. Designs with supplementary cementitious materials (SCMs), including silica fume, can be very effective for SCC, not only giving excellent flow and non-segregation, but also enhancing the finished quality of the concrete. This paper reviews the use of silica fume in SCC, information from the Technically Optimised Piling Concrete (TOPIC) research in the UK, and gives examples of the use in some precast operations in Sweden.

Keywords: flow; precast; rheology; self-consolidating concrete; silica fume

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INTRODUCTION

It must be remembered that Self Consolidating Concrete (SCC) is basically a method for placing concrete, and not a 'new' product of itself. It is a way of modifying the rheology of the mix to obtain better plastic characteristics, to gain benefits from placing at very high workability without segregation and getting improved finished surface quality.

While most SCC mixes in the fluid state may be classed as high performance, it does not mean that an SCC mix will achieve high performance characteristics in the hardened state. This will depend on the original mix design parameters and the required final performance. If a high performance concrete (HPC) is needed, it is best to design for hardened characteristics, and then modify for self consolidation.

This paper looks at the requirements of SCC, the use of SCMs in the mixture design, some research results and the mixes used in some Swedish Precast Operations.

REQUIREMENTS OF SCC

Fluidity

The defining level for SCC is to have a 'flow' of more than 55 cm (22 inches), without segregation of the mix. The rheological properties of SCC are greatly influenced by the amount and composition of the fine particles in the system. Normal practice has been to upgrade a pumpable mix with higher dosages of superplasticisers. The nature of the concrete thus produced is to segregate under the very high fluidity. The corrective factor for this is to increase the fine content by adding a 'filler' – often limestone dust or similar material – to increase the surface area of the finer materials. Resultant powder contents of mixes can be in the region of, or even higher than 600 kg/m^3 (1100 lb/yd^3). This may improve the cohesion of the mix, but will not contribute to the long term, hardened performance – and in some cases is actually detrimental.

Stability

With the special rheology required for SCC, it is necessary to get the best balance on the mix components, between the aggregates, the cement and the additional materials. It can be seen to be a contradiction to have a cohesive, yet very fluid concrete. Hence the proportioning of the mix to achieve both aspects of this performance is very important.

Recent technology has developed viscosity modifying admixtures (VMAs) that can help combat segregation and improve the fluidity of the mix.

However, the method of mixture design that gives very good results, and has been used very effectively in the precast industry in Sweden, is that of Particle Packing. In this method all the components of the concrete are set against a grading 'optimum' and the percentages balanced to create a mix which has a smooth gradation, from coarse aggregate, right through to the smallest fractions of the cementitious materials. The smoother the grading curve, the lower the number of voids, the denser the matrix and the better the rheology of the mix.

With this improved 'packing' of the mix, the action of the water and superplasticiser will be more effective, achieving better flow while the denser matrix provides higher stability.

Cementitious Materials

Blended cements have been found to be very effective in improving the self-consolidating characteristics, due to the increase of fine material, and giving high performance durability results. Using fly ash or blastfurnace slag will improve the cohesion and rheological properties of the mix, although care should be taken if using higher percentages. This may reduce the integrity of the concrete at younger ages, requiring more curing, and a longer period before usable strengths are achieved.

Silica fume, in binary or ternary blends of cementitious materials, due to its extreme fineness and reactivity, can enhance SCC properties, and is a beneficial, and often necessary, component of high performance SCC. By exploiting the superfine spherical nature of the silica fume particles, it is possible to develop mixes, with more moderate cementitious contents, that have high fluidity and improved stability. The pozzolanic reactivity of the silica fume then improves the hardened qualities of the concrete, giving a high performance material that can be placed as SCC.

FRESH CONCRETE PROPERTIES

Flow

The addition of silica fume to the concrete, at between 8 and 10% of the cementitious weight will immediately flood the pore system with between 50,000 and 100,000 microspheres per cement grain. This large surface area increases the cohesion of the mix, resulting in non-segregating concrete. Whilst the increased cohesion negates the potential for the mix to 'fall apart', this does not reduce the higher fluidity required for self consolidation. This is due to the 'ball bearing effect' of the microspheres lubricating the cement grains and fine aggregate. As the pH of the concrete rapidly increases the microsilica particles form a surface gel which also improves this lubricating effect.

The fluidity of the fresh concrete is also a balance between the cementitious components and the superplasticisers. In all cases trial mixes are necessary to review the physical performance of the concrete.

Finish

As the SCC is highly fluid, with a high fine material content, the surface finish (to formwork) will be greatly improved. With silica fume eliminating the bleeding of the concrete, there can be less voids and water streaking on the finished surface. An exposed surface can be finished faster and easier.

Curing

Curing is essential with all concrete. An SCC is no different in that it requires good curing. Due to the fact that it may well be high performance as well – with expected improved durability characteristics – it should be cured in accordance with any recommendations from the concrete producer or instructions from the consultant.

HARDENED CONCRETE PROPERTIES

When using large volumes of filler material, such as limestone dust, or high volumes of a cement replacement, early age strengths can be greatly reduced. The addition of silica fume, with a much faster pozzolanic reaction, can increase the early age strength, giving the concrete a better integrity from early ages. This can be particularly important in large volume pours where very low heat evolution is required, but usable strengths are needed within a short period of time. Ternary cementitious blends have been found to be very effective in producing excellent self-consolidating characteristics and high performance durability results, as shown in the piling concrete of the Burj Dubai (1).