Engineering Properties of Self-Consolidating Concrete for High-Performance Concrete Bridge Applications

by

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Abstract

This paper presents a summary of selected engineering properties of self-consolidating concrete (SCC) mixtures relative to the properties of conventional concrete mixture used in precast/prestressed concrete production. The engineering properties include compressive, flexural and tensile strengths, modulus of elasticity and Poisson's ratio, bond to reinforcement, drying shrinkage, creep, porosity and chloride diffusivity. The SCC mixtures used in the studies reported in this summary were also designed to evaluate the effects of two different high-range water-reducing (HRWR) admixtures and a viscosity-modifying admixture (VMA).

The engineering properties of SCC are found to be comparable to or better than the properties of the conventional concrete mixture. The data also show that highly fluid, yet stable SCC mixtures with excellent engineering properties can be produced either with or without VMA. However, the mixtures with VMA exhibit overall superior properties. The highly stable nature of the SCC mixtures is reflected by the levels of bond strength of bottom reinforcement relative to top reinforcement or top-bar effects that are comparable to or better than the top-bar effects in the conventional concrete mixture.

The data show that SCC has the required properties for implementation in the FHWA high-performance concrete bridge program that is aimed at allowing for greater design efficiencies, shorter construction cycles and lower life-cycle costs.

Keywords: admixtures, bridges, bond strength, creep, drying shrinkage, durability, self-consolidating concrete, top-bar effect

Introduction

The versatility of concrete as a construction material is unparalleled. Its basic constituents are readily available in most parts of the world, it can be made and formed with relative ease into various shapes and aesthetically-pleasing designs, and, in general, it has been reliable and durable. These attributes have made concrete popular as a construction material all over the world. However, there have been durability problems and deterioration of concrete structures has become a focal issue within the construction industry.

A 1998 report on the state of bridges in the United States revealed that 30 percent of bridges 20 ft (6 m) or longer that were surveyed (178,092 out of 589,335 bridges) were substandard [1]. Approximately 15 percent of the surveyed bridges were structurally deficient primarily due to corrosion of reinforcing bars, prestressing strands and structural steel. Deterioration of bridges and other infrastructure elements have a direct impact on productivity and economic development, and there is concern. It was reported in 1999 that two studies were underway in the United States and the United Kingdom to estimate the total current cost of metallic corrosion in the respective countries and to evaluate strategies for effective corrosion prevention and control [2]. The findings of the study in the United States are summarized in a technical brief by the Federal Highway Administration (FHWA), FHWA-RD-01-157, dated March 2002 [3]. In this technical brief, the annual direct cost of corrosion for highway bridges was estimated at $8.3 billion to replace structurally deficient bridges over the next 10 years, $2.0 billion for maintenance and cost of capital for concrete bridge decks and $2.0 billion for maintenance and cost of capital for concrete substructures.

Earlier in December 1994, the Civil Engineering Research Foundation (CERF), an affiliate arm of the American Society of Civil Engineers (ASCE), issued a technical report on a ten-year, $2 billion industry plan for implementing a national program of technological research, development and deployment [4]. The objective of the industry plan was to accelerate the commercialization of high-performance construction materials and systems with the ultimate goal of ensuring a solid infrastructure system to meet the rapidly changing demands of society and industry in the 21st century [4].

One of the ten construction materials identified in the CERF Report is high-performance concrete (HPC), defined as concrete with improved constructibility, improved durability, and improved mechanical properties [4]. HPC by definition has to meet special performance requirements that include: easier placing and compaction; high early-age strengths and superior long-term mechanical properties; volume stability with increased resistance to deformation and cracking; increased resistance to chemical attack, cyclic freezing and thawing, and high temperatures; and enhanced overall durability. Improved durability was singled out as having "…perhaps the highest potential of all for achieving remarkable cost-saving benefits in the infrastructure" [4]. For its part, FHWA has established a 10-year goal of reducing the number of deficient bridges to 25 percent of the total number of bridges. It is expected that this goal can be met by constructing new bridges using HPC to significantly improve durability and reduce future maintenance needs.

Self-consolidating concrete (SCC) is a new class of HPC with greatly enhanced fluidity that can spread readily into place and fill formwork without consolidation and segregation. Thus, SCC provides a significant reduction in the effort required for concrete placement and compaction, especially in heavily congested structural members such as prestressed concrete girders and cast-in-place anchor blocks. In addition to the ease of placement and compaction, SCC also provides a surface finish with very few blemishes thereby enhancing overall aesthetics and quality of the surface. These benefits can translate into lower production costs and enhanced long-term performance of concrete bridges and is one of the reasons why SCC has gained widespread acceptance in the precast/prestressed concrete industry. Major applications of SCC have been carried out in Japan and Europe, including the 180,000 yd^3 (137,600 m^3) placements for the anchor blocks of the Akashi Kaikyo Bridge in Japan, where the use of SCC helped to overcome a shortage in skilled labor.

Depending on the choice of admixtures and proportioning philosophy adopted, SCC can be produced with very minor changes to the proportions of the conventional mid- and high-slump concrete mixtures that are used in the casting of structural elements. However, some of the common techniques for proportioning SCC mixtures include the use of high cementitious materials contents and increases in the sand-to-aggregate ratios. The choice of which proportioning technique is used is influenced by several factors including the specific application, available materials, and the recommendations of the admixture supplier. Consequently, the engineering properties of SCC need to be evaluated relative to the properties of current concrete mixtures to establish the performance basis for use of this new class of HPC in structural applications and to facilitate acceptance by design engineers.

In this paper, the engineering properties of SCC mixtures are compared with the properties of conventional concrete mixture used in precast/prestressed concrete production, with emphasis on bond to reinforcement, drying shrinkage, creep, porosity, and chloride diffusivity. The SCC mixtures were also designed to evaluate the effects of a viscosity-modifying admixture (VMA) and two different polycarboxylate-based high-range water-reducing (HRWR) admixtures, one normal setting and the other with high-early strength development characteristics. The use of a VMA to enhance stability of fluid concrete has been demonstrated in a previous study [5].

Testing Program

SCC mixtures with a nominal slump flow of 27 in. (685 mm) were produced with the normal-set and high-early strength HRWR admixtures for comparison with a conventional 8 in. (200 mm) slump concrete mixture made with the normal-set HRWR admixture. The normal-set SCC mixture was steam cured, whereas the high-early strength SCC mixture was air cured to simulate elimination of steam curing in a precast concrete production. Specimens cast from the SCC mixtures were neither vibrated nor rodded. The conventional concrete mixture specimens were consolidated with a vibrator and either steam cured or air cured.

As reported elsewhere [6], the concrete mixtures had cement and fly ash contents of 640 and 160 lb/yd^3 (380 and 95 kg/m^3), respectively, a water-cementitious materials ratio (w/cm) of 0.37 and sand-aggregate ratios (s/a) by mass of 0.44 for the conventional concrete mixtures and 0.53 for the SCC mixtures. The mixtures were designed for a nominal compressive strength of 4,000 psi (27.6 MPa) at 24 hours. Details of the procedures used for curing, the various strength tests, bond to reinforcement, drying shrinkage, creep, chloride diffusion and porosimetry measurements are also provided in Reference 6.

It should be noted that the bond to reinforcement test procedure used is different from the procedures commonly used to evaluate the bond characteristics of strand in prestressed concrete as reported in Reference 7. The bond to reinforcement procedure reported in Reference 6 was designed to investigate the top-bar effect, which describes the reduction in bond strength for top-cast bars as a consequence of bleeding, segregation and settlement of the concrete. Walls measuring 7 ft (2.1 m) long, 5 ft (1.5 m) high and 8 in. (200 mm) wide were fabricated for pullout tests to determine the bond to reinforcement. In fabricating the walls, the formwork was divided vertically in the middle into two sections. One section had 16 deformed reinforcing bars grouped in four per row and positioned at four levels along the height of the wall. Similarly, 16 pieces of unstressed prestressing strands were positioned in the second wall section. A 2-in. (50-mm) length of each piece of reinforcement was exposed and cleaned to ensure adequate bond to the concrete. Pullout of the 16 reinforcing bars and 16 prestressing strands was performed at 1 and 28 days after casting. At each height level, two of the four bars were tested at each age. The pullout load was applied gradually and recorded using a load cell, and the net slip of the bar was measured with a LVDT connected to the unloaded end of the bar. The ratio of the average bond strength for the bottom-cast bars to that for the bars at each level along the wall height was calculated as the top-bar factor. This factor was used as a measure of the top-bar effect for each concrete mixture.

As stated earlier, SCC mixtures can be proportioned with or without an increase in s/a. Because an increase in s/a requires a decrease in coarse aggregate content, it is reasonable to expect that this approach may lead to an increase in drying shrinkage. Hence, the effects of s/a on drying shrinkage of SCC was investigated using mixtures with a cement content of 850 lb/yd^3 (504 kg/m^3), a water-cement ratio of 0.34 and s/a levels of 0.58, 0.48 and 0.39. A HRWR and a VMA were used to achieve stable SCC mixtures for the target slump flow of 24 to 25 in. (600 to 625 mm) at the lower s/a levels of 0.48 and 0.39. Drying shrinkage tests were performed on the three mixtures in accordance with ASTM C 157 after 28 days moist curing.

Results and Discussions

Compressive, Flexural and Tensile Strengths:

Data presented in Reference 5 and shown in Fig. 1 and 2 indicate that SCC mixtures can be proportioned to have compressive, flexural (modulus of rupture) and tensile strengths that are comparable to the corresponding strengths of the conventional concrete. The desired compressive strength of 4,000 psi (27.6 MPa) at 1 day was easily achieved with or without steam curing, indicating that strength development is not impaired with SCC. Therefore, SCC can be proportioned to achieve high-early strengths for early stripping of forms and release of prestress, which coupled with the elimination of vibration for consolidation would provide reduced project completion time and reduced project costs benefits. The strength development characteristics of the SCC mixture made with the high-early strength HRWR is worth specific mention. This is because of the potential benefit of eliminating or reducing thermal cracking in girders if steam curing is eliminated in the production of such members. Restrain thermal contraction has been identified as the most probable cause of very early-age cracking in large-size, long-span prestressed concrete AASHTO girders [7].

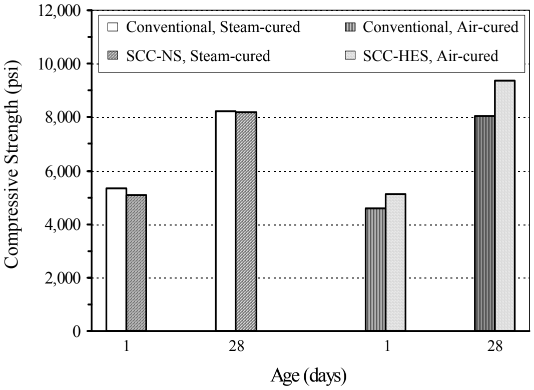

Fig. 1: Compressive Strengths

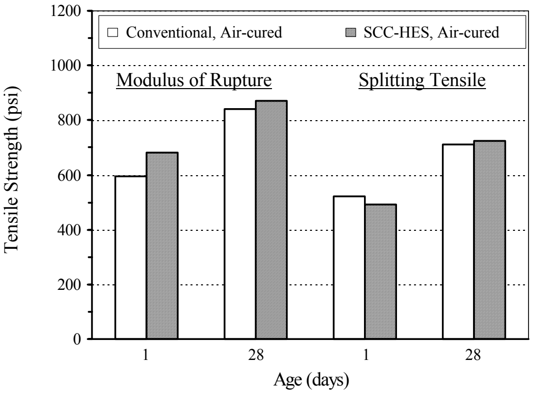

Fig. 2: Flexural and Tensile Strengths

Modulus of Elasticity and Poisson's Ratio:

Comparable values of modulus of elasticity were obtained for the SCC and conventional concrete, with values of approximately 3 x 10^6 psi (20.7 GPa) and 5 x 10^6 psi (34.5 GPa) at 1 day and 28 days, respectively [9]. The Poisson's ratio for both the SCC and conventional concrete was approximately 0.22, indicating that the deformational behavior under load of structural members cast using SCC would not be different than that of members cast using conventional concrete. For bridges this means that a number of key benefits of using HPC, such as longer bridge spans or fewer girders, would not be compromised with the use of SCC.

Bond to Reinforcement:

Pullout loads for the deformed reinforcing bars and unstressed prestressing strands show that the bond of the SCC mixtures to top layers of bars is equivalent to or better than the bond of the conventional concretes to such bars. The top-bar factors at 1 day and 28 days, calculated from the pullout loads, are summarized in Table 1.

Table 1 – Summary of Mixture Proportions and Bond to Reinforcement Data

<table>
<tr><th></th><th>Ref. #1</th><th colspan="2">SCC-HES #1</th><th colspan="2">SCC-HES #2</th><th>Ref. #2</th><th colspan="2">SCC-NS</th></tr>
<tr><td>Curing</td><td colspan="5">Air</td><td colspan="3">Heat</td></tr>
<tr><td></td><td></td><td colspan="2"></td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td>s/a</td><td>0.44</td><td colspan="2">0.53</td><td colspan="2">0.53</td><td>0.44</td><td colspan="2">0.53</td></tr>
<tr><td>w/cm</td><td>0.37</td><td colspan="2">0.37</td><td colspan="2">0.37</td><td>0.37</td><td colspan="2">0.37</td></tr>
<tr><td colspan="9"></td></tr>
<tr><td colspan="9">Admixtures</td></tr>
<tr><td>NS-HRWR[a]</td><td>✓</td><td colspan="2"></td><td colspan="2"></td><td>✓</td><td colspan="2">✓</td></tr>
<tr><td>HES-HRWR[b]</td><td></td><td colspan="2">✓</td><td colspan="2">✓</td><td></td><td colspan="2"></td></tr>
<tr><td>VMA</td><td></td><td colspan="2">✓</td><td colspan="2"></td><td></td><td colspan="2">✓</td></tr>
<tr><td colspan="9"></td></tr>
<tr><td colspan="9">Top-Bar Factor: Deformed Steel Reinforcing Bars</td></tr>
<tr><td>1 day</td><td>1.31</td><td colspan="2">1.26</td><td colspan="2">1.16</td><td>1.28</td><td colspan="2">1.41</td></tr>
<tr><td>28 days</td><td>1.27</td><td colspan="2">1.22</td><td colspan="2">1.23</td><td>1.37</td><td colspan="2">1.34</td></tr>
<tr><td colspan="9"></td></tr>
<tr><td colspan="9">Top-Bar Factor: Prestressing Strands</td></tr>
<tr><td>1 day</td><td>1.43</td><td colspan="2">1.04</td><td colspan="2">1.28</td><td>1.60</td><td colspan="2">1.64</td></tr>
<tr><td>28 days</td><td>1.31</td><td colspan="2">0.93</td><td colspan="2">1.34</td><td>1.98</td><td colspan="2">1.22</td></tr>
<tr><td colspan="9"></td></tr>
<tr><td colspan="9">Ratio of Average Bond Strength (SCC / Reference): Deformed Steel Reinforcing Bars</td></tr>
<tr><td>Height from Wall Bottom</td><td></td><td>1 day</td><td>28 days</td><td>1 day</td><td>28 days</td><td></td><td>1 day</td><td>28 days</td></tr>
<tr><td>0.4 ft (0.12 m)</td><td>--</td><td>1.04</td><td>1.19</td><td>0.95</td><td>1.22</td><td>--</td><td>1.09</td><td>1.15</td></tr>
<tr><td>1.8 ft (0.55 m)</td><td>--</td><td>0.95</td><td>1.32</td><td>0.89</td><td>1.27</td><td>--</td><td>0.93</td><td>1.00</td></tr>
<tr><td>3.2 ft (0.98 m)</td><td>--</td><td>1.19</td><td>1.14</td><td>1.25</td><td>1.18</td><td>--</td><td>0.78</td><td>1.15</td></tr>
<tr><td>4.6 ft (1.42 m)</td><td>--</td><td>1.01</td><td>1.25</td><td>1.08</td><td>1.27</td><td>--</td><td>0.98</td><td>1.18</td></tr>
<tr><td colspan="9">Ratio of Average Bond Strength (SCC / Reference): Prestressing Strands</td></tr>
<tr><td>0.4 ft (0.12 m)</td><td>--</td><td>0.88</td><td>0.83</td><td>1.20</td><td>1.05</td><td>--</td><td>1.12</td><td>1.04</td></tr>
<tr><td>1.8 ft (0.55 m)</td><td>--</td><td>1.16</td><td>1.20</td><td>1.08</td><td>1.15</td><td>--</td><td>0.75</td><td>0.93</td></tr>
<tr><td>3.2 ft (0.98 m)</td><td>--</td><td>0.91</td><td>1.30</td><td>1.23</td><td>1.18</td><td>--</td><td>0.78</td><td>0.91</td></tr>
<tr><td>4.6 ft (1.42 m)</td><td>--</td><td>1.22</td><td>1.22</td><td>1.37</td><td>1.06</td><td>--</td><td>1.14</td><td>1.67</td></tr>
</table>

[a] NS-HRWR: Normal set HRWR.

[b] HES-HRWR: High-early strength HRWR.

It has been reported that the extensive vibration required for consolidation of conventional low-slump concrete mixtures used in fabricating horizontally cast, densely reinforced pretensioned concrete elements, such as prestressed piles, causes bleeding and settlement and, potentially, an increase in top-bar factor [10]. The data in Table 1 therefore indicates that the bleeding, segregation and settlement characteristics of stable SCC mixtures are comparable to those of properly consolidated conventional concrete mixtures. The data also suggest that eliminating vibration during casting of pretensioned concrete elements through the use of SCC would result in better quality concrete and reduce excessive end slip of top strands.

The ratios of the average bond strengths, at 1 day and 28 days, for the SCC to those for the conventional concretes are also presented in Table 1. The ratios were in most instances greater than one, indicating that the pullout loads for the SCC were typically higher than the pullout loads for the conventional concretes at the same wall height. Finally, the comparable bond to top bars for SCC and conventional concrete implies that current design code provisions for development length of reinforcement are applicable when SCC is used.

Shrinkage and Creep:

As would be expected, the magnitude of drying shrinkage increased with increasing s/a, as shown by the 8-month data in Fig. 3. This means that the shrinkage characteristics of SCC mixtures with higher than normal s/a should be evaluated prior to their use in applications where excessive drying shrinkage is of concern. Fig. 3 also show that low to normal values of drying shrinkage can be achieved by maintaining conventional levels of s/a in SCC mixtures with the addition of a VMA.

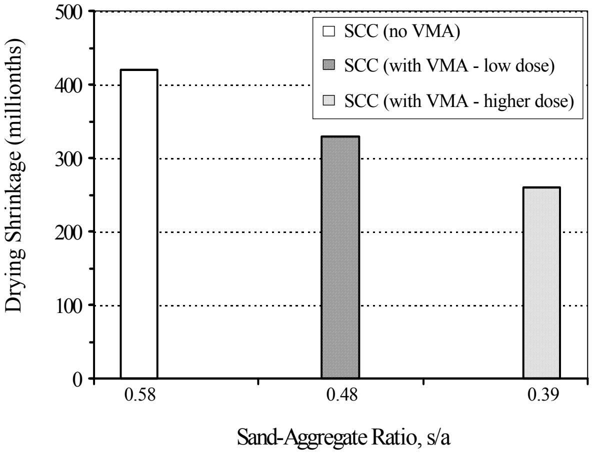

Fig. 3: Drying Shrinkage at 8 Months for SCC Mixtures

Analyses of drying shrinkage and creep data for ultimate values for the conventional and SCC mixtures listed in Table 1 were performed using the form of the equations recommended by ACI Committee 209. The analyses, first presented in Reference 6 as shown in Fig. 4 and 5, show that shrinkage and creep behavior of SCC is fundamentally similar to the behavior of conventional concrete. The ultimate shrinkage values of 600 and 560 millionths for the SCC and the conventional concrete, respectively, are fairly close, so are the ultimate specific creep values of 0.51 and 0.59 millionths/psi for the SCC and the conventional concrete, respectively. These ultimate values indicate that the long-term prestress losses associated with the combined effects of shrinkage and creep would be expected to be similar for SCC and conventional concrete.

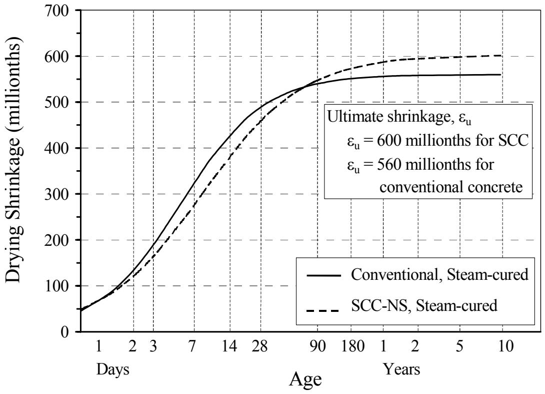

Fig. 4: Ultimate Shrinkage Projection

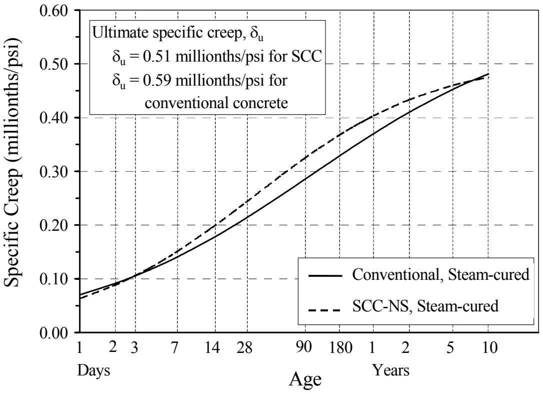

Fig. 5: Ultimate Specific Creep Projection

Durability:

Data from chloride migration tests reported show that chloride diffusion coefficients for SCC mixtures and conventional concretes are comparable [6]. This is consistent with data from mercury intrusion porosimetry measurements that show that the average pore diameter for SCC is either smaller than or comparable to that of the conventional concrete [6]. This implies that the durability of SCC with regard to chloride-induced corrosion would be comparable, if not enhanced, relative to the performance of conventional concrete. The durability potential of HPC is one of the key drivers of the FHWA strategic program for bridges and the data show that this objective would not be compromised by using SCC.

Summary

The data summarized in this paper show that the engineering properties of SCC are comparable to or better than the properties of the reference conventional concrete mixture. The data also show that highly fluid, yet stable SCC mixtures with excellent engineering properties can be produced either with or without VMA. Mixtures with VMA, however, exhibit overall superior properties, particularly with regard to drying shrinkage. The highly stable nature of the SCC mixtures is reflected by the levels of bond strength of bottom reinforcement relative to top reinforcement or top-bar effects that are comparable to or better than the top-bar effects in the conventional concrete mixture.

The data show that SCC has the required properties for implementation in the FHWA high-performance concrete bridge program that is aimed at allowing for greater design efficiencies, shorter construction cycles and lower life-cycle costs. Finally, it should be noted that SCC has been approved for use on various bridge projects within the United States for pretensioned as well as cast-in-place structural members.

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