Accelerated Construction for Pedestrian Bridges: A Comparison between High Strength Concrete (HSC) and High-Strength Self-Consolidating Concrete (HS-SCC)

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ABSTRACT: High-strength concrete (HSC) and glass fiber reinforced polymer (GFRP) bars are materials utilized in bridge construction to lower cost, reduce construction time, and increase service life of bridge structures. Recently, high-strength self-consolidating concrete (HS-SCC), a highly flowable concrete that does not require vibration, has been developed as a viable alternative to HSC for use in situations with congested steel or a need for rapid construction. Coupling HS-SCC with GFRP bars could create durable structures built rapidly. Several performance related issues remain to be investigated such as the behavior of prestress loss, shear, creep, shrinkage, thermal gradients, mechanical property development, time dependent behavior, and serviceability under varying loads before HS-SCC can be implemented in prestress applications.

Two prestressed precast pedestrian bridges designed for rapid construction in Rolla, Missouri, USA, were constructed of HSC and HS-SCC to differentiate the mechanical and material properties between the two materials. In addition, the precast deck panels were reinforced with mild steel and GFRP to determine differences in the interaction between the reinforcement and decking materials. Instrumented systems and material tests were used to monitor the mechanical and material properties. This paper reports the results from fabrication through erection. In addition, a service load test is planned.

INTRODUCTION

Improvements in materials used in bridge construction have lowered costs, reduced construction time, and increased service life. Improvements include the use of high-strength concrete (HSC) in prestressed bridges and glass fiber reinforced polymers (GFRP) in decking systems. By using HSC, large sustainable bridge structures were built with relatively compact sections. GFRP bars have been used in the place of mild steel in decking systems to increase durability of structures. Recently, high-strength self-consolidating concrete (HS-SCC) has been developed as a viable
alternative to HSC. This type of concrete is highly flowable and does not require vibration during fabrication making it beneficial in situations where there is congested steel or a need for rapid construction. In addition, HS-SCC can potentially increase safety, lower noise levels, reduce labor required, and increase production rate at precasting yards (Khayat et. al., 2009). By further implementing HS-SCC with precasting prefabricating bridge section and GFRP bars, construction time can be greatly reduced and durability increased (Shahawy, 2003). However, while HS-SCC appears to be a viable alternative to HSC in prestress applications, several performance related issues remain. For example, the behavior of prestress loss, shear, creep, shrinkage, thermal gradients, mechanical property development, time dependent behavior, and serviceability under varying loads between HSC and HS-SCC remain an issue for investigation (Khayat et. al., 2009).

Two prestressed precast pedestrian bridges designed for rapid construction in Rolla, Missouri, USA, were constructed of HSC and HS-SCC to differentiate the mechanical and material properties between the two materials. The precast deck panels were reinforced with both mild steel and GFRP to determine differences in the interaction between the reinforcement and decking material. The concrete temperature, concrete strain, camber, and deflection were monitored in both the precast spandrel beams and precast deck panels to determine the differences between the thermal gradients, prestress losses, beam curvatures, and time dependent behavior in HSC and HS-SCC. Embedded vibrating wire strain gages (VWSG’s) with built in thermistors, demountable surface mechanical strain (DEMEC) gauges, tensioned—wire deflection measuring systems, and precise surveying for early-age and later-age monitoring was used in this project. A barrage of material tests including compression, elastic modulus, modulus of rupture (MOR), split cylinder, creep, and shrinkage were completed on both materials to determine differences in material characteristics. Many of these tests proved reliable in past research projects on HSC bridge beams and panels (Myers and Yang, 2004). The goal of this project was to determine the feasibility of HS-SCC in precast prestressed applications for rapid construction of pedestrian bridges.

INTRODUCTION OF BRIDGES AND INSTRUMENTATION

To better understand the differences in mechanical, material, and time dependent behavior between HSC and HS-SCC, two precast pedestrian bridges were designed and erected along Lions Club Drive in Rolla, MO, USA. Each bridge has a similar width of 3.0 m (10 ft). The HSC bridge, located near Highway O, spans a length of 14.6 m (48 ft), and the HS-SCC bridge, located near Rolla Street, spans a length of 10.7 m (34 ft). Each of the bridges utilizes precast prestressed “L” beams that function both as the structural support and handrails for the pedestrians. Each beam contains twelve 12.7 mm (0.5-in) diameter pretensioned strands which reinforce the concrete structural member. Each bridge contains two precast deck panels. One deck panel on each bridge is reinforced with mild steel, whereas the others are reinforced with GFRP.

Before the bridges were fabricated, a detailed instrumentation system was created to monitor the bridges. The final plan utilized electronic and mechanical systems to
measure strain and temperature. The internal strain and temperature was monitored by a data acquisition system (DAS) that received data from sixteen VWSG’s with built-in thermistors. Five sensors were placed at a support location within the beam; five were placed at the mid-span of the beam; and three sensors were placed at the center of each precast deck panel. DEMEC strain gauge points were utilized to monitor transfer length. Furthermore, a tension-wire system was utilized to determine early-age serviceability of the bridge members. Finally, precise surveying equipment (i.e. laser based) was planned to be used to monitor later-age bridge deflections.

The precast prestressed spandrel beams and deck panels were fabricated at a precasting plant at Marshall, MO. The structural components were stored at the precasting plant until the abutments were erected at the location in Rolla, MO. Both the HSC and HS-SCC had a target compressive strength of 68.9 MPa (10,000 psi) and a release strength of 24.1 MPa (3,500 psi). The actual strength of the concrete was determined to be 84.3 MPa (12,230 psi) for the 28 day strength and 46.6 MPa (6,770 psi) for the release strength of HSC, and HS-SCC had a 28 day strength of 69.8 MPa (10,130 psi) and a release strength of 44.8 MPa (6,500 psi). The additional strength was contributed to the rapid strength gain associated with the concrete mixes.

The steel arrangement in each of the precast “L” beams is illustrated in Figure 1 below. In the figure shown, the beam is laying down because the “L” beam was prestressed in this manner. Six of the strands within the beams were pretensioned to 66.7 kN (15 kips) and six of the strands were pretensioned to 138 kN (31 kips). None of the twelve strands were draped. Due to the strand arrangement, the beams had an eccentricity of 250 mm (9.86-in). Figure 1 also displays the locations of the VWSG’s within each of the “L” beams that were utilized to monitor strain and temperature in the concrete. The locations of the sensors within the precast deck panels are displayed in Figure 2. The top and bottom sensors within the deck panels were oriented in the lateral direction to monitor flexural strains and the middle sensor was oriented in the longitudinal direction to monitor strains resulting from temperature and shrinkage.

![FIG. 1. Cross Section of HSC and HS-SCC Precast Prestressed Spandrel Beams](image-url)
FIG. 2. Precast Deck Panel Cross Section

The two bridges were rapidly transported and erected in a single day after the abutments were at optimal strength. Currently, the bridges are open for traffic.

MATERIAL TESTS AND RESULTS

In addition to the instrumentation used to monitor the time dependent characteristics of the concrete, a barrage of material tests were utilized to determine the compressive strength, tensile strength, modulus of elasticity, MOR, creep, and shrinkage of HSC and HS-SCC in both the precast prestressed spandrel beams and precast deck panels. All of the specimens were allowed to cure in an environment similar to field conditions, excluding the creep and shrinkage test specimens which were kept inside a laboratory maintained at room temperature. Table 1 lists the tests, test procedures, description of test specimens, and average 28 day test results for HSC and HS-SCC. In addition, Figure 3 illustrates the creep and shrinkage results obtained for both the HSC and HS-SCC test samples to date.

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<th>TESTS</th>
<th>METHOD</th>
<th>SPECIMENS</th>
<th>28 DAY RESULTS</th>
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<tr>
<td>Compressive Strength</td>
<td>ASTM C39</td>
<td>102 mm dia. x 203 mm. long cylinder</td>
<td>84.3-MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>69.8-MPa</td>
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<tr>
<td>Modulus of Elasticity</td>
<td>ASTM C469</td>
<td></td>
<td>31.3-GPa</td>
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<td></td>
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<td></td>
<td>33.6-GPa</td>
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<tr>
<td>Splitting Tensile</td>
<td>ASTM C496</td>
<td>152 mm x 152 mm x (533 mm. or 610 mm)</td>
<td>4.82-MPa</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td>4.70-MPa</td>
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<tr>
<td>Modulus of Rupture</td>
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<td>102 mm dia. x 610 mm long cylinders</td>
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<td>Figure 5</td>
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Table 1. Material Test Method and Results

Units: MPa (1 MPa = 145.0377 psi), mm (1-mm = 0.03937-in.)
The compressive strength, split tension, and MOR of HSC was greater than that of HS-SCC. In addition, the HSC had less creep. These properties were controlled by three factors: water to cementitious (w/cm) ratio, presence of air entrainment, and coarse aggregate (CA) size, type, and amount. The w/cm of the HSC was 0.326, and the w/cm ratio of the HS-SCC was 0.338. The slightly higher w/cm ratio can reduce strength in the HS-SCC. The HS-SCC contained a lower CA percentage of 28% of the total weight when compared to the 45% CA by weight in the HSC. Furthermore, the HS-SCC utilized a softer limestone when compared to the stiffer granite which can contribute to differences in strength and creep. Finally, the air entrainment in the HS-SCC mix can lower the strength of the concrete when compared to the HSC which did not contain any air entrainment (Khayat et al., 2009).

The average modulus of elasticity (MOE) is slightly higher for HS-SCC than HSC. It can be expected that the HSC mix would have a higher MOE due to larger amounts of stiffer granite CA when compared to the softer limestone in the HS-SCC (MacGregor, 2005). When compared to empirical values obtained from ACI 318-08 (ACI, 2008) and ACI 363-10 (ACI, 2010), equations (1) and (2) shown below, the experimental values of HS-SCC and HSC were much lower than predicted. Graphs comparing the results of HSC and HS-SCC to the ACI equations are illustrated in Figure 4. The HSC values were closest to the ACI 363-10 relationship, and HS-SCC values were closest to the ACI 318-08. Due to differences in results between measured and empirical values, more research is recommended to better understand the mechanical properties of HS-SCC such as MOE.

\[
E_c = w_c^{1.533} f'_c^{0.33} \text{ (psi)} \quad \text{ACI 318-08 (1)}
\]

\[
E_c = 4.86 \times 10^6 k_1 k_2 \left( \frac{w_c}{150} \right)^2 \left( \frac{f'_c}{8700} \right)^{1/3} \text{ (psi)} \quad \text{ACI 363-10 (2)}
\]
Typically the w/cm ratio and aggregate type will affect the degree of shrinkage (MacGregor, 2005). Since the HS-SCC mix had a higher w/cm ratio and a softer CA, it could be reasoned that the HS-SCC mix would have greater shrinkage. In this study, however, the HSC had a higher degree of shrinkage. In a previous study, it was discovered that concrete containing limestone displayed less shrinkage when compared to a stiffer aggregate, such as gravel, due to a possible chemical reaction between the paste and limestone creating a stronger bond at the interface zone (All-Attar, 2008). The type of aggregate within the mix could have played a more significant roll on shrinkage because of the w/cm ratio values being relatively close.

TEMPERATURE RESULTS

A VWSG with an embedded thermistor was placed between each prestressing strand to record the internal temperature and strain during fabrication and service life of the beams and deck panels. During hydration, the HSC beam reached a peak temperature of 61.6°C (143°F), and the HS-SCC reached a maximum temperature of 58.0°C (136°F) at the center of the beam. The hydration temperature was slightly higher for the HSC mix than for the HS-SCC (MacGregor, 2005). The increase in temperature could be accredited to the HSC mix containing slightly higher levels of cement when compared to the HS-SCC (MacGregor, 2005).

The temperature of both bridges was monitored after erection on September 28, 2009, to the current date. Daily maximum temperatures are displayed for both the HSC and HS-SCC in Figures 5. Additionally, temperature profiles from within the HSC and HS-SCC bridges from the highest positive gradient on March 23, 2010, at 3:00 pm are compared to the AASHTO LRFD 2007 for Zone 2 in Figure 6 (AASHTO, 2007).
HSC and HS-SCC have similar temperature profiles. However, HS-SCC appears to have a larger thermal gradient when compared to the AASHTO LRFD model and the HSC results. However, continued research is recommended to determine a more accurate model to predict the temperature gradient within HS-SCC.

SUMMARY

This paper provided a description of two bridges, instrumentation system, and material testing program utilized to determine the difference in performance between HSC and HS-SCC. Currently, the following observations have been made:
1. The modulus of elasticity observed was lower than predicted by current empirical models. Furthermore, HSC MOE models did not accurately predict the MOE for HS-SCC.
2. The compressive strength, split tension, and MOR was higher for HSC than HS-SCC.
3. The creep of the concrete was greater for HS-SCC than HSC.
4. The shrinkage of concrete was observed to be slightly greater for HSC than HS-SCC.
5. The hydration temperature of HSC was slightly higher than that of HS-SCC. The temperature profiles of HSC and HS-SCC are fairly close to one another. However, the HS-SCC temperature gradient is slightly higher than that of HSC.

A load test is planned to determine the differences in deflection and serviceability between the material types. Continued monitoring will occur to determine later age mechanical and material properties.

REFERENCES

American Concrete Institute (ACI 318-08), “Building Code Requirements for Structural Concrete”, American Concrete Institute, Detroit, Michigan, 2008.
American Concrete Institute (ACI 363-63), “Report on High Strength Concrete,” American Concrete Institute, Detroit, Michigan, 2010.