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Comparison of Conventional and Self-Consolidating Concrete for Drilled Shaft Construction

by

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16. Abstract

Many entities currently use self-consolidating concrete (SCC), especially for drilled shaft construction. This project investigated the use of SCC and various test methods to assess the suitability of SCC in underwater placement conditions. Eight mixtures were prepared in the laboratory; the fresh properties of slump-flow, J-ring, set time, and washout characteristics were measured. Hardened properties tested included compressive and flexural strength, modulus of elasticity, and surface resistivity.

The fresh concrete results of SCC showed that SCC produced with a No. 8 crushed stone or No. 8 gravel is adequate in terms of workability and strength with the use of a high range water reducer. The L-box test results were varied across all mixtures and the method was abandoned in favor of the washout test. The washout test results showed that for SCC mixtures being placed in an underwater condition, the addition of a VMA greatly enhances the resistance of said concrete to washout.

Compressive and flexural strengths showed that SCC will be adequate for nearly all structural concrete and drilled shaft applications. The modulus of elasticity values for mixtures tested were slightly increased compared to traditional concrete values showing that the SCC mixtures are particularly suited for drilled shaft construction.

Surface resistivity values were slightly depressed for laboratory mixtures at 28-days of age, but field cast SCC mixtures will incorporate, not only additional SCMs but a greater proportion of SCMs, leading to increased resistivity values to meet the specification.
Field construction results showed that the mixture was resistant to washout, exhibited excellent workability properties, and had excellent strength characteristics.

The authors recommend incorporating SCC into the standards and specifications for Departmental use. At a minimum, Sections VIII and IV should be amended to include appropriate language allowing the use of said mixtures. The use of SCC in an underwater placement condition should require the use of a viscosity modifier.

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ABSTRACT

Many entities currently use self-consolidating concrete (SCC), especially for drilled shaft construction. This project investigated the use of SCC and various test methods to assess the suitability of SCC in underwater placement conditions.

Eight mixtures were prepared in the laboratory; the fresh properties of slump-flow, J-ring, set time, and washout characteristics were measured. Hardened properties tested included compressive and flexural strength, modulus of elasticity, and surface resistivity.

The fresh concrete results of SCC showed that SCC produced with a No. 8 crushed stone or gravel is adequate in terms of workability and strength with the use of a high range water reducer.

The L-box test results varied across all mixtures and the method was abandoned in favor of the washout test. The washout test results showed that for SCC mixtures being placed in an underwater condition, the addition of a viscosity modifying agent (VMA) greatly enhances the resistance of said concrete to washout.

Compressive and flexural strengths showed that SCC will be adequate for nearly all structural concrete and drilled shaft applications. The modulus of elasticity values for mixtures tested were slightly increased compared to traditional concrete values showing that the SCC mixtures are particularly suited for drilled shaft construction.

Surface resistivity values were slightly depressed for laboratory mixtures at 28-days of age, but field cast SCC mixtures will incorporate, not only additional supplementary cementitious materials (SCMs) but a greater proportion of SCMs, leading to increased resistivity values to meet the specification.

Field results showed excellent placeability with little to no segregation and washout of the concrete during placement operations. Workability and strength values were excellent.

The authors recommend incorporating SCC into the standards and specifications for Departmental use. At a minimum, Sections VIII and IV should be amended to include appropriate language allowing the use of said mixtures. The use of SCC in an underwater placement condition should require the use of a viscosity modifier.

ACKNOWLEDGMENTS

The U.S. Department of Transportation, Federal Highway Administration (FHWA), Louisiana Department of Transportation and Development (DOTD), and Louisiana Transportation Research Center (LTRC) financially supported this research project.

The efforts of Greg Tullier, Norris Rosser, and Craig Johnson in the concrete laboratory are greatly appreciated.

IMPLEMENTATION STATEMENT

The authors recommend full implementation of SCC. Specifications for inclusion in part IX of the Standard Specifications have been recommended to include the use of SCC mixtures. In addition, the use of VMA is recommended for underwater placement. SCC mixtures may realize a cost savings in terms of speed of construction and better overall construction quality.

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INTRODUCTION

Significant anomalies have been observed in many of the recently drilled shaft construction projects throughout Louisiana. The anomalies typically occur in the form of honeycombing within the zones of heavy reinforcement or sometimes at the shaft bottom. Self-Consolidating Concrete (SCC) has shown great potential to overcome the difficulties as noted in some pilot studies. As an example, SCC was used in the drilled shafts for the Huey P. Long Bridge in New Orleans and performed satisfactorily. In contrast to the Huey P. Long Bridge, conventional concrete was used for the Audubon Bridge. Problems were noted in the construction as well as the shaft resistance. Both projects consist of large size shafts constructed in the Mississippi River in similar conditions.

Literature Review

This section will detail past research work completed in SCC and the current state-of-the-practice. Case studies in the U.S. are also presented.

SCC is a concrete that is able to flow and consolidate under its own weight. SCC will completely fill the formwork even in the presence of dense reinforcement while maintaining homogeneity without the need for additional compaction. The American Concrete Institute (ACI) defines SCC as," . . . highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any consolidation." [*1*] Several states have implemented the use of SCC for such applications including precast structural members and drilled shafts.

SCC can be produced by one of three methods: powder, viscosity, and a combination thereof. A powder type uses large amounts of cementitous materials with a low water to cementitious materials ratio (w/cm) to provide viscosity and the yield stress is controlled by the amount of superplasticizer. The viscosity type uses a lower total cementitous content and incorporates a viscosity modifying agent (VMA) to control segregation resistance and yield stress. The combination type uses both increased powder content and chemical admixtures, including VMA and superplasticizer, to control the segregation resistance and yield stress.

State-of-the-practice

SCC is a relatively new technology in the U.S., but has been used widely throughout Japan and Europe since the late 1980s and has gained wide acceptance in both locals [*1, 2*]. The advantages of SCC are enumerated in ACI 237R including: reduced labor and equipment, accelerated construction, facilitated filling of heavily reinforced and complex sections, increased designer flexibility for reinforcement placement, and smoother surface finish with reduced honeycombing [*1*].

A state highway agency (SHA) survey was completed in 2008 by the Missouri Department of Transportation to determine the extent of SCC implementation and use among various SHAs. Twenty-five SHAs responded and 22 out of 25 respondents noted that they were already using or considered using SCC in 2008. Sixteen were using it in precast applications, and three states responded that they allow it in prestress concrete applications. In 2008, six SHAs noted that they have used SCC for cast-in-place applications. The survey also noted that the main problems with SCC included retention of flowability, lack of experience or familiarity of contractors, segregation, and batch to batch consistency [*3*].

Case Studies

Ozyildirim and Davis investigated bulb-T beams cast with SCC in Virginia. Two 45-inch deep, 60-ft. long test beams were cast with SCC and tested to failure at Federal Highway Administration's (FHWA's) Turner-Fairbank Highway Research Center. Results showed that the test beams behaved at least as well as normally consolidated concrete beams. Eight 74-ft. long, 45-in. Bulb-T beams were cast with SCC and used on the Route 33 Bridge over the Pamunkey River. The research team indicated that they were able to maintain necessary slump flow without segregation with minimal slip between strands and the concrete showing satisfactory bond [*4, 5*].

ACI 237R provides several case studies where SCC was used successfully in North America [*1, 3*].

The Connecticut Department of Transportation commissioned a state-of-the-art review of SCC and recommendations of their review included workability test requirements with specific results for filling ability, passing ability, static stability, and air volume [*3*].

NCHRP Report 628 results showed that common test methods such as slump flow and J-ring can be used to assess the workability characteristics of SCC. The researchers suggested a target value of 23.5 – 29 in. slump flow and 21.5 – 26 in. J-ring value as target values for acceptance. Other notable conclusions include a low w/cm between 0.34 and 0.40 with coarse aggregate at 0.5 in. maximum size. The use of a VMA is recommended to increase the robustness and homogeneity of the SCC. Increased binder contents lead to increased shrinkage. Structural performance of girders is discussed along with other Load and Resistance Factored Design (LRFD) code requirements [*2*].

OBJECTIVE

The objectives of this research were to study the suitability of SCC in drilled shaft construction, determine applicable test methods and acceptance criteria to show and limit washout potential, and demonstrate the methods and materials in a test drilled shaft.

SCOPE

To meet the objectives of this project, samples were produced under laboratory conditions with several mixtures of SCC targeting a 28 to 30 in. slump flow. Fresh properties of slump flow, J-ring, air content, and set time were measured for each mixture. Washout characteristics were determined using the L-box test and U.S. Army Corp. of Engineers (USACE) washout test. Compressive strength was measured at 7- and 28-days of age. Flexural strength, surface resistivity and modulus of elasticity were measured at 28-days of age. A test drilled shaft was placed on the U.S. 80 bridge construction project near Ada, LA.

METHODOLOGY

Materials

The cementitious materials used in the laboratory portion of the study included type I/II portland cement, class C fly ash, and grade 120 slag. The portland cement was from Festus, MO. The class C fly ash was from Headwaters Big Cajun, in New Roads, LA. The grade 120 slag was from Buzzi Unicem New Orleans, LA.

X-ray fluorescence (XRF) was used to determine the chemical constituents of the cementitious materials used in the study. Eight different mixtures were prepared and tested for this study. Control mixtures incorporated No. 67 limestone and No. 67 gravel to produce SCC using both water and a superplasticizer as the slump increasing agent. These mixtures incorporated 564 pounds of total cementitous materials content with class C fly ash incorporated at a 20 percent replacement weight. The initial w/cm was targeted at 0.45 and the coarse to fine aggregate ratio was kept near 60:40.

Traditional SCC was also produced using No. 8 gravel and No. 8 limestone with superplasticizer. Additionally, the No. 8 gravel and limestone mixtures were produced incorporating a VMA. These mixtures incorporated 800 pounds of total cementitous materials content with 25 percent replacement of class C fly ash and 25 percent replacement of grade 120 slag. The target w/cm for these mixtures was 0.33 and the sand to No. 8 materials ratio was kept near 50:50.

Test Methods

Fresh Concrete Property Test Methods

The following test methods were used in characterization of the fresh concrete properties of SCC.

- ASTM C138 [Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete] [*6*]
- ASTM C231 [Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method] [*7*]
- ASTM C403 [Standard Test Method Time of Setting of Concrete Mixtures by Penetration Resistance] [*8*]
- ASTM C1611 [Standard Test Method for Slump Flow of Self-Consolidating Concrete] [*9*]

- ASTM C1621 [Standard Test Method for Passing Ability of Self-consolidating Concrete by J-Ring] [*10*]
- CRD-C 61-89A [Test Method for Determining the Resistance of Freshly Mixed concrete to Washing Out in Water] [*11*]

The L-box test, test apparatus shown in Figure 1, was used in determining the flow characteristics of SCC. The test method involves a steel box in the shape of an L with a gate that is opened to allow concrete to flow into the open channel. The difference in height is measured to determine the self-leveling capabilities of the material. The time to flow from one end of the box to the other is also measured. This test provides an indication of the static and dynamic segregation resistance of SCC.

Figure 1
L-box test apprаratus

Hardened Concrete Property Test Methods

The following test methods were used in characterization of the hardened concrete properties of SCC. All samples were produced in triplicate.

- ASTM C39 [Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens] [*12*]
- ASTM C78 [Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)] [*13*]
- ASTM C469 [Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression] [*14*]
- DOTD TR 233 [Test Method for Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration] [*15*]

DISCUSSION OF RESULTS

Materials Results

The XRF results show that the cementitious materials used in the study are representative of those used in everyday construction projects throughout the state of Louisiana and conform to applicable ASTM, AASHTO, and DOTD standards and specifications. Table 1 shows the XRF results for the cementitious materials used in the laboratory test factorial. Note that all values are in percentage of the oxide.

Table 1
XRF results for the cementitious materials used in the laboratory test factorial

Oxide	Type I/II Portland Cement	Class C Fly Ash	Grade 120 GGBFS
SiO_2	20.24	35.04	34.77
Al_2O_3	4.45	19.30	10.73
Fe_2O_3	3.47	5.32	0.56
CaO	63.28	24.98	40.52
MgO	3.82	5.48	11.99
Na_2O	0.22	1.95	0.29
K_2O	0.44	0.46	0.38
TiO_2	0.28	1.36	0.60
SO_3	2.62	2.81	0.41
LOI	1.10	0.60	0.20

Fresh Concrete Properties

This section will detail the fresh concrete properties for the laboratory test matrix consisting of eight mixtures. Table 2 shows the fresh concrete properties of slump-flow, J-ring, air content, unit weight, and initial and final set time for each mixture. The results are as expected for SCC. Note that the set times for mixture four were measured, but the data was lost between measurement and permanent recording in the project database. Based upon other mixture results, the time to initial set and final set would be similar to mixtures three and five. Mixtures 1 – 4 contained either 67 gravel or 67 limestone as the large aggregate source, and mixtures 5 – 8 contained either No. 8 crushed stone or No. 8 gravel.

Table 2
Fresh concrete properties for the laboratory test matrix mixtures

Mixture	w/cm	Slump – flow (in.)	J-Ring (in.)	Air (%)	Unit Weight (pcf)	Initial Set Time (hours)	Final Set Time (hours)
1 – C4115	0.50	31.0	23.0	1.2	145.1	> 8	>8
2 – C4116	0.33	27.0	24.0	1.9	148.0	> 8	>8
3 – C4117	0.47	25.3	22.0	4.9	146.8	6.55	8.27
4 – C4118	0.33	26.5	24.0	1.5	153.4	*	*
5 – C4119	0.33	26.5	27.0	6.4	141.7	6.33	7.97
6 – C4120	0.33	24.0	20.0	3.3	148.2	6.72	8.10
7 – C4121	0.33	31.0	31.0	6.4	141.8	7.13	9.07
8 – C4122	0.33	23.0	20.0	5.8	141.6	6.68	8.43

***Denotes mixture tested, but data lost**

Segregation is a concern with SCC mixtures and the slump flow test will indicate if segregation is occurring by showing a mortar halo upon completion of the test. A mortar halo is when the aggregate fraction of the mixtures stops flowing laterally, but the mortar and paste fraction of the mixture continues. Mixtures one and three exhibited an extreme mortar halo (red arrows) similar to the one depicted in Figure 2. The halo indicates that the mixture is segregating and would not be suitable for SCC. This is expected for these mixtures as they were produced by taking conventional concrete and adding water until they produced a concrete with acceptable slump-flow properties.

Figure 2
Left: Segregated SCC with a mortar halo indicated by red arrows;
Right: Proper SCC consistency

The J-ring test results, when combined with the slump flow test results, show that mixtures five and seven are well suited to not block. The authors note that even though the difference between J-ring and slump-flow test results may indicate blocking (i.e., a difference greater than 1 in.) for mixtures six and eight, that will most likely not be the case in a real world application since the coarse aggregate fraction is a No. 8 crushed stone or a No. 8 gravel.

The L-box test was also evaluated for this project. The authors noted that although the test method is not yet a standard, it is a widely used test for determining underwater resistance to washout. In this study, the results for L-box test method were highly variable, and often not obtainable due to the high speed of the SCC moving through the L-box. With this information, the L-box test was determined to be unreliable.

The L-box test results led the team to investigate other methods for determining washout resistance of fresh concrete. The most promising method found was the Army Corp. of Engineers test method CRD-C 61-89A [*12*]. This test method involves preparing a small sample (about 2000 g) of plastic concrete in a perforated container, dropping it through a column of water repeatedly, and measuring the mass loss. This test method was evaluated as it simulates perfectly what occurs when placing concrete in an underwater application for a drilled shaft and throughout the rest of the paper is referred to as the washout test. Figure 3 shows the washout test equipment.

Figure 3
Left: Water tube
Right: Perforated container

Figure 4 shows the results for the washout test. The chart shows the cumulative % loss for the four runs of the test. Mixtures 4119, 4120, and 4122 exhibited great washout resistance with less than 25 percent total mass loss as compared to the other mixtures tested in this study. The washout resistance mixtures 4120 and 4122 can be attributed to the addition of a viscosity modifier to the mixture. Figure 5 shows the end result of the washout test for a No. 67 stone mixture. Note the lack of cement paste remaining in the mixture. Figure 6 shows the end result of the washout test for a No, 8 pea gravel mixture with no VMA. Note the lack of cement paste remaining in the mixture. Figure 7 shows the end result of the washout test for a No.8 pea gravel mixture incorporating a VMA. Note the majority of the cement paste structure is still remaining in the sample. These photographs show that the addition of a VMA is an absolute must when considering washout potential of SCC.

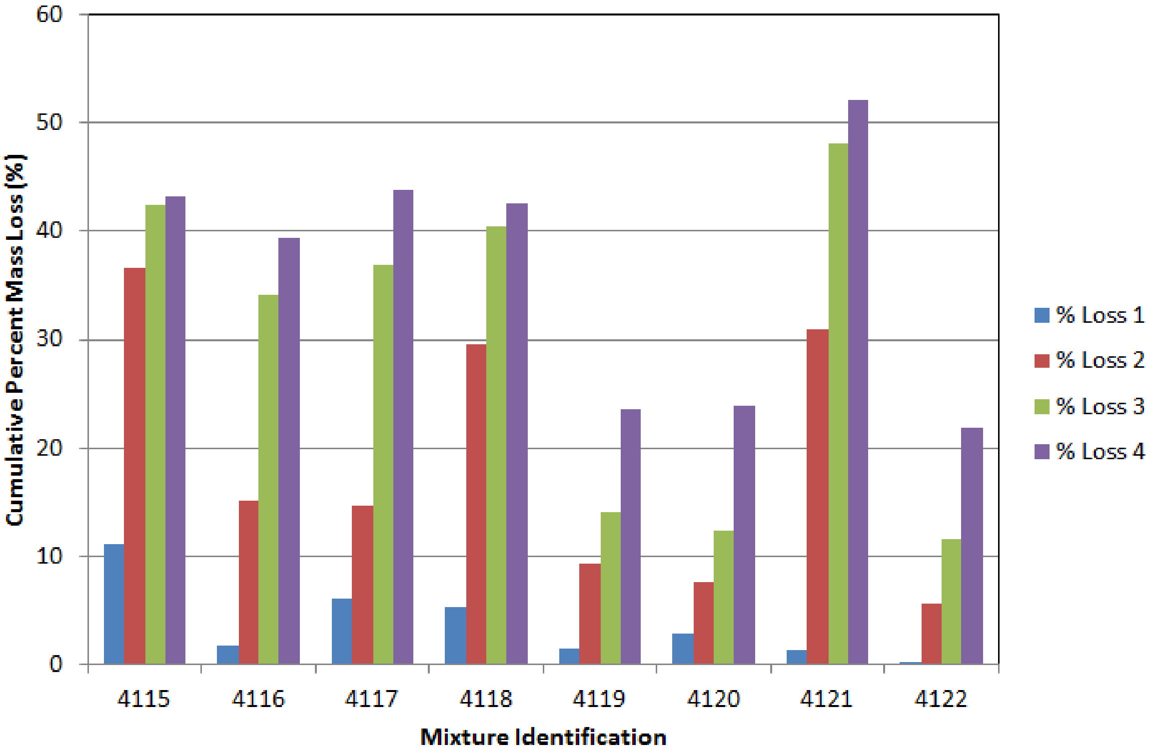

Figure 4
Washout test results showing cumulative percent mass loss for all mixtures

Figure 5
Washout test result for a No. 67 stone mixture showing no cement paste

Figure 6
Washout test result for a No. 8 pea gravel mixture showing no cement paste

Figure 7
Washout test result for a No. 8 pea gravel mixture incorporating a VMA showing cement paste

Hardened Concrete Properties

The hardened concrete properties measured for all mixtures were as expected. The mixtures contained significant cementitous content; therefore the strengths were adequate for drilled shaft and will also meet structural concrete required strengths. The compressive strength results are shown in Figure 8.

Flexural strength results followed the compressive strength results and are shown in Figure 9. Note that all mixtures exceeded 650 psi flexural strength.

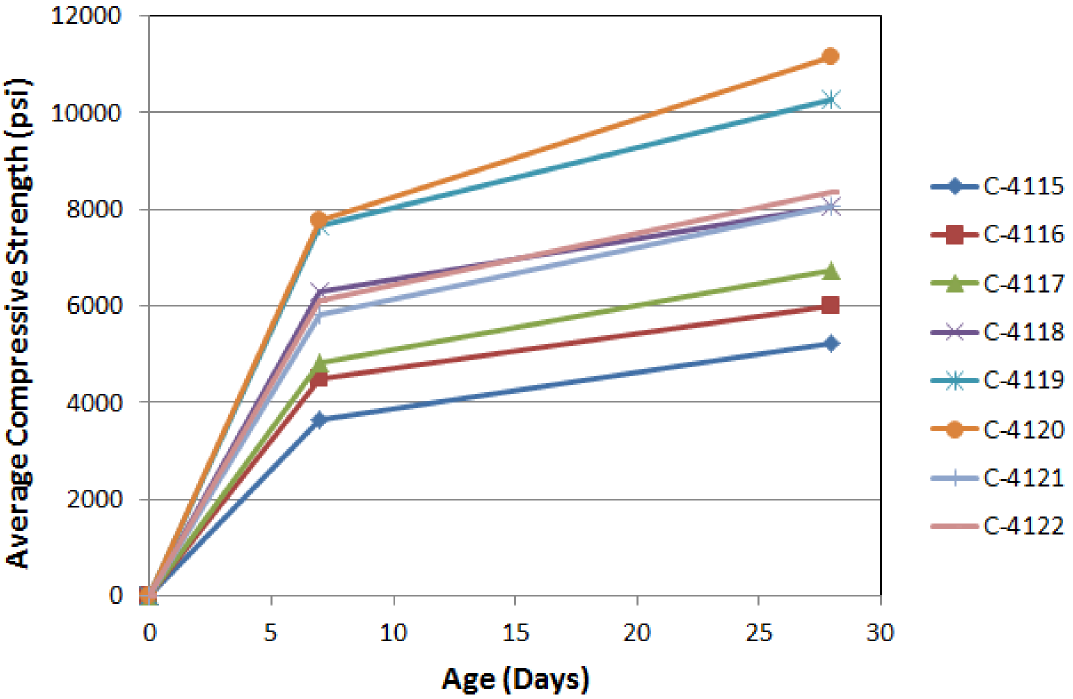

Figure 8
Average compressive strength results for all mixtures

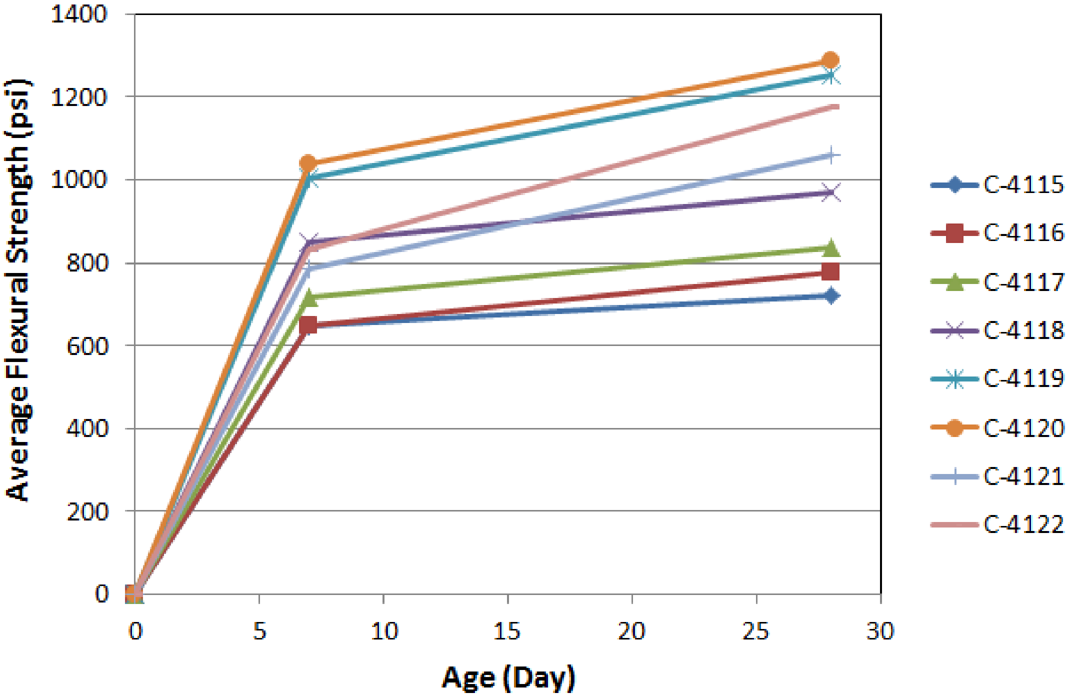

Figure 9
Average flexural strength results for all mixtures

The modulus and Poisson's ratio results for the mixtures were slightly higher than expected with the average modulus of elasticity results being between 5.9 and 7.3 million psi. Traditionally, concrete moduli of elasticity results are between 4 and 6 million psi. The increased modulus of elasticity shows that these mixtures are ideal for drilled shaft construction. Table 3 shows the average modulus of elasticity and Poisson's ratio results for all mixtures.

Table 3
Average modulus of elasticity and Poisson's ratio results for all mixtures

Mixture	Modulus of Elasticity (millions psi)	Poisson's Ratio
1 – C4115	6.50	0.30
2 – C4116	6.35	0.16
3 – C4117	5.90	0.14
4 – C4118	5.70	0.26
5 – C4119	7.30	0.28
6 – C4120	5.90	0.24
7 – C4121	6.13	0.20
8 – C4122	5.65	0.14

The surface resistivity results for these mixtures were not quite what the research team expected with the values being lower than expected. Table 4 shows the average surface resistivity results for all mixtures. The team expected resistivity values between 25 and 35 kΩ-cm and only two mixtures (4119 and 4120) met that expectation. The remaining mixtures fell below 20 kΩ-cm. Although the laboratory resistivity values fell below the newly specified 27 kΩ-cm at 28-days of age, the authors are quick to note that for concrete placements such as these generally a more increased SCM content is used by producers and those mixtures will meet the new requirements. This will lead to most mixtures meeting the specification with little effort when implemented and should not be a concern for the Department.

Table 4
Average 28-day surface resistivity results on 4 in. x 8 in. diameter cylinders for all mixtures

Mixture	**Surface Resistivity (kΩ-cm)**
1 – C4115	10
2 – C4116	14
3 – C4117	15
4 – C4118	18
5 – C4119	31
6 – C4120	27
7 – C4121	18
8 – C4122	19

Field Construction Results

The U.S. 80 bridge construction project location is shown in Figure 10. A drilled shaft consisting of about 50 cubic yards of concrete was constructed on the west side of the railroad tracks and the concrete material and placement techniques were evaluated using the spread test, air content, and compressive strength at 7 and 28-days of age.

Table 5 shows the fresh and hardened concrete test results. Note that the spread for the first truck was low, but 10 gallons of water were added to the truck and the slump-flow increased to 25-inches. The compressive strength results show that the material is sufficiently strong with the results between 6100 and 7400 psi and 8100 and 10,000 psi for 7 and 28-day results, respectively.

The fresh and hardened concrete results showed that the mixture was resistant to washout and exhibited excellent workability properties with acceptable strengths. Cross-hole sonic logging was completed for the drilled shaft constructed with SCC. The results were satisfactory according to the DOTD Geotechnical Group.

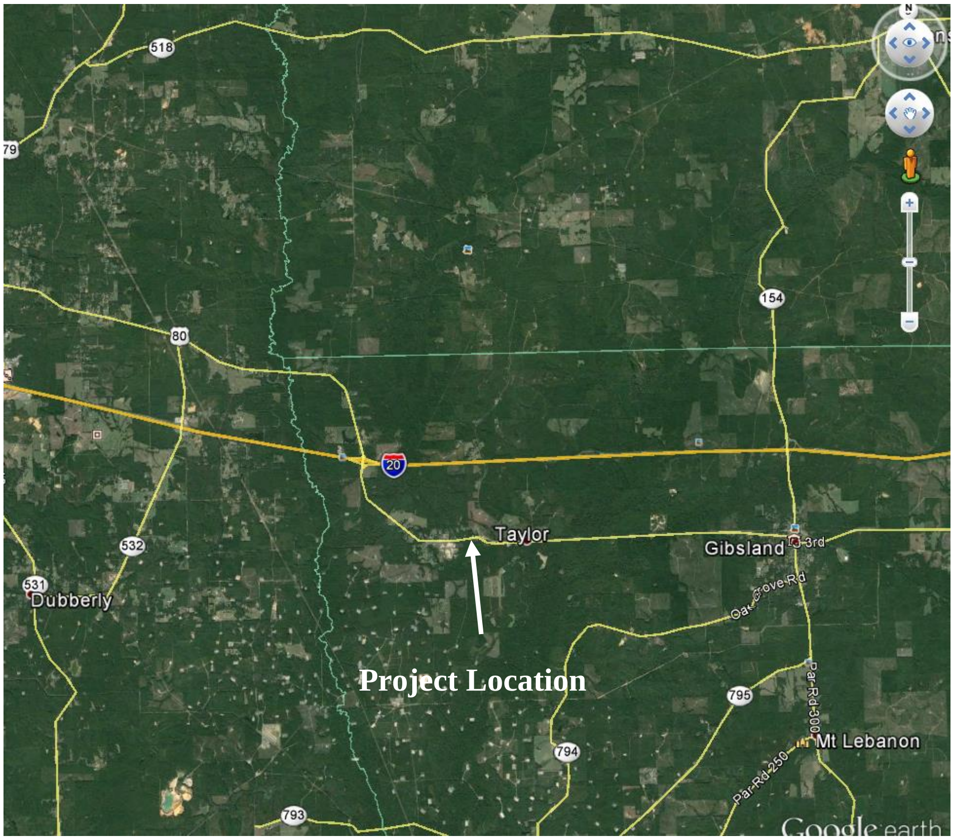

Figure 10
Project location for the U.S. 80 Ada bridge project

Table 5
Fresh and hardened concrete resutls for the field constructed SCC drilled shaft

Truck #	Slump – flow (in.)	Air (%)	Average 7-Day Compressive Strength (psi)	Average 28-day Compressive Strength (psi)
1	19	2.7	7325	9898
4	27.0	1.6	6134	8116

Specification Amendments

The following language is suggested for amending Sections VII and IV of the Department Standards.

The target slump-flow for SCC mixtures is 20 – 28 inches as measured by ASTM C1611. Reject mixtures exhibiting a mortar halo. When placing SCC in underwater conditions, a VMA is required.

CONCLUSIONS

The results of this study warrant the following conclusions. The fresh concrete results of SCC showed that SCC produced with a No. 8 crushed stone or No. 8 gravel is adequate in terms of workability and strength with the use of a high range water reducer.

The L-box test results were varied across all mixtures and the method was abandoned in favor of the washout test. The washout test results showed that for SCC mixtures being placed in an underwater condition, the addition of a VMA greatly enhances the resistance of said concrete to washout.

Compressive and flexural strengths showed that SCC will be adequate for nearly all structural concrete and drilled shaft applications. The modulus of elasticity values for mixtures tested were slightly increased compared to traditional concrete values showing that the SCC mixtures are particularly suited for drilled shaft construction.

Surface resistivity values were slightly depressed for laboratory mixtures at 28-days of age, but field cast SCC mixtures will incorporate, not only additional SCMs but a greater proportion of SCMs, leading to increased resistivity values to meet the specification.

Field construction results showed that the mixture was resistant to washout, exhibited excellent workability properties, and had excellent strength characteristics.

RECOMMENDATIONS

The authors recommend incorporating SCC into the standards and specifications for Department use. At a minimum, Sections VIII and IV should be amended to include appropriate language allowing the use of SCC mixtures. The use of SCC in an underwater placement condition should require the use of a VMA.

Specific specification language should include a note that SCC produced exhibiting a mortar halo when using ASTM C1611 shall be rejected as it is an indication of a high segregation potential. A target spread in the inverted slump method should be between 20 and 28 in.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
PCC	portland cement concrete
FHWA	Federal Highway Administration
QA	quality assurance
QC	quality control
in.	inch(es)
pcf	pounds per cubic foot
DOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
ASTM	American Society of Testing and Materials
w/cm	water to cementitious materials ratio
XRF	X-ray fluorescence
SCC	self-consolidating concrete
VMA	viscosity modifying agent
SCM	supplementary cementitous materials
SHA	State Highway Agencies
ACI	American Concrete Institute
Ft.	feet
USACE	United States Army Corp of Engineers

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