
Research Report No. 2

**EVALUATION OF SELF-CONSOLIDATING CONCRETE
FOR DRILLED SHAFT APPLICATIONS AT THE
LUMBER RIVER BRIDGE PROJECT,
SOUTH CAROLINA**

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ABSTRACT

Case studies have shown that when conventional concrete mixtures are used in congested drilled shafts, lack of adequate workability or flow between reinforcing bars may lead to trapped laitance or segregation between the inside and outside of the reinforcing cage. Due to its flowability and resistance to segregation, the use of Self-Consolidating Concrete (SCC) was evaluated as a viable material to overcome this problem. Several 6 ft diameter drilled shafts were constructed using SCC as part of a field trial during the Lumber River Bridge Project, South Carolina. Identical shafts were constructed with SCC and a very high slump gravel-aggregate concrete mixture typically used in coastal South Carolina. Both mixtures were observed to have excellent workability characteristics. The observations of the hardened concrete from exhumed drilled shafts indicate that generally good performance can be achieved in difficult construction conditions (congested cage, tremie placement, lengthy placement times) if highly workable concrete is utilized. Some imperfections in the concrete were observed, even under these closely monitored conditions, and some degree of imperfection in this type of construction appears to be practically unavoidable. The imperfections observed in these field trials were detected by crosshole sonic logging, but do not appear to have significant adverse consequences to foundation performance. Based on the results of this project, it is concluded that SCC may be feasible for the use in congested drilled shaft applications.

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Chapter 1

INTRODUCTION

Recently developed techniques in integrity and load testing have given engineers and contractors the improved ability to assess the in-place quality of drilled shaft foundations. These techniques have also provided insight to problems that are associated with materials and construction practices that have lead to defects or less than optimal performance in drilled shaft foundations. In recent years, drilled shaft concrete mixtures are facing increased demands for passing ability and flowability. Seismic design considerations have resulted in congested reinforcing cages due to tight spiral and longitudinal steel spacings. Many specifications have not kept appropriate workability considerations as a project specific aspect of drilled shaft concrete to meet these increasing demands. These conditions are an invitation to trap debris around the cage, as the flow through the cage only occurs after sufficient head within the cage is developed to push the concrete through. Some of the most common concreting issues that compromise the quality of drilled shaft foundations come from the failure to consider one or more of the following: 1) blockage of the coarse aggregate due to congested rebar cages, 2) retained workability of the concrete mixture for the duration of the pour, and 3) segregation and bleeding of the drilled shaft concrete (1). Self-consolidating concrete (SCC) is not routinely used for drilled shaft construction in North America; however, due to its flowability and resistance to segregation, the use of SCC was evaluated in this project as a viable material to improve in-place shaft quality.

ACI 237 (2) defines SCC as “highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation.” The high slump concrete traditionally used for drilled shaft construction, has over the years been developed from conventional concrete with the additional fluidity obtained by adding some combination of water and/or high-range water reducing (HRWR) admixtures. In a sense, drilled shaft concrete has traditionally been depended upon to “self-consolidate”, since no vibration is used as an aid to placement. However, the term SCC is generally used with concrete mixtures designed to flow with much greater workability than is commonly specified for conventional drilled shaft concrete.

SCC was first developed by Professor Hajime Okamura in Japan during the 1980s, and it can be produced by a number of approaches (2). One approach involves incorporating a sufficient amount of fine particles (usually from additional cementitious materials) to increase the viscosity necessary to avoid segregation within the mixture. With this approach, the amount of fine aggregate is also increased from the normal 40% to 45-50% by volume of the total aggregate content. Another

approach to develop SCC is one that requires the use of a viscosity-modifying admixture (VMA). The VMA provides the necessary viscosity to the mixture, preventing excessive bleeding and segregation. Yet a third approach is to increase the amount of fine material as well as the use of a relatively small amount of VMA.

As a part of a Federal Highway Administration (FHWA) program for implementation of new technology, a bridge project in South Carolina was used to experimentally evaluate the use of SCC in drilled shaft construction. Fieldwork was performed at the Lumber River bridge replacement on US 76/SC 9 along the Horry and Marion County line, South Carolina. Drilled shafts were constructed as experimental castings and as load test shafts using both SCC and a conventional mixture with high workability. The experimental castings were 6 ft in diameter and 30 ft deep and served as test installations of the two concrete mixtures constructed under slurry. These shafts were exhumed, and cut in several places with a diamond wire saw in order to examine the concrete. Cores were retrieved at various locations to assess the strength, wavespeed, and permeability of the concrete. The load test shafts were 6 ft in diameter and 72 ft deep and were subjected to an equivalent axial static load of 2,500 kips using Statnamic testing. In addition, six piers for one of the bridges at this project were completed with SCC.

This specific report presents the finding and observations from the construction, examination, and testing of the experimental castings and load test shafts. Additional reports were developed for this project, and these documents may be referenced for additional information. The reports developed for this project are:

1) S&ME, Summary Report, September 2005: (3)

This document summarizes all construction observations, on-site testing, additional laboratory test data, as well as field and test reports from SCDOT, Trevilcos (shaft contractor) and Applied Foundation Testing (statnamic testing contractor).

2) Auburn University, Research Report No. 1, October 2005: (1)

This report documents all the laboratory tests that were used to develop and evaluate various SCC mixtures for use in drilled shaft applications. Chapter 3 of this document also provides a summary of some of the common problems associated with drilled shaft foundations.

3) Auburn University, Research Report No. 2, December 2006:

This is the current document and it provides a summary of the overall research work and is the conclusion of this research effort.

Chapter 2

DEVELOPMENT OF SELF-CONSOLIDATING CONCRETE MIXTURE PROPORTIONS

A laboratory-testing program was completed to develop a SCC mixture for the Lumber River Project. The fresh properties evaluated include filling ability, passing ability, segregation resistance, workability over time, bleeding characteristics, and setting (1). The hardened properties include the comparison of the compressive strength, elastic modulus, permeability, and drying shrinkage. Based on the results of the laboratory testing program, the SCC mixture proportions listed in Table 1 were recommended for further evaluation during the construction of full-scale shafts in the Lumber River Project (1).

2.1 CONCRETE REQUIREMENTS

Since the field portion of this project is located in South Carolina, all ordinary drilled shaft concrete (ODSC) mixtures prepared in the laboratory, conformed to specification requirements of the South Carolina Department of Transportation (SCDOT). However, due to the nature of SCC, these mixtures only conformed to the 28-day compressive strength criteria set forth by the SCDOT. No entrained air was required for any of the mixtures. The quality control limits for the SCC mixtures were based on past research and careful consideration of drilled shaft construction requirements (1,3). Hodgson et al. (4) concluded that when SCC is used in drilled shaft applications, a slump flow (5) of approximately 24 in. should provide sufficient workability while showing limited signs of segregation. Based upon this literature, it was concluded that a slump flow of 18 in. would provide an increase in workability compared to ODSC and displace the drilling slurry upward in a uniform motion. The project specification was thus set at a slump flow range of 18 to 24 in. Workability retention was controlled by requiring a slump of no less than 4 in., two hours after completion of concrete placement in the shaft. In addition, a visual stability index (VSI) rating of 1.0 or less was required to limit possible segregation of the mixture (5).

Table 1: Mixture proportions used for test shafts

Item	Mixture Type		
	SCC	SC Coastal	Conventional SCDOT
Target Consistency Requirement	18 to 24 in. Slump Flow	9 to 10.5 in. Slump	7 to 9 in. Slump
Type I Cement Content, lb/yd ³	500	540	560
Class F Fly Ash Content, lb/yd ³	250	162	140
Water Content, lb/yd ³	306	283	289
No. 67 Coarse Aggregate, SSD, lb/yd ³	1071	1020	1778
No. 789 Coarse Aggregate, SSD, lb/yd ³	395	775	0
Fine Aggregate Content, SSD, lb/yd ³	1366	1149	1181
Water-to-Cementitious Materials Ratio	0.41	0.40	0.41
Sand-to-Total Aggregate Ratio (by volume)	0.48	0.39	0.40
Extended-Set Control Admixture, oz/cwt	9	4	4
Viscosity-Modifying Admixture (VMA), oz/cwt	2	0	0
Mid-Range Water Reducing Admixture, oz/cwt	4	0	8
HRWR Admixture, oz/cwt	10	9	0

2.2 MATERIAL PROPERTIES

All aggregates and cementitious materials were obtained from sources in South Carolina. The main properties of the raw materials are as follows:

- **Type I Portland Cement:** Manufactured by Giant Cement Company located in Harleyville, South Carolina. Tricalcium silicate (C₃S) of 65.28%, Dicalcium silicate (C₂S) of 9.03%, Tricalcium aluminate (C₃A) of 6.69%, Tetracalcium aluminoferrite (C₄AF) of 10.77%, Na₂O + 0.658K₂O of 0.15%, Blaine specific surface area of 367 m²/kg, and a specific gravity of 3.15.
- **Class F Fly ash:** Supplied by the SEFA Group in Wateree, South Carolina. Calcium oxide (CaO) of 1.7% and Silicon dioxide (SiO₂) of 52.19%, Blaine specific surface area of 350 m²/kg, and a specific gravity of 2.28.
- **Coarse Aggregates:** River gravel obtained from the Marlboro Quarry, South Carolina that consisted of No. 67 and No. 789 gradation. Saturated-surface dry specific gravity of 2.65, and absorption capacity of 0.40.
- **Fine Aggregate:** Natural river sand obtained from the Marlboro Quarry, South Carolina that consisted of a South Carolina FA-10 gradation, which met the fine aggregate gradation

requirements of ASTM C 33. Saturated-surface dry specific gravity of 2.63, and absorption capacity of 0.50.

- **Chemical Admixtures:** A polycarboxylate-based mid-range and high-range water reducing (HRWR) admixtures were used. All chemical admixtures were provided by BASF Admixtures, Inc., formerly known as Master Builders Technologies. PolyHeed 1025 was used as mid-range water reducing admixture and Glenium 3030 NS was used as HRWR admixture, which can be classified as a ASTM C 494 Type F high-range water reducing admixture. Delvo Stabilizer was used as ASTM C 494 Type B retarding and Type D water reducing and retarding admixture. Rheomac 358 was used as a polyethylene glycol based viscosity modifying admixture (VMA).

2.3 MIXTURE PROPORTIONS

Two mixtures were used during the fieldwork phase of this project; these included the SCC mixture and the “conventional-slump” drilled shaft mixture (the latter referred to herein as the SC Coastal mixture). The proportions of these mixtures are summarized in Table 1. Also shown for comparison, are the proportions of a conventional drilled shaft mixture typically utilized in South Carolina. Prior to construction, the field performance of the SCC mixture was evaluated by producing a 4 yd³ batch at the concrete producers plant under warm weather conditions. The SC Coastal mixture was actually a mixture with workability higher than what the SCDOT specifications normally allow, utilizing a rounded gravel aggregate and slump ranging from 9 to 10.5 in. This mixture (or similar) has been used with success on numerous bridge projects in coastal South Carolina, where rounded gravel aggregates are available and the need for high workability is recognized. Most of the drilled shafts in this area are large and deep due to poor soil conditions, are designed with congested rebar cages due to seismic detailing requirements, and the construction is typically performed using tremie placement under slurry. The following noteworthy features are present in Table 1:

- Both the SCC and SC Coastal mixtures use a blend of pea gravel (No. 789 gravel) and larger size (No. 67) gravel. This blend gave very good workability and passing characteristics.
- The SC Coastal mixture also utilized water reducers to achieve an unusually high slump compared to most conventional drilled shaft mixtures. Conventional drilled shaft concrete is typically specified to have slump ranging from 7 to 9 inches for tremie placement (6).
- The workability characteristic of the SCC mixture is based on a measurement of slump flow rather than slump. Slump flow is determined by placing the mixture within a conventional slump cone (without rodding) on a nonabsorbant surface, then withdrawing the slump cone and measuring the diameter of the resulting concrete “patty”. The slump flow test has recently been standardized in ASTM C 1611 (5).

- The SCC mixture utilizes a high sand-to-total aggregate ratio and a higher fly ash content than the other drilled shaft mixtures. Even though the SCC mixture has the highest total cementitious content, its portland cement content is the lowest of all mixtures. The reduced portland cement content and the use of a supplementary cementitious material such as Class F fly ash will help delay setting and reduce the maximum in-place concrete temperatures (7). The increased fines content and the use of a viscosity modifying admixture provides a SCC mixture with high flowability, increased stability (reduced likelihood of segregation of the coarse aggregates), and reduced bleeding.

Chapter 3

SHAFT CONSTRUCTION

The shafts constructed at the Lumber River Project for this study include: 1) two experimental shafts 6 ft in diameter by 30 ft deep to be cast and exhumed, 2) two load test shafts 6 ft in diameter by 72 ft deep, and 3) the foundations of two bridges. One each of the experimental and load test shafts were constructed using SCC and the SC Coastal mixture, respectively. The smaller of the two bridges includes 6 shafts to be constructed using SCC, and the larger of the two bridges includes 20 shafts to be constructed using the SC Coastal drilled shaft mixture.

3.1 STEEL REINFORCEMENT

All of the shafts for the project include a full-length rebar cage with longitudinal No. 14 bars at approximately 6 in. center-to-center spacing and 6 in. cover, as shown in Figure 1(A). The cage was confined using No. 5 hoops at 6 in. center-to-center over most of the length of the shaft and at 3 in. center-to-center spacing within the upper 12 ft. In addition to the longitudinal bars, there were six metal tubes (approximately 1.5 in. in diameter) tied into the cage for crosshole sonic logging (CSL) tests. Within the upper 13 ft of the shaft, a second cage of column reinforcing was positioned inside the shaft reinforcing, with the column steel composed of No. 11 bars at 5 in. center-to-center spacing and No. 5 hoops at 6 in. on center. The upper 12 ft of the shaft thus represents a very difficult requirement for concrete passing ability and flowability, with the concrete required to flow through two dense cages and one of these cages containing hoops with only 2.37 in. clear space between bars. This space is 3.2 times the maximum coarse aggregate size of 0.75 in.

3.2 DRILLING AND CONCRETE PLACEMENT

The 30 ft long experimental shafts were constructed using bentonite slurry and temporary casing within the upper 15 ft. The shafts extended through interbedded layers of clay and silty sand alluvium. The casing was installed using a vibratory hammer, and then the shaft was excavated using a combination of augers and drilling buckets. Final cleaning of the base was performed first with a flat bottom bucket and then using an air-lift pipe. Inspection of the base was accomplished by sounding with a short section of a No. 14 bar attached to a wire, and the shaft was accepted if the bottom was sound and free of soft debris according to the judgment of the SCDOT inspector.

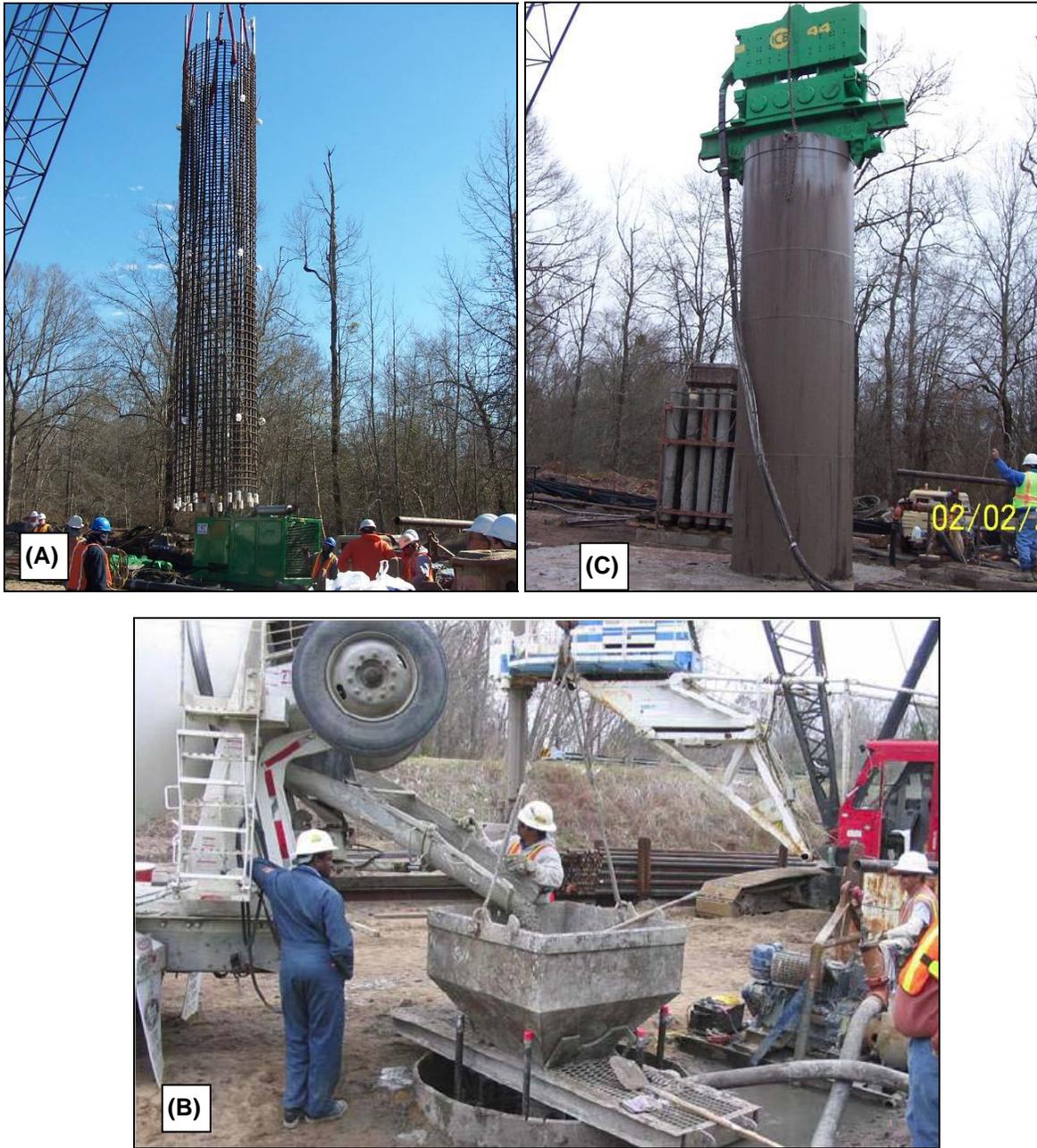


Figure 1: Construction of shafts: (A) Reinforcement cage, (B) Tremie placement of concrete, (C) Removal of permanent casing

After drilling and cleaning, the concrete was placed via a 12 in. diameter segmental tremie pipe. The tremie was placed into the hole as an open tube, as shown in Figure 1(B) and concrete flow was initiated through the tube using a traveling plug. The tremie was maintained at least 10 ft into the concrete at all times; concrete was placed with the tremie held stationary until the concrete was 20 ft

above the tremie discharge end, then the tremie was lifted and a 10 ft section removed. After completion of the shaft, the temporary casing was removed using a vibratory hammer, as shown in Figure 1(C). The load test shafts were constructed in much the same manner, except that the shafts were 72 ft long and they were encased in a 24 ft long permanent casing, which had a 74 in. inside diameter.

In order to evaluate the concrete flow patterns in the experimental shafts, color-dyed concrete was used in portions of the shafts. The 30 ft long shafts required approximately 31 yd³ of concrete for filling, slightly more than 1 yd³/ft of shaft. The first 4 yd³ were dyed black, followed by 16 yd³ of normal gray concrete, followed by 4 yd³ of red concrete, followed by the remainder of the natural gray concrete. Because of the requirement of 10 ft minimum tremie embedment and the segmental tremie composed of 10 ft long sections, the tremie discharge point remained within about 0.3 m (1 ft) of the bottom of the shaft until the 4 yd³ of red concrete was placed. After this load had been discharged (a total of 24 yd³ now in the shaft), the tremie was lifted 10 ft and a section removed so that the subsequent gray concrete started with the tremie 10 ft above the bottom. In order to simulate a potential delay in concrete delivery, an intentional delay of 30 minutes was imposed after the first 24 yd³ had been placed and prior to continuation of concrete placement.

The construction of the shafts occurred easily without significant incident. The concrete from both mixtures appeared to flow very well through the tremie, and at no point was there any difficulty achieving flow from the tremie (even after the intentional 30 minute delay). The jobsite was quite far from the batch plant, and approximately 45 minutes elapsed during traveling for each truck. Other than the two 4 yd³ colored batches and the 30 minute delay, each truck delivered 8 yd³ at approximately 15 minute intervals. Both mixtures had slump (or slump flow) values slightly higher than the target value, with slump for the SC Coastal gravel mixture of around 10 to 10.5 in. and slump flow for the SCC of around 24 to 27 in. Slump and slump flow retention was measured from the start of placement until the completion of each shaft. These tests were performed by keeping a sample of concrete in a sealed container that was stored in the shade. The slump loss for the conventional concrete was 3.5 in. over a period of 2 hrs 33 minutes on the first load and 0.5 in. over 2 hrs on the second load. The slump flow loss for the self-consolidating concrete was 8 in. over a period of 2.5 hrs on the first load and 3 in. over 2 hrs 35 minutes on the second load. After completion of the pour and removal of the temporary casing, both mixtures were observed to discharge significant quantities of bleed water from the surface. The bleed water appeared to be concentrated within the center of the shaft around the location from which the tremie was removed. It was not possible to measure the quantity of bleed water with any degree of precision, but rough visual estimates suggest that a volume of water equal to around 6 to 10 in. of shaft height may have occurred - around 0.5 to 0.75 yd³. The next day after construction, the centers of the shafts were depressed from the reduction in volume.

Chapter 4

ASSESSMENT OF THE QUALITY OF THE EXPERIMENTAL SHAFTS

4.1 CROSSHOLE SONIC LOGGING TESTING

All shafts were subject to integrity testing using crosshole sonic logging (CSL) via the six metal tubes. CSL tests were typically performed 6 to 8 days after casting, at which time concrete compressive strengths determined from cylinders were in excess of 22.8 MPa (3,300 psi). The CSL data revealed large energy attenuations in the upper 4.0m (13 ft) of the SC Coastal shaft; however, a first-arrival time indicative of sound concrete was obtained. The experimental shaft cast with the SCC mixture had an indication of a significant anomaly at a depth of 4.0 m (13 ft) as indicated in Figure 2. This measurement indicated 100% loss of signal between Tube 3 and several other tubes. As will be explained in the following sections, the shaft was exhumed, sawed at the location of the anomaly, and it was revealed that the defect was a soil inclusion lodged in the rebar cage. This is a problem that will be encountered in drilled shaft construction using any type of concrete.

4.2 OBSERVATIONS OF EXHUMED EXPERIMENTAL SHAFTS

After completion of the CSL testing, the two experimental shafts were exhumed for further examination. The exhumed shafts were pressure washed and cut at select locations using a diamond wire saw. Cuts were made across the diameter of the shafts at depths of 1.8 m (6 ft) from the base and 4.0 m (13 ft) from the top (corresponding to the location of the most significant anomaly). Both the bottom 1.8 m (6 ft) long segment and the top 4.0 m (13 ft) long segment were then cut longitudinally through the center, with the cut centered across the shaft through tube numbers 3 and 6. Photographs of the entire operation are shown on Figure 3.

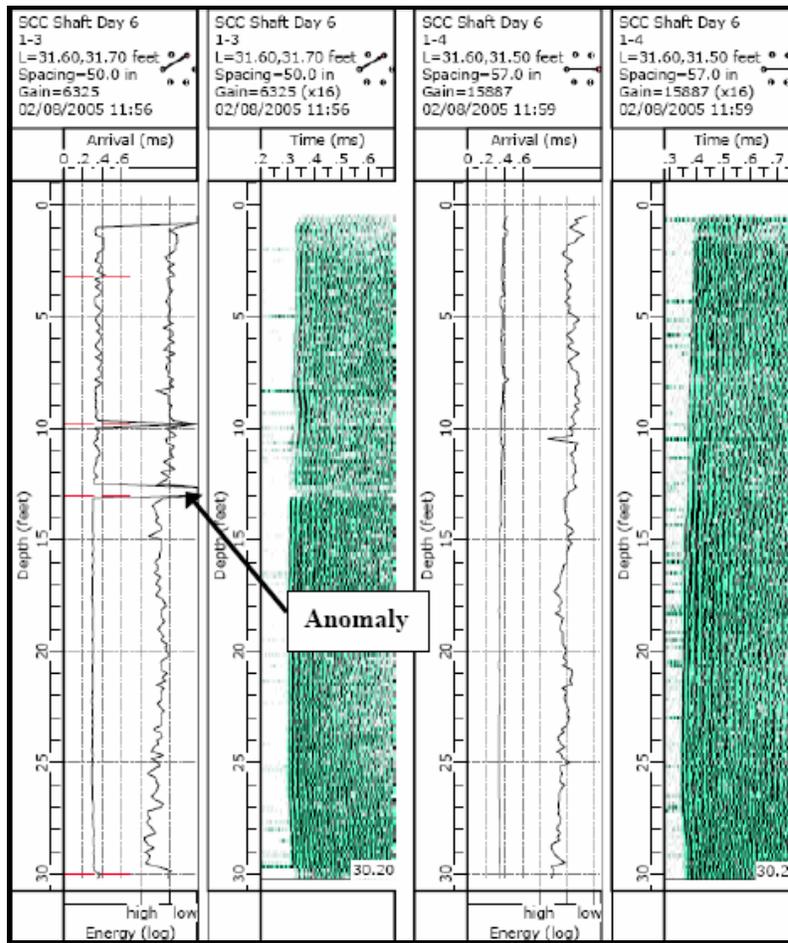


Figure 2: CSL test data from SCC experimental shaft

The exterior surface of both shafts looked excellent, with no appearance of surface irregularities even at the location of anomalies from the CSL data. The bottoms of the shafts showed the pattern left by the clean-out bucket as shown on Figure 3(B). There were some irregularities around the perimeter of the base of the shafts. According to the inspector on the project, the bottom hole soundings were within acceptable tolerance for cleanliness according to typical construction in South Carolina. The following observations are noted from the exhumed shafts:

- The base cleaning process appeared to provide an adequate cleaning of the shaft excavation at this site, even with inspection performed only by sounding in lieu of bottom-hole camera inspection.
- The more fluid SCC mixture resulted in flow very much closer to the tremie as indicated by the differences in diameter of the red concrete in Figures 3(E) and 3(F), and 4(A). The upward flow of concrete from the discharge point on the tremie is apparently confined to a central portion of

the shaft. Some mixing of new fresh concrete with older and previously placed concrete appears to occur, as evidenced by the patterns in Figure 4(B) and the concentric rings of colored concrete present in both shafts.

- Small pockets of trapped laitance or silt occurred as evident in Figure 5. These pockets tended to concentrate between the inner and outer cages, where obstructions cause concrete flow to be disrupted. Note also that the inner cage was displaced at the bottom and the small pocket adjacent to Tube 3 occurred within the space between the tube and the inner cage where the two cages were very close. The large velocity reduction appears to be associated with the near proximity of the inclusion pocket to Tube 3. The size of the inclusions observed in this shaft is not sufficient to produce any measurable reduction in the structural capacity of this shaft.
- Bleed water produced small but visually noticeable channels of vertical erosions (or bleed water channels) about 0.25 to 0.5 in. wide that ranged in length from 3 to 38 in. within the interior upper 13 ft of both shafts. Examples of these channels are shown in Figure 6. It is suspected that bleed water, unable to migrate out laterally in a cased shaft, may be creating vertical flow paths within the shaft and possibly adjacent to the CSL access tubes. No significant defects were detected in the CSL data in the in the upper portion of both shafts, probably because the average modulus of the mass of concrete was not affected to a significant degree. However, the first author is aware of several instances of drilled shaft projects at bridge sites in coastal areas of the Carolinas where unexplained reductions in CSL velocity have occurred within the upper 20 ft of the shaft and only within the center of the shaft; in these cases there was no reduction in velocity between tubes around the perimeter. The small bleed water channels may be a possible explanation of these conditions. Attention to mixture properties in order to avoid excessive bleeding could be of benefit in such instances.
- Although segregation is a logical concern with such highly fluidity concrete mixtures, there was no indication of any significant segregation in either of the exhumed shafts. In fact during the development of the SCC mixture, it was shown that this mixture accumulated significantly less bleed water than the conventional South Carolina drilled shaft mixture when tested with ASTM C 232 (1). There was also no indication of any significant poor-quality concrete at the base of the shaft which could be attributed to mixing in the tremie associated with a poorly performing plug.
- In spite of the use of two very congested rebar cages, both of these highly workable mixtures passed through the cages to fill the surrounding space with sound concrete. There was some trapping of small pockets of laitance or debris, but one would generally conclude that a sound protective cover is provided over the rebar cages by the construction practice used with either of these two mixtures. Note that the cages were designed with a 6 in. cover thickness, which may be helpful in this regard.



Figure 3: Exhuming and cutting of shafts: (A) Exhuming shaft, (B) Bottom 6 ft of shaft, (C) Wire saw cutting operation, (D) SCC Shaft after first cut, (E) Section of SC Coastal shaft, (F) Section of SCC shaft (6 ft from base)



Figure 4: Cut sections of shafts: (A) SC Coastal shaft, view through bottom 6ft (top of photo is bottom of shaft), (B) SCC shaft, View of mixing in upper 13 ft



Figure 5: Cross section at location of anomaly with 100% velocity reduction in CSL measurements



Figure 6: Segregation channels thought to be associated with bleed water: (A) Core from SC Coastal load test shaft, (B) Top portion of SCC experimental shaft

4.3 CONCRETE PROPERTIES

Temperature probes were positioned in the experimental shafts during construction. The concrete temperature at placement was approximately 50°F for both experimental shafts. The concrete temperature recorded in the center of the shafts reached 106 and 97 °F in the SC Coastal and SCC shaft, respectively. These results indicate that the use of a larger cementitious content in the SCC mixture does not necessarily cause an increased in-place temperature in the shaft.

Molded 6 x 12 in. cylinders were made from the fresh concrete delivered to site. These cylinders were moist-cured and produced 28-day compressive strengths of 6,810 and 6,260 psi for

the SC Coastal and SCC shaft, respectively. Both mixtures exceeded the required compressive strength and the slightly higher 28-day compressive strength of the SC Coastal mixture can be attributed to its higher portland cement content.

At a concrete age of around 14 days, a total of 20 cores, 3.74 in. in diameter, were removed from the following distinct areas of each shaft: 1) the interior region within the reinforcement cage, and 2) the cover region outside the hoops. Cores were recovered at depths of 7.5, 13, 18.5 and 24 ft from the top of the shaft, which allows one to compare the hardened concrete properties at various depths. The cores were tested to determine their 14-day compressive strength (ASTM C 39), 14-day pulse velocity (ASTM C 597), and 6-month rapid chloride ion permeability (ASTM C 1202). The results obtained from the cores are summarized in Table 2.

Table 2: Test results obtained from cores

Test	Shaft Type	Location on Cross Section	Approximate Depth of Core from Top of Shaft			
			7.5 ft	13 ft	18.5 ft	24 ft
14-Day Compressive Strength, (psi)	SCC	Interior Region	3,560	6,010	-	6,550
		Cover Region	7,780	3,600	-	5,950
	SC Coastal	Interior Region	2,790	7,845	-	7,640
		Cover Region	6,450	7,530	-	8,365
14-Day Pulse Velocity, ft/sec.	SCC	Interior Region	12,960	13,780	-	14,100
		Cover Region	14,320	12,730	-	14,150
	SC Coastal	Interior Region	12,530	14,200	-	14,150
		Cover Region	13,850	14,610	-	14,580
6-Month Permeability, Coulombs	SCC	Interior Region	1,290	-	2,870	-
		Cover Region	1,020	-	-	-
	SC Coastal	Interior Region	2,670	-	1,250	-
		Cover Region	1,710	-	-	-

Note: - represents data not collected.

The following is a summary of the results obtained from the cores:

- **Compressive Strength:** In general, the cores of both mixtures exhibited strengths in excess of the required design strength. Both mixtures had low results for the cores removed from the *interior region* at a depth of 2.3 m (7.5 ft) from the top of the shaft. This reduced strength may have been caused by the presence of localized bleed water channels. Only at a depth of 13 ft from the top of the SCC shaft, did the strength of the cover region test significantly lower than the strength of the interior region. A visual inspection of the concrete in this area showed no reason why these results were obtained. The strength data reveal that the concrete in the cover region was of acceptable quality.
- **Pulse Velocity:** Wavespeed data, as measured by the pulse velocity meter on cores extracted from the exhumed shafts, were similar for both mixes. The average wavespeed was 14,077 and 13,767 ft/sec. in the SC Coastal and SCC shaft, respectively. There are also only minor differences in the wavespeed data between the interior and cover regions of both mixtures. The wavespeed data also show that the concrete in the cover region was of the same quality as at the interior region of the shaft.
- **Rapid Chloride Ion Permeability:** The rapid chloride ion permeability results varied between 1,020 and 2,870 Coulombs and indicate that both these concretes have a moderate to low permeability as per ASTM C 1202. The *cover region* had the lowest permeability for both shaft types. Interestingly, the two highest permeability values were measured in the *interior region* of the shaft. The permeability test results show that the cover region concrete for this experimental project was of equal or better quality than concrete in the interior region.

Chapter 5

LOAD TEST SHAFTS

Two additional shafts were constructed similarly to the exhumed shafts, except with the addition of the top 24 ft permanent casing and with shaft length of approximately 72 ft. Each of these shafts were loaded using a Statnamic device. The conventional mix shaft was loaded to an equivalent static axial load of 2,462 kips with a total displacement of 0.35 in. and a permanent displacement of 0.19 in. The SCC shaft was loaded to an equivalent static axial load of 2,521 kips with a total displacement of 7.6 mm (0.30 in.) and a permanent displacement of 0.15 in. The geotechnical capacity was not fully mobilized on either shaft. More importantly though, the SCC and conventional mix shafts both performed well and exhibited similar load-displacement behavior.

Chapter 6

SUMMARY AND CONCLUSIONS

The Lumber River Bridge project in coastal South Carolina has provided an opportunity to evaluate the use of self-consolidating concrete and high-workability conventional concrete in drilled shaft construction. Both the SCC mixture and the somewhat unconventional SC Coastal gravel mixture appeared to perform very well under construction conditions that present challenges for concrete placement without defects. The appearance of the base of the shaft with fairly conventional slurry construction techniques suggests that good performance can be obtained with relatively modest attention to quality control and inspection. Some small trapped inclusions were observed and correlated with major loss of signal from CSL test results; these observations suggest that conventional interpretation of CSL data may greatly exaggerate the magnitude of potential defects within the concrete. Small bleed water channels were found within the interior upper 13 ft of both shafts. Mixtures for cased drilled shafts should be proportioned to minimize bleeding under the hydrostatic pressure conditions experienced in these shafts.

Based on the in-place temperatures measured, it was found that the use of a larger cementitious content in the SCC mixture does not necessarily cause an increased in-place temperature in the shaft. The SCC mixture used a larger dosage of Class F fly ash and this reduced the in-place temperature developed in the shaft. Both mixtures exceeded the required compressive strength. Cores were removed from the interior region within the reinforcement cage and from the cover region outside the hoops at various depths. Based on the compressive strength, pulse velocity, and rapid chloride ion permeability data, it may be concluded that the concrete in the cover region was of acceptable quality as compared to the concrete in the interior region. The SC Coastal and SCC shafts were both load tested using a Statnamic device to an equivalent static axial load of around 2,500 kips and both shafts performed well and exhibited similar load-displacement behavior. Based on the performance of the self-consolidating concrete used in this project, it can be concluded that it is a feasible choice for use in drilled shaft construction. The higher slump flow, and subsequent improved workability, could prove especially useful where seismic detailing requirements result in congested reinforcement. As a result of the initial observations from the exhumed shafts and load tests, the drilled shafts for the smaller of the two bridges at this site were successfully constructed by using entirely the SCC mixture.

REFERENCES

- (1) Bailey, J.D., Schindler, A.K., and Brown, D.A. *An evaluation of the use of self-consolidating concrete (SCC) for drilled shaft applications*. Research Report No. 1, Highway Research Center, Auburn University, Alabama, October 2005, 162 p.
- (2) ACI Committee 237. *Self-consolidating concrete*. Emerging technology document, American Concrete Institute, Farmington Hills, Michigan, 2005.
- (3) Holley, D. W., Goldberg, A.D., and Camp, W.M. *Self consolidating concrete (SCC) in drilled shafts research project*. Summary Report for S&ME Project No. 1133-03-670, S&ME, Mt. Pleasant, South Carolina, September 2005.
- (4) Hodgson, D.N., Schindler, A.K., Brown, D.A., and Stroup-Gardiner, M. Self-consolidating concrete (SCC) for use in drilled shaft applications. *ASCE Journal of Materials in Civil Engineering*, Vol. 17, No. 3, 2005, pp. 363-369.
- (5) ASTM C 1611. *Standard test method for slump flow of self-consolidating concrete*. ASTM International, West Conshohocken, Pennsylvania, 2005.
- (6) O'Neill, M.W., and Reese, L.C. *Drilled shafts: Construction procedures and design methods*. Publication No. FHWA-IF-99-025, 1999, U.S. Dept. of Transportation, 537 p.
- (7) Schindler A.K., and Folliard K.J. Heat of hydration models for cementitious materials. *ACI Materials Journal*, Vol. 102, No. 1, 2005, pp. 24-33.