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Preparation and Testing of Drilled Shafts with Self-Consolidating Concrete

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During placement, properties of the fresh concrete were tested and specimens were prepared to determine the hardened properties. The integrity of the shafts within the reinforcing cage was determined using CSL, with sonic echo/impulse response also used to evaluate several test shafts. The use of acousto-ultrasonic (AU) measurements to determine the cover depth outside the reinforcing cage was also evaluated during laboratory testing. In addition to the Route 28 shafts, three test shafts with conventional and SCC concretes were cast in an area headquarters. These shafts had intentional voids created through the use of sand bags and Styrofoam to investigate further the ability of the nondestructive test equipment.

The results indicated that SCC is highly desirable for drilled shafts; it flows easily, filling the hole, and the removal of the temporary casing is facilitated by this highly workable material. CSL is a satisfactory nondestructive method to determine the integrity of shafts. Sonic echo/impulse response also showed promise as a method that complements CSL for determining the integrity of a shaft.

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FINAL REPORT

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ABSTRACT

In this study, self-consolidating concrete (SCC) was evaluated in drilled shafts and the integrity of drilled shafts was determined using cross-hole sonic logging (CSL), a low-strain nondestructive integrity testing technique. SCC has very high flowability. It was placed in the drilled shafts of the bridge on Route 28 over Broad Run in Bristow in Prince William County, Virginia. There were two bridges at the site; the one carrying the northbound traffic had drilled shafts using conventional concrete with high consistency (i.e., flowability). Half of the shafts of the bridge carrying the southbound traffic were cast with SCC.

During placement, properties of the fresh concrete were tested and specimens were prepared to determine the hardened properties. The integrity of the shafts within the reinforcing cage was determined using CSL, with sonic echo/impulse response also used to evaluate several test shafts. The use of acousto-ultrasonic (AU) measurements to determine the cover depth outside the reinforcing cage was also evaluated during laboratory testing. In addition to the Route 28 shafts, three test shafts with conventional and SCC concretes were cast in an area headquarters. These shafts had intentional voids created through the use of sand bags and Styrofoam to investigate further the ability of the nondestructive test equipment.

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FINAL REPORT

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INTRODUCTION

A drilled shaft is a deep foundation that is constructed by placing fresh concrete in a drilled hole (Michael and Lymon, 1999). These massive shafts have diameters ranging from 18 in to 12 ft or more and contain a high concentration of reinforcement bars. Drill shafts offer economic advantages because pile caps are not necessary and the shafts tie directly into columns. A typical shaft is easily adaptable to varying site conditions and can carry a high load. Drilled shafts are not recommended for contaminated sites since contamination may spread within the site; other drawbacks include a lack of associated construction expertise, difficulty of concrete placement, and difficulty of inspecting the finished product.

Drilled shaft excavation requires either cased or uncased methods. If soils are not prone to caving, as with stiff clay, shale, or limestone, a casing is not required. Generally, bentonite slurry is used to support the sides of the hole and keep it from collapsing (Jalinoos et al., 2005). However, if soils are prone to caving, casings are used to support the sides of the excavation.

During placement by tremie or pump line, the discharge end is placed near the bottom of the hole and the concrete flow is started. The concrete fills the shaft from the bottom and displaces the sediments. The placement continues until fresh concrete overflows the top of the shaft. The concrete placed first rises to the surface; therefore, it is important to provide concrete that stays plastic until the placement is completed. Generally, concretes with high consistency (flowability) are placed, which can lead to bleeding and segregation. Consolidation of deep shafts is not practical, and the presence of large air pockets because of the lack of consolidation has been a concern.

In the past, the Virginia Department of Transportation (VDOT) permitted free fall into the excavation of dry shafts up to 75 ft in depth. The new specifications being developed will allow free fall only with a drop chute and when approved by the Engineer. The maximum coarse aggregate size is reduced to 3/8 in from the commonly used size of 3/4 in. Concrete should be deposited without striking the reinforcement cage during free fall to minimize segregation. Accumulation of water at the base of excavation is also a concern because of voids and weak concrete at the bottom adversely affecting the bearing resistance.

Drilled shafts are routinely tested to ensure that proper placement has been accomplished, providing uniform concrete, and that the structural integrity is maintained. There are two common test methods: the load test and the integrity test. In the load test, the shaft is subjected to a load and the load-carrying capacity is compared with calculated values. For the integrity testing, sonic tests are common. In the sonic-echo test, the top of the drilled shaft is struck with a hand-held hammer. A sonic wave is generated that travels down the drilled shaft. The wave is reflected from the bottom of the shaft or from a defect within the shaft and is picked up by a transducer at the head of the shaft. It is a quick, easy, and inexpensive test performed on installed shafts. However, this test may show false positives and miss voids or inclusions in the concrete that are obscured by other defects. In addition, it is not effective in locating deep defects (depth > 60 ft) and cannot detect contact problems between the concrete and the soil or rock. Cross-hole sonic logging (CSL) provides a more accurate testing alternative. Small access tubes are attached to the sides of the reinforcing cage. An acoustic transmitter is lowered into one of the access tubes filled with fluid, and a receiver is lowered to the same depth in another tube. The signal emitted by the transducer is picked up by the receiver. The test is repeated at different depths. CSL is more time-consuming and requires that tubes be inserted in the shaft prior to concrete placement when compared with the sonic echo/impulse response (SE/IR) technique, which is a low-strain integrity test technique. In addition, the placement of the concrete caps on shafts prohibits access to the tubes. The SE/IR method is applicable if access to the pile or cap is possible and shafts can be easily tested.

CSL can detect the condition of the concrete within the reinforcement cage; however, it does not provide data for the concrete outside the cage, i.e., the concrete cover. Concrete cover is important for protecting the reinforcing cage. Lack of cover will expose steel to early deterioration. For determining the quality of the concrete cover, possible tests are impact response tests to detect the cross section of the shaft; thermal logging to differentiate the temperature of the hydrating concrete versus the soil; or the gamma-gamma nuclear method to determine the density of the cover material (Jalinoos et al., 2005).

Conventional concretes used in drilled shafts usually have high slump since vibration of the concrete in the deep drilled shafts is not practical. However, placement-related defects in the shafts are common because of lack of consolidation. Self-consolidating concrete (SCC) is introduced that provides very high workability, indicated by high slump flow values, compared to conventional concrete. Therefore, unlike conventional concretes that require consolidation through vibration, SCC is self-consolidating because of the exceptional workability. SCC has been used in Japan and Europe advantageously since the early 1990s (Okamura and Ouchi, 1999). SCC easily fills congested spaces between the reinforcement and the formwork under the influence of its own mass, and without additional consolidation energy. Easy flowing SCC would permit convenient and fast placement of concrete in drilled shafts (Hodgson et al., 2005). Eliminating the consolidation problem would enhance the strength and reduce the permeability of concretes, which is essential for longevity.

Studies show that SCC can be used to address many of the problems associated with drilled shaft construction because of the inherent high workability, passing ability, resistance to segregation, and reduced bleeding (Schindler et al., 2005). Further, the data suggest that the use of SCC in drilled shaft applications can provide similar or improved hardened concrete properties, which includes compressive strength, elastic modulus, drying shrinkage, and permeability (Schindler et al., 2005; Nassif et al., 2008). SCC can address the congestion and lengthy placement times encountered with drilled shafts (Brown et al., 2007).

PROBLEM STATEMENT

In drilled shafts, concrete with high consistency is placed and vibration is not performed except near the top surface where access is possible. Concrete is expected to stay plastic in the shafts placed by pump or tremie so that the rising concrete can move up to the top without stiffening and blocking the flow. Therefore, conventional concretes with high consistency are used, which may lead to bleeding and segregation. Loss of slump during placement raises the concern of honeycombing within the cage and lack of concrete cover outside the cage since vibration is not used. A concrete that flows easily even in the presence of congested reinforcement and that remains stable is needed.

Testing the integrity of the drilled shafts in a fast convenient way is highly desirable. Access from outside such as with the SE/IR methods on the exposed surface for testing would be beneficial. In addition, the determination of the cover depth using simple test procedures is needed.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the use of SCC for drilled shafts; investigate the effect of nondestructive methods to determine drill shaft integrity; and evaluate different nondestructive test methods in test shafts. For this study, two adjacent bridges on Route 28 over Broad Run in Bristow, in Prince William County, Virginia, were selected. The bridge carrying the northbound traffic was built in 2006; it had 24 drilled shafts using conventional concrete with high consistency. The bridge carrying the southbound traffic was built in 2007; it also had 24 shafts, 12 shafts with conventional concrete and 12 with SCC. During placement, properties of the fresh concrete were tested and specimens were prepared for the determination of the hardened properties. Comparisons of concrete properties and placement operations between the SCC and conventional concretes were made. The integrity of the shafts within the reinforcing cage was determined using CSL.

In addition, in a controlled environment, in a VDOT area headquarters, three 8-ft-deep test shafts were cast with conventional and SCC concretes. These shafts had intentional voids created using sand bags and Styrofoam to investigate further the ability of other nondestructive test methods. In the test shafts, the CSL and SE/IR methods were used to determine the integrity. In the laboratory, the acousto-ultrasonic (AU) method was evaluated to determine the cover depth. However, because of scheduling, the AU test was not performed in the field for the Route 28 bridges.

RESEARCH METHODOLOGY

Overview

The evaluation involved the following:

1. *Placing conventional and SCC concrete, testing the concrete mixtures, discussions with the contractor, and testing for integrity in the Route 28 Bridges.* For integrity, the CSL test was used.

2. *Placing various concretes with various voids in three test shafts at a VDOT area headquarters and testing for integrity.* For integrity, the CSL and SE/IR tests were used.

3. *Laboratory testing using AU for cover depth.*

The following sections describe:

- materials testing
- observations by the contractor
- discussions with the drilled shaft contractor
- integrity testing,
- cover depth evaluations
- information, placement, and mixture designs for the Route 28 bridges
- conventional concrete shafts
- SCC shafts
- test shafts.

Conventional and SCC Material Tests

Both the conventional and SCC mixtures were tested in the field. SCC trial batches were also tested in the laboratory and labeled SCCT1 and SCCT2. Concretes were tested at the fresh state as indicated in Table 1, except that for conventional concretes, slump was determined and for SCC, slump flow values were determined for a measure of consistency. The hardened concrete specimens were subjected to the tests listed in Table 2.

Table 1. Fresh Concrete Tests

Test	Specification
Slump	ASTM C143
Air content	ASTM C173
Temperature	ASTM C1064
Slump flow	ASTM C1611
Slump flow with J-ring	ASTM C1621
Time to reach 20 in	ASTM C1611
Unit weight (density)	ASTM C138

Table 2. Hardened Concrete Tests

Test	Specification	Size (in)
Compressive strength	ASTM C39	4 x 8
Elastic modulus	ASTM C469	4 x 8
Splitting tensile strength	ASTM C496	4 x 8
Permeability[a]	AASHTO T 277, T 259	2 x 4
Drying shrinkage[b]	ASTM C157	6 x 6 x 14
Freeze-thaw durability[c]	ASTM C666	3 x 4 x 16

[a] One week at room temperature in moist room and 3 weeks in water at 100 °F.
[b] Prisms were moist cured for 28 days and then left to dry.
[c] Two weeks in moist room then at least 1 week dry and tested in 2% NaCl solution. The specimens were tested for weight loss, durability factor, and surface rating (in accordance with the ASTM C672 rating).

Observations by Contractor

Discussions with the drilled shaft contractor staff were conducted to obtain their impressions of SCC.

Integrity Testing

Cross-Hole Sonic Logging

Integrity testing was performed using ultrasonic cross-hole testing. This technique, also known as cross-hole sonic logging, is sensitive to the properties of the concrete material, test geometry, and wavelength (ASTM International, 2008). The wave velocity (V) for an ultrasonic compression wave is a function of the dynamic modulus of elasticity (E), density (ρ), and dynamic Poisson's ratio (μ) in an elastic homogeneous solid material.(Naik et al., 2004). This relationship is shown in Equation 1:

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad \text{[Eq. 1]}$$

Since the ultrasonic wave interacts with the material, CSL can be used to determine the condition of the concrete between the tubes. It is mainly used to detect the voids attributable to lack of consolidation or the presence of weak areas attributable to mixing with soil during placement. These anomalies affect the variables in Equation 1. The software determines the average velocity between the transducers for the entire depth of the shaft. The analyzer then compares the sonic velocity at any point along the length of the specimen to the average velocity. The analyzer looks for "questionable" concrete where there is a drop of 10% to 20% in the sonic velocity or "poor" concrete where there is a drop of greater than 20%.

Once the software finds a location where there is a drop in velocity of greater than 10%, the analyzer looks at the data prior to the drop to determine the last location where the velocity was average. Then the analyzer looks at the data after the drop and locates the point where the sonic velocity returns to average. These two points define the range of the anomaly zone in the material.

In Figure 1, the line shows the velocities found throughout the entire depth of the concrete. This graph shows slight variations but no large variations that would be indicative of questionable and poor concrete. A defect would be shown in the form of a large spike. The occurrence of these spikes at different depths in the concrete could indicate voids or areas of weak material within the drilled shaft.

Other plots are also available in the software that can be used for detecting anomalies. Figure 2 is a stack plot and Figure 3 is an energy / first arrival time plot. Both plots were generated using data gathered from a sample that had a known void location. It can be seen clearly in both plots that when a void exist, the arrival time increases and the energy decreases.

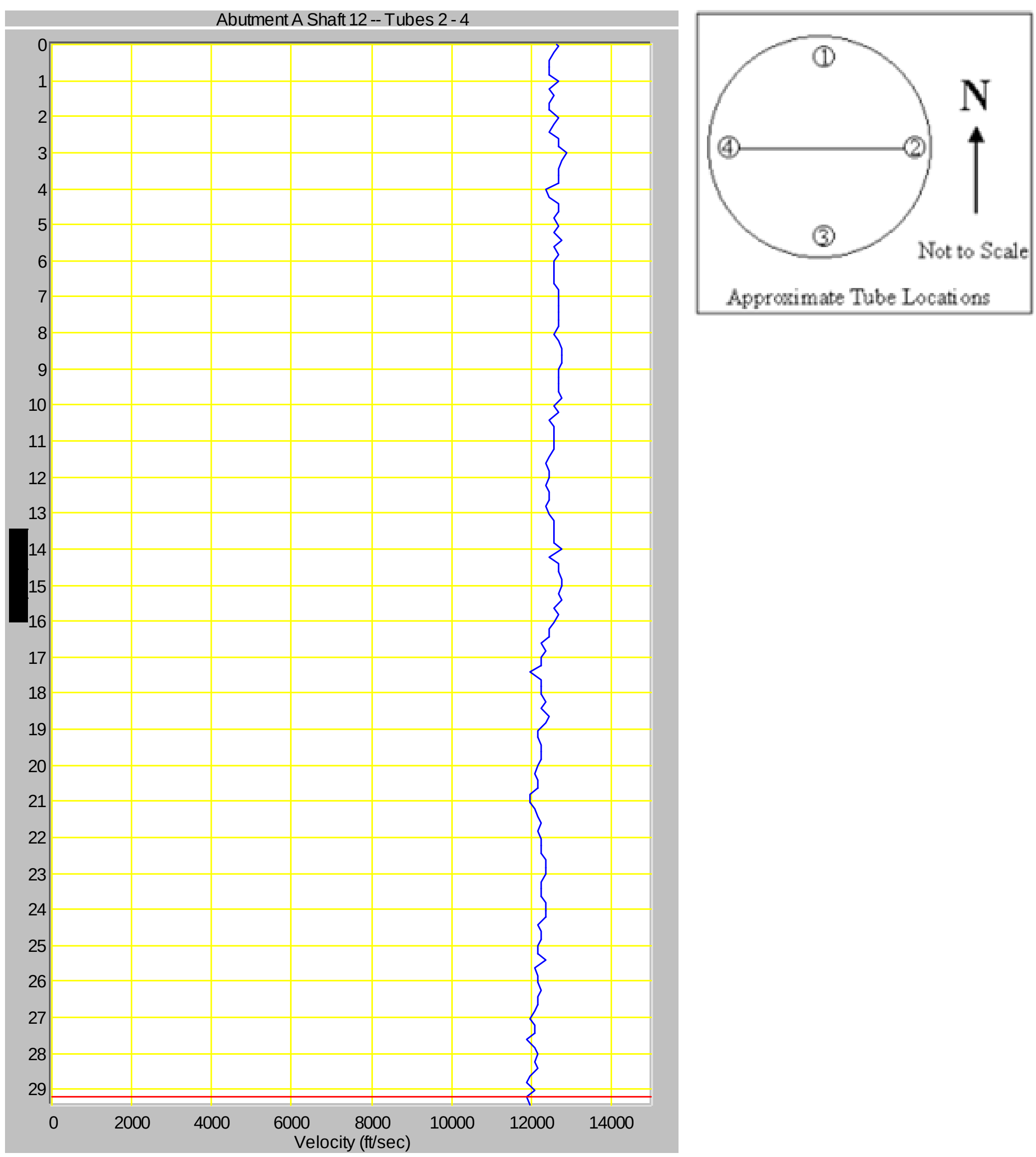
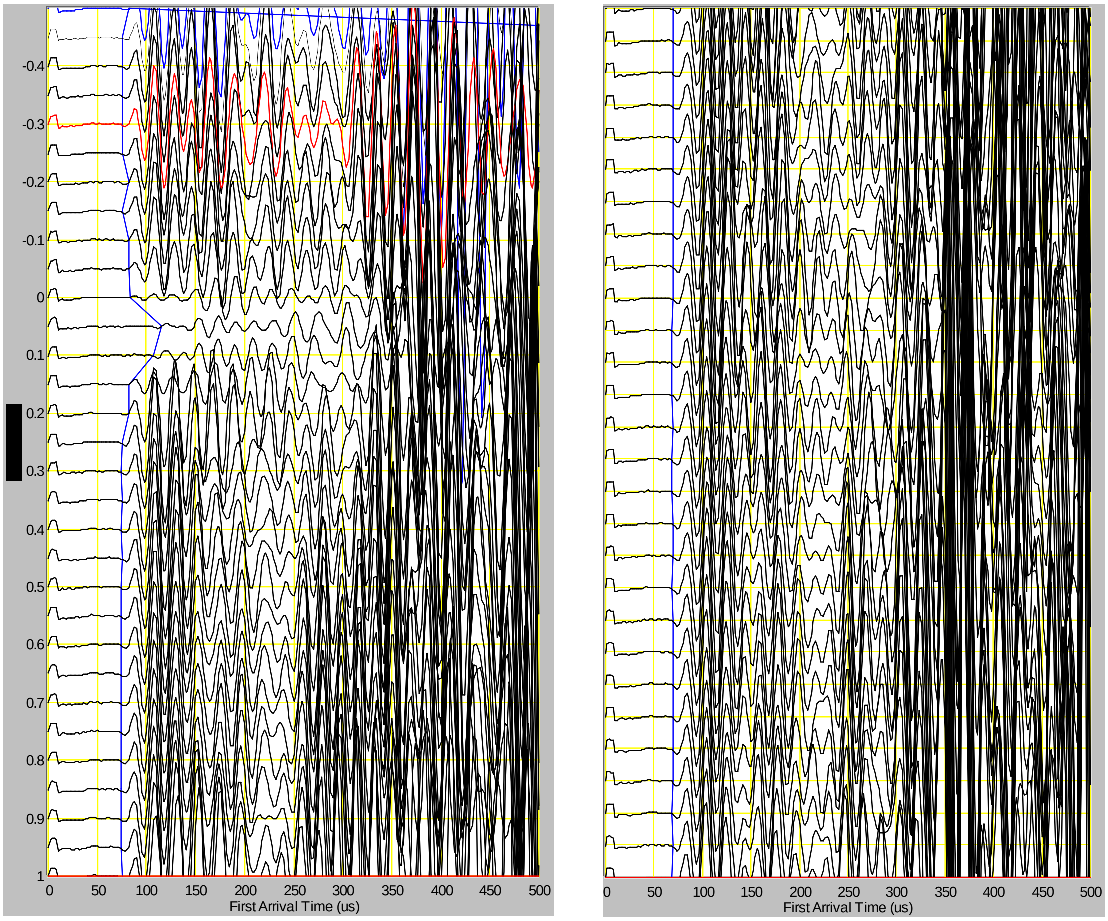


Figure 1. Velocity data for Abutment A, Shaft 12. Tube spacing is 36.5 in.



(a) (b)

Figure 2. CSL stack plot output on test specimen *(a)* indicating void between 0 and 0.1 ft depth mark and *(b)* with no void present.

Cover Depth

In the laboratory, concrete specimens of different thicknesses were created to evaluate the idea of determining cover depth using AU. An illustration of this technique is shown in Figure 4. Wedges were used to ensure the transducers were kept at a constant incline to the surface. Vaseline was used to couple the transducers to the wedge and the wedge to the concrete. The linear distance was then varied until the maximum acoustic pulse was achieved for the different specimen thicknesses.

Route 28 Bridges

On Route 28, there were two bridges adjacent to each other with drilled shafts. Each bridge was constructed with two piers and two abutments, each containing six drilled shafts, totaling 24 shafts in each bridge. The conventional concrete in the shafts of the bridge carrying northbound traffic was sampled twice in 2006 (C1 and C2). These samples were taken from the trucks after 2 ft^3 was discharged. Sample C2 was placed using the truck chute. Sample C1 was pumped; however, it was also tested from the truck for convenience

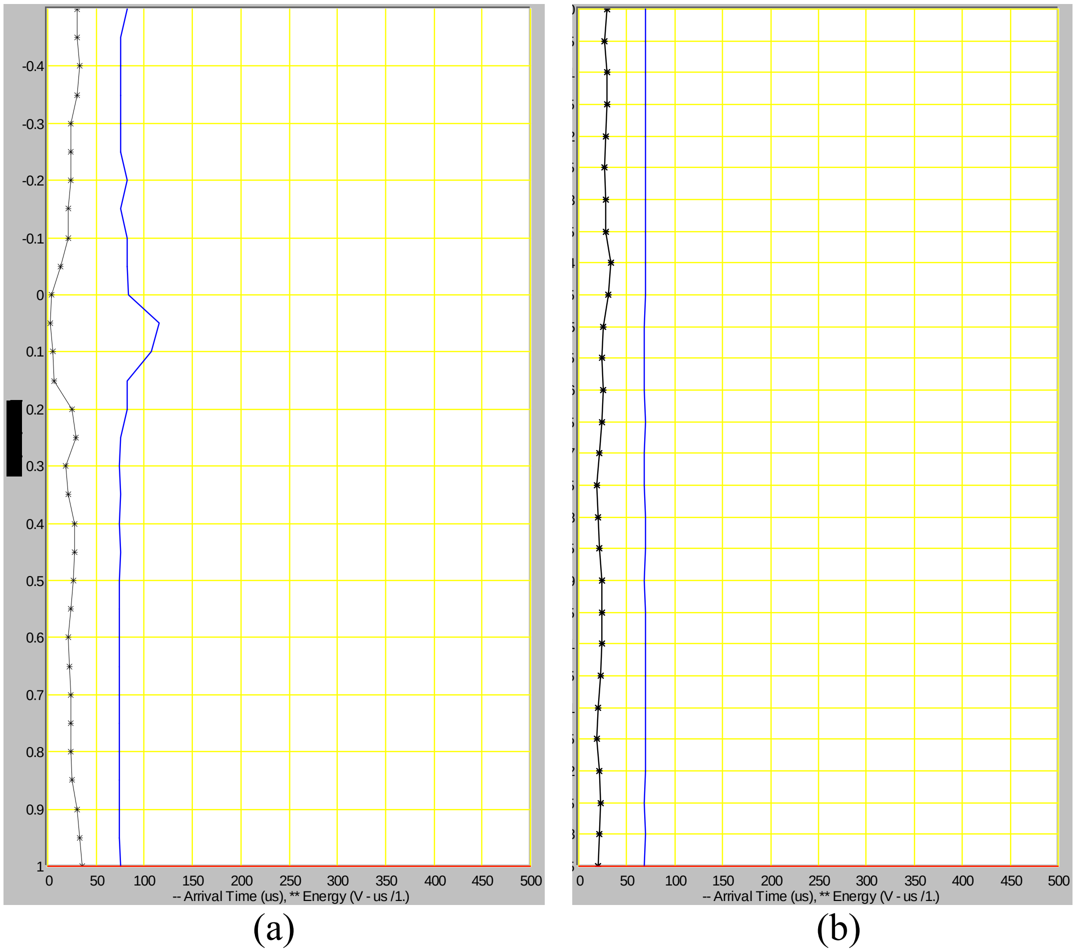


Figure 3: CSL plots output showing arrival time and energy profiles for a test specimen *(a)* indicating void between 0 and 0.1 ft depth mark and *(b)* no void present.

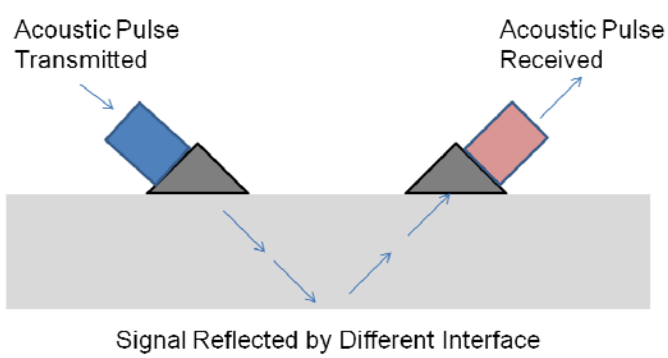


Figure 4. Illustration showing the transducers, wedges, and concrete thickness being measured using an acoustic pulse.

except that a small sample was obtained after pumping to determine the air content. In 2007 the bridge carrying the southbound traffic was built. The conventional concrete was sampled twice (C3 and C4). Sample C3 was taken after pumping, and C4 was collected directly from the truck. SCC was sampled 3 times (SCC1-SCC3). In 2007, the first SCC mixture (SCC1) was sampled after the pump, and the second and third samples (SCC2 and SCC3) were sampled from the truck. VDOT specifications for the drilled shaft concrete of this project are summarized in Table 3.

Table 3. VDOT Specifications for Drilled Shaft Concrete of Route 28 Bridge

Property	Control	SCC
Minimum compressive strength (psi)	4,000	4,000
Nominal maximum aggregate size (in)	3/8	1/2
Minimum. cement content (lb/yd^3)	635	635
Maximum w/cm	0.45	0.45
Slump (in)	7 ± 1	
Slump flow for SCC (in)		21 ± 3
Air content (%)	6.5 ± 1.5	6 ± 2

w/cm = water-cementitious material ratio. When a high-range water-reducing admixture (HRWRA) is used, the upper limit for entrained air may be increased by 1%.

Placement

Placement of concrete in the drilled shafts was observed during construction. The shaft holes were drilled and stabilized by metal casings, which were removed after the placement of the concrete. The shafts had varying lengths from 18 to 32 ft. Inside the hole, circular reinforcement cages were placed and the specified cover was maintained using spacers. Four metal tubes, with an interior diameter of 2 in, were attached to the inside of the reinforcement cages for the CSL testing. Concrete was delivered in ready-mixed concrete trucks and was then either dropped directly from the truck (shown in Figure 5), pumped from bottom up, or placed through a tremie located in the center of the shaft. The drilled shafts in the piers near the creek usually had water at the bottom, which pumping was unable to remove. If the water depth was 3 in or more, concrete was placed using either a pump truck or a tremie, which allowed concrete flow from bottom up displacing the water. In the shafts for the abutments, the bottoms were dry and concrete was dropped in directly from the truck into the shaft. In the new specifications being developed, such placement would not be permitted; a drop chute to avoid hitting the reinforcement would be required and the Engineer’s approval would be needed.

To ensure that the SCC with the high flow rate would not segregate during placement, a simple drop test was devised. The SCC in the air meter bucket was dropped on the ground from the top of the bridge as shown in Figure 6. In an approximate 20-ft drop, SCC spread about a 3-ft diameter without any segregation.

During placement, the properties of the fresh concrete were determined. CSL testing (ASTM D6760) was used to evaluate nondestructively the quality of the concrete in the shafts.

(a) (b)

(c)

Figure 5. Placement of conventional concrete mixture in drilled shaft. *(a)* Concrete flows down the chute into shaft; (*b)* steel caisson is lifted slightly; and *(c)* then completely removed. Completed drilled shafts are visible in the forefront of Figure b and Figure c.

(a)

(b)

Figure 6. Drop test *(a)* SCC mixture allowed to drop approximately 20 ft, and *(b)* result of impacting ground (no segregation was observed).

Conventional Concrete Drilled Shafts

Mixture Design

For the conventional mixture, Type II cement, natural sand, No. 8 crushed stone coarse aggregate with a nominal maximum aggregate size of 3/8 in, air-entraining admixture (AEA), water-reducing and retarding admixture, and a polycarboxylate-based high-range water-reducing admixture (HRWRA) were used. The proportions for the conventional mixtures are provided in Table 4.

Table 4. Mixture Proportions of Conventional Concrete

Ingredient	(lb/yd^3
Type II cement	388
Slag	388
Fine aggregate	1,282
Coarse aggregate	1,458
Water	350
Maximum w/cm	0.45

w/cm = water-cementitious material ratio.

SCC Drilled Shafts

Trial Batch Mixture Design

Prior to the placement of the SCC drilled shafts, two SCC batches were prepared in the laboratory. Type II cement, natural sand, No. 7 gravel coarse aggregate with a nominal maximum size of ½ in, AEA, water-reducing and retarding admixture and a polycarboxylate-based HRWRA were used. The mixture proportions developed in the laboratory are shown in Table 5. The first batch SCCT1 was tested at the hardened state for strength; the second batch SCCT2 for strength and permeability at 28 days.

Table 5. Mixture Proportions for SCC Trial

Ingredient	lb/yd^3
Type II cement	363
Slag	363
Fine aggregate	1,365
Coarse aggregate	1,435
Maximum w/cm	0.41

w/cm = water-cementitious material ratio.

Field Cast Drilled Shaft Mixture Design

For the drilled shafts cast for the bridge, the SCC mixture developed in the laboratory and given in Table 5 was used.

Test Shafts

At VDOT's Boyd Tavern area headquarters, holes were drilled, molds simulating casings were inserted into the holes, and steel cages with voids were placed in the molds (Figure 7). In the shafts, both metal and plastic tubes were placed for the CSL. There is concern that plastic tubing may lose its bond with concrete, adversely affecting the wave propagation needed for the CSL readings. There were three drilled shafts measuring 2 ft in diameter and 8 ft high. In one of the shafts, the top 3 ft was 3 ft in diameter to provide a larger cover depth.

On June 29, 2010, 4 yd^3 of conventional concrete was delivered in a ready-mixed concrete truck. The mixture proportions are given in Table 6.

Figure 7. Cage is lowered into mold in ground.

Table 6. Mixture Proportions of Test Shafts

Ingredient	Amount (lb/yd^3)
Portland cement	560
Fly ash	140
No. 78 coarse aggregate	1,350
Fine aggregate	1,504
w/cm	0.40

w/cm = water-cementitious material ratio.

Initially, the concrete had a conventional slump and was placed in the bottom 5 ft of the first shaft. Then concrete was put in wheelbarrows and the water content was increased, which also increased the slump. This concrete with a higher water-cementitious material ratio (w/cm) was placed in the top portion of the first shaft. Then HRWRA was added to the concrete in the truck to make it SCC. The slump flow was measured. SCC was placed in the bottom 5 ft of the second shaft and in the entire third shaft with the larger top. Then the remaining concrete in the truck was tempered with water to increase the w/cm. The SCC with high w/cm was added to the top section of the second shaft.

Sonic Echo/Impulse Response

In addition to evaluating the test shafts using CSL, SE/IR was used to nondestructively measure the depth and determine the location of the voids. The system used complied with the requirements of ASTM D5882. It is important to note that sonic echo testing is sometimes referred to by other names, which also comply with the requirements of ASTM D5882.

RESULTS

Overview

The following sections summarize the results of the following:

- materials testing for the conventional (control) concrete
- materials testing for the trial batches and field batches of SCC
- observations of the contractor
- CSL integrity tests for the Route 28 Bridge
- cover depth evaluations
- test shafts with different concretes, plastic and metal tubes, and voids.

Drilled Shafts with Conventional Concrete for the Route 28 Bridge

Materials Testing

The fresh concrete properties for the conventional concrete are given in Table 7, and the hardened properties are given in Table 8. The air content values were within the specifications, and the mixture had high consistency.

The strength values were high; close to 5,000 psi and higher at 28 days and close to 7,000 psi and more at 1 year. The splitting tensile strengths were close to 500 psi and higher at 28 days. The elastic modulus was higher than 3 million psi at 28 days and above 4 million psi at 1 year. The permeability values were in the low and moderate range. The average shrinkage values at 28 days were about 500 microstrain, and at 32 weeks about 800 microstrain, which are high, mainly attributable to the high water content and small size aggregates in the mixtures. The freeze/thaw data indicated satisfactory durability factors and surface ratings but marginal weight loss.

Table 7. Fresh Concrete Properties of Conventional Concrete From Route 28 Bridge, C1-C4 (with Batch Cast Date)

Property	C1 9/7/2006	C2 10/16/2006	C3 5/2/2007	C4 5/9/2007
Concrete temperature (°F)	80	70	80 (80)	79
Air (%)	8.4 (8.2)	7	6.6 (3.3)	7.8
Unit weight (lb/ft^3)	-	140.4	145.2 (149.6)	-
Slump (in)	7.2	8	6.0 (6.3)	5.8

Values in parenthesis denote properties after pumping.

Table 8. Hardened Concrete Properties of Conventional Concrete From Route 28 Bridge, C1-C4 (with Batch Cast Date)

Property	Age	C1	C2	C3[a]	C4
		9/7/2006	10/16/2006	5/2/2007	5/9/2007
Strength (psi)	1 d	1510	710	810	920
	2 d	-	1440	-	-
	4 d	2750	-	-	-
	7 d	3490	3020	3360	2830
	28 d	6160	5530	5910	4910
	365 d	7830	-	8370	6840
Elastic modulus (ksi)	1 d	2340	-	-	-
	2 d	-	2300	-	-
	4 d	2560	-	-	-
	7 d	2990	2810	2740	2710
	28 d	3970	3870	3900	3040
	365 d	4650	-	5020	4180
Permeability (coulombs)	28 d	1644	1751	2134	2895
Splitting tensile strength (psi)	28 d	625	595	590	495
	365 d	-	-	670	565
Drying shrinkage (microstrain)	28 d	477	563	445	530
	8 wk	620	653	565	655
	16 wk	747	803	660	740
	32 wk	750	803	795	915
	64 wk	830	880		
Freeze-thaw Data[b]					
WL (%)		-	-	7.6	6.1
DF		-	-	107	111
SR		-	-	2.3	1.9

Values are an average of 3 specimens except that the permeability, freeze-thaw, up to 7 day data for C1 and C2, and the drying shrinkage of C3 and C4 are an average of 2 specimens.
[a] Sampled after pumping. Rest obtained from truck after 2 ft^3 was discharged.
[b] Satisfactory performance: weight loss (WL) $\leq$ 7%, durability factor (DF) $\geq$ 60, surface rating (SR) $\leq$ 3.

SCC Trial Batches

Materials Testing

The fresh properties for the SCC trial batches are listed in Table 9 and for the hardened properties are listed in Table 10. Mixtures were workable and had the proper air content.

Table 9. Fresh Concrete Properties of SCC Trial Batches (with Batch Cast Date)

Property	SCCT1	SCCT2
	12/13/2006	2/5/2007
Concrete temperature (°F)	66	72
Air (%)	6.2	8
Unit weight (lb/ft^3)	141.3	137.2
Slump flow (in)	26.75	20
Slump flow T_{20} (s)	1.8	3.1
J-ring (in)	26.8	18

Table 10. Hardened Concrete Properties of SCC Trial Batches (with Batch Cast Date)

Property	Age	SCCT1	SCCT2
		12/13/2006	2/5/2007
Strength (psi)	7 d	-	4760
	28 d	8143	7380
	90 d	-	8455
Elastic modulus (ksi)	7 d	-	3850
	28 d	-	4430
	90 d	-	5360
Permeability (C)	28 d	-	1418
Splitting tensile strength (psi)	28 d	-	655
Drying shrinkage (microstrain)	28 d	-	310
	8 wk	-	425
	16 wk	-	465
	32 wk	-	505
	64 wk		530

Values are an average of 2 specimens.

The results of the SCC trial batches indicated high 28-day strengths exceeding those of the control mixtures. The permeability value and the drying shrinkage values were lower and more desirable than for the control.

Drilled Shafts with SCC for Route 28 Bridge

Materials Testing

The fresh concrete properties for the SCC drilled shafts are provided in Table 11, and the hardened properties are summarized in Table 12. Slump flow values were as desired but were a little higher in the SCC2. The variability in consistency was high. The slump flow values with the J-ring were lower than the regular slump flow value, as expected. The slump flow values are generally in the lower range of SCCs for shafts; this is more economical since less admixture can be used and the mixtures are more stable, which is desirable since concrete is being dropped into the shaft and segregation is a concern.

The SCC flowed easily, allowed for expedited placement, and made the removal of the temporary casing easy. Casing removal is a critical issue because if the concrete is stuck to the casing when the casing is lifted, voids can occur at the bottom of the shaft. SCC has thixotropic characteristics attributable to the HRWRA used; if the stiffening SCC binds to the casing, the SCC responds well to agitation or jarring and begins to flow again.

It was difficult to maintain the specified air content in the SCC mixtures. Since the shafts were in the ground, air contents lower than those specified were allowed; the air content was

Table 11. Fresh Concrete Properties of Drilled Shafts with SCC (with Batch Cast Date)

Property	SCC1 5/31/2007	SCC2 6/7/2007	SCC3 7/6/2007
Concrete temperature (°F)	87 (91)[a]	80	88
Air (%)	6.2 (4.5)	3.8	5.0
Unit weight (lb/ft^3)	143.6 (142.8)	144.8	141.2
Slump flow (in)	21.8	25	20
Slump flow T_{20} (s)	2.1	2.3	2.4
J-Ring (in)	19.8	23.3	17
J-Ring T_{20} (s)	2.7	2.7	-

[a] Values in parenthesis denote properties after pumping. Samples for this batch (SCC1) were obtained after pumping. The rest of the samples were obtained from the truck after 2 ft^{3}was discharged.

Table 12. Hardened Concrete Properties of SCC Drilled Shafts (with Batch Cast Date)

Property	Age	SCC1[a] 5/31/2007	SCC2 6/7/2007	SCC3 7/6/2007
Compressive strength (psi)	1 d	2320	1630	-
	3 d	-	-	3290
	7 d	5210	4830	4300
	28 d	7910	7970	7120
	365 d	9670	10270	9330
Elastic modulus (ksi)	7 d	-	3940	3480
	28 d	4300	4610	3910
	365 d	5370	5390	5730
Permeability (C)	28 d	1427	1250	1360
Splitting tensile strength (psi)	28 d	725	695	590
	365 d	775	775	780
Drying shrinkage (microstrain)	28 d	310	305	400
	8 wk	385	345	535
	16 wk	440	435	580
	32 wk	565	510	670
Freeze-Thaw Data				
WL (%)		26.5	---	46.9
DF		19	---	0[b]
SR		5.0	---	5.0

Values are an average of 3 specimens except that permeability, freeze-thaw, drying shrinkage of SCC1, and 365-day data for SCC3 are an average of 2 specimens.
[a] Sampled after pumping. Rest obtained from the truck after 2 ft^3 was discharged.
[b] Cannot obtain a frequency at the first 50 cycle. Satisfactory performance: weight loss (WL) $\leq$ 7%, durability factor (DF) $\geq$ 60, surface rating (SR) $\leq$ 3.

mainly to improve workability, reduce bleeding and segregation, and determine the air-entraining characteristics of such mixtures with high flow. The air requirement was mainly to determine the feasibility of entraining air for future applications. Table 11 shows the variability of and the difficulty of increasing the air content.

The strength values were higher than 7,000 psi at 28 days. The elastic modulus values were close to or higher than 4 million psi. The permeability values were low. The drying shrinkage ranged from 300 to 400 microstrain at 28 days and 500 to 700 microstrain at 32 weeks.

Two of the batches had similar results, but the third batch had different values, indicating reduced properties implying the presence of more water. The resistance to cycles of freezing and thawing was poor even though the concretes were air entrained and had satisfactory total air contents at the fresh state.

An interesting observation was that there were some large clumps (balls filled with cement and sand) in the SCC mixtures, as shown in Figure 8. Mixing was unable to break these large clumps. Such clumps were rare in the control mixtures.

Except for the resistance to freezing and thawing, the properties of the SCC mixtures were improved compared to those of the control mixtures.

Figure 8. Large clumps from SCC mixtures.

Observations by Contractor

Discussions with the drilled shaft contractor indicated that SCC had high workability, flowed well, and was easy to place. In addition, the casings were easier to remove compared to those for the conventional mixtures.

Integrity Testing for Route 28 Bridge

In general, the shafts evaluated had velocity values that were relatively consistent. Velocities were generally in the range of those values associated with good quality concrete. A typical example of the CSL results for the shafts with conventional concrete is shown in Figure 9; one for SCC is shown in Figure 10. These two figures show clear fluctuations in velocity up or down the shaft. However, according to Olson Instruments, a condition rating of "good" applies if there is less than a 10% decrease in signal velocity with no distortion, of "questionable" if the signal velocity decrease is between 10% and 20% with minor signal distortion and lower signal amplitude; and is "poor" if it exceeds the previous conditions listed.

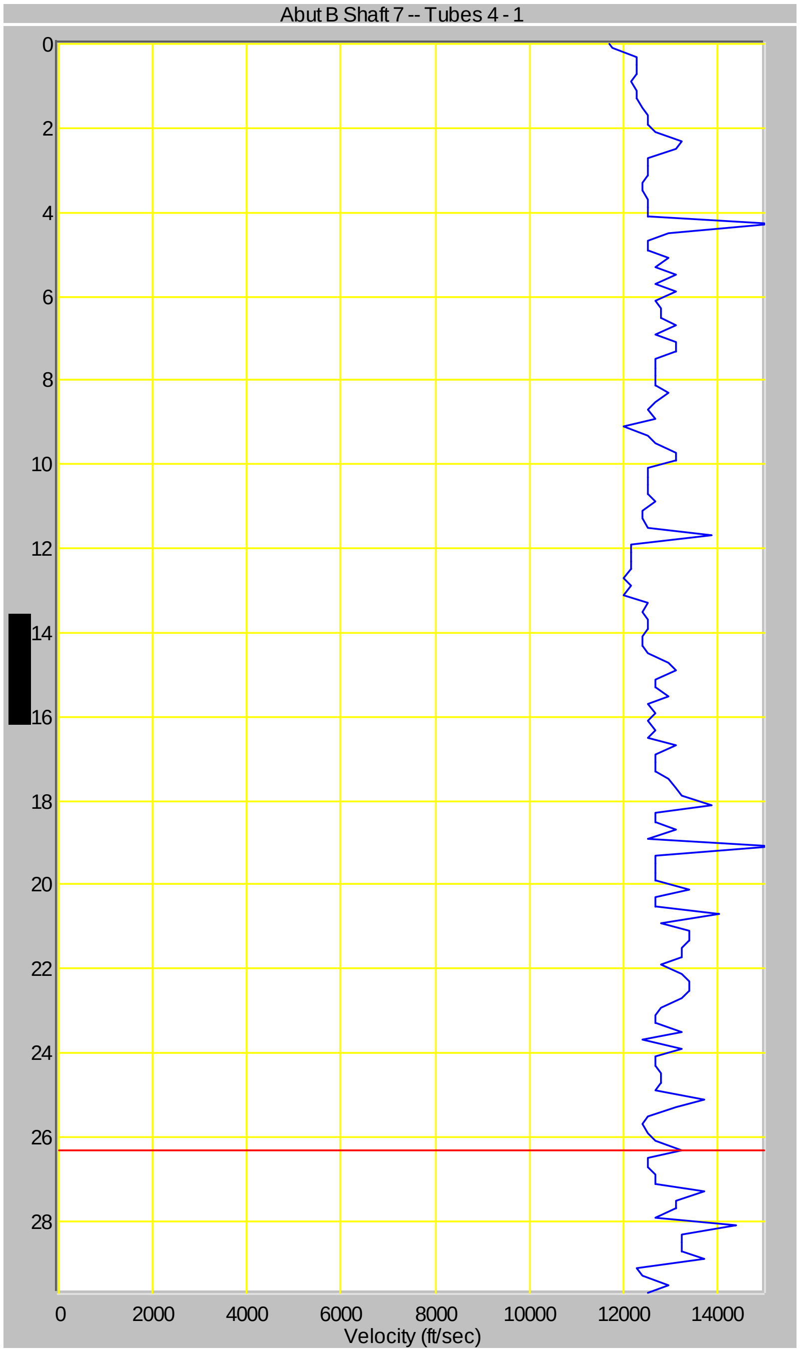
Comparison of Conventional and SCC Concrete in Drilled Shafts

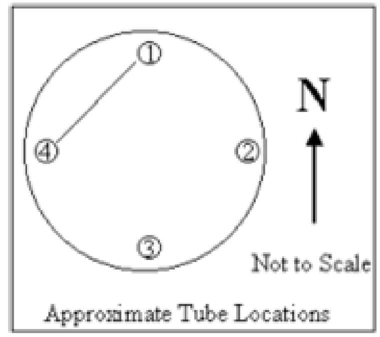
A comparison of the CSL velocity data for the two types of concrete using box plot diagrams is shown in Figure 11. More variability in the ultrasonic velocities was observed in general for the SCC. The SCC data were skewed slightly as compared to the conventional data, which more closely matched a normal distribution.

A comparison between shafts was also conducted using box plot diagrams for each shaft. Figure 12 shows the distribution of the velocity measurements for each conventional concrete mixture that was placed in each shaft. In Figure 12, the mean velocity values are between 12,000 and 13,000 ft/s. Further, except for Pier 2, Shaft 7, the median is generally near the mean. Finally, the 0.5 standard deviation limits indicate the majority of the data has a value between 12,000 and 13,000 ft/s. Therefore, the conventional mixtures appear to be consistent from shaft to shaft according to the box plot results.

A comparison between entire shafts with SCC was also conducted using box plot diagrams for each shaft. Figure 13 shows the distribution of the velocity measurements for each SCC concrete mixture that was placed in each shaft.

The integrity tests indicated that shafts with either type of concrete had adequate consolidation without the presence of large honeycombed concretes. The higher range in observed velocity for the SCC mixture is expected since SCC is a relatively new mixture with a high flow rate. However, the average velocity of SCC mixtures is higher than that for the conventional mixtures, as shown in Figure 11. Although the SCCs had higher variability in velocity, they still had satisfactory integrity because the low velocity values were still high and comparable to those of the conventional mixtures, which can be also seen in Figure 11. Sonic velocity in concrete is related to the modulus of elasticity and density, as shown in Equation 1, which are also related to strength. Therefore, higher velocities are sought because of the relationship to strength. When there is high variability in concrete strength, higher average strength values are sought to ensure that the minimum values are above the specification limits.





Shaft Name: Abut B Shaft
Tube Spacing: 28 inches
Cursor Depth: 29.7 ft
Velocity = 12545 ft/sec
First Arrival Time = 186 µs
Signal Energy = 150.1 V-µs

Figure 9. Example of velocity plot for conventional concrete placed in Abutment B, Shaft 7, Tubes 4-1.

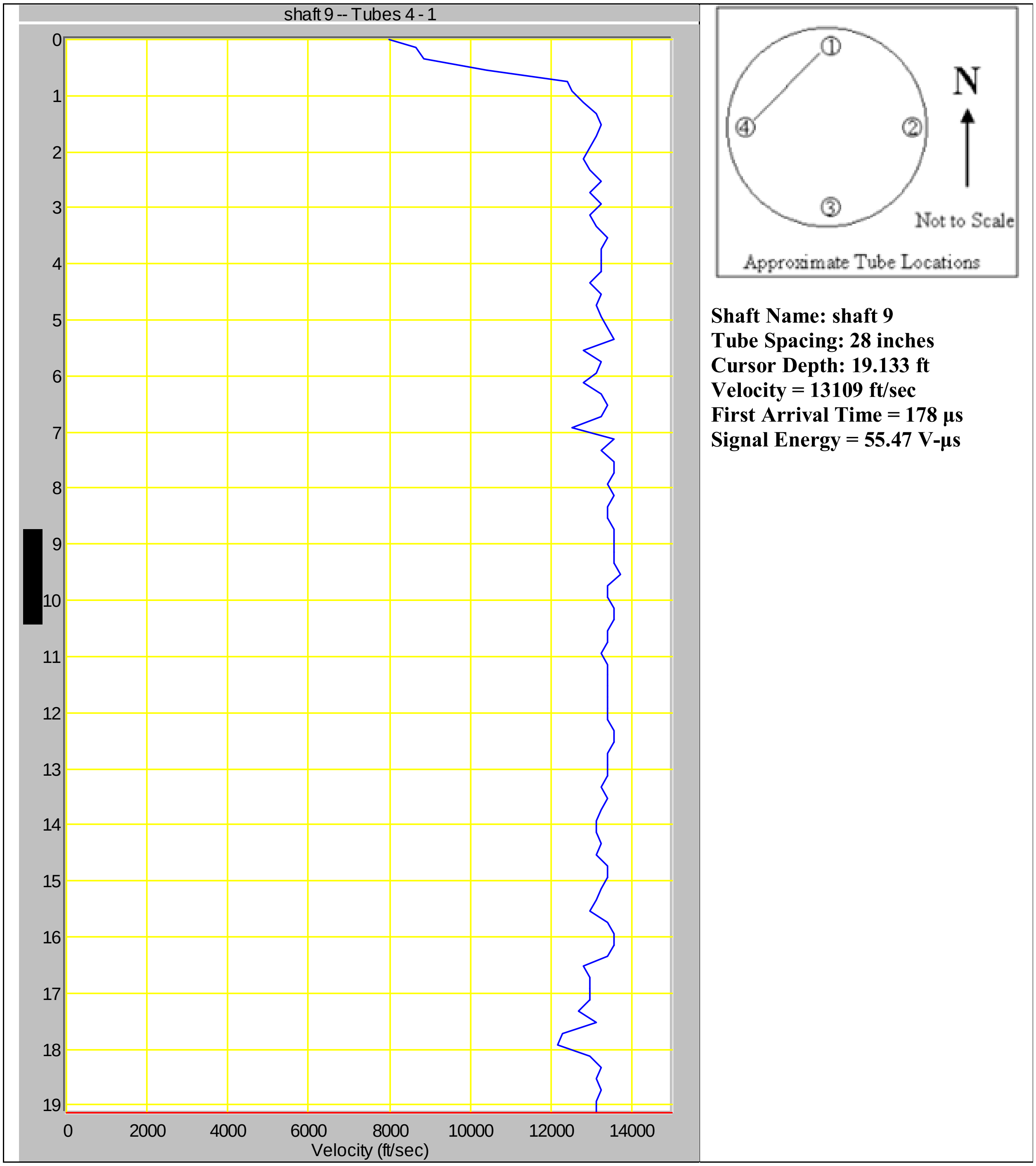


Figure 10. Example of velocity plot for SCC mixture placed in Pier 1, Shaft 9, Tubes 4-1.

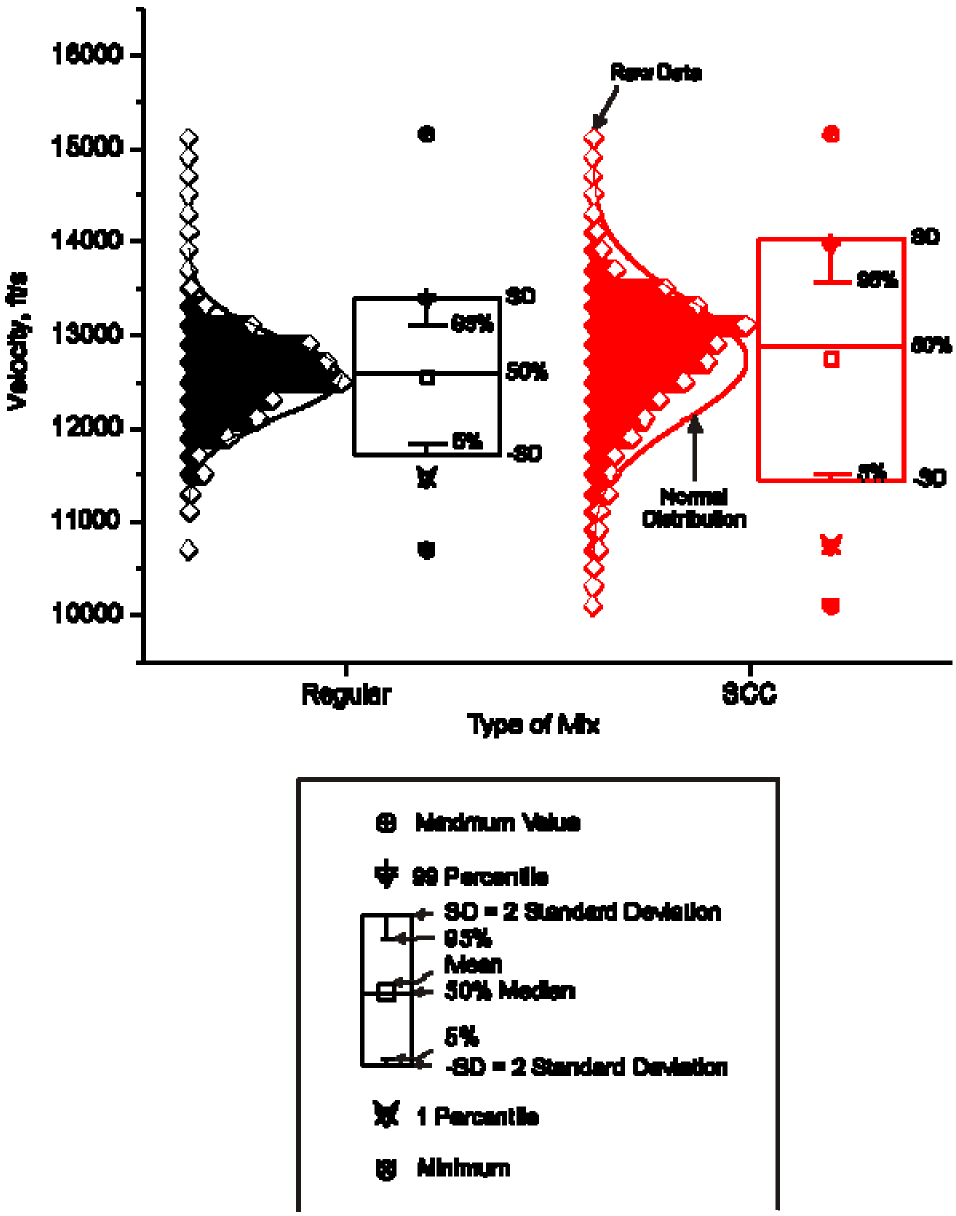


Figure 11. Box plot comparing the ultrasonic signal velocities through the two types of concrete mixtures.

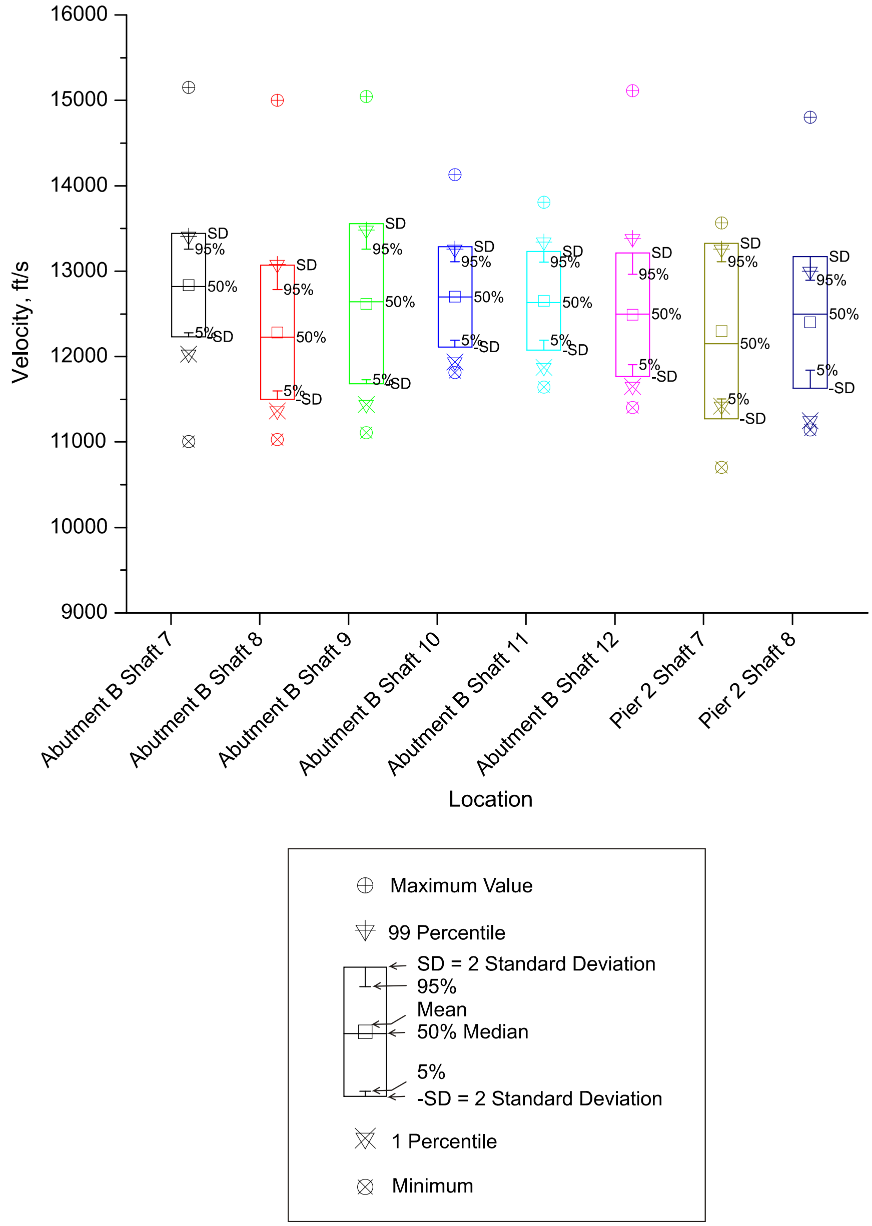


Figure 12. Box plots for the recorded velocities for each shaft containing conventional concrete.

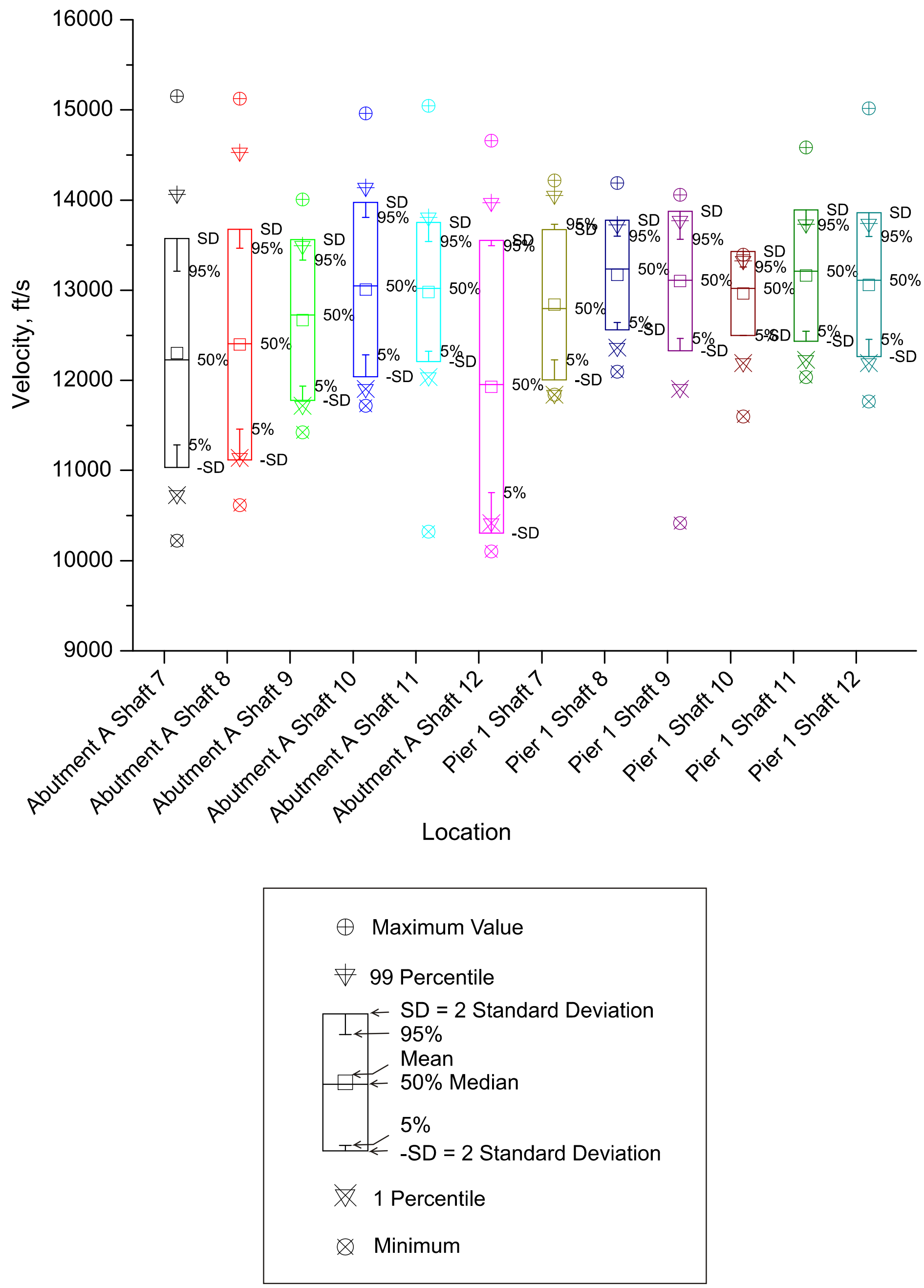


Figure 13. Box plots for recorded velocities for each shaft containing an SCC mixture.

Cover Depth

An attempt was made to determine the cover depth using the AU method in the laboratory. Two sensors were used facing each other but at an incline, as shown in Figure 14. A wedge covered with a thin layer of petroleum jelly was used to ensure the sensors were maintained at the appropriate angle to the concrete surface and properly coupled during testing. The sensors were then adjusted laterally and the AU signal response was monitored. One sensor transmitted the sound wave into the concrete, and the other sensor was used to detect the sound

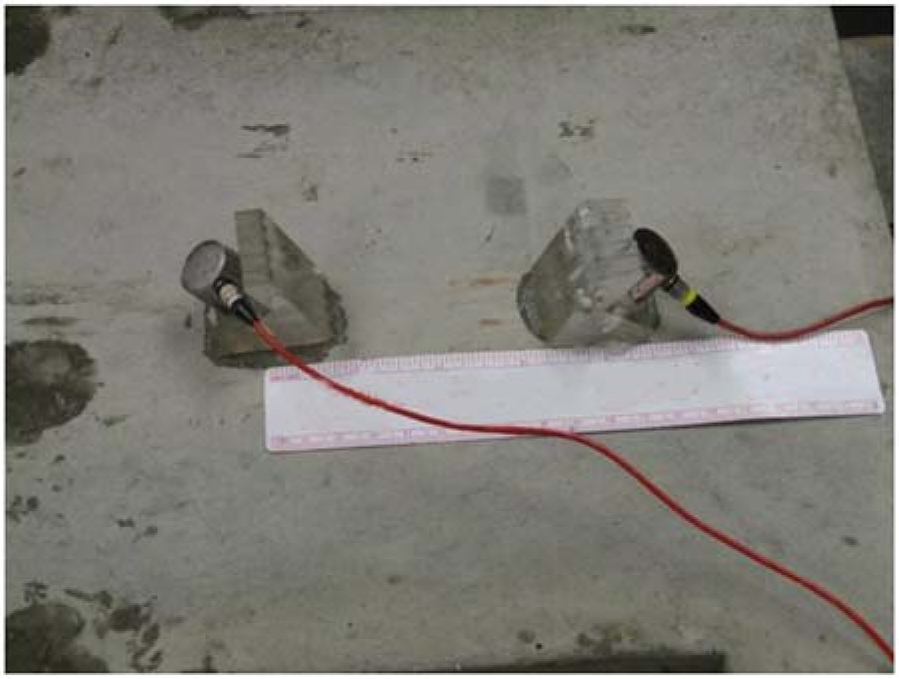


Figure 14. Sensors measuring depth by being placing on incline but still coupled to concrete using wedges.

wave reflected from the back side of the concrete. In the laboratory, the sensors were tested on concrete blocks of varying depth to determine the feasibility of this approach. This was successful since the lateral distance could be easily manipulated; however, it was quickly determined that a much more complex device that ensured the transducers always faced the external shaft surface would be required for this to be performed in the field on actual drilled shafts. Because of the amount of time required to develop such a device and the limited schedule, field testing was not possible and was postponed to future projects. The cover depth measurements were promising in the laboratory; however, further work is needed to adapt the AU test for use in the field on actual shafts.

Test Shafts

Concrete was tested at the fresh and hardened states. The w/cm of the concretes including those tempered and the fresh concrete properties are summarized in Table 13. In Shaft 1, conventional concrete was used, and in Shafts 2 and 3, SCC was used. The hardened concrete properties summarized in Table 14 indicated that concretes tempered to increase the w/cm had lower strength and higher permeability. SCC made from the conventional concrete had lower strength and higher permeability than the conventional concrete. The densities of SCC were lower and the fresh air contents higher. Low density may be attributed to the high air contents and would be consistent with low strengths. There may also be more water introduced when making the conventional mixture an SCC mixture; that would contribute to higher permeability and lower strength.

Table 13. Fresh Concrete Properties with Different w/cm

Concrete	Drilled Shaft	w/cm	Slump (in)	Slump flow (in)	T_{20} (sec)	Air (%)	Concrete Temp (F)	Density (lb/ft^3)
1 conventional	Shaft 1 bottom 5 ft	0.40	3.2			2.0	99	146.0
2 conventional	Shaft 1 top 3 ft	0.54	6.5			1.1	93	143.2
3 SCC	Shaft 2 bottom 5 ft and Shaft 3	0.40		26.0	2	3.3	95	139.6
4 SCC	Shaft 2 top 3 ft	0.50		32.0	1.5	3.3	95	135.6

Table 14. Strength and Permeability Data

Concrete	w/cm	1-d Strength (psi)	3-d Strength (psi)	7-d Strength (psi)	28-d Strength (psi)	Permeability (Coulombs)
1	0.40	2470	3790	4470	5640	1823
2	0.54	1350	2270	2880	3930	5804
3	0.40	1840	2780	3210	4190	5794
4	0.50	1070	1960	2250	3000	10914

Values are an average of 2 specimens.

Integrity Testing for Test Shafts

It became immediately clear that the metal tubes bonded better and stayed bonded longer when compared to the plastic tubes. CSL measurements at later ages exhibited better sonic energy transmission for the metal tubes as compared to the plastic tubes, as shown in Figure 15 and Figure 16.

SE/IR data gathered on the shafts demonstrated the ability of this technique to locate defects. The importance of care when selecting the velocity used to evaluate the location of a defect and shaft length was also shown. Table 15 shows the depth measured using SE/IR with different velocities. The calculated depths appear deeper when higher velocity values are used, as shown in Table 15. For example, the test shafts were 8 ft deep; thus the velocity value of 10,000 ft/sec is the more accurate velocity in this situation. However, in all cases shown in Table 15, SE/IR indicated the presence of a defect near the halfway point in the shaft.

A second interesting integrity test that was performed using one of the test shafts was to compare the CSL results in a region where the concrete when tested in compression exhibited lower strength to a region that had higher strength. These box plots showing the velocity values in 1-ft increments are shown in Figure 17. This is consistent with what would be expected near the surface of a shaft if a sufficient quantity of concrete has not been allowed to displace the poorer quality concrete that had formed by mixing with water during the placement of a shaft.

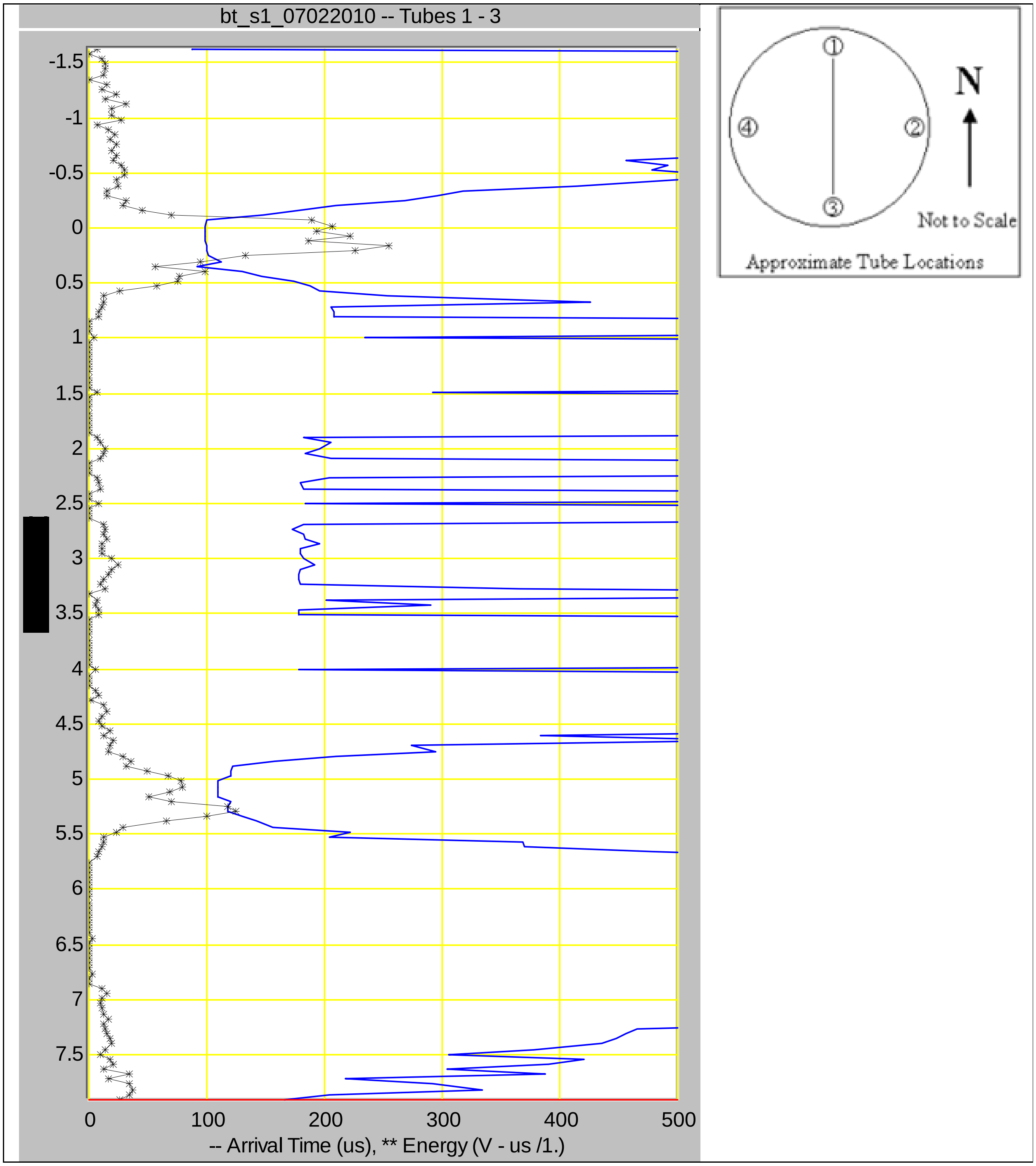


Figure 15. Typical CSL response when both tubes are plastic.

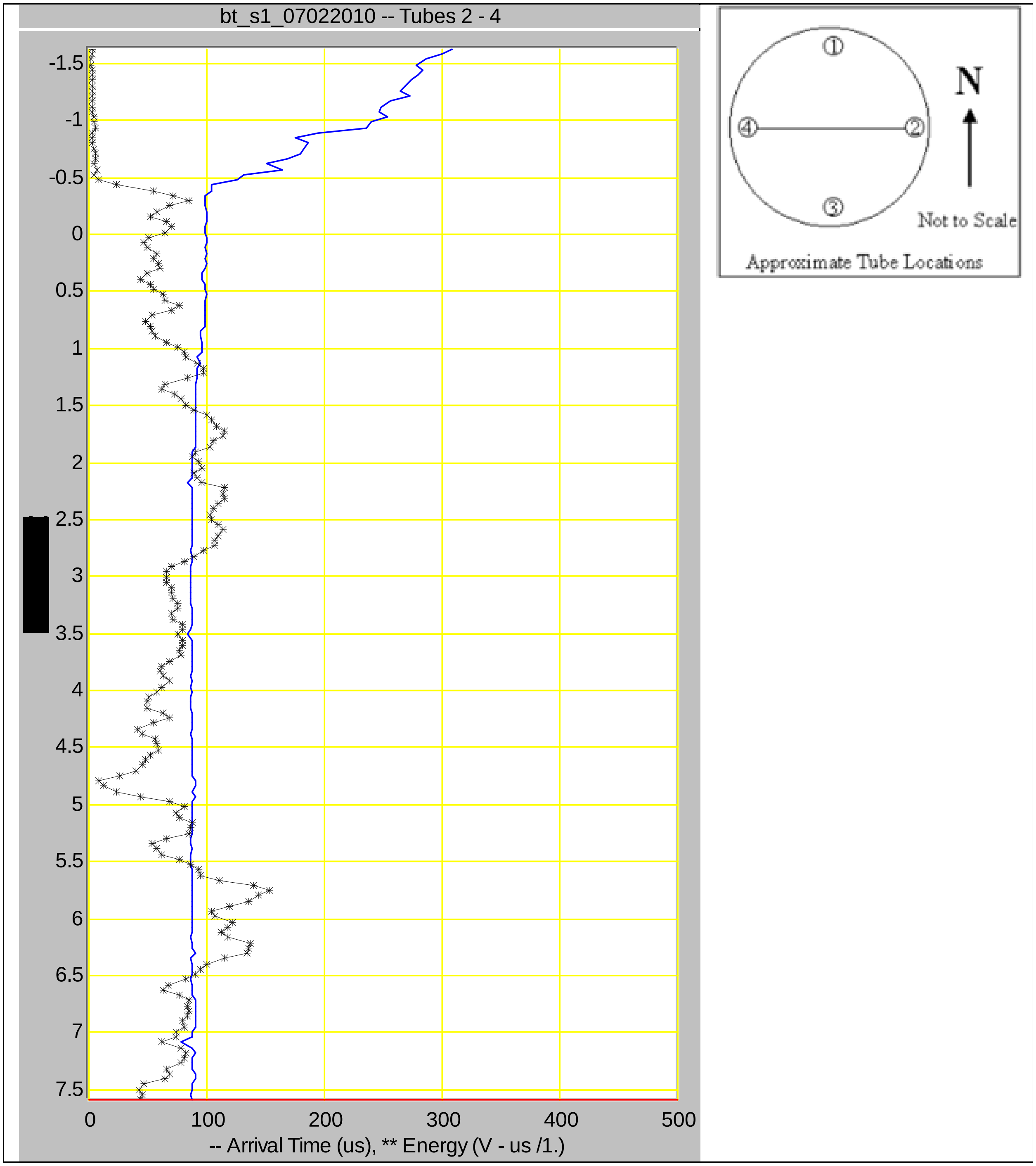


Figure 16. Typical CSL response when both tubes are metal.

Table 15. Influence of Different Velocity Values on Feature Depth

Description	**Calculated Depth for Following Velocities, ft**				
	For Velocity = 9,000 ft/s	**For Velocity = 10,000 ft/s**	**For Velocity = 11,000 ft/s**	**For Velocity = 12,000 ft/s**	**For Velocity = 13,000 ft/s**
Void location	3.7	4.1	4.5	4.9	5.3
Shaft length	7.5	8.4	9.2	10.0	10.9

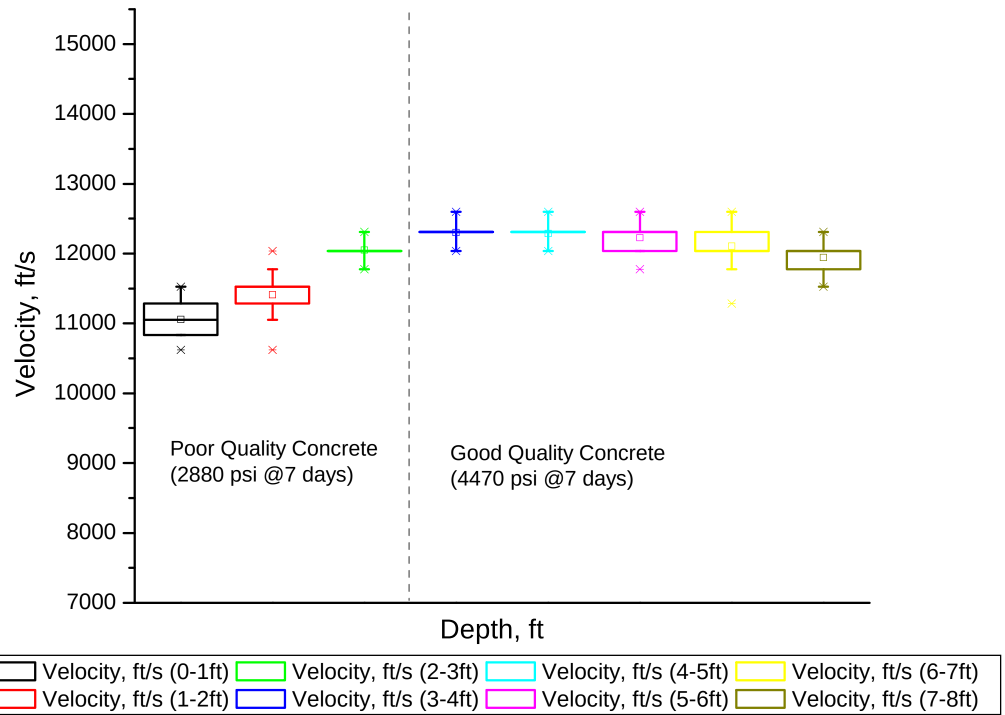


Figure 17. Comparison of compression test results for two areas of the concrete and the velocities in those regions.

CONCLUSIONS

- *Conventional and SCC mixtures with satisfactory workability and strength can be produced. SCC mixtures have higher workability and are easier to place.*
- *It is difficult to produce SCC that complied with the specification limits for air content; however, air is not needed for durability in these drilled shafts and was tested only to improve understanding of entraining air in future SCC applications.*
- *Temporary casings are easier to remove from drilled shafts with SCC.*
- *There is higher variability in the velocity measurements of SCC mixtures; however, the average values are also higher and the lowest velocity is similar to that of conventional concretes and are acceptable.*
- *CSL testing is easy to conduct and can detect large voids attributable to honeycombing but must be conducted early before the placement of the concrete cap. In addition, metal tubes provide much clearer signals than plastic tubes, especially at later ages.*
- *Voids inside the shaft can be detected by using SE/IR.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge and Materials Divisions should use SCC in drilled shafts because of its high workability; the easy removal of the casing; and the quality of the concrete as determined by the evaluation of concrete properties and the integrity testing.*

2. *VDOT's Structure and Bridge and Materials Divisions should use CSL to determine the integrity of drilled shafts because of its ability to detect large detrimental voids and its convenience.*

3. *The Virginia Center for Transportation Innovation and Research (VCTIR) should train VDOT personnel in the use of CSL so that the available equipment can be used routinely in VDOT projects.*

4. *VCTIR should continue to investigate nondestructive methods to determine the concrete cover depth outside the reinforcing cage.*

5. *VCTIR should work with VDOT's Structure and Bridge to continue evaluating SE/IR and other shaft evaluation techniques as they become available*

BENEFITS AND IMPLEMENTATION PROSPECTS

SCC would be highly desirable in drilled shafts where concrete consolidation is not possible because of geometry, location (in the ground), and the reinforcement. Implementation of SCC in drilled shafts would eliminate the large voids (honeycombing) that would adversely affect the integrity of the shafts. Removal of temporary casing is another concern where there is the possibility of lifting the shaft, leaving a void underneath; SCC would eliminate such concern. VCTIR has a CSL unit and is prepared to train other VDOT personnel. Availability of the equipment for routine testing by central office or district personnel would provide an urgent service and could also be used to verify questionable results.

ACKNOWLEDGMENTS

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