VTRC
Virginia Transportation
Research Council

Bridge Beams and Pier Caps With Self-Consolidating Concrete at Nimmo Parkway

http://www.virginiadot.org/vtrc/main/online_reports/pdf/16-r11.pdf

CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist

GAIL M. MORUZA, E.I.T.
Graduate Research Assistant

Final Report VTRC 16-R11

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 16-R11	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Bridge Beams and Pier Caps With Self-Consolidating Concrete at Nimmo Parkway		5. Report Date: February 2016
		6. Performing Organization Code:
7. Author(s): Celik Ozyildirim, Ph.D., P.E., and Gail Moruza, E.I.T.		8. Performing Organization Report No.: VTRC 16-R11
9. Performing Organization and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS):
		11. Contract or Grant No.: 91013
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219	Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final
		14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract:

Self-consolidating concrete (SCC) has a very high level of workability as it easily fills formwork under the influence of its own mass without any additional consolidation energy. SCC can be placed in narrow and congested areas, fit the geometry of the element, and provide smooth surfaces. The purpose of this study was to investigate innovative, cost-effective, and aesthetically pleasing SCC mixtures for use in bridge beams and pier caps.

The Virginia Department of Transportation used SCC in two bridges located south of Virginia Beach on the same project and in close proximity to each other. The bridges carry Nimmo Parkway traffic over Hunt Club Tributary and West Neck Creek. The bridge over West Neck Creek has 18 spans, and the bridge over Hunt Club Tributary has 2 spans. Precast SCC was used in the 220 beams on the two bridges, and cast-in-place SCC was used in three pier caps on one of the bridges. SCC mixtures were prepared at a prestressed concrete plant for the beams and a ready mixed concrete plant for cast-in-place applications. Cast-in-place SCC was delivered to the site by ready mixed concrete trucks.

SCC for the bridge beams had high flow rates and attained high strength and low permeability. The surface of the beams had minimal blemishes. The cast-in-place SCC also had high strength and low permeability. In one of the four loads used in the first pier cap, marginal stability and lower but satisfactory strength were obtained. On the second and third day of the placements, SCC of uniform quality was obtained.

Thus, compared to conventional mixtures, SCC is expected to have greater material-related costs because of changes in ingredients, particularly the addition of more and higher dosages of chemical admixtures. However, the ease of placement, speed of construction, and reduced labor requirements are expected to result in overall cost savings in structures with SCC. Further, the lack of problems with consolidation is expected to lead to improved surface appearance, strength, and durability; an increased service life; and lower life cycle costs.

The study recommends that SCC be an option for precast and cast-in-place applications, and the Virginia Department of Transportation will include this option in its new 2016 *Road and Bridge Specifications.*

17 Key Words: Concrete, self-consolidating concrete, beams, pier caps, strength, permeability, shrinkage, freeze/thaw	18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.		
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 25	22. Price:

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

BRIDGE BEAMS AND PIER CAPS WITH SELF-CONSOLIDATING CONCRETE AT NIMMO PARKWAY

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

Gail M. Moruza, E.I.T.
Graduate Research Assistant

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

February 2016
VTRC 16-R11

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

ABSTRACT

Self-consolidating concrete (SCC) has a very high level of workability as it easily fills formwork under the influence of its own mass without any additional consolidation energy. SCC can be placed in narrow and congested areas, fit the geometry of the element, and provide smooth surfaces. The purpose of this study was to investigate innovative, cost-effective, and aesthetically pleasing SCC mixtures for use in bridge beams and pier caps.

The Virginia Department of Transportation used SCC in two bridges located south of Virginia Beach on the same project and in close proximity to each other. The bridges carry Nimmo Parkway traffic over Hunt Club Tributary and West Neck Creek. The bridge over West Neck Creek has 18 spans, and the bridge over Hunt Club Tributary has 2 spans. Precast SCC was used in the 220 beams on the two bridges, and cast-in-place SCC was used in three pier caps on one of the bridges. SCC mixtures were prepared at a prestressed concrete plant for the beams and a ready mixed concrete plant for cast-in-place applications. Cast-in-place SCC was delivered to the site by ready mixed concrete trucks.

SCC for the bridge beams had high flow rates and attained high strength and low permeability. The surface of the beams had minimal blemishes. The cast-in-place SCC also had high strength and low permeability. In one of the four loads used in the first pier cap, marginal stability and lower but satisfactory strength were obtained. On the second and third day of the placements, SCC of uniform quality was obtained.

Thus, compared to conventional mixtures, SCC is expected to have greater material-related costs because of changes in ingredients, particularly the addition of more and higher dosages of chemical admixtures. However, the ease of placement, speed of construction, and reduced labor requirements are expected to result in overall cost savings in structures with SCC. Further, the lack of problems with consolidation is expected to lead to improved surface appearance, strength, and durability; an increased service life; and lower life cycle costs.

The study recommends that SCC be an option for precast and cast-in-place applications, and the Virginia Department of Transportation will include this option in its new 2016 *Road and Bridge Specifications.*

FINAL REPORT

BRIDGE BEAMS AND PIER CAPS WITH SELF-CONSOLIDATING CONCRETE AT NIMMO PARKWAY

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

Gail M. Moruza, E.I.T.
Graduate Research Assistant

INTRODUCTION

Consolidation of concrete is a critical process in the construction of elements. Regular concretes are affected by improper consolidation, ending with large voids that reduce service life. These large voids adversely affect strength and permeability, leading to frequent maintenance needs mainly because of corrosion problems in reinforced structures. In addition, delays in construction because of the handling of concretes with stiff consistencies and safety-related issues because of consolidation equipment and procedures increase the cost of construction. The use of self-consolidating concrete (SCC) as an alternative to regular concretes allows for faster placement, which leads to improved jobsite productivity.

SCC has very high workability. High workability is expected to reduce surface imperfections such as bugholes. These imperfections are generally aesthetically objectionable and require corrective measures such as rubbing in paste or mortar. SCC easily fills the congested spaces between reinforcement (both mild reinforcement and prestressing steel) and formwork under the influence of its own mass and without any additional consolidation energy (American Concrete Institute, 2007). The elimination of large air voids is essential for the longevity of precast units. Consolidation efforts would be needed to eliminate large air voids in conventional concrete. However, easily flowing SCC minimizes large air voids and permits convenient and rapid concrete placement.

SCC has been used in Japan and Europe advantageously since the 1990s (Okamura and Ouchi, 1999). Some of the benefits of using SCC are the following:

- reduced labor
- increased construction speed
- improved durability characteristics
- ease of placement in heavily reinforced and congested areas common in beams with strands and shear reinforcement

- consolidation without vibration and without segregation

- reduced noise level at manufacturing plants and construction sites.

Some concerns about SCC include the following:

- the degree of uniformity
- the potential for segregation
- increased shrinkage
- the questionable quality of the air-void system (Ozyildirim, 2004)
- the quality of the bond between strands and concrete.

However, the bond strength of SCC to reinforcing steel at 28 days has been shown to be greater (16% to 40%) than that of a mixture with normal workability (Sonebi and Bartos, 1999). Producers are seeing the advantages of SCC, and many are using SCC in precast and cast-in-place applications.

The Virginia Department of Transportation (VDOT) used normal weight SCC in the beams of the bridge on Route 33 over the Pamunkey River (Ozyildirim, 2008). In the casting of the beams, uniformity was an issue. Variation in consistency led to marginal stability in some beams and the need for limited consolidation in others. Prior to using SCC in the actual structure, the precast plant that produced the actual bridge beams cast two test beams These two test beams were evaluated at the Federal Highway Administration's Turner-Fairbank Highway Research Center Structures Laboratory (Ozyildirim, 2008; Ozyildirim and Davis, 2007). The test beams exhibited small amounts of bleeding (Ozyildirim, 2005). Bleeding is indicative of segregation. During the evaluation, pieces of concrete from the test beams revealed some segregation where coarse aggregates had settled to the bottom. However, the test beams performed at least as well as would be expected for normally consolidated concrete beams (Ozyildirim and Davis, 2007). These positive results from the test beam evaluations justified the use of SCC in the beams placed in the actual structure.

VDOT also used SCC in the lightweight high performance concrete bulb-T beams of the bridge on Route 17 over Route 15/29 in Fauquier County, Virginia (Ozyildirim, 2014). The bridge has two spans, each 128 ft long. Eight beams were cast at a prestressed concrete plant and had high workability and strength and low permeability.

VDOT used cast-in-place SCC in the limited applications of a slab, median barrier, and column in early 2000 (Ozyildirim, 2005). In the slab, some of the concrete did not have a high flow rate, resulting in difficulty in placement and finishing. In the median barrier, some of the concrete was lost through formwork gaps. Later, cast-in place SCC was used satisfactorily in drilled shafts (Ozyildirim and Sharp, 2012) and in a study for the repair of bridge substructures as an alternative to shotcrete.

PROBLEM STATEMENT

Difficulty in consolidation leading to improper consolidation adversely affects the strength and permeability of concretes. SCC does not require consolidation; however, during construction, slump loss can occur that would require consolidation. SCC has a high flow rate that must be maintained during construction. Otherwise, mechanical vibration would be required. SCC mixtures do not tolerate a high water–cementitious materials ratio (w/cm), as stability (resistance to segregation) becomes an issue. A low w/cm also leads to concretes with high strength and durability. Since SCC is very sensitive to water content, in some cases, high variability in consistency has been an issue and has led to marginal stability.

PURPOSE AND SCOPE

The purpose of this study was to investigate innovative, cost-effective, and aesthetically pleasing SCC mixtures for use in bridge beams and pier caps. SCC mixtures were prepared at a prestressed concrete plant for the beams and a ready mixed concrete plant for cast-in-place applications.

For this study, VDOT used SCC in two bridges located south of Virginia Beach on the same project and in close proximity to each other. The bridges carry Nimmo Parkway traffic over Hunt Club Tributary and West Neck Creek. The bridge over West Neck Creek has 18 spans, and the bridge over Hunt Club Tributary has 2 spans.

METHODS

The 220 beams of the two bridges and three pier caps of one bridge structure had SCC. The specified minimum 28-day compressive strength for beams was 8,000 psi with a release strength of 6,000 psi and a maximum permeability of 1500 coulombs. The pier cap minimum compressive strength was 3,000 psi and the maximum permeability was 2500 coulombs.

The beams, which all had SCC, were transported and erected at the jobsite. No. 68 aggregate with a nominal maximum size (NMS) of ¾ in was used in the beams. In the laboratory, the fresh and hardened concrete properties of the SCC for the beams were determined. After the completion of the beams, the plant shifted to using No. 8 aggregates with an NMS of 3/8 in. The shift was for facilitating the production and placement of the SCC. In the laboratory, another mixture with the smaller size No. 8 aggregate was made to compare with the mixture with larger size aggregate. The cast-in-place concrete for pier caps was batched at the ready mixed concrete plant and transported to the jobsite in trucks. SCC was used on only three of the pier caps for the westbound lane of the long bridge over West Neck Creek. To gain experience, three pier caps were thought to be sufficient.

Overview of Bridges

Bridge Over West Neck Creek

The bridge consists of 18 spans with 11 bulb-T beams in each span including the eastbound and westbound lanes. The beams are 53-in bulb-T beams. The total length of the beam line is approximately 17,611 ft. The total width of the bridge is 104.8 ft including two 11-in rails on both sides.

Eastbound Lane Beams and Spans

The eastbound lane of the parkway over West Neck Creek has 5 bulb-T beams per span over 18 spans, resulting in a total of 90 bulb-T beams per lane. The length of the first span is 88.8 ft, and the length of the others is 89.0 ft.

Westbound Lane Beams and Spans

The westbound lane of the parkway over West Neck Creek has 18 spans with 6 bulb-T beams per span, resulting in a total of 108 bulb-T beams per lane. The length of the first span is 88.8 ft, and the length of the other spans is 89.0 ft.

Bridge Over Hunt Club Tributary

The bridge is 120 ft in length and has two 60-ft spans. There are 11 bulb-T beams at each span including the eastbound and westbound lanes. The total number of beams is 22. The beams are 37-in bulb-T beams. The total length of the beam lines is approximately 1,320 ft. The total width of the bridge is 105.8 ft including two 11-in rails on both sides.

Eastbound Lane Beams and Spans

The eastbound lane of the bridge over Hunt Club Tributary has two spans with 5 bulb-T beams per span, resulting in a total of 10 bulb-T beams.

Westbound Lane Beams and Spans

The westbound lane of the bridge over Hunt Club Tributary has two spans with 6 bulb-T beams per span, resulting in a total of 12 bulb-T beams.

Mixture Proportions

Laboratory Concretes

Laboratory concretes were prepared with two aggregate sizes: No. 68 and No. 8. The cementitious content was a mixture of Type III portland cement and Class F fly ash. The No. 68 coarse aggregate had a specific gravity of 2.66. The No. 8 aggregate had a specific gravity of

2.63. The fine aggregate was natural sand with a specific gravity of 2.64 and a fineness modulus of 2.71. Air entraining admixtures, retarding admixtures, and high-range water-reducing admixtures (HRWRAs) were used. The mixture proportions of the laboratory concretes using No. 68 and No. 8 aggregates are given in Table 1. Both mixtures had the same amount of cementitious material and w/cm. The mix designs were provided by the plant.

Table 1. Mixture Proportions (lb/yd^3)

Ingredient	No. 68 Aggregate	No. 8 Aggregate
Type III cement	638	638
Fly ash	212	212
Coarse aggregate, No. 68	1425	0
Coarse aggregate, No. 8	0	1450
Fine aggregate	1240	1240
Water	304	304
w/cm	0.36	0.36
Air (%)	3-7	3-7

w/cm = water–cementitious materials ratio.

Beams

In the production of the beams, the mixture proportions given in Table 1 for No. 68 aggregate were used.

Pier Caps

The mixture proportions for the pier caps are given in Table 2. For comparison, a conventional pier cap mixture used at the project from the same ready mixed concrete plant is also included. The cementitious materials used were Type II portland cement and Class F fly ash. The coarse aggregate size was No. 57 with an NMS of 1 in. The fine aggregate was natural sand with a fineness modulus of 2.95. Chemical admixtures used were air-entraining admixtures, water-reducing or retarding admixtures, and HRWRAs. For SCC, a viscosity modifying admixture (VMA) was added for stability. VMAs change the rheology of the mixtures, making them more cohesive and stable (i.e., resistant to segregation).

Table 2. Mixture Proportions (lb/yd^3)

Ingredient	Conventional Concrete	SCC
Type II cement	508	508
Fly ash	127	127
Coarse aggregate	1775	1700
Fine aggregate	1208	1321
Water	267	250
w/cm	0.42	0.39
Air (%)	5-8	5-9

SCC = self-consolidating concrete; w/cm = water–cementitious materials ratio.

The conventional and SCC mixtures had the same amount of cementitious materials. However, the SCC mixture had increased amounts of fine aggregate and decreased amounts of coarse aggregate. This change allowed for improved workability and stability. In both mixtures, No. 57 stone with an NMS of 1 in was used. The coarse aggregate did not have a good particle shape. As expected in a SCC mixture, increased amounts of HRWRA were used. On the first day of placement, a retarding admixture was also used to delay the time of set. On the second day of placement, the retarding admixture was replaced with a water-reducing admixture and a small dosage of accelerator to reduce the time of set.

Concrete Testing

Laboratory Concretes

The laboratory concretes were steam cured in a manner similar to that for the concretes at the plant. The curing temperature was raised 20°F per hour after the initial set but was then held at 155°F for 7 hours. The following fresh concrete properties were tested for each mixture:

- *slump flow and slump flow time to reach 20 in:* ASTM C1611-09 (ASTM, 2009a)
- *air content:* ASTM C231-10 (ASTM, 2010a)
- *density:* ASTM C138-13 (ASTM, 2013).

In the hardened state, compressive strength, elastic modulus, length change for drying shrinkage, and permeability were determined. The tests for the hardened state concrete properties and the specimen sizes are summarized in Table 3. For permeability, two sets were prepared and subjected to different curing procedures and then tested at 28 days. After the initial steam curing, one set was kept in the moist room until testing. The second set was subjected to the accelerated curing, which involved standard moisture curing at room temperature up to 1 week and then 3 weeks in a 100 °F water bath. The accelerated curing is a standard curing procedure used by VDOT. However, when steam curing is used, accelerated curing may not be necessary. This would depend on the duration and the temperature level during the steam curing.

Concrete for Beams

The SCC for the beams was tested in the fresh and hardened states. Fresh concrete samples were tested for slump flow, slump flow with J-Ring in accordance with ASTM C1621-09 (ASTM, 2009b), air content, and density. In the hardened state, compressive strength and permeability were tested.

Concrete for Pier Caps

The SCC for the pier caps was tested in the fresh and hardened states. Fresh concrete samples were tested for slump flow, slump flow with J-Ring, air content, and density. In the hardened state, the tests shown in Table 3 were conducted. The resistance to cycles of freezing and thawing was determined in accordance with ASTM C666 (ASTM, 2008a), Procedure A, except that the specimens were air dried at least 1 week before the test and the test water contained 2% NaCl.

Table 3. Test and Specimen Sizes for Hardened Concrete

Test	Specification	Specimen Size, in
Compressive strength	ASTM C39-12 (ASTM, 2012a)	4 x 8
Elastic modulus	ASTM C469-10 (ASTM, 2010b)	4 x 8
Splitting tensile strength	ASTM C496-11 (ASTM, 2011)	4 x 8
Permeability	ASTM C1202-12 (ASTM, 2012b)	2 x 4
Drying shrinkage	ASTM C157-08 (ASTM, 2008b)	3 x 3 x 11.3
Freeze-thaw durability	ASTM C666-08 (ASTM, 2008a)	3 x 4 x 16

Placement

Beams

Beams for both bridges were cast at the same prestressed concrete plant between June 25 and September 27, 2012. They were steam cured and stored at the plant until delivery to the jobsite. The use of SCC facilitated fabrication, and beams with minimal surface blemishes were obtained. Figure 1 shows the beams in place at the jobsite.

Figure 1. Beams in Place at Jobsite

Pier Cap

Three pier caps were selected for SCC application. All pier caps used conventional concrete except the last three. The first one was placed April 21, 2014. Each cap had 39.2 yd^3 of concrete delivered in four truckloads. The trucks parked on the bridge next to the pier cap. SCC was discharged into the cap mold through the truck chute and flowed from one end to the other in the pier cap. The length of the pier cap was 58 ft. Buckets were used to supply SCC to the farthest end of the pier cap. Limited internal vibration was used.

The SCC mixtures had a slump flow range of 20 to 24 in; these flow values are at the lower acceptable range for SCC. The finishers noticed that the SCC was not setting the first day of placement and that the top surface of the cap was still not set the next morning. The mixture contained a retarding admixture that worked well with the HRWRA and provided good workability, although it delayed setting time. The air temperature was around 50 °F, and the mixture temperature was 60 °F to 64 °F. At night, the ambient temperature was in the 40s °F. On the first day of placement, the last load had marginal stability. The geometry of the pier cap was a sloping surface with raised areas for the beam seats. The load with marginal stability was the last load placed on the top where the geometry made it difficult to keep it in place.

For the second cap placed on April 23, 2014, changes in the admixture dosages and type were made as follows:

- The slump flow range was reduced to 18 to 22 in.
- The retarding admixture was replaced with a water-reducing admixture.
- The dosage of HRWRA was reduced.
- The dosage of VMA was increased.
- A low dosage of an accelerator was added.

The concrete was stable, and finishing was accomplished without any delays. The air temperature was around 60 °F, and the concrete temperature was 66 °F to 68 °F. At night, the temperature was in the 50s °F. For the third day of placement for the third cap on April 25, 2014, the previous day's admixtures were continued except that the dosage of the accelerator was reduced by one half. The air temperature this day and night was in the 50s °F.

The contractor was skeptical of using SCC before placement. The results after the first day of placement did not reduce his skepticism. However, later placements went so well that the contractor chose to use SCC in the patterned rail walls.

RESULTS

Laboratory Concretes

The fresh concrete properties for the mixtures made in the laboratory are given in Table 4. Workable concretes with satisfactory and similar air contents were obtained. The hardened concrete properties of these mixtures are given in Table 5. The values for strength, elastic modulus, and length change were an average of three specimens, and the permeability values were an average of two specimens.

Table 4. Fresh Concrete Properties

Property	No. 68 Aggregate	No. 8 Aggregate
Air content (%)	5.0	5.2
Density (lb/ft^3)	142.4	141.2
Slump flow (in)	21	20
Slump flow time (sec)	7	9
Mix temperature (°F)	72	72

Table 5. Hardened Concrete Properties at 28 days

Test	Age	No. 68 Aggregate	No. 8 Aggregate
Compressive strength (psi)	1 day	7080	7360
	7 days	8600	8650
	28 days	9590	9780
Elastic modulus (ksi)	28 days	4150	3960
Drying shrinkage (microstrain)	28[a] days	353	397
	4[a] months	413	517
Permeability (C)	28 days[b]	229	213
	28 days[c]	2260	1224

[a] Drying shrinkage specimens were moist cured for 7 days; the age does not include the moist-curing period.
[b] After steam curing, specimens were moist cured up to 1 week at room temperature and then 3 weeks at 100 °F (accelerated curing).
[c] After the steam curing, specimens were moist cured at room temperature for the remaining 28 days.

Compressive strengths were high and comparable in the two mixtures but were slightly higher in the mixture with the smaller aggregate. Elastic modulus values were also comparable but slightly higher in the mixture with the larger aggregate. The shrinkage values were lower for the mixtures with the larger aggregate as larger aggregate provides more resistance to shrinkage. The permeability values were very low and similar when accelerated curing was used because of the increased hydration and pozzolanic reactions with high temperatures.

Beams

Fresh and hardened samples of the SCC were tested for mixture qualification prior to the casting of beams and for quality control and acceptance during production.

Mixture Qualification

For the mixture qualification, 40 cylinders were tested for compressive strength from a batch of concrete. For permeability, 5 cylinders were tested from the same batch. Compressive strength tests were conducted after 1, 7, and 28 days, and permeability tests were conducted at 28 days. The average strength value at 28 days was 11,067 psi, which is higher than the minimum 8,000 psi specified (Table 6). Average permeability was 270 coulombs at 28 days, which is lower than the maximum 1500 coulombs specified. Specimens for compressive strength were subjected to moist curing. The permeability samples were subjected to accelerated curing in a moist environment for 1 week at room temperature and then 3 weeks at 100 °F. The test data were satisfactory, and the mix design was approved by VDOT.

Table 6. Compressive Strength and Permeability Data for Mixture Qualification

Age (days)	n	Compressive Strength (psi)	n	Permeability (coulombs)
1	40	5,076	-	-
7	40	8,429	-	-
28	40	11,067	5	270

n = number of specimens.

Quality Control and Acceptance

During production, fresh and hardened concrete properties were monitored periodically. Table 7 shows the minimum, maximum, and average values for slump flow, air content, and density (unit weight) for specimens placed at the live end and dead end. Specimens were subjected to the same curing environment as the beams, i.e., steam curing and then storage exposed to air. The maximum temperature reached during steam curing was 169 °F.

Specimens were tested for compressive strength at 1, 7, and 28 days. Since the specified strengths were obtained at 7 days, further testing at 28 days was limited to a few specimens. Table 8 summarizes the strength values, including the live end, dead end, and average results. Dead end and live end specimens produced similar 1-day strengths, just above 7,000 psi, with standard deviations over 900 psi. The large standard deviation was attributed to the testing of only one cylinder for each end of the bed each day and to the short time period between casting and testing. The 7-day average strengths exceeded the specified minimum 28-day strength of 8,000 psi, with average values over 9,000 psi. The relatively low standard deviations of the 7-day strength tests were attributed to the average of three cylinders for each test value and indicate good quality control in production. The 28-day strength was around 8,500 psi, and since it was less than the 7-day strength, this result was attributed to the relatively small number of specimens. The strength of the specimens was considered acceptable since it exceeded 8,000 psi at 7 and 28 days. The results in Tables 6 and 8 show that all values for 1-day and 7-day strengths were higher during the production compared to the initial phase of the mixture qualification tests. This indicates satisfactory quality control and the benefits of steam curing at an early age.

Table 7. Quality Control Data for Fresh Concrete Samples During Production

Test	Live End				Dead End			
	n	Minimum	Maximum	Average	n	Minimum	Maximum	Average
Slump flow (in)	64	18.0	27.0	22.6	64	17.5	27.0	24.0
Air content (%)	64	3.0	7.0	4.7	64	3.0	6.8	4.8
Density (lb/ft^3)	64	139.0	147.0	144.0	64	141.0	145.6	143.1

n = number of specimens.

Table 8. Quality Control Tests for Concrete Strengths During Production

Age (days)	Live End			Dead End			Average		
	n	Strength (psi)	SD	n	Strength (psi)	SD	n	Strength (psi)	SD
1	63	7,254[a]	987	63	7,234[a]	956	126	7,244	936
7	62	9,100[b]	258	59	9,068[b]	439	121	9,074	310
28	1	8,745[b]	-	4	8,579[b]	349	5	8,612	312

n = number of samples; SD = standard deviation.
[a] From 1 specimen each day.
[b] The test result was an average of 3 cylinders.

The surface quality of the SCC was also inspected and compared to the surface quality of the conventional concrete. The surfaces of the SCC and the conventional concrete are shown for comparison in Figure 2. Although there are surface blemishes in both concrete types, there are fewer in the SCC and they are less pronounced than in the conventional concrete.

Figure 2. Surface of SCC (left) and of Conventional Concrete (right)

Pier Caps

The cast-in-place concretes were sampled and tested for fresh concrete properties at the jobsite. Specimens were also made for hardened concrete tests. The specimens were kept overnight at room temperature in the trailer at the jobsite and then brought to the laboratory for moist curing. The permeability specimens were subjected to accelerated curing.

Fresh Concrete

Each of the four loads for each cap was tested, and the results are given in Table 9. The mixtures had high workability and adequate air. Air contents ranged from 5.5% to 7.5%. The fourth load from the first day (04/21/14) had marginal stability, and there was a slight halo around the spread. There were concerns about strength and permeability values because of the marginal stability, which could have resulted from a higher than anticipated water content in that load. In general, stable mixtures were obtained even with a moderate cementitious material content attributed to the presence of the VMA.

Table 9. Fresh Concrete Properties

Date	Load	Slump Flow (in)	Air (%)	Density (lb/ft^3)	Concrete Temp (°F)	Air Temp (°F)
04/21/14	1	24.0	7.0	---	61	46
04/21/14	2	23.0	7.5	---	59	48
04/21/14	3[a]	23.8	7.6	142.0	60	49
04/21/14	4[a]	24.0	5.1	145.2	64	51
04/23/14	1	20.0	6.0	147.2	66	62
04/23/14	2[a]	17.0	5.8	145.6	68	62
04/23/14	3	19.0	5.8	145.6	66	59
04/23/14	4[a]	22.0	5.8	146.0	68	64
04/25/14	1	22.0	7.0	---	69	48
04/25/14	2	23.0	5.5	---	68	50
04/25/14	3	22.0	6.0	---	69	55
04/25/14	4	20.0	6.2	---	68	60

[a] Load was tested at the hardened state.

Hardened Concrete

The strength, elastic modulus, splitting tensile strength, permeability, and length change data are given in Table 10. The fourth load (L4) placed in Bent 15 on the first day had lower compressive strength than the other batches; however, the strength was still higher than the 3,000 psi required at 28 days. The splitting tensile strength test also indicated the lowest value in that load. The load also had the lowest elastic modulus, as expected because of the lower strength. But all strength values were satisfactory. The permeability value for that load was the highest; however, the values were very low, indicating very low permeability. L4 Bent 15 also had the highest shrinkage value, indicating the addition of extra water, which was consistent with the lower strength values. However, the shrinkage value at 28 days for this load was very close to the 400 microstrain recommended for reduced cracking for bridge decks (Babaei and Fouladgar, 1997). At 4 months, all the values were less than the recommended maximum of 700 microstrain.

Table 10. Hardened Concrete Properties

Test	Age	L3 Bent 15 04/21/14	L4 Bent 15 04/21/14	L2 Bent 16 04/23/14	L4 Bent 16 04/23/14
Compressive strength (psi)	2 days	-	-	3780	3790
	3 days	4350	3120	-	-
	7 days	5150	3780	4940	4710
	28 days	6570	4950	6270	6250
Elastic modulus (10^6 psi)		5.09	5.09	5.40	5.31
Splitting tensile strength (psi)	28 days	590	555	650	640
Permeability (C)	28 days	444	729	453	543
Drying shrinkage (microstrain)	28[a] days	307	407	373	383
	4[a] months	393	560	510	543
	6[a] months	433	610	560	597

Strength and permeability values are an average of 2 specimens; length change data are an average of 3 beams.
[a] Specimens were moist cured for 7 days; the age does not include the moist curing period.

The data for the resistance to cycles of freezing and thawing are given in Table 11. The VDOT acceptance criteria at 300 cycles are a weight loss of 7% or less, a durability factor of 60 or more, and a surface rating of 3 or less. The data given in Table 9 indicate that concretes made on the second day of placement (4/23/14) had higher density, indicating a lower air content than those prepared on the first day of placement (4/21/14) even though all air contents were within the acceptable range. The concretes prepared the second day with the higher densities had low durability factors and high weight loss compared to the specimens cast the first day. However, the field performance of these concretes was expected to be satisfactory since they had very low permeability and would be difficult to saturate critically under the deck.

The splitting tensile test specimens from the first day are shown in Figure 3. The specimen on the right is from L4, which showed marginal stability and had a lower strength than the other batches. The specimen on the left is from L2, which did not exhibit any halo and had a high strength. The specimen on the right has a paste layer 1/8 to 3/16 in deep on the top surface that is attributed to the marginal stability attested by the slight halo. However, the aggregate distribution within the specimens did not indicate any objectionable segregation.

Table 11. Freeze/Thaw Data

Data	L3 Bent 15	L4 Bent 15	L2 Bent 16	L4 Bent 16
Weight loss (%)	0.1	4.5	5.1	7.3
Durability factor	104	102	47	46
Surface rating	0.1	0.9	0.9	1.4

Figure 3. Sample Concrete From Pier Caps. The specimen on the left is from L2, which did not exhibit any halo and had a high strength. The specimen on the right is from L4, which showed marginal stability and had a lower strength than the other batches. The specimen has a paste layer 1/8 to 3/16 in deep on the top surface that was attributed to the marginal stability attested to by the slight halo.

CONCLUSIONS

- *Beams with SCC can be successfully produced at a precast prestressed concrete plant from SCC mixtures with high workability, satisfactory strength, and the low permeability essential for durability.*

- *No. 57, No. 68, or No. 8 aggregates can be successfully used in making SCC.*

- *Cast-in-place SCC with high workability and satisfactory strength and permeability can be produced.* Care should be exercised to prevent segregation in the SCC. Marginal stability indicated by a slight halo did not cause objectionable segregation within the concrete. However, a separate thin surface paste layer was observed.

- *VMAs help achieve stable mixtures.* Dosages will need to be adjusted for the desired stability.

- *Accelerating admixtures help minimize the time of setting.* Extended setting time causes delays in finishing. Thus, accelerating admixtures provide timely finishing operations, especially in cold weather.

- *Freeze/thaw tests indicated that concretes with high density had low durability factors.* High density indicates a low air content. However, the field performance of these concretes in pier caps is expected to be satisfactory since they have very low permeability and will be difficult to saturate critically under the deck.

RECOMMENDATION

1. *VDOT's Structure and Bridge Division and Materials Division should approve the use of SCC as an option in prestressed concrete beams and cast-in-place applications to facilitate fabrication, improve surface condition, and improve strength and durability.*

BENEFITS AND IMPLEMENTATION

Benefits

Compared to conventional mixtures, SCC is expected to have greater material-related costs because of changes in ingredients, particularly the addition of more and higher dosages of chemical admixtures. However, the ease of placement, speed of construction, and reduced labor requirements are expected to result in an overall cost savings in structures with SCC. Further, the lack of problems with consolidation is expected to lead to improved surface appearance, strength, and durability; an increased service life; and lower life cycle costs.

The acceptance of SCC as an option is expected to facilitate construction because of SCC's high workability and the absence of the need for consolidation. In addition, SCC is expected to be of high quality because of its lack of entrapped air voids and its low w/cm.

Implementation

VDOT's Structure and Bridge Division and Materials Division have approved SCC as an option in prestressed concrete beams and cast-in-place applications to facilitate fabrication, improve surface condition, and improve strength and durability. VDOT will include this option in its new 2016 *Road and Bridge Specifications.*

ACKNOWLEDGMENTS

Appreciation is extended to the Virginia Transportation Research Council (VTRC), VDOT, and the Federal Highway Administration for their support of this research. The authors thank VTRC staff Mike Burton, Lewis Lloyd, and Andy Mills for the preparation and testing of samples and Catherine Hyland and Abigail Leonard for the evaluation of the data.

REFERENCES

American Concrete Institute. *237R-07: Self-Consolidating Concrete.* Farmington Hills, MI, 2007.

ASTM International. ASTM C666: Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. In *Annual Book of ASTM Standards,* Vol. 04.02. West Conshohocken, PA, 2008a.

ASTM International. ASTM C157: Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. In *Annual Book of ASTM Standards,* Vol. 04.02. West Conshohocken, PA, 2008b.

ASTM International. ASTM C1611: Standard Test Method for Slump Flow of Self-Consolidating Concrete. In *Annual Book of ASTM Standards,* Vol. 04.02. West Conshohocken, PA, 2009a.

ASTM International. ASTM C1621: Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2009b.

ASTM International. ASTM C231: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2010a.

ASTM International. ASTM C469: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2010b.

ASTM International. ASTM C496: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2011.

ASTM International. ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. In *Annual Book of ASTM Standards,* Vol. 04.02. West Conshohocken, PA, 2012a.

ASTM International. ASTM C1202: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2012b.

ASTM International. ASTM C138: Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. In *Annual Book of ASTM Standards,* Vol. 04.02. West Conshohocken, PA, 2013.

Babaei, K., and Fouladgar, A.M. Solutions to Concrete Bridge Deck Cracking. *Concrete International*, Vol. 19, No. 7, 1997, pp. 34-37.

Okamura, H., and Ouchi, M. Self-Compacting Concrete: Development, Present Use and Future. In *Self Compacting Concrete: Proceedings of the First International RILEM Symposium*, A. Skarendahl, and O. Petersson, Eds. RILEM Publications, Cachan Cedex, France, 1999.

Ozyildirim, C. Air-Void Characteristics of Concretes in Different Applications. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1893. Transportation Research Board of the National Academies, Washington, DC, 2004, pp. 70-74.

Ozyildirim, C. Virginia Department of Transportation Early Experience With Self-Consolidating Concrete. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1893. Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 81-84.

Ozyildirim, C. *Bulb-T Beams With Self-Consolidating Concrete on the Route 33 Bridge Over the Pamunkey River in Virginia.* VTRC 09-R5. Virginia Transportation Research Council, Charlottesville, 2008.

Ozyildirim, C. *Lightweight High-Performance Concrete Bulb-T Beams With Self-Consolidating Concrete in a Bridge Structure.* VCTIR 14-R15. Virginia Center for Transportation Innovation and Research, Charlottesville, 2014.

Ozyildirim, C., and Davis, R.T. Bulb-T Beams With Self-Consolidating Concrete on Route 33 in Virginia. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2020. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 76-82.

Ozyildirim, C., and Sharp, S. *Preparation and Testing of Drilled Shafts with Self-Consolidating Concrete.* VCTIR 12-R15. Virginia Center for Transportation Innovation and Research, Charlottesville, 2012.

Sonebi, M., and Bartos, P.J.M. Hardened SCC and Its Bond With Reinforcement. In *Self Compacting Concrete: Proceedings of the First International RILEM Symposium,* A. Skarendahl, and O. Petersson, Eds. RILEM Publications, Cachan Cedex, France, 1999.

APPENDIX

FRESH CONCRETE PROPERTIES AND STRENGTH DATA

Table A1. Fresh Concrete Properties of Live (L) and Dead (D) Ends

	Spread (in)		Air Content (%)		Density (lb/ft^3)	
Date	**L**	**D**	**L**	**D**	**L**	**D**
6/25/2012	24	24	7.0	3.6	144.6	---
6/26/2012	25.5	24	3.3	3.9	---	---
6/27/2012	22	22	4.0	3.3	---	---
6/29/2012	25	25.5	3.0	3.3	---	---
7/2/2012	26.5	23	4.0	4.8	---	---
7/3/2012	24	22.5	4.5	4.5	144.0	---
7/5/2012	25	24	4.6	4.6	---	---
7/6/2012	25	24	5.0	4.8	---	---
7/7/2012	26	25	5.3	5.0	---	---
7/10/2012	22	27	5.3	4.7	---	---
7/11/2012	26	26	3.5	5.0	145.4	---
7/12/2012	19	25	4.8	4.9	---	---
7/13/2012	26	23	4.2	5.2	---	---
7/16/2012	21	24	4.8	5.0	---	141.6
7/17/2012	20	24	4.9	4.9	144.8	---
7/18/2012	22	25	5.7	3.0	---	---
7/19/2012	21	23	5.4	5.5	144.4	---
7/20/2012	19	25.5	4.0	5.5	146.2	---
7/23/2012	23	27	4.5	4.3	146.0	---
7/24/2012	22.5	25	4.0	5.5	145.0	---
7/25/2012	22	24.5	4.7	4.6	146.2	---
7/26/2012	25.5	24	4.9	5.5	---	144.8
7/27/2012	22	23	4.6	6.0	---	---
7/30/2012	20	26	3.8	4.4	---	143.2
7/31/2012	20	26	4.5	4.9	---	142.8
8/1/2012	20	23	4.9	5.2	---	141.0
8/2/2012	19	17.5	4.3	5.6	---	142.8
8/3/2012	20	19	4.5	5.3	---	---
8/6/2012	19	26	5.0	3.0	---	---
8/8/2012	24	25.5	4.3	3.4	---	---
8/9/2012	18	19	4.6	4.6	---	---
8/10/2012	21	22	4.7	5.2	143.4	---
8/11/2012	23	23	4.5	5.2	139.0	---
8/13/2012	20.5	26.5	5.5	5.3	---	---
8/14/2012	24	23.5	4.1	5.4	143.1	---
8/15/2012	19	25	5.5	5.3	142.6	---
8/16/2012	20	18	5.0	5.3	143.6	---
8/17/2012	24	24	4.9	5.3	---	---
8/21/2012	20	25	6.8	4.6	140.0	---
8/22/2012	22	22	5.1	5.4	141.8	---
8/23/2012	23	25	5.3	5.5	---	---
8/24/2012	23	23	5.4	5.3	141.8	---
8/25/2012	24	23	5.4	5.0	143.4	---
8/27/2012	23	23	5.8	5.4	143.2	---
8/29/2012	23	24	4.9	5.0	145.0	---

8/30/2012	25	23	4.6	5.0	---	---
8/31/2012	21	24	4.7	4.4	144.8	---
9/4/2012	24	25	4.3	3.5	143.6	---
9/5/2012	25	27	6.0	5.0	---	---
9/6/2012	19	25	6.1	6.8	---	---
9/7/2012	23	25	4.0	4.7	145.6	---
9/10/2012	25	25	4.7	4.5	145.6	---
9/11/2012	25	23	3.8	5.0	---	---
9/12/2012	21	24	4.3	4.5	145.6	---
9/13/2012	24	26	5.0	3.7	144.0	---
9/14/2012	24	23	3.6	5.0	145.4	---
9/17/2012	25	25	3.2	5.0	147.0	---
9/21/2012	23	23	5.1	4.9	---	---
9/20/2012	27	24	4.8	5.2	---	---
9/19/2012	24	26.5	4.6	3.6	---	145.6
9/24/2012	23	24	5.2	5.8	---	---
9/25/2012	19	21	5.0	6.0	---	---
9/26/2012	25	25.5	4.0	5.7	144.6	---
9/27/2012	23	25.5	6.1	4.3	141.2	---

--- Indicates no data.

Table A2. Strengths (psi) of Concrete at Live (L) and Dead (D) Ends

Date	1-day		7-day	
	L	D	L	D
6/25/2012	6191	6330	8891	9461
6/26/2012	6369	6568	9143	9143
6/27/2012	7086	7465	9249	9382
6/29/2012	6170	6250	9368	9222
7/2/2012	6568	6608	9183	9222
7/3/2012	7803	7763	9474	9727
7/5/2012	6051	6170	8838	9209
7/6/2012	6091	6170	9050	9222
7/7/2012	7683	8041	9143	9209
7/10/2012	7245	7365	9541	9236
7/11/2012	6051	6011	9209	8440
7/12/2012	6529	6011	9076	8240
7/13/2012	8161	8360	8970	8731
7/16/2012	6051	7166	8904	8665
7/17/2012	6568	6091	8811	8731
7/18/2012	6170	6369	8798	8134
7/19/2012	6369	6011	8731	8267
7/20/2012	7564	7564	8771	9289
7/23/2012	6529	6369	8758	---
7/24/2012	6170	6051	8661	8028
7/25/2012	6967	6369	8983	8214
7/26/2012	6210	6051	8718	8174
7/27/2012	8758	7964	8851	8705
7/30/2012	6568	6369	8772	---
7/31/2012	7006	6091	8835	---
8/1/2012	7763	6369	9130	9103
8/2/2012	6568	6967	9222	9368
8/3/2012	7882	7404	9010	9156
8/6/2012	6170	6131	8585	---
8/8/2012	6568	6768	8944	8997
8/9/2012	6011	6011	9130	8506
8/10/2012	6369	7006	8798	8837
8/11/2012	6568	7166	9116	9236
8/13/2012	6967	6011	9236	8546
8/14/2012	6768	7165	9329	9302
8/15/2012	6011	6369	9249	9196
8/16/2012	6768	6887	9209	9421
8/17/2012	7564	7964	8824	8957
8/21/2012	6011	6131	---	9129
8/22/2012	7166	7564	9169	9408
8/23/2012	6568	7365	9169	9265
8/24/2012	7404	7683	8731	8944
8/25/2012	7166	7564	8837	8824
8/27/2012	6369	6967	8731	8851
8/29/2012	7365	7763	8798	8864
8/30/2012	8360	9156	9130	9209
8/31/2012	9355	9156	9236	9355
9/4/2012	7564	7166	9196	9289
9/5/2012	7803	7404	9275	9276
9/6/2012	7962	7763	9408	8944
9/7/2012	8559	9314	9130	9647

9/10/2012	7564	7803	9408	9355
9/11/2012	8559	7763	9541	9315
9/12/2012	7763	7365	9369	9236
9/13/2012	7723	7763	9422	9315
9/14/2012	8360	7962	9328	9435
9/17/2012	9156	8788	9368	9368
9/21/2012	8559	9156	9494	10058
9/20/2012	7962	8360	9488	9395
9/19/2012	9952	8758	9395	9965
9/24/2012	8838	8161	9130	9315
9/25/2012	8400	8559	9316	9275
9/26/2012	8559	8758	9262	9302
9/27/2012	8280	6967	9461	8440

--- indicates no data.