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Concrete Beams Prestressed Using Carbon Fiber Reinforced Polymer

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The Virginia Department of Transportation (VDOT) placed beams with carbon fiber reinforced polymer reinforcement in a two-span bridge in Halifax County, Virginia. The bridge has two 84-ft spans, continuous for live load, and each span has four 45-in-deep prestressed bulb-T beams. The first two beams were cast using a traditional concrete mixture with conventional slump. The remaining six beams were cast with self-consolidating concrete to facilitate the placement operation.

The deck was cast with conventional concrete and corrosion-resistant reinforcing bars. Concrete for both the beams and the deck was tested at the fresh and hardened states. The structure was inspected visually immediately after construction and 8 months and 3.5 years later. The beams were performing well with no deficiencies. The deck was also performing well except that the continuity diaphragm over the pier had several longitudinal cracks. The continuity diaphragm concrete was placed, in accordance with normal VDOT practice, after the deck concrete had been placed on both sides of the pier. Cracks at the deck level in the continuity diaphragms are generally attributed to restrained shrinkage when the diaphragm concrete is placed after the deck concrete.

The study recommends that VDOT's Structure and Bridge Division use beams with self-consolidating concrete and carbon fiber reinforced polymer reinforcement as an option in severe environments since the fabrication and constructability challenges described herein were successfully overcome.

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FINAL REPORT

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ABSTRACT

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INTRODUCTION

Corrosion of steel reinforcement in reinforced concrete leads to damage in both the concrete and the reinforcement that requires costly repairs and causes inconvenience to the traveling public. Corrosion is the leading cause of distress in reinforced concrete structures (Koch et al., 2001).

When concrete is reinforced with prestressed steel strands that are under sustained tensile stress, corrosion is more critical than in concrete with mild steel reinforcement. With full implementation starting in 2010, the Virginia Department of Transportation (VDOT) has been using corrosion-resistant reinforcing bars (VDOT, 2016a). VDOT recognizes the importance of corrosion-resistant or corrosion-free prestressing strand and reinforcing bars in prestressed concrete bridge elements. Recent VDOT standards and specifications require corrosion-resistant or corrosion-free reinforcement in piles exposed to severe environments, including piles exposed to brackish water, saltwater, or deicing salts (VDOT, 2018). Prestressing strand in beams is also prone to corrosion in severe exposure conditions; corrosion-resistant or corrosion-free strands and bars would enhance the durability and extend the service life of beams in severe environments.

Prestressing strand and reinforcing bar made of carbon fiber reinforced polymer (CFRP) were available when this study was initiated. It has been used to eliminate corrosion in prestressed beams (Enomoto et al., 2012; Grace et al., 2002; Roddenberry et al., 2014; Seracino et al., 2016). The corrosion-free characteristic of CFRP is demonstrated in Figure 1; exposure to water does not induce corrosion in composite carbon. The American Association of State Highway and Transportation Officials (AASHTO) has also recognized the importance of CFRP for corrosion mitigation in prestressed elements and has included it in its innovation initiative on CFRP (AASHTO, n.d.).

Figure 1. Water Drops on a Corrosion-Free Carbon Fiber Reinforced Polymer Strand

CFRP strands, called carbon fiber composite cable (CFCC) by the manufacturer, are manufactured by Tokyo Rope Mfg. Co, a Japanese company. Initially, this type of CFRP strand was manufactured only in Japan, but the company recently expanded and now produces CFRP in Canton, Michigan. There have been many applications of CFRP technology in Japan over the past 25 years (Enomoto et al., 2012). VDOT used these same CFRP strands in 18 piles of the Nimmo Parkway Bridge (AASHTO, n.d.; Ozyildirim and Sharp, 2014).

The first use of CFRP in prestressed beams was in the Shinmiya Bridge at the Sea of Japan. This bridge has been in service for 30 years with no corrosion problem. The previous bridge located at this site contained beams with conventional steel reinforcement, which lasted only 20 years (Enomoto et al., 2012).

CFRP is made of premium innovative materials and costs more than conventional steel. However, even though elements with CFRP reinforcement cost more initially, they are expected to be cost-effective and have a longer service life (Grace et al., 2012).

PURPOSE AND SCOPE

The purpose of this study was to determine if concrete beams with CFRP reinforcement could be successfully produced, delivered, and erected. CFRP is sensitive to temperature, has limited elongation, is brittle, and is highly anisotropic; this study was conducted to gain insight into managing and coping with these characteristics during fabrication and construction and to determine if the high flowability of self-consolidating concrete (SCC) would alleviate some production concerns regarding the durability of CFRP elements by reducing or even eliminating the use of vibrators during concrete placement.

A bridge structure on Clarksville Road / Earl Davis Gregory Highway (Route 49) over Aaron's Creek in Halifax County, Virginia, was selected for study. It has a low traffic volume and is away from the aggressive coastal environment. Although this location will not expose the beams to an aggressive environment, it was thought that this bridge would provide valuable information with regard to the production of beams with CFRP reinforcement and advance the state of practice for future use of CFRP in bridge elements placed in a severe environment.

METHODS

Description of the Halifax Bridge

The Halifax Bridge is 168 ft 10 in long and 30 ft wide to the face of the rail. It has two 84-ft spans, each with four 45-in-deep bulb-T beams, for a total of eight identical beams. Beams were constructed with CFRP strands and CFRP bars. Every beam had 48 CFRP strands, each 0.6 in in diameter. All CFRP bars were made of the same seven-wire CFRP strand used for prestressing, but they were fabricated by the supplier either straight or bent and were used without prestressing as reinforcing bars. The construction and erection of the CFRP-reinforced beams were monitored, and concrete specimens were tested. The deck concrete was also investigated since the deck affects the long-term behavior of the beams. The reinforcing bars in the deck concrete were made of ASTM A1035 low carbon, low chromium steel. ASTM A1035 bars can be categorized as corrosion-resistant reinforcing bars (VDOT, 2016a). The beams and deck were surveyed immediately after placement and then 8 months and 3.5 years later for any sign of distress such as cracking.

The concrete beams for the Halifax Bridge were cast in June 2015 and erected in July 2015. The deck concrete was placed in September 2015, and the bridge was opened to traffic on December 4, 2015. All reinforcement in the beams was CFRP; an illustration of the cross section is shown in Figure 2. Transverse flange reinforcement was cut to short straight segments in Japan. The remaining reinforcing bars, including continuity bars, beam end confinement, and stirrups were preformed to various complex shapes at the plant in Japan in accordance with the given design dimensions and shipped to the prestressing plant. The cost of the CFRP strand used as reinforcing bars in the beam was more than the cost of the CFRP prestressing strand because of the cost of the forming process. The same CFRP material was used for reinforcing bars and the prestressing strands. However, the effective strength of the CFRP bar was significantly reduced because of the curvature introduced to make the shape. Any radius "bend" of the reinforcing bars reduces the strength of the stirrup because of the anisotropic nature of CFRP. It is possible that a lower grade stirrup material of the same type with a lower cost may be adequate, but the lower grade would also result in a strength reduction at each bend because of the anisotropic nature of the CFRP bars that might offset any cost savings.

Since the ratio of radius of reinforcing bar and bend radius figures prominently in the determination of the strength of the bent bars, a study was performed to determine if a smaller diameter strand or even a small wire would perform as well as the 0.6-in-diameter strand for stirrups. After a review of the results, no economic advantage appeared likely for either the stirrups or the continuity bars. Since confinement bars are lower stressed, it may be possible to change to a lower grade or smaller diameter material and gain an economic advantage.

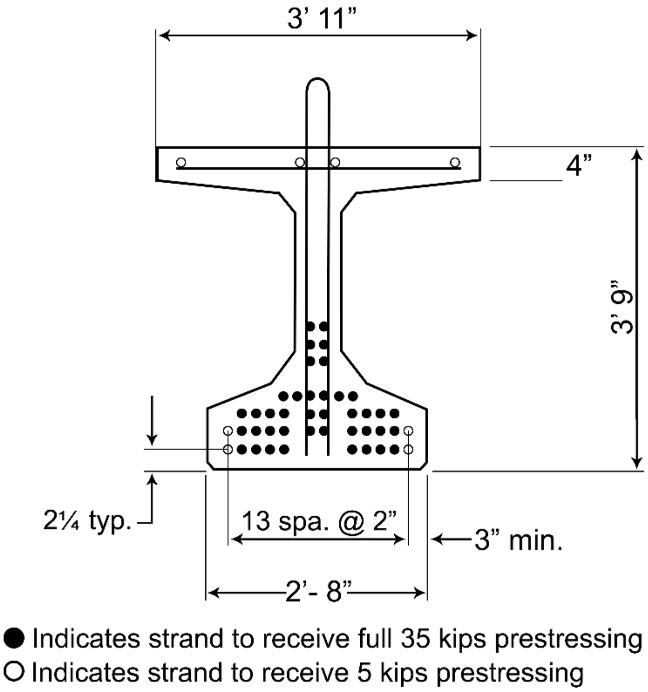

Figure 2. Cross Section of VDOT's First Carbon Fiber Reinforced Polymer 45-in-Deep Bulb-T Beam

A change in material form may also reduce cost. Efforts are underway to find an alternative stirrup material such as a CFRP grid to reduce the cost.

The CFRP strand was shipped from Japan on spools to the precast prestressing plant in Virginia. The reinforcing bars were shipped in cardboard boxes.

Forty strands were tensioned to 35 kips. Eight of the strands in each beam had a low prestressing force of only 5 kips. Four of the low stress strands were courtesy strands in the top flange of the bulb-T beams. The remaining four low stress strands were placed in the bulb of the bulb-T beams. The low stress strands were included in the design to enable a ductile failure of the prestressed beams as loads approach or exceed the specified minimum strength.

The beams were designed by VDOT's Structure and Bridge Division with technical assistance from Grace from Michigan Technological University. The design followed the guidelines of the American Concrete Institute (ACI) (2004) and AASHTO (2011) and used the mechanical properties pertinent to CFRP. The prestressing force was kept at 65% of the guaranteed ultimate tensile strength.

Two beams, in one long casting bed, were prepared on each casting day, and two batches of concrete were sampled, one from each beam. The first batch was the first load of concrete representing the first beam in the bed. Each beam required about 16 yd^3 of concrete, and each load of concrete was 4 yd^3. Batch 2 was selected from the fifth or sixth load to ensure that the second beam was also represented. The concrete in the beams was required to have a minimum 28-day compressive strength of 8,000 psi. The minimum release strength specified was 6,500 psi, and the maximum permeability specified was 1500 C. Six of the eight beams contained SCC. SCC has high flowability and passes through congested reinforcement without any mechanical vibration (ACI, 2007). VDOT has used SCC successfully in elements with conventional and prestressed reinforcement (Ozyildirim, 2004; Ozyildirim and Moruza, 2015). The deck concrete had conventional concrete with a minimum 28-day compressive strength of 4,000 psi and a maximum permeability of 2500 C.

Concrete Testing

Concrete was tested at the fresh state for slump (ASTM C143), slump flow (ASTM C1611), slump flow with J-ring (ASTM C1621), air content (ASTM C231), density (ASTM C138), and initial concrete temperature (ASTM C1064). At the hardened state, the tests listed in Table 1 were conducted.

Permeability specimens were subjected to accelerated curing: moist cured for 1 week at room temperature and then for 3 weeks at 100 °F. Drying shrinkage test specimens were moist cured for 7 days and then kept at 50% relative humidity to dry. The resistance to cycles of freezing and thawing was determined in accordance with ASTM C666, Procedure A, except that the specimens were air dried for at least 1 week before the test and the test water contained 2% NaCl solution. The acceptance criteria at 300 freeze-thaw cycles are a weight loss of 7% or less, a durability factor of 60 or more, and a surface rating of 3 or less.

Table 1. Hardened Concrete Tests

Test	Test Standard	Sample Size
Compressive strength	ASTM C39	4 x 8 in
Elastic modulus	ASTM C469	4 x 8 in
Splitting tensile strength	ASTM C496	4 x 8 in
Permeability	ASTM C1202	4 x 4 in
Drying shrinkage	ASTM C157	3 x 3 x 11 in
Freeze-thaw resistance	ASTM C666	3 x 4 x 16 in

Determination of CFRP Characteristics

Mechanical Properties of CFRP

CFRP strand is anisotropic in that it has high tensile strength in the longitudinal direction and low strength transverse to the longitudinal direction; it is unidirectional. It is light but has limited elongation, about one-half that of conventional steel strand; it also has a lower elastic modulus and coefficient of linear expansion, as shown in Table 2 (Tokyo Rope Mfg. Co., 2014).

Compared to commonly used ASTM A416 prestressing steel strands, because of limited ductility and high sensitivity to heat, CFRP must be handled with great care. It should be free of scoring, nicks, and gouges to prevent premature failure under load. A high-speed rotary grinder is used to cut the CFRP strand since cutting with a torch would burn it. All supports, such as chairs and tie wires, must be non-metallic to maintain the corrosion-free nature of CFRP designs.

Table 2. Mechanical Properties of Carbon Fiber Reinforced Polymer

Property	Limit	Value
Guaranteed tensile capacity[a]	Greater than	2.33 kN/mm[b] (338 ksi)
Tensile modulus[a]	Greater than	155 kN/mm^2 (22,481 ksi)
Elongation at break	Equal to	1.7%
Specific gravity	Equal to	1.6
Relaxation[b]	Less than	1.3%
Creep strain[c]	Less than	0.07 x 10^{-3}
Coefficient of linear expansion[d]	Less than	0.6 x 10^{-6}/°C (0.333 x 10^{-6}/°F)
Specific resistance	Equal to	3000 micro-ohm cm (1,181micro-ohm in)
Creep failure load ratio[e]	Greater than	0.85
Fatigue capacity stress range[f]	Greater than	780 N/mm^2 (113 ksi)
Bending stiffness	Greater than	56.9 kN/cm^2 (82.5 ksi)
Heat resistance	Greater than	130 °C (266 °F)

[a] Pu calculated by effective cross section.
[b] 0.7*Pu, 1,000 hr (20 ± 2 °C) according to JSCE-E534.
[c] 0.6*Pu, 1,000 hr (20 ± 2 °C).
[d] 20 °C to 200 °C according to JSCE-E536.
[e] At 1 million hours according to JSCE-E533.
[f] 2 x 10^6 cycles at 0.75*Pu according to JSCE-535.

Handling CFRP

CFRP strands need special end preparation to avoid crushing of the ends during prestressing (Roddenberry et al., 2014). The end preparation involved wrapping the strand in a buffer material of mesh sheet and braided grip, attaching four wedges, placing the assembly in a chuck, and then threading together the couplers shown in Figure 3. The wedges and chucks used were longer than those used with steel strand so that the CFRP strand could be held without damaging it. The longer chuck was placed in one end of a coupler; the other end had a conventional chuck holding a steel strand. The prestressing force was applied to the steel strand.

The bed for the casting of two beams was 218 ft long. After prestressing, the strands were left in tension overnight to reduce the probability of failure during the concrete placement. The couplers were placed at the ends of the prestressing bed, and the temperature in those areas was kept below 122 °F to prevent slippage in the coupling.

Figure 3. Elements of End Preparation: left, disassembled wedge, chuck, and braided grip; right, couplers in a pile

Most of the special handling of CFRP is needed only during beam production. Once fabricated, beams with CFRP are handled, delivered, and erected in the same manner as with any other beam with steel reinforcement except where CFRP extends outside the concrete beam. For instance, stirrups extending into the deck and bars extending into the continuity diaphragms still require careful handling.

Concrete Mixture and Placement

CFRP Beams

Restrictions on the use of vibrators commonly used with steel reinforced beams were required so that the CRFP strand would not be damaged by the vibrator. The regular concrete in the first set of two beams had conventional slump and was difficult to place because of the loss of workability. The plant used SCC in the remaining six beams (three sets of two). Table 3 shows the mixture proportions for the regular concrete and the SCC. A commercially available air-entraining admixture and high-range water-reducing admixture were used in all mixtures.

The cementitious material content was higher in the SCC mixture, and the water–cementitious material ratio was lower than in the regular mixture. In addition, a smaller maximum size aggregate was used in the SCC to attain high workability without segregation. The concrete with conventional slump was consolidated using rubber tipped vibrators to avoid damaging the CFRP strands. SCC does not require mechanical vibration. However, limited internal vibration was conducted in the top flange to facilitate the flow, and limited external vibration was conducted on the sides to avoid bugholes. During placement, specimens were prepared for testing at the hardened state. The specimens were placed on top of the beams under cover to simulate similar temperature development. The bed and the specimens were covered with an insulating blanket. There was no steam curing in this outside bed. After the release strength was reached, the beams were demolded and the specimens were delivered to the laboratory and placed in a moist room for additional curing.

Table 3. Mixture Proportions for Beams (lb/yd^3)

Material	Regular	SCC
Type III portland cement	600	637
Class F fly ash	200	213
Coarse aggregate No. 57	1,472	-
Coarse aggregate No. 8	-	1,439
Fine aggregate	1,284	1,261
Water	280	272
Water–cementitious material ratio	0.35	0.32

SCC = self-consolidating concrete.

Bridge Deck

The mixture proportions for the bridge deck are shown in Table 4. A commercially available air-entraining admixture and a water-reducing and retarding admixture were used. The cementitious material content at 710 lb/yd^3 was higher than the minimum specified value of 635 lb/yd^3 in the specification. It should be noted that VDOT recognizes the seriousness of cracks in concrete and their effects on durability. VDOT's new low shrinkage concrete specification, which was not in effect at the time of this study, has a maximum cementitious material content of 600 lb/yd^3 when normal weight aggregates are used for a low amount of paste for crack control; also, a maximum shrinkage of 0.035% is allowed (VDOT, 2016b).

Table 4. Mixture Proportions for Deck Concrete (lb/yd^3)

Material	Amount
Type I/II portland cement	568
Class F fly ash	142
Coarse aggregate No 57	1,737
Fine aggregate	989
Water	298
Water-cementitious material ratio	0.42

RESULTS AND DISCUSSION

The fabrication of beams, properties of concrete used in beams, delivery and erection of beams, properties of deck concrete, and the visual inspection of the beams and the deck are described in this section.

CFRP Beam Fabrication

Installing each coupler takes time. There were 96 coupled connections for each pair of beams cast. The couplers used to connect CFRP and ASTM A416 steel prestressing had a diameter greater than the spacing of the strands; therefore, the couplers were staggered at the ends of the bed to prevent contact during tensioning. The prestressing force was applied in increments; initially, a low tensioning force of 5 kips or less was applied to the strands. The uniform low tension helped ensure that all couplers had been installed correctly and that no strands had been cross coupled to different end positions. After the initial prestressing load, the 40 strands that had been designated to be fully stressed were tensioned to the full load of 35 kips. During prestressing, an error in the staggered layout resulted in two of the couplers coming in contact, causing the steel chuck to slip, which bent and broke the strand. This strand was replaced.

During the production of the third set of two beams, three of the strands were replaced. Two of the strands ruptured in the bed. The prestressing force was about 10 kips lower than the planned 35 kips; the failure was attributed to improper handling of the cables by the workers. The third defect was close to the stressing bulkhead. There was no complete strand rupture, but one wire in the seven-wire strand was broken. Once detected, it was replaced. The failed strands were not saved by the plant for evaluation, so information on the failures is limited. The manufacturer indicated that there were no other strand failures during prestressing known to the manufacturer elsewhere; the manufacturer attributed these failures to improper handling and drew attention to better training. Such strand failures were not observed earlier in the production of 18 prestressed concrete piles with CFRP in two other Virginia plants. It should be noted that the spacing of the strands in the piles did not require staggering the chucks.

CFRP Beam Concrete Properties

Concrete was prepared at the batch plant of the prestressing facility and traveled a short distance, about 100 yards, to the outdoor casting bed. At the first casting day, for Set 1, regular concrete with conventional slump was used. The remaining three sets had SCC. Table 5 summarizes the fresh concrete properties.

The results indicated that air-entrained concrete with satisfactory workability was obtained. The conventional slump values were high; however, slump loss was occurring, and placement in the beam and specimen preparation had to be done fast to enable proper consolidation. Thus, placement with the conventional slump concrete was difficult. In addition, care had to be exercised to prevent damaging the CFRP reinforcement with the internal vibrators. The SCC used in the last three sets of beams was easier to place. In the last set, the first batch had the lowest slump flow value with and without the J-ring. In addition, in this batch, the difference between the slump flow values with and without the J-ring was 3 in, which is higher than the 2 in indicated in ASTM C1621. The second batch in that set also had a marginal difference in slump flow of 2 in, whereas the other sets had differences in slump flow of 1 in or less. The hardened concrete properties are given in Table 6.

The release strength of 6,500 psi was difficult to achieve overnight since there was no steam curing. It took 2 to 3 days to reach the release strength. Thus, a daily production cycle could not be maintained because of the end preparation and lack of steam curing. The demolding was done when both batches for each set had strengths exceeding 6,500 psi. The first batch of the last set had the lowest 1-day, 7-day, and 28-day strength. The concrete was prepared after a rain, and the aggregate stockpiles were wet, so there is the possibility of higher water content because of improper moisture correction or a non-uniform moisture situation. This batch also had the lowest slump flow with and without the J-ring, raising issues regarding the adequate consolidation of the specimens since SCC specimens were not rodded or mechanically consolidated. The expected high water content and improper consolidation could lead to lower strength, as was the case with that batch.

Table 5. Fresh Properties of Beam Concrete

Set	**Set 1**		**Set 2**		**Set 3**		**Set 4**	
Date Cast	**6/10/15**		**6/15/15**		**6/19/15**		**6/29/15**	
Concrete	**Conventional**		**SCC**		**SCC**		**SCC**	
Batch	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Slump (in)	9.3	9.5	-	-	-	-	-	-
Slump flow (in)	-	-	25.5	25.5	25.5	26.0	22.5	24.5
J-Ring slump flow (in)	-	-	24.5	26.0	24.5	25.0	19.5	22.5
Air content (%)	5.0	5.0	4.7	4.5	5.0	6.4	7.0	7.4
Concrete temp. (°F)	84	82	89	89	86	86	80	84
Air temp. (°F)	80	83	93	93	83	82	70	74
Density (lb/ft^3)	144.8	-	145.2	143.2	146.6	146.0	145.6	138.4

SCC = self-consolidating concrete.

Table 6. Hardened Properties for Beam Concrete

Property	Date	6/10/15		6/15/15		6/29/15	
	Concrete	**Conventional**		**SCC**		**SCC**	
	Test age	**B1**	**B2**	**B1**	**B2**	**B1**	**B2**
Compressive strength (psi)	1 day	6,290	5,740	-	7,090	5,590	7,090
	7 days	-	-	-	9,350	7,180	9,350
	28 days	10,220	9,320	11,110	10,900	7,500	8,530
Elastic modulus (10^6 psi)	28 days	5.60	5.74	-	-	4.48	4.54
Splitting tensile strength (psi)	28 days	635	650	825	760	575	635
Permeability (C)	28 days (3 weeks at 100 °F)	544	679	193	210	227	227
Length Change (Drying Shrinkage) Data (microstrain)							
28 days		93	127	343		323	
4 months		203	225	487		443	
Freeze-Thaw Data at 300 Cycles							
Weight loss (%)		3.3	8.8	4.5	-	0.0	-
Durability factor		29	83	43	-	100	-
Surface rating		0.90	1.28	0.80	-	0.11	-

However, the second batch had the highest 1-day strength even with the highest air content and lowest density, indicating that satisfactory concretes were placed on this day. To confirm the adequacy of strength in the last set of beams in comparison to other beams, camber measurements were taken. The beams with SCC cast on 6/15/15 and 6/19/15 had camber values ranging from 2 13/16 in to 3 in. Comparatively, this last set of SCC cast on 6/29/15 had values of 2 13/16 in and 2 15/16 in. Thus, the camber values were similar, indicating that, in general, similar concretes were placed in the beams and the beams were behaving as expected.

When accelerated curing was used, in which the specimens are kept moist at 73 °F up to 1 week and then are kept moist at 100 °F the remaining 3 weeks, the permeability values were very low, ranging from 193 C to 679 C. Accelerated curing is the standard cure for permeability specimens tested by VDOT. The SCC specimens had lower permeability than the concretes with conventional slump.

The length change data in Table 6 indicate that SCC mixtures had higher drying shrinkage compared to the concrete with conventional slump. However, the values for both were below the value of 0.035% (350 microstrain) for the low cracking bridge deck concrete at 28 days (VDOT, 2016b) and less than the 0.07% (700 microstrain) at 4 months recommended by Babaei and Fouladgar (1997). The higher shrinkage values for SCC compared to the concrete with conventional slump were attributed to the use of smaller size aggregate with a nominal maximum aggregate size of 3/8 in compared to 1 in in the other.

The freeze-thaw data given in Table 6 show that the best test results were obtained for SCC that had an air content of 7%, which is the highest value among the specimens tested for freeze-thaw resistance. The remaining specimens with 4.7% and 5% air had varying results, such as a low durability factor or high weight loss. The result indicated the need to have a high air content for satisfactory resistance to freezing and thawing when a high-range water-reducing admixture is used since it makes air bubbles larger, reducing the spacing factor needed for durability (Ozyildirim, 2004). However, the beams are protected from the environment since they are under the low permeability deck; therefore, it is unlikely that the beams will become critically saturated and undergo freeze-thaw damage.

CFRP Beam Delivery and Erection

After the beams reached the minimum 28-day strength, they were delivered to the jobsite, with each truck and trailer transporting one beam. Two cranes were then used to place each beam. Figure 4 shows the erection and placement of the beams, with each span requiring four beams. The fabricator and contractor collaborated on a special connection to lift the beams that included blockouts in the flange and web to avoid conventional strand lifters being added to the beams and creating a corrosion issue. Conventional strand lifters using the CFRP strand were not used because of the reduction in strength when bent. The blockout is shown in Figure 4(a).


(a) (b)

Figure 4. Bridge Construction: (a) beams being delivered to the jobsite and erection of first beam; (b) three beams in place

Deck Concrete Supported by CFRP Beams

The concrete for the deck was mixed and delivered in ready-mixed concrete trucks. The fresh and hardened concrete properties for the deck concrete, including the spans and closure pour, are given in Table 7.

The results indicated that VDOT specifications were met; satisfactory strengths and very low permeability values were obtained. The deck has two spans, and both were placed on the same night. Figure 5 shows the night placement. The deck was placed at night since a reduced rate of evaporation would minimize the early cracking potential. The closure over the pier, with a length of 4 ft and a width of 32 ft 4 in, was placed during the daytime.

Table 7. Fresh and Hardened Properties of Deck Concrete

Date	**9/2/15**	**9/3/15**	**9/30/15**
Time	**11:59 P.M.**	**3:30 A.M.**	**9:20 A.M.**
Location	**Span B**	**Span A**	**Closure**
Fresh Concrete			
Air (%)	5.5	5.5	7.0
Slump (in)	4.0	3.5	4.0
Hardened Concrete at 28 Days			
Compressive strength (psi)	4,730	5,130	4,610
Permeability (C)	784	878	949


9/ 3/2015 1:07

Figure 5. Bridge Construction Showing Nighttime Deck Concrete Placement

Visual Survey of CFRP Beams and Deck

The beams and deck were surveyed 2 weeks after deck placement, and there were no visible cracks. In July 2016, when the air temperature was 90 °F, another survey revealed that the beams and the two spans were performing well after a winter's exposure. There were no deficiencies in the beams, and there was only one 2-ft-long crack with a width of 0.2 mm on the bridge deck span at the west end perpendicular to the joint. However, the closure pour placed during the daytime had eight longitudinal cracks parallel to the centerline ranging from 0.2 mm to 0.4 mm in width. The closure pour, a continuity diaphragm concrete, was placed, in accordance with normal VDOT practice, after the deck concrete had been placed on both sides of the pier. Cracks at the deck level in the continuity diaphragms are generally attributed to restrained shrinkage when the diaphragm concrete is placed after the deck concrete. The last survey for this study was conducted in May 2019, about 3.5 years later. There were no deficiencies in the beams. The 2-ft-long crack in the deck spans exhibited little change, with a length increased to 32 in and an average width of 0.2 mm. The eight cracks in the closure pour remained almost the same with the exception of a new transverse crack with a width of 0.2 mm running most of the way through the width of the pour.

CONCLUSIONS

- *Beams prestressed and reinforced with CFRP can be fabricated successfully at a local prestressing plant with a local crew.*

- *Handling of CFRP requires proper care to avoid damage and potentially dangerous rupture events.*

- *End preparation of CFRP using existing couplers takes time, and improvements in this area are needed.*

- *A 24-hour production cycle for the CFRP prestressed beams was not achieved because of time spent installing couplers and delay reaching the release strength.*

- *Once fabricated, the beams with CFRP were handled, delivered, and erected in the same manner as with any other beam.*

- *SCC was much easier to place in beams than concrete with conventional slump.*

- *Shrinkage of SCC was higher than for the concrete with conventional slump, mainly because of the smaller size aggregate. However, all shrinkage values were low.*

- *The best results for resistance to freezing and thawing in the beam specimens were obtained with the highest air content of 7%. At the lower air content, around 5%, varying results were obtained. However, the performance of all the beams is expected to be satisfactory; it would be difficult for the concretes to become critically saturated since they are under the deck and are made of very low permeability concrete.*

- *The deck concretes had high cementitious material contents. However, nighttime placement helped control cracking.*

- *A visual survey after one winter indicated that the beams and deck were in good shape except that the closure pour placed in the daytime had several longitudinal cracks. Cracks at the closure pour are generally attributed to restrained shrinkage when the concrete for the closure pour is placed after the deck concrete.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should use beams with corrosion-free CFRP reinforcement as an option in severe environments since the fabrication and constructability challenges described herein were successfully overcome.*

2. *VDOT's Structure and Bridge Division should use SCC in beams with CFRP since conventional slump concrete requires internal vibrators for consolidation that can damage the strands and because SCC reduces placement difficulties.*

IMPLEMENTATION AND BENEFITS

Implementation

Recommendation 1 should be implemented by VDOT's Structure and Bridge Division by educating bridge designers about the successful use of CFRP in various prestressed beam and slab applications.

The use of SCC, as recommended in Recommendation 2, should be required by the Structure and Bridge Division when CFRP strands are used. SCC is easy to place since it has high flowability; in addition, SCC does not require internal vibrators that may hit and damage the CFRP reinforcement.

These recommendations should be implemented within 2 years after the publication of this report.

Benefits

The beams under a deck are difficult to replace, and the cost of replacement or repair of corrosion-damaged beams is high. The use of corrosion-free CFRP reinforcement eliminates the critical corrosion problem facing bridge beams exposed to severe environments.

The intrusion of aggressive solutions can initiate deterioration of the concrete. SCC has high workability that can improve the uniformity of concrete and eliminate the large voids that can adversely affect strength and permeability. The vibrators used in the consolidation of conventional slump concrete can damage the CFRP strands. The use of SCC would eliminate the possibility of such damage.

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