Bridge Views

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Piles with Corrosion-Free Carbon Fiber Composite Cable in Virginia

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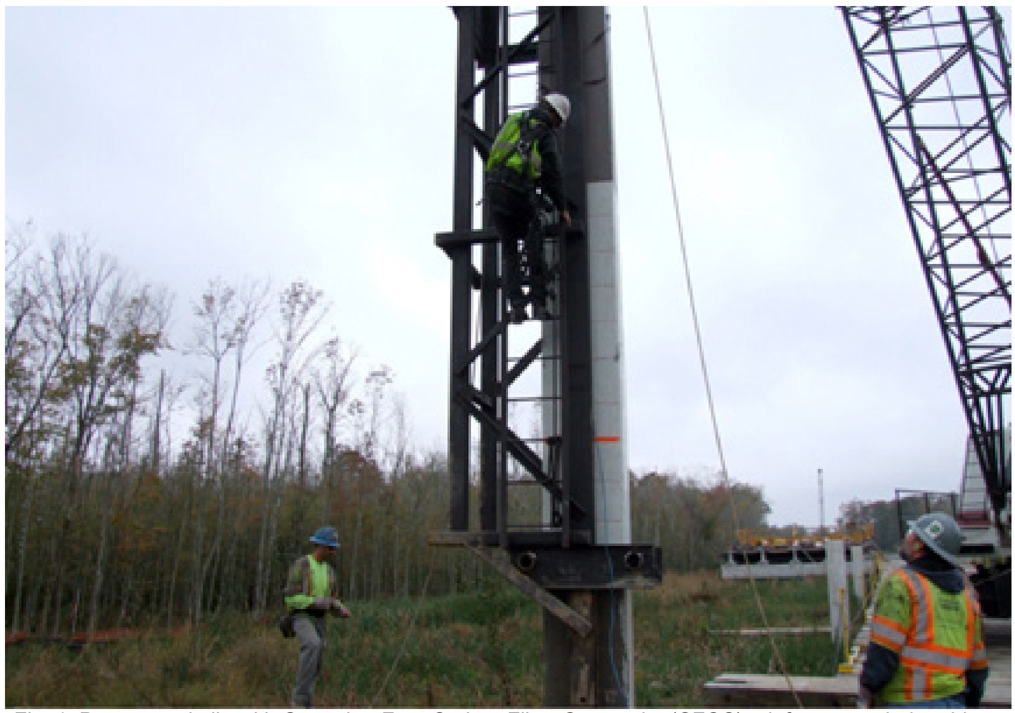

Fig. 1. Prestressed pile with Corrosion-Free Carbon Fiber Composite (CFCC) reinforcement being driven at the Nimmo Parkway Bridge site in Virginia Beach

Introduction

The corrosion of steel reinforcement in concrete structures is a common problem for state departments of transportation (DOTs) due to exposure to the marine environment or deicing salts (see Figures 2 and 3). The Virginia Department of Transportation (VDOT) has been using corrosion resistant reinforcement, such as solid stainless steel reinforcing bars (rebar), in bridge structures to extend their life by mitigating corrosion and thereby reducing concerns associated with maintenance costs, traffic congestion, and public safety. As a continuation of such efforts, VDOT has initiated research into improving prestressing strand materials. Corrosion is of great concern in strands, which are under high stress and used in load-carrying structural elements.

Solution

A possible solution is the use of corrosion-free carbon fiber composite cable (CFCC), which is also known as carbon strand. It was developed

Fig. 2. Strands corroding in beams caused by leaking joints.

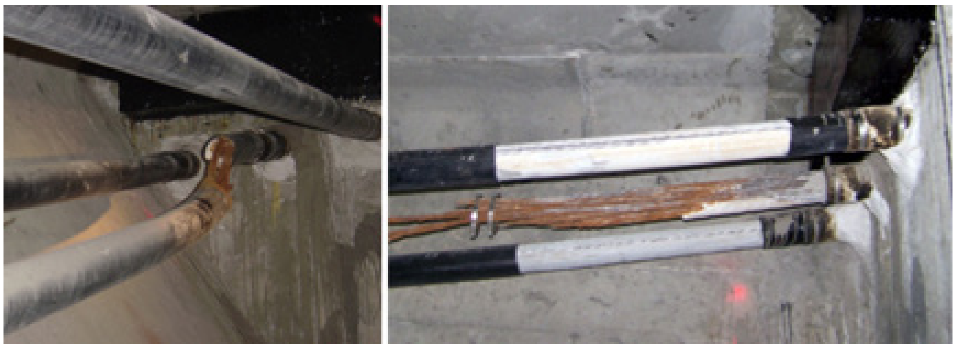

Fig. 3. Tendon failure in the Varina Enon Bridge because of strand corrosion.

and first used on a bridge built in 1988 off the coast of Japan. This bridge, which replaced a 20-year-old structure that failed due to corrosion, continues to show no signs of corrosion. (Enomoto et al., 2012). CFCC does not corrode because it is corrosion-free. Around the world there are examples of CFCC used in prestressed elements. Here in the United States, the same strand material was placed in a bridge structure in Michigan and has undergone continuous monitoring since construction was completed in 2001 (Enomoto et al., 2012). Currently two other bridges in Michigan are being constructed using CFCC strands. Moreover, even the cables of a cable-stayed bridge in Maine were constructed with CFCC (Berube et al., 2008). The rationale behind using CFCC is that even though it costs more per unit length than conventional steel strand, repairs to elements with steel strands are costly and difficult since these elements generally are load-carrying members under the bridge deck.

Nimmo Parkway Project

Construction of Nimmo Parkway in Virginia Beach, Virginia includes two 1600 foot long bridges, which carry in both directions traffic over West Neck Creek and adjacent wetlands. The $58 million project is under construction and is expected to be completed in the summer of 2014. Once completed, it will provide major congestion relief in the vicinity of the Virginia Beach Municipal Center, a vital part of city's tourist economy.

The Nimmo Parkway bridges have 272 piles supporting the two long bridges. Eighteen of the piles, located adjacent to West Neck Creek, contain CFCC reinforcement. All of the piles have square cross-sections that measure 2 feet by 2 feet. Although the cross-sectional dimensions are the same for each pile, there were two allowable pile reinforcement designs: The CFCC-reinforced piles employed the circular spiral design because it eliminated a sharp corner radius.

Carbon-fiber composite cable is a very strong composite material with an ultimate strength of at least 270 ksi. In design, however, the prestressing stress of this composite material was limited to 65% of the ultimate strength following ACI 440 recommendations rather than up to 75% for the conventional steel strand. Although the same number of strands was used in the CFCC and conventionally reinforced piles, a larger diameter CFCC strand was used compared to the conventional steel strand; for the CFCC 0.6 inch instead of the 0.5 inch used for the conventional piles.

Unlike conventional steel, special end preparation requirements were used to avoid crushing the CFCC at the chucks during stressing. At the ends, CFCC was wrapped with a mesh, and a braided steel grip was slid over the top of the mesh. Long wedges were placed before seating the wedges in the chuck. This chuck was placed in one end of a coupler, and a conventional chuck holding a steel strand was placed in the other end of the coupler. The prestressing force was provided by pulling the steel strand with a traditional jack.

Initially two test piles with CFCC were cast and driven (see Figure 1) to determine the length for the production piles. These concrete test piles were instrumented to determine the behavior during driving. The data indicated that during driving the behavior between the CFCC and the conventional piles was similar. After the successfully completion of the test piles, 16 production piles were cast with no problems.

Because it is important to properly prepare the ends for stressing, technicians from Japan performed the end preparation of the test piles while local workers observed the process. Later, during fabrication of the production piles, local workers prepared the ends at the plant. Further work is underway by the CFCC producer and VDOT to simplify and reduce the time for end preparations.

This project demonstrated that the fabrication and placement of corrosion free piles reinforced with CFCC is possible. VDOT is looking for more applications not only in piles but also other prestressed elements to extend their life and thereby avoid costly repairs, traffic interruption, and unsafe conditions.

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Corrosion of Reinforcement in High Performance Concrete

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Introduction

Controlling corrosion of the reinforcement continues to be the most controversial challenge for professionals responsible for reinforced concrete structures exposed to chlorides. Decades ago quality concrete had lower strength, higher permeability and fewer and tighter cracks than the concrete used today which is often called high performance concrete (HPC). Today's HPC mixtures typically have higher strength and lower permeability, but may also lead to wider cracks (>0.2 mm) in the finished structure. Over the past 20 years, DOTs have reduced the cracking in HPC by using less cement, shrinkage reducing admixtures, and internal curing. However, cracking continues to be one of the most significant problems facing the concrete industry. The control of cracking induced by volume changes in plastic and hardened concrete has been identified as an Industry Critical Technology (ICT) by the Strategic Development Council (SDC) of the American Concrete Institute and a $1 million, 5-year project was initiated on 1-1-13 titled Reducing Volume Change-Induced Cracking of Concrete: Field Implementation and Evaluation of Crack-Reduction Technologies.[1]

The low permeability of HPC can be achieved by replacing a portion of the portland cement with fly ash and/or slag. Typical additions are 25 percent type F ash or 50 percent slag. Unfortunately, because the fly ash and slag contribute little to early strength, 25-50% of the portland cement is often not removed and the total cementitious materials content of HPC is higher than in the past, often more than 700 lb/yd^3. The additional cement

Fig. 1. Full depth leaking transverse cracks in a new HPC deck on US 123 over the Occoquan River constructed in 2007.

used to achieve the higher early strength to facilitate accelerated construction causes an increase in curing temperature, potentially leading to increased drying shrinkage and additional cracking. Prestressed and post-tensioned structures cast with HPC should last more than 100 years because of the high quality of the HPC and the lack of cracks because the HPC is compressed by the strands.

On the other hand, conventionally reinforced HPC structures may well have a shorter life than the structures of the past because of the wide cracks in the concrete that are typically caused by shrinkage and temperature differentials. Figure 1 shows full depth leaking transverse cracks in a new HPC deck on US 123 over the Occoquan River constructed in 2007.[(2)] Figure 2 shows full depth leaking transverse cracks in concrete placed in a deck on I81 near Marion in 2009. These decks are typical of the HPC decks constructed by VDOT over the past 20 years. The cracks typically align with the reinforcement that is parallel to the cracks and intersect with the reinforcement that is perpendicular to the cracks. The cracks allow chlorides and moisture direct access to the reinforcement. The liquid calcium applied today provides a more corrosive environment than the granular chloride and abrasives used in the past. Repeated cycles of wetting and drying and liquid chloride applications on bridge decks in particular provide a corrosive environment in wide cracks comparable to the splash zone in piers in a marine environment and aggressive accelerated lab tests. The steel surface corrodes rapidly in an environment with no protection provided by the concrete in the vicinity of the crack because the pH drops as the concrete carbonates. Water washes the corrosion deposits away allowing the steel surface to rapidly corrode and the cycle continues until the steel section fails because it is too weak to handle the shear, tensile and compressive stresses. The steel section that intersects a crack provides a small anode that is driven by a large cathode in the HPC. The section necks rapidly in the wet dry chloride contaminated low pH environment. A615 steel reinforcement has a short service life when exposed to a corrosive environment in a crack.

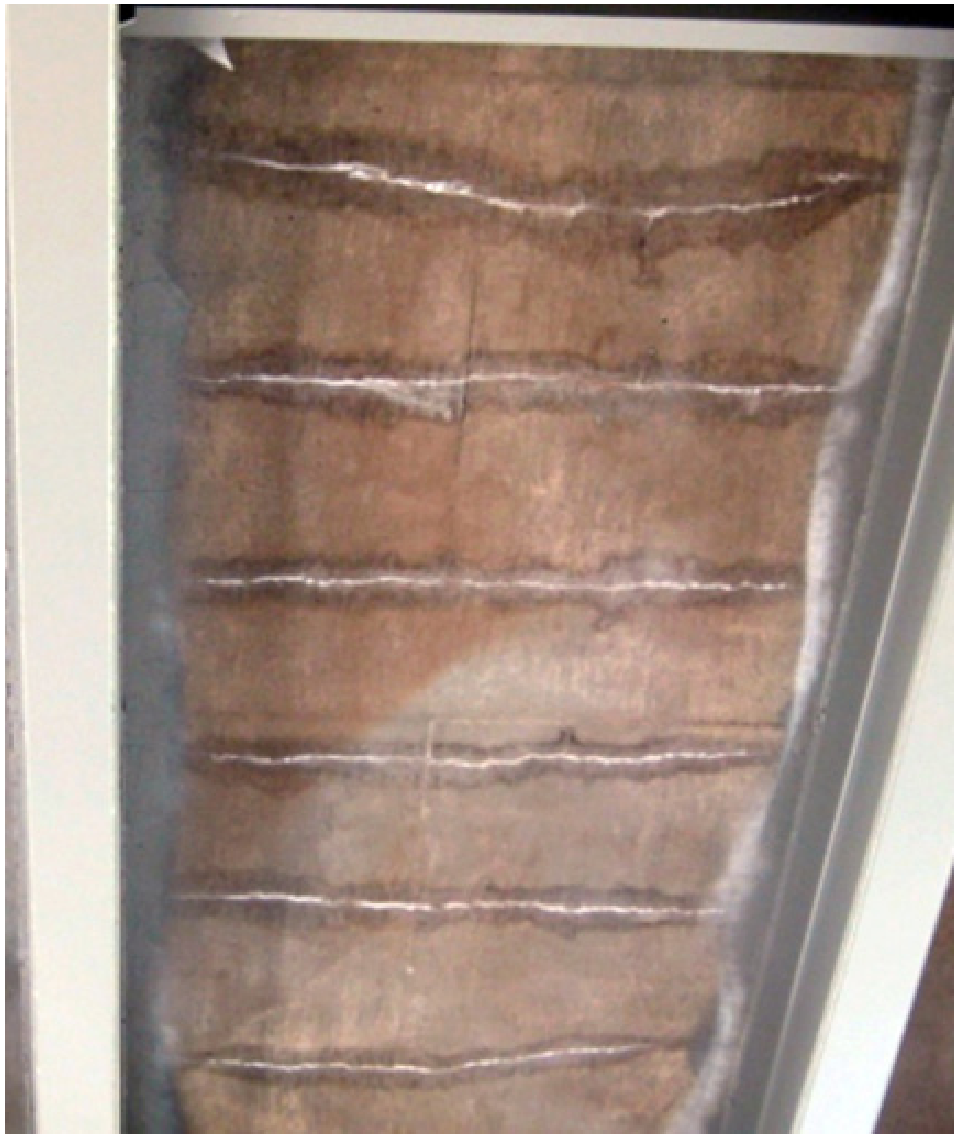

Fig. 2. Full depth leaking transverse cracks in concrete placed in a deck on I81 near Marion in 2009.

Epoxy coated reinforcement (ECR) continues to be the preferred corrosion protection system of most DOTs.[(3)] Research conducted by the VDOT indicates that the initial corrosion protection provided by the coating depends on its condition and quality, but over time, the coating can delaminate allowing water and chlorides direct access to the steel surface.(4) The coating can trap moisture, preventing the water from evaporating and increasing the rate of corrosion. Figure 3 shows the corroded ECR in a section of deck that failed in shear in 2009 on I81 near Marion Virginia after 17 years in service.[(4)] The green coating has turned brown in the vicinity of the leaking construction joint that was approximately 0.5 mm wide, the typical width of cracks in decks constructed with HPC. For a number of reasons, including geometry, cracks may create a more corrosive environment than joints.

VDOT's preferred low cost solution to the problem of corrosion of reinforcement in wide cracks is alloyed corrosion resistant reinforcement (CRR). CRR can last more than 100 years and like HPC contribute to a structure service life in excess of 100 years even when the structure is exposed to cycles of wetting and drying in a chloride environment. VDOT discontinued the use of ECR in 2010 and initiated the use of CRR. Other more expensive solutions include cathodic prevention that must be maintained, flexible polymer membranes and asphalt wearing surfaces that must be replaced periodically, routing and sealing of cracks with polymer crack filling materials that must be replaced periodically and epoxy injection of cracks. Use of A955 solid stainless reinforcement increases the installed cost approximately \$1.24/lb compared to ECR and increases the cost of a deck approximately \$74/yd² based on VDOT bid tabulations for 2011 and 2012. Alternative treatments cost far more approaching or exceeding \$150/yd² either initially or over the life of the deck. VDOT has had no issues with the supply of solid stainless reinforcement and use of lower cost A1035 CRR which costs approximately the same as ECR can also be justified for many applications. VDOT uses solid stainless for the construction of bridges on Interstate and heavily travel primary routes. It uses A1035 CRR for rural and urban low volume roads.

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Stainless Steel Prestressing Strand for Durable Bridge Piles

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In order to develop "corrosion-free" precast prestressed concrete bridge piles with design life greater than 100 years, the Georgia Department of Transportation (DOT) initiated research in 2009 at the Georgia Institute of Technology (Georgia Tech) to develop high-strength stainless steel prestressing strand to replace the conventional grade 1080, 270 ksi low-relaxation, seven wire strand. To determine corrosion resistance of conventional and stainless steel prestressing reinforcement, test specimens containing either a single wire or 7-wire prestressing strands were exposed to various simulated concrete pore solutions made with various concentrations of NaCl. The specimens were evaluated using cyclic potentiodynamic polarization (CPP) techniques (ASTM G61) to determine corrosion potentials in marine environments. Cl- concentrations were varied in steps of 0.1 M from 0.0 M to 1.0 M. A 0.5 M solution represents typical seawater which occurs along the Georgia coast from I-95 to the Atlantic Ocean, and a 1.0 M represents concentrated salts which occur in cracks in piles within the tidal zones.

Working with Sumiden Wire Products Corporation, researchers identified six stainless steel alloys for potential application: grades 17-7, 304, 316, 1080, 2101, 2205, and 2304. The performances of all alloys were compared with that of conventional 1080 steel used for standard prestressing strands. When the austenitic stainless steel grades 304 and 316 were cold-drawn to wire diameters for use in ½-in. diameter, 7-wire strand, the ultimate strengths were about 181 ksi, but the structure was changed from principally austenite to ferrite, and their generally excellent corrosion resistance was lost. Cold drawing of the martensitic grade 17-7 also resulted in poor corrosion resistance of that alloy. Of the modern duplex stainless steels, grade 2205 and grade 2304 developed ultimate tensile strengths between 240 ksi and 250 ksi along with good corrosion resistance. However, tensile strength tests of seven-wire strand made using the grade 2304 stainless steel showed that the strand failed in the standard prestressing anchors at loads between 40% and 60% of its ultimate strength due to the material's notch sensitivity. Therefore, the grade 2304 stainless steel was not used for further production tests. Cold-drawn grade 2101 showed unsatisfactory corrosion resistance. Table 1 shows the corrosion resistance of the various strands in alkaline concrete solutions (pH of 12.5) and in carbonated concrete solutions (pH of 9.5). As anticipated, conventional high-strength steel strand (1080 steel) demonstrated very poor corrosion reistance with extensive pitting corrosion initiating in the grooves between wires.

Fig. 1. 16-in. square pile with stainless steel grade 2205, ½-in. diameter 7-wire strands and with grade 304 stainless steel wire spiral.

Induction heating processes were used in the trial manufacture of both 2205 and 2304 strand by Sumiden Wire Products, Dixon, Tennessee. The induction heat treatment worked well and increased the ultimate tensile strength from 225 ksi to between 240 ksi and 250 ksi. Further, relaxation tests of the strands showed that relaxation losses were less than 2.5% after heat treatment, whereas relaxation losses were about 8% before treatment (Schuetz et al., 2012).

Solution		Alkaline – pH 12.5				Carbonated – pH 9.5			
[Cl-] (M)		0.00	0.25	0.50	1.00	0.00	0.25	0.50	1.00
Alloy	1080	No Corrosion Initiation	Stable Pitting	Stable Pitting	Stable Pitting	Metastable Pitting	Stable Pitting	Stable Pitting	Stable Pitting
	304	No Corrosion Initiation	No Corrosion Initiation	Metastable Pitting	Stable Pitting	No Corrosion Initiation	Metastable Pitting	Stable Pitting	Stable Pitting
	316	No Corrosion Initiation	Metastable Pitting	Stable Pitting	Stable Pitting	No Corrosion Initiation	Stable Pitting	Stable Pitting	Stable Pitting
	2101	No Corrosion Initiation	No Corrosion Initiation	Stable Pitting	Stable Pitting	No Corrosion Initiation	Stable Pitting	Stable Pitting	Stable Pitting
	2205	No Corrosion Initiation	No Corrosion Initiation	No Corrosion Initiation	No Corrosion Initiation	No Corrosion Initiation	No Corrosion Initiation	No Corrosion Initiation	No Corrosion Initiation
	2304	No Corrosion Initiation	No Corrosion Initiation	No Corrosion Initiation	Metastable Pitting	No Corrosion Initiation	No Corrosion Initiation	Metastable Pitting	Stable Pitting
	17-7	No Corrosion Initiation	Metastable Pitting	Stable Pitting	Stable Pitting	No Corrosion Initiation	Stable Pitting	Stable Pitting	Stable Pitting

Corrosion Behavior
No Corrosion Initiation
Metastable Pitting
Stable Pitting

Table 1. Corrosion resistance of conventional and stainless steel alloys (from Moser et al., 2012)

Based on the superior strength and corrosion resistance of the 2205 alloy, ½-in. diameter strand was produced and was used to construct three70-ft long, 16-in. square precast prestressed concrete piles. The strand was stressed to 70% of its 250 ksi ultimate strength. The stressing and construction operations were performed at Standard Concrete Products Company, Savannah, Georgia and proceeded identically to those for two companion piles made with conventional grade 1080 strand. Construction using 2205 stainless steel strands and grade 304 stainless steel wire spirals was completed with no difficulties and with no need for any special operations. Grade 304 with yield stress of 50 ksi was used for the spirals so that the small radius bends could be made; the high-strength 2205 wire could not be bent without fracturing. The same 5000 psi design strength concrete was used for all piles (28 day strength was 8100 psi).

Transfer length measurements at each end and on each side of all piles were made using external DEMEC gauges. The average transfer length was 18 in., 36 times the nominal strand diameter. This length is less than the 60 times the diameter maximum specified in the AASHTO LRFD Bridge Design Specifications [2012].

About six months following pile construction, three of the stainless steel reinforced piles and two piles with conventional strands were driven to refusal in the Savannah River. They were then extracted for future flexural, shear, and development length tests. No cracking, spalling or other damage was noted in any pile.

Further tests of the reinforcement and of the piles are being conducted at Georgia Tech. The author's preliminary conclusion is that high-strength stainless steel strand, wire, and spiral show excellent promise for providing 100-year service life for prestressed concrete piles in marine environments. The Georgia Tech researchers are working with Georgia DOT to standardize specifications and design of corrosion-free piles for use in exposed pile bents along Georgia's coast.

Acknowledgments

The research reported herein was sponsored by the Georgia DOT through Research Project Number 10-26. For more information, please contact Lawrence F. Kahn, lawrence.kahn@ce.gatech.edu

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Fig. 2. 16-in., 70-ft long piles with stainless steel reinforcement being extracted after driving to refusal in Savannah River.

Further Improvements in Post-Tensioning Grout Materials

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In 2012, the Post-Tensioning Institute (PTI) published the updated PTI M55.1-12, Specification for Grouting of Post-Tensioned Structures.[1] The reason for this update was to address concerns related to high chloride content, grout segregation, and to strengthen the provisions to minimize bleed water, as well as ensure proper construction. An article in the Fall 2012 issue of ASPIRE™ gave a background and details of this update.[2] An addendum to the grouting specification issued in 2013 includes further steps in ensuring quality grouting that is essential for durability of post-tensioned structures.[3]

Fig. 1. The inclined tube test is a large scale bleed test. Photo: Structural/VSL

2012 Grouting Specification

- A summary of the changes in the 2012 edition of the grouting specification follows.
- Additional and independent field testing for acid-soluble chloride ion (Cl-) was introduced to be performed in accordance with ASTM C1152 on the mixed grout once per project and a minimum every 40,000 lb of grout.
- Limits on the Blaine value[4] of the cement used in grout were introduced. The Blaine value is a measure of the cement's fineness. It has a strong effect on the homogeneity of grout. Cements with a Blaine value too low tend to easily flocculate (form lumps) and may cause segregation. Cements with a too high value require more water and admixtures to wet the surface, and tend to have earlier setting times.
- The bleed testing is enhanced with the introduction of the inclined tube test that is much more realistic reflection of a draped tendon in the structure, with its length of 16 ft at an angle of 30 degrees and with 12 strands in each sample (Fig. 1).
- The wick induced test has also been revised to be more representative of actual conditions in a tendon by increasing the length of the test specimen using a 40-in.-long tube instead of the old short graduated cylinder.

- The range of the constituent materials is now also given for the Class C (prepackaged grouts); in the previous edition, this was only given for the Classes A and B (the basic and engineered site-mixed grouts).
- The grouting operations and production testing were adjusted as well; the wet density and flowability are now measured at the mixer as well as at the outlet so that the grout quality and consistency within the tendon can be monitored (Fig. 2). The flushing of tendons is no longer permitted. Prewetting of ducts inadvertently adds water to the mix and flushing in cases of grout problems creates a situation that is very difficult to repair. Finally, low grouting pressures and no pressurization of the tendons after grouting are recommended.

Specification Addendum

The changes introduced in the 2012 edition of the PTI specification, if properly followed and enforced, will be very effective in controlling bleeding and the level of chloride in grout. However, research and field investigations by the Florida Department of Transportation (FDOT) and others continue to raise concern regarding the causes of and problems associated with segregated grout. Under some circumstances, the constituents of some prepackaged grouts can separate during grout injection leading to areas where the grout does not harden (for example, "soft grout"). The segregated material has been observed to be corrosive in some cases, even without the presence of chloride.

In June 2013, the PTI M-55 Grouting Committee published Addendum No. 1 to PTI M55.1-12 Specification for Grouting of Post-Tensioned Structures[5] to further address the "soft grout" issue. This document is now officially a part of the grouting specification and should be referenced with it.

Ongoing research at the University of Florida at Gainesville is attempting to determine the exact cause(s) of grout segregation. Preliminary findings indicate that the addition of aggregates and inert fillers to the grout mix, and improper storage of grout may contribute to the segregation of the constituent materials.

Other research by FDOT and Florida International University has found that when grout segregation (soft grout) occurs, there is often a very high concentration of sulfate in the segregated material, which is believed to increase the corrosion potential in the tendon.

- In response to this research and the ongoing concern about grout segregation, the following changes were included in Addendum No. 1:
- For jobsite (Class A and B) and prepackaged (Class C) grout mixes, the addition of aggregates and inert fillers is now prohibited. These materials can only be used in special Class D grout approved by the design engineer for a specific project need.
- Mineral additives and admixtures shall not contain sulfates.
- The limits for Blaine values for cement were revised to be between 300 to 400 m2/kg to more closely match cements produced in the United States.

Fig. 2. The wet density and flowability are tested at mixer as well as at the the outlet

- Only mineral additives and admixtures specifically listed in the specification may be used. Only undensified silica fume shall be permitted.

Although sulfates in high concentration occur only in the areas of soft grout, no supplemental cementitious materials or chemical admixtures may include sulfates, besides those already contained in the permitted constituent materials. The grout ingredients are limited to those specifically permitted.

Summary

The PTI M-55 Grouting Committee is actively working with all stakeholders on the next edition of the grouting specification to include the latest knowledge and research. The present specification with the addendum should be referenced by specifiers as it represents the latest developments and research performed in the field.

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