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By

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Over the past 25 years, the Virginia Department of Transportation (VDOT) has used different materials to grout its post-tensioned (PT) structures. Prior to 2001, PT tendon grouts were a mixture of water and cement and sometimes an expansive admixture. VDOT worked with the industry to develop prepackaged high-performance grouts (HPGs) to improve the quality of grouts, and in 2001, the Smart Road bridge was the first to be grouted with an HPG. In 2012, VDOT performed a tendon mockup which demonstrated that one of the approved HPGs could bleed and segregate, producing soft grout and leaving voids, and another approved grout could perform well. VDOT has experienced corrosion of strands, bleeding and segregation of grout, voids in tendons, and a tendon failure. While the VDOT experience has identified many issues with grouts and grouting, PT structures continue to provide service. PT segmental bridges can be properly grouted with HPG.

KEYWORDS

bridge; corrosion; grout; grouting; post-tensioning; soft grout; voids.

INTRODUCTION

Over the past 25 years, the Virginia Department of Transportation (VDOT) has used different materials to grout its post-tensioned (PT) structures. Prior to 2001, PT tendon grouts were a mixture of water and cement, and sometimes an expansive admixture. This paper covers 16 years of technical assistance efforts that were focused on the evaluation and improvement of the grouts and grouting practices used to grout PT tendons in bridges.

The first effort was directed at trying a grout containing 7% silica fume to grout the tendons in the pier caps of the Coleman Bridge. The caps were widened and post-tensioned in 1998 to accommodate the prefabricated truss structure that was used to replace the superstructure. While the addition of silica fume produced a grout that had lower permeability and higher strength, the grout bled and segregated like the water-cement grouts being used at that time. The horizontal curved tendon in the mockup done in the yard of a PT contractor exhibited voids along the top of the tendon.

The next effort involved working with grout suppliers to develop a high-performance grout (HPG) with low permeability that would not bleed and segregate. The first grout to be developed and approved by VDOT is referred to as Grout 1. By work order, Grout 1 was used to grout the tendons in the segmental bridge on the Smart Road in 2001. This bridge was the first in the world to be grouted with a high-performance grout. VDOT approved prepackaged Grout 2 later in 2001 and by work order Grout 2 was used to grout approximately the last 60% of the bridge spans on the 895 project. Finally, in 2001, VDOT approved prepackaged Grout 3. VDOT had accomplished the goal of implementing the use of high-performance grouts in Virginia. Because of tendon failures in Florida, DOT's, like Florida, followed VDOT's lead and began to require the use of prepackaged HPGs; this was also required by the PTI Specification for Grouting of PT Structures (Second Edition, April 2003). In 2001, VDOT found voids in the tendons in the Varina Enon Bridge using a borescope to probe the vent tubes in the end caps. The voids were believed to be caused by the bleeding and segregation of the water-cement grout used to grout the tendons in the two parallel 28-span Varina Enon bridges (Fig. 1) in 1990. A properly mixed grout would leave voids at the high points in the tendon that were approximately 4% the length of the tendon (6 ft [1.8 m] of void in a 150 ft [45.7 m] long tendon). It is believed grout leaking from the tendons contributed to some additional length of voids. Like many other major structures, these precast PT structures were constructed with the latest concrete and post-tensioning technologies and were expected to provide relatively maintenance-free performance for more than 100 years. In addition to cables that hang from two towers, the structures are supported by 480 tendons with grouted PT strands. The voids confirmed the need to implement the use of high-performance grouts. In 2003 and 2004, contracts were awarded to grout the voids in the Varina Enon Bridge. Grouts 1 and 2 were used.

On May 22, 2007, Tendon SP12T15 was found in a state of failure (Fig. 2) during a biannual inspection. The failed tendon raised concerns about the condition of other tendons in the structures and the FHWA authorized emergency funding to replace the failed tendon, determine the condition of other tendons, and make needed repairs. During the repairs, short sections (approximately 18 in. [460 mm] long) were removed from ducts at 20 locations. Eight sites were selected for monitoring. The sites represented various conditions ranging from corroding and broken wires to exposed wires with no grout but no corrosion.

In 2010, tendons in Florida and Texas that had been grouted with Grout 2 were found to have voids; segregated grout; grout with high chloride content; and grout that was not set, called soft grout.[1] It was obvious that lab tests used to approve HPG needed to be improved. In 2012, FHWA published a sampling protocol for DOTs to use to identify tendons with grout that contained unacceptable levels of chloride.[2]

Fig. 1—Varina Enon Bridge.

Fig. 2—Failed draped tendon found during inspection on May 22, 2007.

In 2012, VDOT did a mockup by work order to identify a suitable grout for use in the US 460 segmental bridge project near Grundy, VA. The mockup determined that Grout 3 was suitable for use because the tendon was properly grouted. Grout 2 bled and segregated and left voids and soft grout at the high points in the tendon in the mockup and was rejected for use.

OBJECTIVE

The objective of the research and technical assistance reported in this paper was to identify problems with grouts and grouting practices used to grout tendons in PT structures, and to develop and recommend grouts and grouting practices that will provide for properly grouted tendons in structures that should have a long service life.

METHODOLOGY

Specific activities included identifying deficiencies with the water-cement grouts used prior to 2001, as reflected by evaluations of the condition of the Varina Enon Bridge, and implementing the use of HPG and grouting practices that provide for properly grouted tendons.

RESULTS

Deficiencies with water-cement grouts used prior to 2001, as reflected by evaluations of condition of Varina Enon Bridge

Failures—The tendon failure in the Varina Enon Bridge after only 17 years in service was not unique to this bridge. A number of bridges have had PT and prestressed strand failures in recent years.[3]

PT strands failed in three major structures in Florida:

- 1999: Niles Channel Bridge in the Florida Keys after 16 years in service;
- 2000: Sunshine Skyway Bridge in Tampa after 13 years; and
- 2000: Mid Bay Bridge in Destin after 6 years. Pretensioned strands failed in two structures in recent years:
- 2000: Lowe's Motor Speedway Bridge in Charlotte, NC, after 5 years; and
- 2005: I-70 overpass in Pennsylvania after 45 years.

While the I-70 failure was mostly a result of the aging infrastructure, other failures were caused by design and construction issues that resulted in early-age corrosion of the strands. The failures in Florida were associated with either no grout or poor-quality grout surrounding the strands. The high humidity and temperatures likely reduced the time to failure of the tendons in Florida. The I-70 failure was caused by salt water from a leaking joint migrating through the strands, and the failure in North Carolina was caused by a chloride accelerator being added to a patching grout that was placed around the strands.

Varina-Enon Bridge—The tendons in the Varina-Enon Bridge were first inspected in 2001 after failures were noted in similar bridges in Florida. A number of 1 in. (25 mm) diameter inspection holes were found in the plastic ducts. The strands were corroded slightly in the vicinity of the holes and small voids were found in the tops of the ducts. Another problem was a floor drain that was plugged with grout that leaked out while a tendon was being grouted, allowing water from a nearby leaking joint to surround a tendon. The water was acidic from pigeon droppings. The acidic water accelerated corrosion of the strands. A third problem was vent tubes in most draped tendons were found to be open. Borescope inspections made through the open vent tubes revealed voids in the tendons adjacent to the anchor plates (Fig. 3) and traces of grout on the strands and walls of the vent tubes. The traces of grout indicated that the tendon and vent tube had been filled with grout but the grout had bled and segregated, leaving water on the topmost surface of the grout that later evaporated, leaving a void of approximately 4% of the length of the tendon. Longer sections of voids that were found provided an indication that grout had leaked from the tendons prior to setting.

Contracts to vacuum grout from known voids in the tendons and seal vent tubes in the Varina Enon bridge were awarded in 2003 and 2004.

Corrosion of strands—While later-age failures (45 years or more) of prestressing strands are typically associated with exposure to years of deicing chemical applications, a number of factors have been identified as contributing to the early-age failures. There is evidence that early-age failures are caused by one or more of the following:

- Grout material problems;
- Design problems;
- Construction problems;
- Exposure to a corrosive environment; and
- Repair problems.

A grout material problem that may contribute to a reduction in the service life of a tendon is bleeding and segregation. For corrosion protection, the strands are supposed to be surrounded by a high-quality portland cement grout. Prior to 2001, grouts were typically cement, water, and an expansive admixture. These grouts would bleed and segregate after being pumped into a tendon. A wick-induced bleed test indicates that bleeding in grouts used prior to 2001 was approximately 4%. In a typical 150 ft (45.7 m) long tendon in the Varina Enon Bridge (Fig. 4), 4% bleeding can cause 6 ft (1.8 m) of void at the

Fig. 3—Typical voids adjacent to anchor plates in draped tendons.

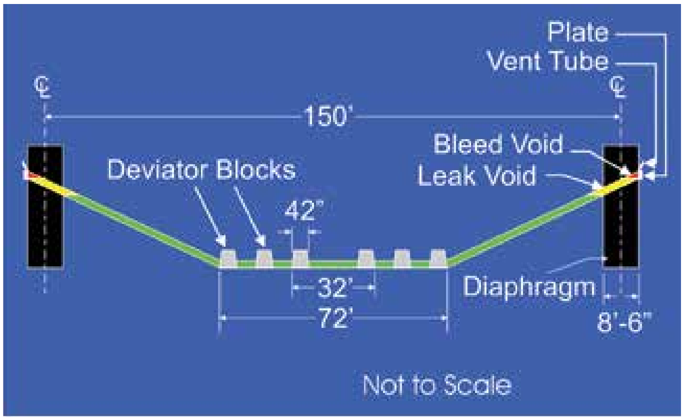

Fig. 4—Typical Varina Enon span with draped tendon and bleed and leak voids. (Note: 1 ft = 0.305 m; 1 in. = 25.4 mm.)

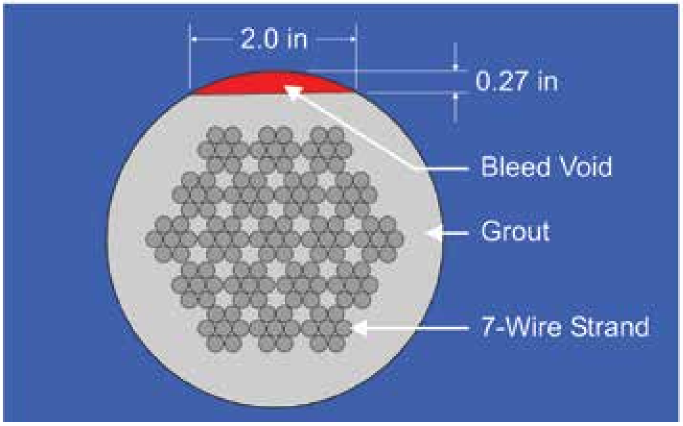

Fig. 5—Typical Varina Enon horizontal tendon section with bleed void. (Note: 1 in. = 25.4 mm.)

high points in the draped tendons and a void along the top of a horizontal tendon (Fig. 5). Six of the eight tendons in a typical span of the Varina Enon bridge are draped. While strands that were not surrounded by grout were found to be not corroded after 11 years (Fig. 3 and 6), strands that were found to be corroded and having broken wires were either not surrounded by grout or were surrounded by low-quality grout that segregated around the strands following the bleeding of the grout. No corrosion was found in strands that were surrounded by grout of the quality specified for the construction that was not diluted by bled water. The strands in the failed tendon failed at a location where the strands were surrounded by the low-quality grout that forms at the highest level in the tendon as a result of bleeding and segregation of the grout. Typically, the poorest-quality grout surrounds the strands near the anchor plates in draped tendons because the anchor plates are located at the highest point. High-performance grouts specified for use beginning in 2001 do not bleed and segregate and consequently the material problem of corrosion caused by bleeding and segregation of the grout has been eliminated for new structures grouted with HPG.

A design problem is that the strands in a draped tendon are not centered in the plastic duct but rather pressed against the top side of the duct, and the topmost strands are not completely surrounded by grout (Fig. 6). The problem of corrosion caused by strands bearing against the top of the duct cannot be solved, but has not caused failures as long as the duct is intact and the strands are not exposed to moisture, oxygen, and chlorides.

Fig. 6—Typical grouted draped tendon, indicating it is not possible to surround strands with grout.

A construction problem that can result in strands not being surrounded by grout is voids due to incomplete grouting and leaks. Many draped tendons in the Varina Enon Bridge were found to have these voids. Strands in many of the void areas were not corroding. The condition of the strands in the low-quality grout that contains bled water just below the voids is not easy to determine. However, it is believed that stands are most likely to corrode at this location because the quality of the grout is low and the sulfate content of the grout is elevated because of bleeding and segregation. The presence of sulfates can accelerate corrosion. Strands corroded at this location in the failed tendon.

Exposure to a corrosive environment is typically not a cause of early-age failure. The plastic duct and the grout provide protection for the strands. Also, the tendons are either encased in high-performance concrete or located inside the high-performance concrete structure, which provide protection from the elements. Hundreds of years of exposure are required for chlorides to penetrate the high-performance concrete used today. Additional protection is provided by the crack-free concrete, which is a product of the post-tensioning. Anchor plates are typically sealed from the elements by encasing them in concrete and coating the concrete with an epoxy. Leaking joints can allow deicing chemicals to make contact with the epoxy and concrete that protects the anchor plates and cause a reduction in service life.

Repair problems have become apparent when attempts have been made to repair tendons. Repair requirements for deficiencies found in PT structures have not been established because failing prestressing strands was not recognized as more than an occasional problem prior to 1999. Some argue failing strands is not a major problem and early failures are anomalies rather than indicators of things to come. Voids in tendons are not easily found. Most DOTs that have found voids in tendons have awarded contracts to fill the voids with HPG. Contracts to vacuum grout known voids in the tendons in the Varina Enon Bridge were awarded in 2003 and 2004. The tendon that failed in 2007 was vacuum grouted. The strand inside the vacuum-grouted section was in original condition. The strand failed in the section with low-quality grout just below the high-performance vacuum grout. Did the vacuum grout increase or decrease the time to failure of the tendon? The jury is out, with some arguing the difference in the properties of the grouts may have accelerated the corrosion. Others argue the strands were exposed to oxygen and moisture when the vacuum grouting was done, which accelerated

Table 1—Moisture content and absorption of grout in two tendons selected for detailed inspection

Tendon	Broken wires	Section loss	Color	Moisture content, %	Absorption, %
NP13T10	2	7 wires 5.3%	Gray	32.8	35.5
SP12T9	1	4.8 wires 3.6%	Gray (bottom)	36.6	39.5
SP12T9	1	4.8 wires 3.6%	White (top)	21.6	36.5

the corrosion. On the other hand, some argue the high-performance grout provided enhanced protection for the strands, and the strands that failed would have failed with or without the repair because of the corrosive condition of the bleed water grout surrounding the strands at the location of the failure.

Approximately 45% of the tendons in the Varina Enon Bridge were not vacuum grouted, yet in theory, all the tendons should have voids caused by bleeding and segregation. Voids that are not connected to the void that is being grouted will not be grouted. Corroded and failed wires are not easily found. The failed tendon had corroded strands in a 6 to 8 ft (1.8 to 2.4 m) section with bleed water grout where the failure occurred. Strands in the rest of the 150 ft (45.7 m) length were not corroded. Section loss in tendon SP12T9 was identified by magnetic flux testing. However, magnetic flux testing did not find section loss in the other 479 tendons. The magnetic flux test cannot be done where the duct goes through deviator blocks and end diaphragms (Fig. 4), which is where most voids would likely occur in draped tendons. Visual inspection identified rust stains coming from an inspection hole in the duct of tendon NP13T10. Further inspection revealed two broken wires and a 5.3% section loss.

Tendon replacement is an expensive and time-consuming activity. In 2007, emergency funding was used to replace two tendons (one that had failed, and one with three broken wires), to evaluate the condition of all tendons using magnetic flux testing (approximately 80% of the length of each tendon), and to do other inspections and repairs deemed appropriate. In addition to the failed tendon, a second tendon was replaced that was found to have three failed wires caused by exposure to water laden with pigeon droppings that had ponded around the tendon in the vicinity of a drain that was plugged with grout that had leaked from the tendons. The failed tendon had already been detensioned and was easier to replace than the second tendon that still had to be detensioned. The second tendon had an anchor plate at a joint between continuous spans. Access to the anchor plate was not adequate to allow easy removal of the anchor plate. Exposure to deicing chemicals is more likely at joints, and the most difficult tendons to replace are those with anchor plates at joints.

Twenty tendons were inspected in detail by removal of a 2 ft (0.6 m) section of duct (18 of those because of possible corrosion seen in borescope pictures taken in 2003 and 2004; one because magnetic flux measurements indicated section loss; and one because a visual inspection revealed rust). The quality of the borescope pictures was so poor that it was difficult to tell if the strands were corroding. Section loss in Tendon SP12T9 was identified by magnetic flux testing. Magnetic flux testing did not find section loss in the other 479 tendons. Visual inspection identified rust stains coming from a hole in the duct of Tendon NP13T10. Removal of a 2 ft (0.6 m) section of plastic duct revealed two broken wires and 5.3% section loss. No chlorides were found in the grout in the failed tendon or tendons NP13T10 and SP12T9, where broken wires were found.

Access is a problem when repairs are done. Access to the inside of each of the two Varina Enon bridges is limited to an opening that is approximately 3 ft^2 (0.3 m^2) located in the floor of the spans next to the abutments. The opening is approximately 20 ft (6.1 m) above the sloping riprap. All personnel, repair equipment, and repair materials must enter through the opening. The replaced tendons had to be cut into short sections to allow personnel to carry them out of the structures.

Grout moisture content—Strands not protected by grout with a high pH will corrode in the presence of water and oxygen. The grout in the tendons in the Varina Enon Bridge was found to have a high pH. The only grout found with a low pH was the grout in the vicinity of the failed tendon. This grout may have carbonated after the tendon failed, as no one knows the actual date of the failure. Table 1 shows the high moisture content and absorption of the grout in two tendons with corroding strands. Water in the grout that had not reacted with the cement was available to promote corrosion in the tendon for at least 17 years. An external source of moisture was not needed for corrosion. The grout has high absorption and, consequently, if the grout is exposed to corrosive elements through a breech in the duct, it would likely absorb them readily. Grout that is vented or otherwise exposed and allowed to dry shrinks and cracks, resulting in a reduction in protection.

Monitoring six tendon conditions—What is the future of the tendons in the Varina Enon Bridge? Some believe the failed tendon is an anomaly caused by faulty workmanship and is not representative of the other 479 tendons. Yet detailed inspections of only 20 tendons revealed six different conditions associated with corrosion and possible reduced service life. The six conditions include:

1. Voids, no vacuum grout (NP2T15) (approximately 45% of tendons were not vacuum grouted);
2. Voids, incomplete vacuum grout (NP3T16);
3. Drying shrinkage cracks in grout (SP12T16);
4. Minor corrosion (NP5T8, NP5T16);
5. Pitting corrosion and several broken wires (NP13T10); and
6. Vacuum grouted tendon with broken wires (SP12T9).

A consultant recommended to repair the six tendons representing the six conditions and consider the bridge repaired. After all, only five of the 480 tendons have been found to have a corrosion problem (1%). Another way to look at the situation is that eight of the 22 tendons (including two that were replaced) that were inspected by removing the plastic duct were found to have voids and or corrosion problems (36%). The conditions represented by the eight tendons may be representative of the conditions of 175 tendons. Consequently, six of the 20 tendons selected for detailed inspections were selected for long-term monitoring. As shown in Table 2, additional corrosion has occurred at the worst two locations since the strands were exposed and first inspected in 2007. Table 2 shows two wires of 133 wires in Tendon NP13T10 have failed over the past 6 years, which suggests a tendon life of 99 years if the failure of 33 wires causes a tendon to fail (0.33 wires per years × 33 wires = 99 years until a tendon failure). A section loss of 1.1 wires per year for 33 wires suggests a life of 30 years until failure and a section loss of 0.065% per year projects to a life of 300 years. Overall, despite the perceived inadequate corrosion protection in the VE bridge, few tendons or wires have failed and corrosion is slow. Two of the 480 tendons have been replaced after 24 years.

Summary—Approximately 45% of the tendons in the Varina Enon Bridge have voids; approximately 55% of the tendons were vacuum grouted to fill voids; the grout typically has a high pH, high moisture content, and high absorption; strand corrosion is typically associated with

Table 2—Monitoring bridge tendons with broken wires

Tendon	Broken wires in 2007	Broken wires in 2013	Average broken wires/year*	Section loss in 2007	Section loss in 2013	Average section loss/year*
NP13T10	2	4	0.33	7 wire 5.3%	10 wire 2.9%	0.5 wire 0%
SP12T9	1	1	0	4.8 wire 3.6%	15 wire 4.4%	1.7 wire 0.13%
Average	1.5	2.5	0.17	5.9 wire 4.4%	12.5 wire 3.7%	1.1 wire 0.07%

*Change per year for 6-year period.

Table 3—Requirements for HPG and test results for approved HPGs (Lab 1/Lab 2)

Test	Value	Grout 1	Grout 2	Grout 3
Water-cementitious material ratio	Max 0.45	0.43/0.41	0.33/0.33	0.38/—
Fluidity, initial (ASTM C939[4]), s	11 to 30	12/22	18/15	15/—
Fluidity after 30 minutes (ASTM C939[4]), s	Max. 30	14/26	19/21	17/—
Cube strength at 28 days, wet (ASTM C109[5]), psi	Min. 5000	9035/7800	7100/8039	8240/—
Permeability at 28 days, wet (AASHTO T 277[6] at 30 V), coulombs	Max. 2500	1975/2070	2011/1119	—/1076
Total chloride ion content, % by weight of cementitious material	Max. 0.08	0.03/.003	—/<0.01	—/0.02
Volume change at 28 days (ASTM C1090[7]), %	0.0 to +0.2	+0.0/+0.1	—/+0.023	—/+0.045
Expansion, 0 to 3 hours (ASTM C940[8]), %	≤2.0%	+0.0/+1.1	—/1.25	—/0
Bleeding at 3 hours (ASTM C940[8]), %	Max. 0.0	0.0/0.0	—/0.0	—/0

Note: 1 psi = 0.00689 MPa.

Fig. 7—Cast-in-place segmental bridge on Smart Road near Blacksburg, VA.

Fig. 8—External tendons in precast segments (left) and internal tendons in cast-in-place segments (right) in 895 interchange.

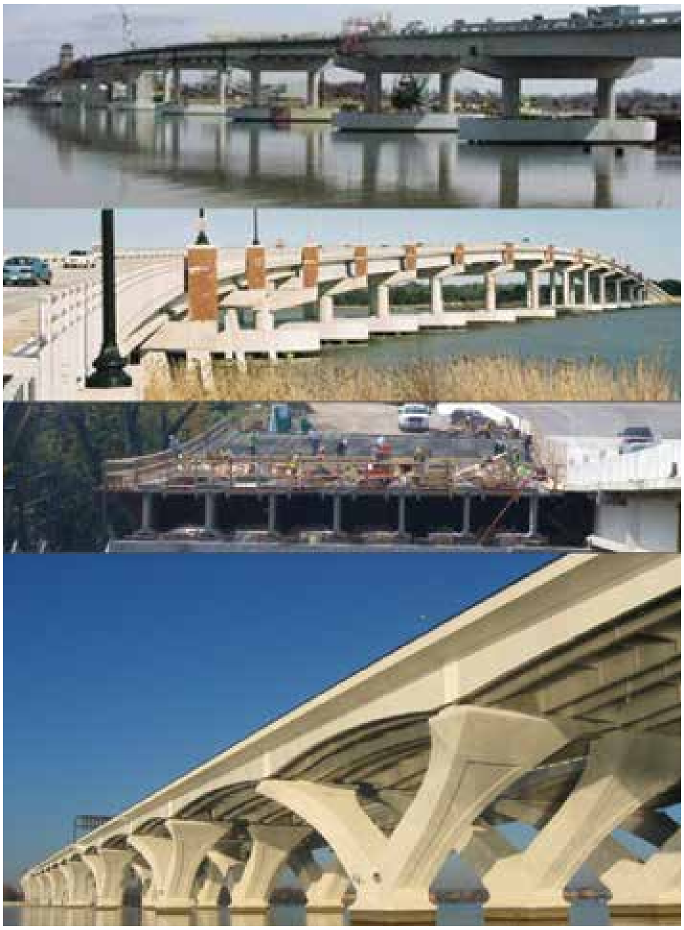

Fig. 9—Internal tendons in bridges on US-33, US-123, and I-95 were grouted with Grout 2, containing chlorides.

access to oxygen and absence of grout; and strand corrosion is occurring at some transparent duct test sites that are being monitored, but the rate is so low that the worst projection indicates 30 years until tendon failure and the best projection is 300 years.

Tendon failures have not occurred in the vast majority of the PT bridges or in the vast majority of the tendons in the bridges where tendon failures have occurred. However, there is clear evidence that upper strands in draped tendons are not surrounded by grout in the vicinity of the deviator block, voids are present in the tendons, the strands are surrounded by low-quality grout at the higher points in the tendon, the grout contains sufficient moisture to promote corrosion, and corrosion is occurring in strands in some tendons. Given the life of the tendons likely controls the life of the bridge, attention needs to be focused on methods to monitor the condition of tendons in existing bridges and future bridges need to be designed to eliminate the problems seen to date. For existing bridges there is much need for new and improved nondestructive evaluation techniques, new and improved repair techniques, monitoring systems and guidelines for bridge posting, and closing when tendons fail. For future bridges, there is a need for new designs that use corrosion-resistant strands such as stainless steel or carbon fiber, and new designs that accommodate tendon inspection and replacement.

Implementing use of HPG and grouting practices that provide for properly grouted tendons

In 2001, a specification for prepackaged HPGs was developed by working with industry representatives and testing grout mixtures. The test methods and requirements for HPGs are shown in Table 3. Three HPGs were approved by VDOT for use in 2001 and placed on an approved product list. The test results for these grouts are also shown in in Table 3.

The Smart Road Bridge (Fig. 7) was the first to be grouted with a HPG. Grout 1 was used to grout the internal tendons in 2001 and it is assumed the tendons were properly grouted. The 895 Interchange Bridges (Fig. 8) were also grouted in 2001. Forty-five percent of the cast-in-place segments with internal tendons and precast segments with external tendons were grouted with Grout 2. Grout 2 was later used from 2005 to 2007 to grout internal tendons in the webs of I-beams used in bridges on US-33 at West Point and US-123 at Occoquan, VA (Fig. 9). In 2008, Grout 2 was used to grout the internal tendons in the V piers of the Woodrow Wilson Bridge on I-95 between Virginia and Maryland (Fig. 9).

The implementation of HPG seemed to be going well until, in 2011, the supplier of Grout 2, the most-used HPG, announced that the grout contained chlorides that were in the cement in the prepackaged grout. Despite test reports indicating acceptable levels of chlorides, the problem had gone undetected for approximately 10 years. The grout had been used to grout many of the most significant bridges built since 2001. It was clear that placing the grout on an approved products list was not a good decision because it was assumed the product was meeting the specification and little testing was done. Later, the Texas DOT reported chlorides as well as soft grout in pier bends grouted with Grout 2, and Florida reported similar problems with tendons grouted with Grout 2.

In 2012, a cast-in-place segmental bridge was being constructed on US-460 in the western part of Virginia next to the Kentucky/Virginia state line. The contractor was proposing to use Grout 2 and the decision was made to require a mockup to compare the performance of Grouts 2 and 3. The mockup was done to simulate the worst grouting condition with respect to the length and

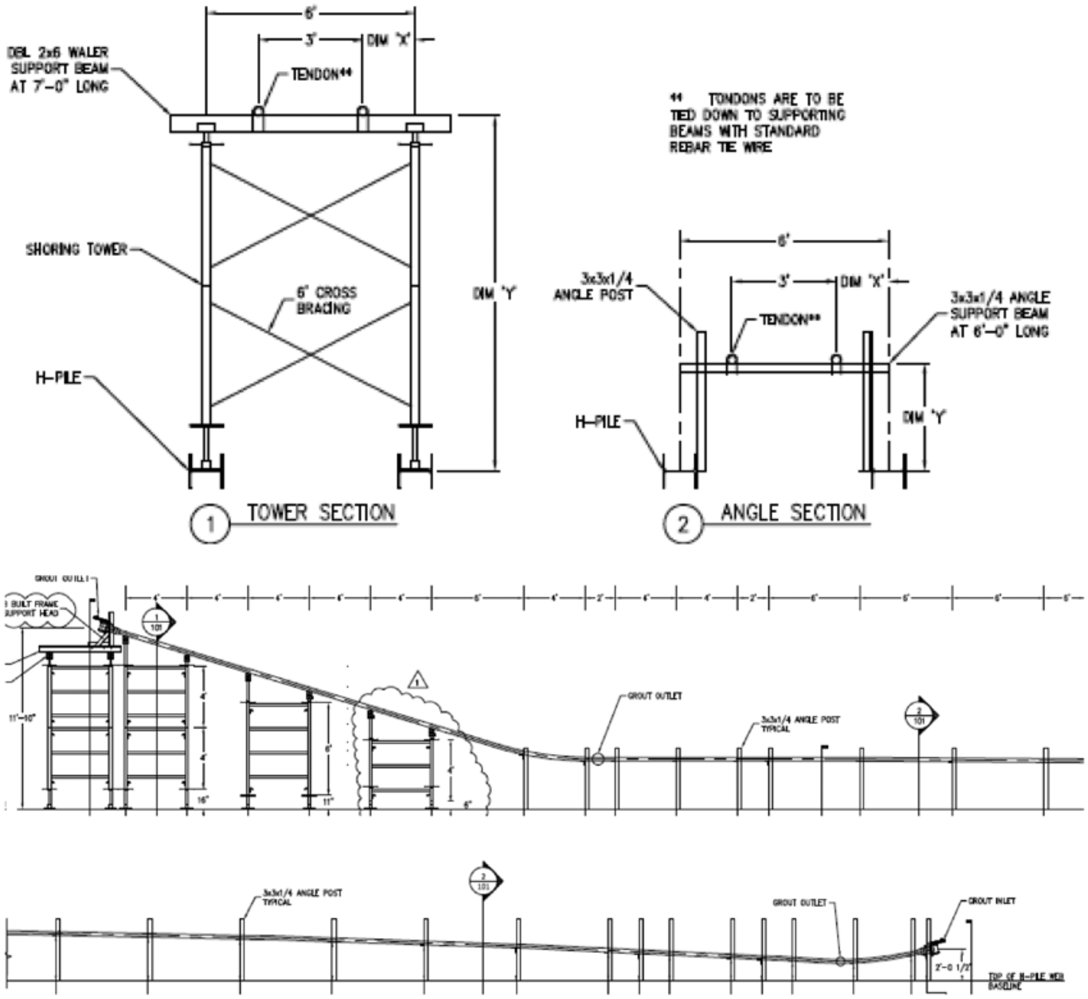

Fig. 10—US-460 mockup.

vertical rise of the tendon. Figure 10 shows the mockup section. Nine seven-wire strands were placed in the ducts but were not stressed.

The mockup revealed that Grout 2 was not acceptable for use. Grout 2 produced voids along the top of the tendon and at the end caps and left soft grout that never set at the end caps (Fig. 11 and 12). The soft grout had a high sulfate content and is very corrosive. Grout 3 performed exceptionally well and fully grouted the tendon. Grout 3 was used to grout the bridge.

Following the mockup and prior to grouting the structure, lab tests were done to identify other potential problems with the HPG. Given that Grout 3 performed well in the mockup when batched at the correct water-bag ratio (w/b), grout specimens were cast when batched with extra water to see the effect of increasing the water content. Grouts 1, 2, and 3 were batched at w/b of that specified by the manufacturer as well as 0.45, 0.5, 0.55, 0.6, and 0.65. Results were quite interesting. As the w/b increased, Grout 1 exhibited diminished properties; Grout 2 bled, segregated, and produced soft grout in increasing amounts; and Grout 3 produced a lower-strength foam in increasing amounts. Results are pictured in Fig. 13 and 14. Figure 15 shows that the compressive strength decreases as the w/b

Grout 2 tendon has void along top.

Grout 3 tendon is fully grouted.

Fig. 11—Grouted tendons.

Grout 2 outlet end cap has void and soft grout.

Grout 3 outlet end cap fully grouted.

Fig. 12—Grouted end caps.

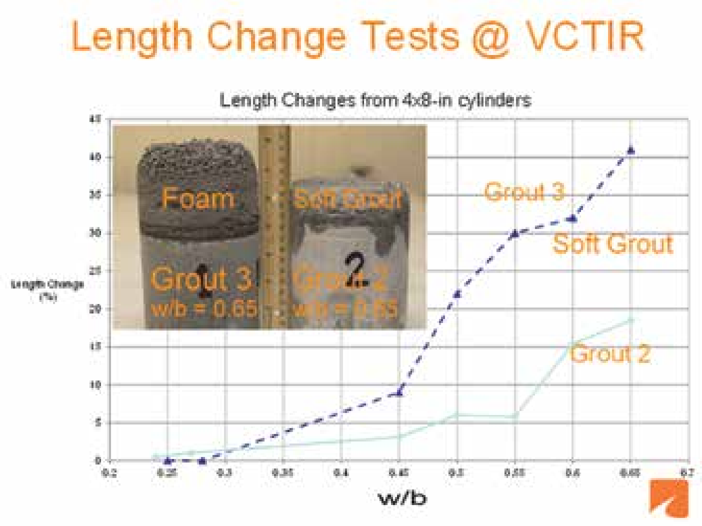

Fig. 13—Length change with w/b *for Grouts 2 and 3.*

Fig. 14—Specimens cast with Grouts 1, 2, and 3 (right to left) and specified to 0.65 w/b *(top to bottom).*

increases for Grouts 2 and 3, and that cube strengths can be used to detect *w*/*b* that are too high.

Water-bag ratios that exceed the manufacturer's recommendations should not be a problem, because Section 5.5.1 of PTI M55.1-12[9] requires that batching and mixing equipment consist of measuring devices; and Section 5.6.1 requires that all materials shall be batched by weight except liquids, which may be batched by volume. Also, tendons should be capped and sealed to prevent water from entering prior to grouting. Finally, sampling and testing the grout at the outlet end of the tendons can identify excess water in the grout, regardless of the source.

HPG has the potential to solve the material problem of bleeding, segregation, and voids.

Lab tests developed to approve HPG include:

1. Schupack pressure bleed test (ASTM C1741[10]), 0 to 4%;
2. Volume change test (ASTM C1090[7]), 0 ± 0.2%;
3. Wick-induced bleed test (ASTM C940[8]), 0%; and
4. Inclined tube test (EN 445[11]), <0.3% bleed.

Unfortunately, tendons with segregated grout, soft grout, and voids have been identified that were grouted with HPGs that pass lab tests. Given the importance of

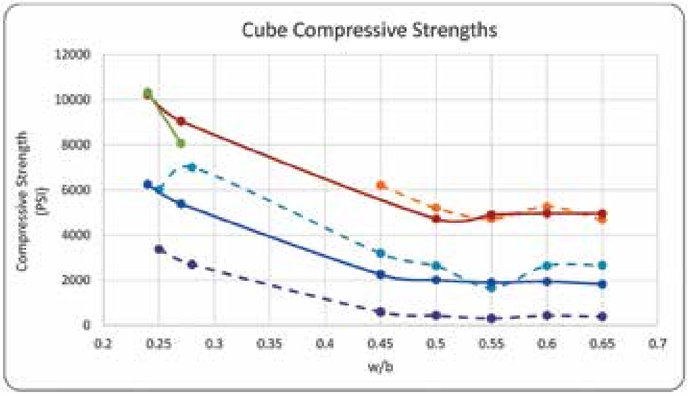

Fig. 15—2 in. (50 mm) cube compressive strengths for Grouts 2 (solid lines) and 3 (dashed lines) at 24 hours, 7 days, and 28 days for different w/b.

Table 4—Results of sampling Grout 3 on US-460 project based on three samples taken from outlet end (average of two samples)

Batch	14-day compresive strength, psi	28-day compresive strength, psi	Permeability of top 2 in., coulombs	Permeability of bottom 2 in., coulombs
1	6135*	8705	—	—
2	5420*	7885	1964	1998
3	4665	7895	1839	1916
Average	5407	8162	1902	1957

*One sample; compressive strength based on ASTM C109 cubes; permeability based on AASHTO T 277 at 30 volts.
Notes: 1 psi = 0.00689 MPa; 1 in. = 25.4 mm.

properly grouting tendons and that better lab tests are needed, mockups should be done to identify problems. The mockup should include the most critical tendon situation (greatest height change and length) using grouts proposed for the project. The mockup done in 2012 for the US-460 bridge was successful. As tendons are grouted, grout should be sampled at the outlet end of the tendons, inspected for segregation and tested for fluidity, density, and cube strength. Table 4 shows cube strength and permeability test results obtained for three samples collected on the US-460 project. Both tests indicate the grout is uniform and not segregating, and that cube strengths are similar to those obtained 11 years earlier when the grout was approved for use.

CONCLUSIONS

- Ninety-nine percent of the tendons in the Varina Enon Bridge appear to be performing well. Strand corrosion is slow.
- HPG 3 passed the mockup and is being successfully used to grout the US-460 bridge.
- Poor-performing HPG 2 failed the mockup.
- Tests for identifying acceptable grouts need to be improved (bleeding and segregation are issues).
- Grouts need to be robust so that minor amounts of extra water that get into the tendon prior to grouting or into the grout during batching are not an issue.
- Mockups should be used to identify acceptable grouts.
- Bag and water weights need to be correct during batching.

RECOMMENDATIONS

Until there are lab tests that can identify acceptable grouts, perform a mockup test of the most critical tendon situation (greatest height change and length) using grouts, equipment, and staff proposed for the project.

The mockup can be waived if the tendon design is similar and the proposed grout and grouting contractor are the same as approved for another project.

While grouting, the water in each batch must to be carefully measured and the bags of grout weighed to provide the required *w/b*.

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