Evaluation, Design and Implementation of a Holistic Repair Strategy to Extend the Service Life of the Post-Tensioned Wando River Bridge

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IBC 24-85

ABSTRACT: Post-tensioning (PT) tendons have been a staple of concrete design and innovation for many years. Generally, concrete structures utilizing post-tensioning have performed well. However, PT tendons have had various issues stemming predominantly from grouting deficiencies that have become more prominent in some older structures in recent years. Grout deficiencies often result in voids, chloride contamination, soft/segregated grout, water intrusion, or any combination of the aforementioned factors. These grout deficiencies can segue into more critical problems such as high corrosion potential which can ultimately lead to failure of the affected tendons.

This paper describes evaluation techniques that can be used to identify the presence of voids, grout segregation, and potential for corrosion potential of PT tendons. Mitigation methods and construction considerations are also discussed.

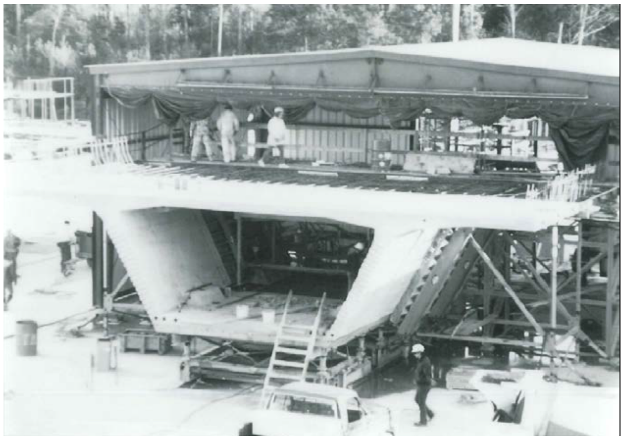
The James B. Edwards Bridge is a post-tensioned segmental box girder bridge that carries I-526 over the Wando River in Charleston, SC. The structures have experienced corrosion of PT tendons with grout deficiencies, which overtime eventually led to corrosion and tendon failures. In response SCDOT teamed up with engineering consultant HDR and proactively evaluated the post-tensioning in both structures. They jointly developed a comprehensive strategy to mitigate corrosion and extend the service life of the structures.

The James B. Edwards Bridge case study illustrates how proper evaluation, engineering analysis, and implementation of a comprehensive repair strategy can be used to preserve and maintain critical transportation assets.

JAMES B. EDWARDS BRIDGE BRIEF DESPRIPTION AND HISTORY

The James B. Edwards Bridge over the Wando River is an important 7,900-foot long, segmental box girder bridge located along the I-526 corridor in Charleston, South Carolina, USA. Built by the South Carolina Department of Transportation in 1989, the bridge crosses the river with twin structures of 49 spans each and connects Mount Pleasant on the east side of the river to Daniel Island on the west side. The bridge facilitates the movement of vehicles and goods serving as a critical link not only for public transportation, but for the port operations of the Wando Welch Terminal in the Charleston area.

James B. Edwards Bridge pictured present day looking east towards Mount Pleasant from Daniel Island, SC

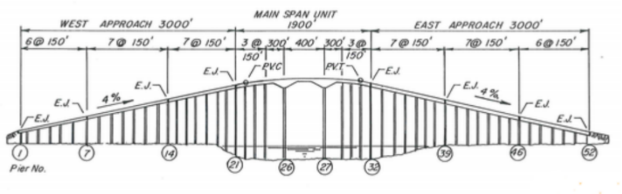


Completed segment being stripped from the formwork at the precast yard

The James B. Edwards Bridge as viewed from the west shore of the Wando River facing east towards Mount Pleasant, SC

Shows the erection of the balanced cantilever portion of the James B. Edwards Bridge

The interior of the box girder typical for the approach spans of the structures



Overall elevation view of the James B. Edwards Bridge

OVERVIEW OF POTENTIAL ISSUES WITH POST-TENSIONING TENDONS

Without proper protection, post-tensioning tendons can be subject to corrosion over time due to various factors such as environmental exposure conditions, water intrusion, and grout issues. Post-tensioned structures are at increased risk of corrosion and failure of the post-tensioning tendons when there are deficiencies in the installed grout. The most common grout problems include the following:

VOIDS

Voids may result from improper mixing, grout leakage or incomplete filling of the ducts. More commonly, voids are a result of grout bleed where excess water floats to the top of the grout resulting in a pocket of water or a void when the water is re-absorbed into the grout or evaporates. The Wando River Bridge tendons were grouted with cement / water grout which was the industry standard at the time this bridge was constructed. Grout bleed of cement / water grouts was a normal occurrence and typically ranged between 3 and 5% of total grout volume.

VARIATIONS IN GROUT PROPERTIES

Grout is intended to provide a uniform, protective environment around post-tensioning strands. Variations in grout properties can create differences in corrosion potentials which can initiate and sustain corrosion. A variation in properties such as pH, density, porosity and chemical composition (eg. chlorides, sulfates) can result in corrosion.
Excess water in cement / water grouts can also result in a layer of porous, soft, chalky grout along the interface of the grout and the bleed water void. Excess water used with prepackaged grouts can result in segregation and the creation of porous and / or soft grout with a different chemical composition than the remainder of the bulk grout. These conditions can hasten corrosion initiation without the need for other environmental contaminants.

SOFT GROUT

High water-cement ratio can result in soft grout . Florida Department of Transportation defines soft grout as grout which can be penetrated more than 1/16" by an awl with 10 to 15 pounds of force (1).

CHLORIDE-CONTAMINATED GROUT

The detrimental effect of chlorides and their ability to initiate corrosion is well known. Despite this knowledge and the desire of owners, engineers and suppliers to avoid chlorides, chloride contamination may still occur. Chloride contamination can occur in a number of ways, including:

Exposure to chlorides in the environment.

- Chlorides may accumulate over time if the structure is exposed to seawater or de-icing salt contaminated water. Susceptible areas include grout voids, improperly sealed grout vents, and tendons near joints and cracks in the structure.

Chloride contamination of the grout.

- Strands and ducts in marine bridges may be exposed to salt spray during construction.
- Grout can be contaminated through the use of mix water containing chlorides.
- In some cases, the grout itself may contain chlorides.

INVESTIGATION AND TESTING

Several methods are available to investigate and test the condition of grouted PT tendons. Different methods will be used depending on the structure. These methods include:

Location of PT strands using GPR
Ground penetrating radar (GPR) can be used to conduct localized or large area surveys for locating PT tendons and steel reinforcement (Figure 1) on concrete bridge structures. The Ground Penetrating Radar (GPR) sends an electromagnetic pulse into the concrete and subsurface objects cause reflections that are acknowledged by the GPR receiver. The collected data can be extracted as a 2-D plot as shown in Figure 2 below.

Capacitive Probe Inspection for Locating Grout Voids
This inspection method is used to locate grout deficiencies with external tendons in HDPE ducts

Figure 1: Locating PT tendons using GPR

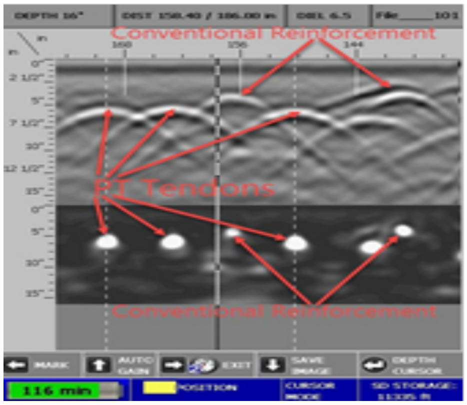


Figure 2: 2D GPR Scan Plot

filled with cement grout. The approach indirectly measures the capacitance utilizing a pair of electrodes placed on the surface of the HDPE duct. Since capacitance is related to the permittivity of the material and the permittivity of air and water contrast significantly from cement grout, anomalies with voids or poor grout conditions result in a significant variation in measured capacitance. Once an anomaly is identified, the equipment can be rotated around the duct to effectively create a cross section of the tendon. Multiple cross sections can be recorded to estimate the volume of the detected anomaly.

Detection of grout voids with sonic/ultrasonic techniques

Figure 3: Sonic/Ultrasonic Equipment

Sonic/Ultrasonic (S/US) methods can be used to evaluate the tendon along its length in 0.3 m (1 ft) increments. The S/US device uses a four-sensor array with an energy input device (Figure 3). The sensor array is comprised of four piezoelectric sensors that record the imparted compression wave. When the thickness and the compressional wave velocity remain constant, which is the normal condition for a fully grouted duct, the resonant frequency is directly related to the thickness of the slab/wall. When anomalies such as soft grout or air voids are encountered along the wave path it takes longer for the compression wave to travel around the anomaly and come back to the sensor than locations without defects (Figure 4).

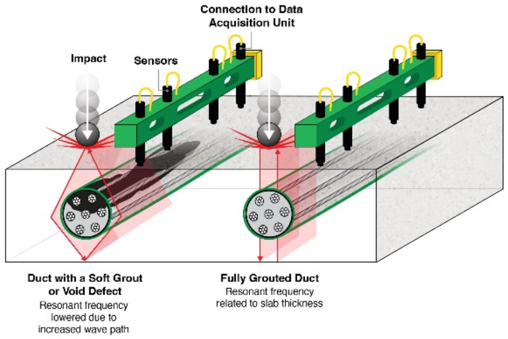


Figure 4: How Sonic/Ultrasonic Methods Detect Voids

Figure 5: Sonic/Ultrasonic Testing of PT Tendons

Visual Inspection of PT Tendons in Openings

Non-destructive testing can be used to identify areas of concern and areas with high probability of voids. Visual inspection of PT tendons in certain identified areas is recommended to confirm the results and allow visual inspection of tendon condition in these areas and allow grout samples to be collected for testing (Figure 6).

Figure 6: PT Tendon Opening

As an alternative to making large openings to visually inspect a section of a PT tendon, in some cases it may be preferred to make a small hole, typically less than 1 inch in diameter and use a borescope to determine the size of a grout void and to inspect the condition of the exposed strands (Figure 7).

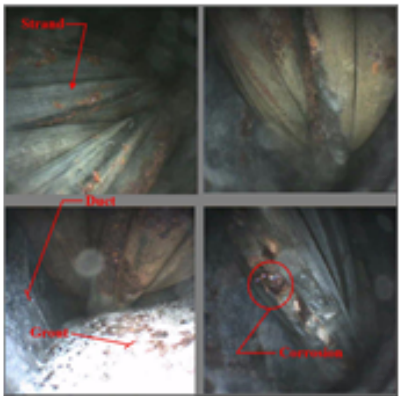


Figure 7: Borescope Images

Corrosion Potential by Measuring Moisture Condition

The process for evaluating the potential for corrosion involves testing the moisture condition within the tendon assembly. An air sample is extracted and directed through the PT Corrosion Evaluation Testing Unit (Figure 8) which determines the moisture content of the air within the cable duct. This information is analyzed and processed to determine the potential for corrosion in that cable. Information is tabulated for all cables tested to provide an overall picture of the corrosion risk to the PT tendons.

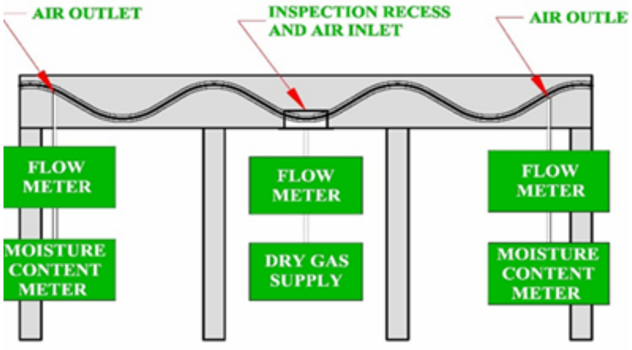


Figure 8: Field Setup for PT Corrosion Evaluation

Chloride Analysis of PT Grout Samples

Chloride analysis of grout samples can determine the residual water-soluble chloride content in the grout in accordance with AASHTO T260-94. The chloride ion content in percent by weight of concrete is measured using the 'Revised SHRP Chloride Analysis Procedure'. The chloride concentration threshold for corrosion of steel in uncarbonated concrete is between 0.20 to 0.40 percent by mass of cement in accordance with the ACI 222R "Protection of Metals in Concrete Against Corrosion." If the chloride level exceeds the corrosion threshold concentration at the depth of the reinforcing steel, the reinforcing steel may begin to corrode.

Chemical And Ph Testing of Grout Samples

Chemical and petrographic testing can be performed on collected grout samples along with carbonation (pH) testing.

Carbonation of cement-based materials occurs when carbon dioxide in the air reacts with calcium and hydroxyl ions in the concrete pore solution to form calcium carbonate. This reaction releases a proton, or hydrogen ion, which over time lowers the pH of the concrete or grout from above 12 to between 9 and 10. When this occurs, the pH is no longer sufficiently alkaline to maintain the passivating film on the reinforcing steel or prestressing strand and leaves the steel more susceptible to corrosion.

Carbonation testing can be conducted in the field (Figure 9) by immediately spraying the freshly exposed concrete or grout surface with a 0.15% solution of phenolphthalein in ethanol. The solution turns pink when applied to surfaces with a pH greater than 10. The solution will remain colorless if the surface pH is less than 10, indicating carbonation is present.

Figure 9: Field Carbonation Depth Testing at PT inspection Opening

Detection of Broken PT Strands or Wires with Magnetic Methods

X-Ray and magnetic flux techniques have been used to locate fractures in post-tensioned systems. The PT Cable Break Detection (CBD) System is an effective non-destructive method for locating fractures in both bonded and unbonded prestressed strands and bars.

The magnetic field resulting from a magnetized prestressing strand is comparable to the magnetic field of a bar magnet (Figure 10). In the vicinity of a fracture, a magnetic dipole is formed and, accordingly, a magnetic field is created. The magnetic field can be measured on the duct or at the concrete surface using appropriate sensors. Under ideal conditions, the characteristic magnetic field can allow detection of a single broken wire in a 0.6″ (15.2 mm) diameter prestressing strand.

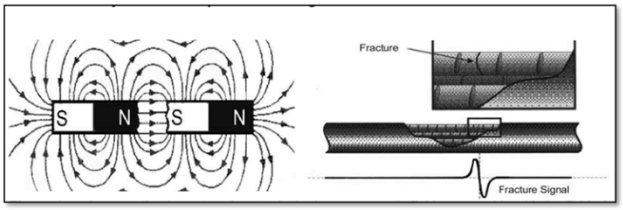


Figure 10: Physical Principle of the Magnetic Measurement

These systems detect fractures by magnetising the PT tendons and measuring the resulting magnetic field. Depending on the equipment, this can be done one cable at a time or several cables at the same time.

The effectiveness of each method depends on the type of structure, the location of the tendons, and the size of defect to be identified.

POST-TENSIONING TENDON CORROSION AND PREVIOUS WORK

Corrosion of post-tension tendons on the Wando River Bridge has been an issue for several years. In August 2010, the first indication of tendon corrosion was noted during an inspection walk-through of both structures. In 2016 a post-tensioning tendon failed in the main span of the westbound bridge and was replaced. The repair team used hydro-demolition to remove the tendon from the box girder. The removed tendon was saved for closer inspection and testing. Corrosion of the failed tendon was evident along with deviation in the color of the grout in the location of the failure.

Following the 2016 tendon rupture, an immediate and thorough post-tensioning assessment program was initiated. The investigation focused on the existing condition of the external tendons to identify active strand corrosion and deficiencies in grout quality that may lead to future tendon corrosion. A representative number of low, mid, and high point locations along the tendons were investigated for active corrosion. Grout was sampled for moisture content, sulfates, and chlorides along with petrographic analysis.

The post-tensioning assessment program was the basis for the development of a targeted repair and comprehensive preservation plan. This included:

- Replacement of the two tendons that had ruptured in the WB main span unit.
- Installation of two supplemental tendons in the main span unit of each structure.
- Construction of an innovative expandable post-tensioning system across three approach spans. This replaced the effect of a slackened tendon, added redundancy in the affected and adjacent spans, and allowed for the addition of additional tendons in the future if needed.
- Repair of two damaged segment joints in the main span unit. The damage was the result of low longitudinal compression and differential stiffness between specific diaphragm and typical segments. The repairs involved the installation of steel frames and precast drop slabs.
- Variety of concrete deck repairs
- Installation of a polyester polymer concrete deck overlay.

POST-TENSIONING IMPREGNATION

After completion of the work above, SCDOT, in consultation with engineering consultant HDR and FHWA, began preservation work to mitigate corrosion and extend the service life of the post-tensioning tendons.
The first portion of this additional work was to perform a pilot project to evaluate the applicability of the post-tensioning tendon impregnation technique to the Wando River Bridge. The pilot project was important to verify material quantities and durations as well as to develop site-specific procedures for some unique construction details that exist on this bridge. In particular, the pilot project was necessary to confirm that the impregnation technique would be successful in protecting high points through tendon couplers. The pilot project was completed in February of 2020.

POST-TENSIONING IMPREGNATION SYSTEM

The Post-Tensioning Impregnation system is an innovative technique which has been developed to mitigate corrosion of post-tensioning tendons caused by grout voids, moisture and defective grout. This system utilizes the interstitial spaces between the wires of each strand (Figure 11) as a longitudinal channel (capillary) along the length of the strand.

Figure 11: Interstitial spaces between wires

The corrosion impregnation material forms a film on exposed steel surfaces such as steel strands which are exposed in grout voids. The impregnation material also soaks into the grout adjacent to the strand and improves the resistance of the grout to moisture and corrosion.

The impregnation material is introduced into the tendon and is able to travel along the tendon as illustrated in Figure 12 and Figure 13. The material, which flows inside an individual strand, is able to seep between the wires of the strand into the grout surrounding the strand as shown graphically in Figure 12 and Figure 13, as well as photographically in Figure 14.

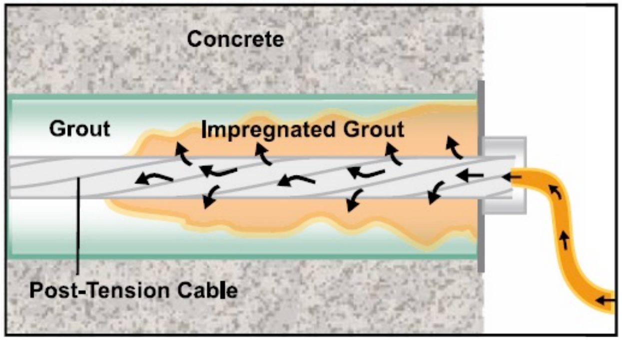


Figure 12: Impregnation from the end of a PT tendon

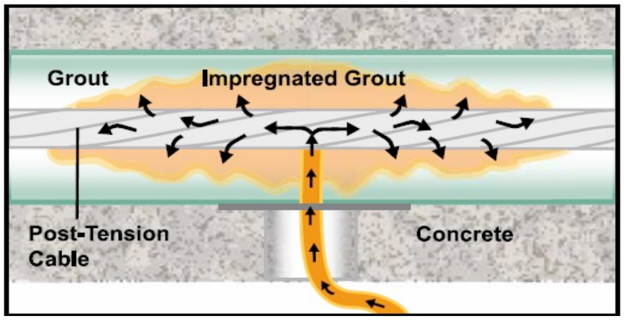


Figure 13: Impregnation from an intermediate location

Figure 14: Concrete surrounding a single seven wire strand shows a radial pattern of Impregnation

DESCRIPTION AND PURPOSE OF THE PT TENDON CORROSION MITIGATION PROJECT

Following completion of the pilot project, plans, specifications and construction documents were prepared. The scope of work included impregnation of the tendons based on four types of conditions:
1. High points with PT couplers
2. high points with exposed PT anchorages,
3. full-length approach span tendons, and
4. full-length main span tendons.

An example of Condition 1 is shown in Figure 15.

Depending on the condition and geometry, impregnation or venting was often necessary at the tendon anchors. In these locations, the existing anchor protection and grout caps were removed. After the wedge plate and strand tails were cleaned and prepared (Figure 16), new caps that included a port were installed (Figure 17).

Along the length of the external tendon port locations were prepared by removing a small portion of the tendon duct and grout to expose the strands. Ports were installed at the prepared locations (Figures 18 and 19).

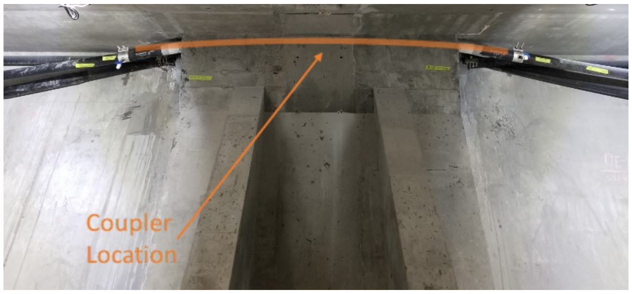


Figure 15: Tendon across diaphragm - Condition 1

Figure 16: Grout cap and grout removed, with wedge plate and tendon tails cleaned and prepped for testing and PTI Impregnation

Figure 17: Grout Cap Installed with Impregnation Port

Figure 18: Side of Tendon Opened and Prepared for Port Installation

Figure 19: Tendons and Anchor Caps Ported.

Once the ports were installed, leak testing was performed to verify communication of air between the ports installed on the tendon and to identify potential leaks. Cracks and transitions (duct to concrete) where air leaking occurred were sealed with an epoxy paste. Moisture testing was then performed to evaluate the tendons for the probability of corrosion (Figure 20).

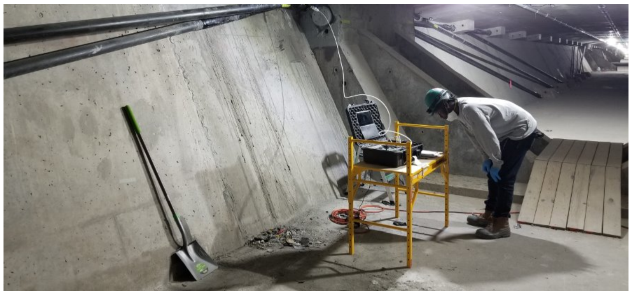


Figure 20: Moisture Testing Prior to PTI Impregnation

In instances where the moisture content of the tendon was in the "high" range, or where free visible water was found in the port, the process of 'micro-drying' was used. Microdrying reduces high moisture levels along segments of a tendon utilizing dried compressed air. Once the moisture level of the tendon is below threshold levels, the PTI Impregnation process can proceed.

Tendons were impregnated using a combination of pressure pumps and vacuum devices. For Conditions 1 and 2, and for full-length tendons with couplers (Condition 3), impregnation was considered complete when the material was visible at an outlet port, indicating it had reached the intended limits of the tendon length to be impregnated, or there was evidence that it had reached the anchor. For full-length tendons with anchors (Condition 3) and full-length main span tendons (Condition 4), the pressure was maintained for a specified period of time after it was visible at an outlet port and the anchor.

Figure 21: PTI Technician Monitoring the Impregnation of a Tendon

After completion of the PTI Impregnation, the side ports in the tendon ducts were drained, grouted, and then wrapped with a heat shrink seal (Figure 22). For tendon impregnation that included anchorages, the fluid was drained from the grout cap, the grout cap was filled with grout and it was sealed with an elastomeric coating (Figure 23).

Figure 22: Repaired Port Locations After PTI Impregnation

Figure 23: Repaired Grout Caps Sealed with Elastomeric Coating after PTI Impregnation

The project was bid in December 2022, work on site began in April 2023, and impregnation was completed in April 2024. The work included treatment of:

- 76 Condition 1 High Point Couplers
- 325 Condition 2 High Point Anchors
- 57 Condition 3 Full-Length Approach Span Tendons
- 12 Condition 4 Full-Length Main Span Tendons

Approximately 900 gallons of PTI Impregnation material was used.

SERVICE LIFE EXTENSION OF BRIDGES AND ENVIRONMENTAL BENEFIT OF KEEPING THIS BRIDGE IN SERVICE

The Wando River Bridge case study also allows us to discuss sustainability in a meaningful way.
In addition to keeping existing structures in service, shortening construction time, and maintaining satisfaction of the traveling public, the demand for concrete and other construction materials is reduced by extending the service life of existing structures. While this is a challenge, it is possible if we make it a priority.

Concrete is the most widely used man-made building product in the world with over 33 billion tons of concrete produced each year. Due to the shear volume concrete being produced, concrete is a huge consumer of materials and energy. Despite the environmental impact, concrete is still one of the most environmentally friendly materials available if it is used in a sustainable way. Concrete is extremely durable and has the ability to last for many years. Keeping existing concrete structures in service has very clear environmental and economic benefits.

The strengthening, overlay application, and subsequent PTI impregnation performed on the Wando River Bridge will extend the service life of this important structure. In doing so 85,046 yd^3 (65,025 m^3) of concrete will be maintained in service. Keeping this quantity of concrete in service will reduce CO_2 emissions by 42,500 tons (equivalent to the annual emissions of 8,500 people).

CONCLUSIONS

Post-tensioned bridges have performed very well overall, with the exception of very limited situations where PT tendons have experienced corrosion issues due to grouting deficiencies.

Evaluation techniques should be used to identify the location of voids, moisture, and corrosion if any, so appropriate corrosion mitigation techniques can be implemented on the specific PT tendons where it is required.

The I-526 post-tensioned segmental box girder bridge over the Wando River in Charleston, SC was experiencing PT tendon corrosion and tendon failures which had resulted from these conditions. SCDOT and engineering consultant HDR were proactive in evaluating the bridge and developed a repair and maintenance strategy to mitigate corrosion and extend the service life of the structure.

Extending the service life of existing bridges like the Wando River Bridge saves significant quantities of resources for future generations to use and mitigates the release of large quantities of pollutants and waste heat into the environment when compared to the option of demolition and replacement.

The Wando River Bridge case study illustrates how proper evaluation, engineering analysis, and implementation of a holistic repair strategy can be used to preserve and maintain critical transportation assets.