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Bridge girders in the United States are commonly constructed using multistrand post-tensioned (PT) tendons. PT tendons are constructed by placing ducts inside bridge girders and then post-tensioning strands into the ducts. PT tendons exist in two configurations, known as bonded or unbonded. In the case of bonded tendons, these ducts are filled with cementitious grout to bond tendons to the surrounding concrete and provide corrosion protection to the post-tensioning strands. However, grout defects have been found in some recently constructed bridges. One of the primary defects is known as soft grout. Soft grout consists of segregated and unhardened grout with free moisture and is often related to corrosion of prestressing strands, which can severely impact the serviceability and safety of the bridge.

Repair of corroded tendons can be difficult and expensive. Oftentimes, external tendons with defective grout can be replaced; however, replacement of internal tendons is impractical. This paper investigates one remediation alternative consisting of removing free moisture from the grout by injecting dry air into the tendon and ejecting the moisture at a distant point in the tendon. Nearly complete removal of moisture will arrest further corrosion as long as additional moisture is prevented from penetrating the tendon.

In this research, drying of soft grout was monitored using relative humidity (RH) readings measured at different locations along the specimens. After drying terminated, the moisture content of grout inside the tendon was measured to evaluate the drying technique. The study showed that drying technique successfully reduced moisture content of soft grout to less than 1%.

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DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the author(s) and not necessarily those of the Florida Department of Transportation or the U.S. Department of Transportation.

RESEARCH SIGNIFICANCE

Corrosion problems discovered in grouted multistrand post-tensioning internal tendons used in bridge construction have led to the discovery of defective grout in several post-tensioned (PT) concrete bridge structures both in the United States and abroad. Remediation of such tendons is particularly difficult and expensive if significant corrosion is expected to occur. The research reported in this paper is aimed at the remediation of the defective grout using a minimally invasive technique. The proposed technique consists of accessing the grouted duct and pumping dry air through the duct to remove moisture from the defective grout. Testing was conducted on four mockup post-tensioning tendons to evaluate the efficacy of the technique.

INTRODUCTION

Post-tensioned concrete is commonly used in the United States to construct highway bridges. They are typically prestressed with multistrand bonded tendons. After the strands in the tendon are stressed, the ducts are usually filled with PT grout to provide corrosion protection and create bond with the surrounding concrete. PT grout is a mixture of portland cement, supplemental cementitious materials, admixtures, and water. PT grout provides bond between prestressing strands and the surrounding concrete, which reduces the reliance on stress transfer through anchorages at ends of girders. Common practice in the United States is to use a proprietary, prepackaged

Fig. 1—Deficient grout in PT tendon in Sicily, Italy (Anania et al. 2018).

PT grout that is delivered to the field in bags with the dry ingredients already premixed. Prepackaged grout avoids the necessity of proportioning the materials on site, with the exception of the specified water dosage.

Corrosion has been found during inspection of several grouted post-tensioned (PT) bridges in Florida (Azizinamini and Gull 2012) as well as in PT bridges outside of Florida (Sprinkel and Balakumaran 2017; Anania et al. 2018). Generally, corrosion occurs when the PT grout is deficient or due to incorrect grouting practices. One grout deficiency is when all or a portion of the injected grout does not harden (Fig. 1), resulting in soft, unhardened grout. This "soft grout" has been found to form due to higher-than-recommended water dosage, use of large proportion of filler materials, or prehydration of the prepackaged cementitious material (Randall et al. 2015).

Mid-Bay Bridge in Okaloosa County, FL, was one of the several bridges in Florida detected with corrosion in external post-tensioned tendons (Vigneshwaran and Lau 2016; FDOT 2001). Excess water in the grout and the presence of oxygen was the primary cause of corrosion in Mid-Bay Bridge. These external tendons were replaced to rehabilitate the Mid-Bay Bridge. The cost to replace 11 tendons was $999,680 and the associated engineering cost was $657,340. Replacing the tendons involved destructive operations on the tendons, such as cutting strands. This method of rehabilitation was expensive and dangerous to both the bridge and the workers. On the other hand, this type of rehabilitation cannot be performed on internal tendons with soft grout because that would involve removal of surrounding concrete and grout along the entire length of the tendon, which is impractical and cost-prohibitive.

BACKGROUND

As mentioned earlier, defective PT grout called soft grout was found in several post-tensioned bridges (Azizinamini and Gull 2012). Soft grout can form due to several reasons, including prehydration of prepackaged grout and addition of excess water on site to increase grout flowability. Prehydration of prepackaged grout occurs due to improper storage of grout bags and premature hydration of cementitious material when in contact with moisture from the surroundings. Segregation and bleed of prehydrated cement or filler following injection can result in layers of unhydrated solids with high moisture content along the length of the tendon. Moisture content has been found to be in the range of 35 to 50% in soft grout (Randell et al. 2015; Sprinkel et al. 2017).

Moisture is part of the chemical reaction that results in corrosion. Therefore, presence of high moisture content without the protection of a high-alkaline hydrated cement matrix can result in corrosion of reinforcing steel. Even with negligible chloride content, high moisture levels can result in a reduction in steel tensile capacity by 11.4% over a 12-month period due to corrosion (Trejo et al. 2009). Trejo et al. (2009) also found that if high levels of both chlorides and moisture are present, then steel tendons could lose as much as 27% of their tensile capacity over a 12-month period. In a bridge in West Point, WV, corrosion was found in a concrete bulb-tee girder at locations with soft grout (Sprinkel and Balakumaran 2017). During inspection of Mid-Bay Bridge in Florida, corrosion was also found along with bleed water present due to soft grout (FDOT 2001). Therefore, soft grout with its characteristic high moisture content is a major concern.

The discovery of soft grout in a spliced girder bridge with internal tendons prompted the Florida Department of Transportation (FDOT) to investigate possible remediation techniques for the repair of this bridge. Research by the University of Florida in collaboration with FDOT evaluated two possible remediation techniques: hydrodemolition removal of grout and drying of grout. Hydrodemolition was attempted on several mockup tendons, but the technique did not completely remove soft grout and was abandoned. The second technique was to pass air through the tendon to dry the grout. Vector Corrosion Technologies proposed the use of dry air to remove chemically unbound moisture from the tendon. Removal of moisture was thought to reduce the rate of corrosion and increase grout resistivity (López and González 1993). Vector has successfully used this technique to repair unbonded single-strand tendons in parking garages (Velde 2002). For unbonded tendons, the technique involves passing dry nitrogen gas through greased and sheathed unbonded, single-strand tendons, and measuring relative humidity and temperature of gas at outlet of cable to determine corrosion potential of the tendons. In addition, Vector had conducted a similar technique on anchorage areas of bonded, multistrand tendons in which dry air is pumped through the tendon to remove moisture. The research reported in this paper covers the approach and results of mockup tests of this grout remediation technique.

RESEARCH APPROACH

Four tubular specimens with dimensions of 31 ft (9.4 m) long and 4 in. (100 mm) diameter were constructed to evaluate the effectiveness of the proposed drying technique (Fig. 2). These specimens were filled with layers of soft grout mixtures with different moisture contents, which were prepared by mixing cement and ground dolomite limestone mixtures in various proportions based on previous studies (Randell et al. 2015). Two of the four specimens did not undergo the air drying process to serve as control and allow for comparison with the drying specimens. The drying system consisting of a compressor and desiccant dryer that was set up to produce dehumidified air for removing moisture from air. Each specimen had an inlet and outlet to allow for the flow of the dehumidified air. Relative humidity (RH) of air discharged at the outlet was measured at regular intervals to monitor the drying process. Once the RH of the outlet air was reduced to that of the inlet air, drying was terminated, and specimens were dissected. For comparison, non-drying control specimens, which were replicates of drying specimens, dissected at the same time as drying specimens. The moisture content of grout samples collected from control and drying specimens were used to determine the effectiveness of the drying technique. RH readings collected during drying were further analyzed to determine the criteria for drying termination.

MATERIAL PROPERTIES AND MIXTURE DESIGN

Grout mixtures were formulated to produce grout with physical characteristics similar to soft grout. Soft grout's physical characteristics consist of a high moisture content (35 to 50%), segregation, and bleed. The grout mixture formulations were based on results from a previous study (Randell et al. 2015). Randell et al. (2015) found that mixtures with more than 45% replacement of portland cement with ground limestone and a water-solids ratio (*w/s*) above 0.45 resulted in grout with physical characteristics consistent with soft grout. The grout mixtures for this research were formulated in a similar manner using portland cement, non-reactive filler (grounded dolomite limestone), and water with *w/s* of 0.46.

Trial grout mixtures were developed as shown in Table 1 with the intent to alternate layers of normal grout—grout having high percent of cement—and soft grout in the mockup specimens. The nomenclature for identity (ID) of each grout mixture was based on the percentage of portland cement (PC) present in each mixture. For example, 5 PC mixture consisted of 5% portland cement and 95% ground limestone. 5PC had the lowest cement percentage, which led to the formation of grout with the highest moisture content, whereas 100PC had the lowest moisture content. Table 1 shows that compressive strength decreased as the cement percentage decreased, indicating reduced hydration. 100PC, 15PC, and 5PC were ultimately selected for use in the mockup specimens to evaluate the drying technique on grout with the least and most moisture content.

SPECIMEN DESIGN

Four 31 ft (9.4 m) long specimens were designed to represent a typical tendon profile at support sections of bridge girders where soft grout was typically found in bridges. The specimens were positioned on a 5-degree slope to simulate the slope of a draped PT tendon. The PT ducts were simulated with 4 in. (102 mm) diameter polyvinyl chloride (PVC) pipe to simplify connections necessary to pump air through the duct. Each PVC pipe was filled with 15 unstressed 0.6 in. (15 mm) diameter low-relaxation prestressing strands (ASTM A416 Grade 270).

Two grout configurations were tested. The first configuration was designed to evaluate drying of tendons

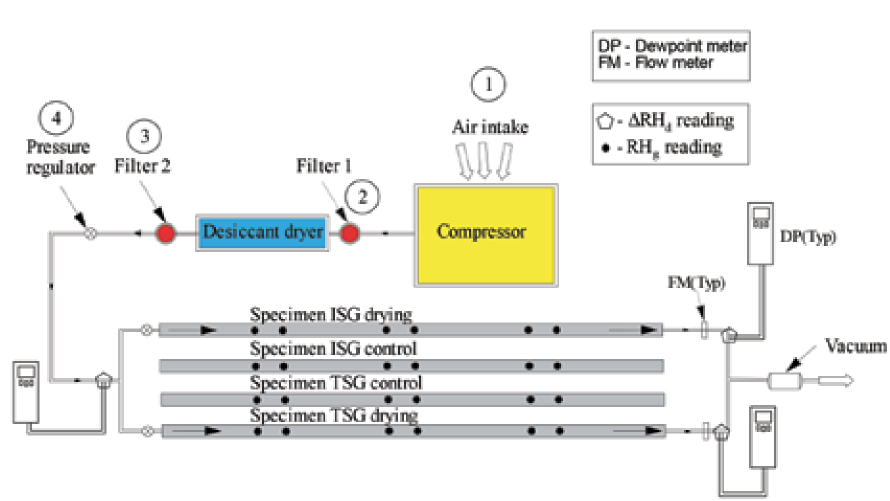


Fig. 2—Drying test setup.

containing isolated soft grout and consisted of alternating 5PC and 15PC soft grout layers (named "Isolated Soft Grout" ISG in Fig. 3). The second configuration was designed to study the effectiveness in drying of soft grout trapped between normal grout layers and consisted of alternating 5PC and 100PC layers (named "Trapped Soft Grout" TSG in Fig. 3). Normal grout has lower porosity than soft grout and was anticipated to obstruct airflow and delay moisture removal. Specimen TSG was designed to evaluate this behavior. Two identical specimens were constructed for each configuration for a total of four specimens. One specimen of each configuration was dried, and one was held as a control for comparison. Grout layers were formed using four PVC tees spaced evenly along the length (Fig. 4). The layer at the low end of the slope was placed first by placing the prepared grout through the tee into the specimen and visually gauging the proper level of grout. This layer was allowed to harden before placing the next layer. Each subsequent layer was placed in a similar fashion until the specimen was full.

PVC tees with high-density polyethylene (HDPE) tubing were installed at each end to facilitate inlet and exit of air in drying specimens. To encourage airflow through the strand interstitial spaces, soft grout was placed at the inlet and outlet PVC tees and removed after construction to access the strands. To monitor the drying of each grout layer, two ports were drilled through the PVC and into each grout layer for measurement of relative humidity using humidity probes and concrete moisture meter (refer to "RH" in Fig. 3).

Table 1—Soft grout formulation

ID	Portland cement, kg/m^3 (lb/ft^3)	Ground limestone filler, kg/m^3 (lb/ft^3)	Water, kg/m^3 (lb/ft^3)	Compressive strength, MPa (psi)
100PC	1255 (78)	0	583 (37)	60.6 (8790)
40PC	495 (31)	756 (47)	585 (37)	10.1 (1465)
30PC	376 (23)	875 (55)	585 (37)	9.7 (1410)
15PC	192 (12)	1067 (67)	587 (37)	1.9 (280)
10PC	129 (8)	1130 (71)	587 (37)	0.8 (120)
5PC	63 (4)	1188 (74)	588 (37)	0.2 (30)

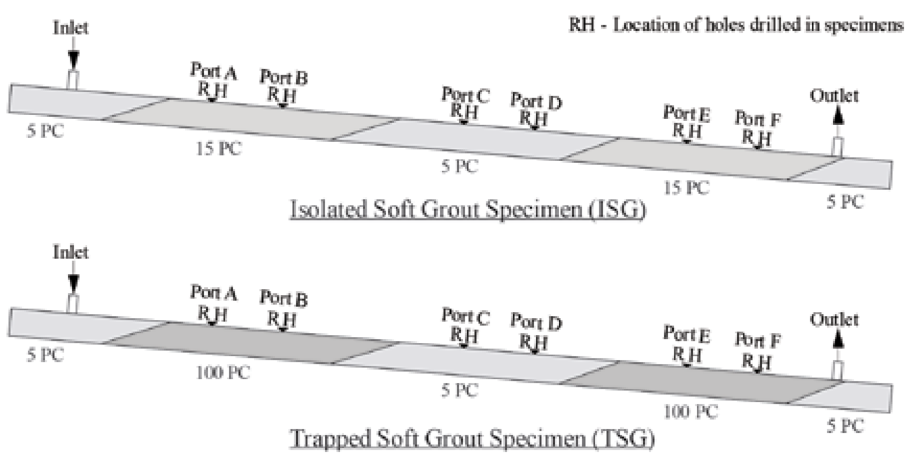


Fig. 3—Types of specimens.

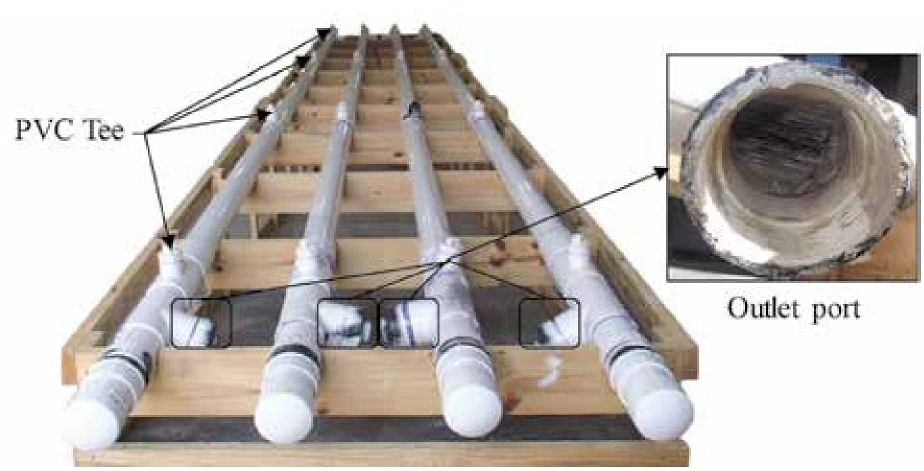


Fig. 4—Fully assembled specimens with downward angle of PVC tee.

TESTING PROCEDURES

Drying process

A drying system was set up to dry mockup specimens filled with grout, which injected pressurized dried air into one end of the mockup specimens; this air flowed through the specimen and was discharged at the opposite end (Fig. 2). The drying system was designed to generate dry air with relative humidity (RH) less than 10%. Compressor, desiccant dryer, and filters in the drying system produced dry air and the pressure regulator reduced the inlet air pressure to approximately 20 psi (0.14 MPa) to prevent leaks through joints in specimens.

Drying was initiated after drying system setup and specimen construction was completed. Total drying time, including downtime, was approximately 177 days (~26 weeks) for Specimen ISG and 182 days (~27 weeks) for Specimen TSG. After 3 weeks of drying initiation, a vacuum pump was connected to the exit on specimens to increase flow of air by increasing pressure difference between inlet and exit of specimens. Drying equipment was regularly monitored and maintained during the entire drying time.

Relative humidity (RH) of air inside holes drilled in soft grout and drying air at inlet and outlet of mockup tendons was measured to monitor the progress on drying technique. In general, relative humidity (RH) inside holes drilled into slabs has been used to check the moisture condition of concrete before installing floor coverings. ASTM F2170(2016) provides a procedure for measuring RH in slabs. This procedure was modified to measure RH required to monitor the drying technique. ASTM defines relative humidity as ratio of the amount of water vapor actually in the air compared to the amount of water vapor required for saturation at that particular temperature, expressed as a percentage (ASTM F21702006). Therefore, higher relative humidity indicated higher moisture content at a particular temperature.

The change in measured RH of drying air from inlet to outlet of specimens was defined as change in drying air RH (ΔRH_d), whereas RH of grout measured inside ports drilled into the specimens was defined as grout RH (RH_g) (Fig. 5). Figure 2 shows measurement locations of ΔRH_d and RH_g readings. ΔRH_d was measured at least once a month, whereas RH_g was measured at least twice a week. A Vaisala DM70 handheld Dewpoint Meter (Vaisala, 2007) was used to measure ΔRH_d, whereas Tramex CMEXpert was used to measure RH_g.

Along with monitoring drying progress, ΔRH_d readings were measured to determine if significant free moisture remained in the specimen and the procedure, called dryness check, to determine this was as follows:

1. Turn off drying equipment.
2. After resting for at least 12 hours, restart the drying equipment.
3. Measure ΔRH_d immediately when equipment is restarted and note the reading as ΔRH_{di}.
4. Measure ΔRH_d 2 hours after restarting equipment and record the reading as ΔRH_{df}. If ΔRH_{df} is not measured at exactly 2 hours after restarting of drying, it is calculated based on interpolation of RH readings measured before and after the second hour of drying.

The mockup specimens were deemed to be dry when ΔRH_{df} was equal to ΔRH_{di} with a tolerance of +5% due to possible leaks in specimens.

Dissection process

Dissection was directed toward measuring moisture content for comparison and possible calibration with the ΔRH_d and RH_g. Both control and dried mockup specimens were dissected after drying termination. Dissection occurred 176 days and 179 days after drying started for ISG and TSG specimens, respectively.

To determine the most appropriate techniques when cutting and sampling, trial specimens were dissected using circular saw, chisel, and hammer. Trial dissection showed that heat generated due to use of circular saw caused loss of moisture in soft grout (5PC and 15PC) samples, resulting in reduced measured moisture content. Based on this finding, grout samples were planned to be collected at least 4 in. away from saw cuts. Trial dissection also showed that moisture content of grout varied over the height of the specimen cross section. Therefore, samples were collected at varying locations over the height of the cross section. Results obtained from the trial dissection guided the development of the following procedures for the dissection of mockup specimens:

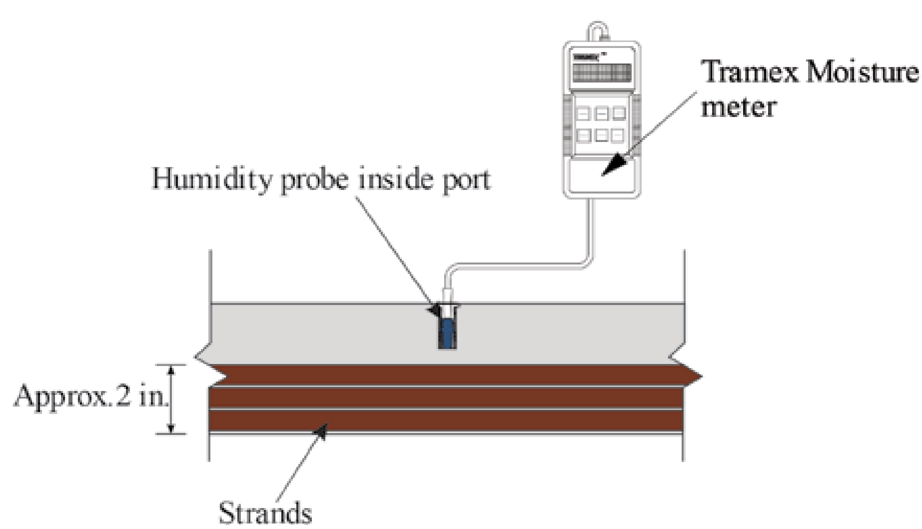
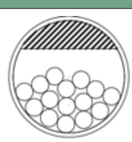
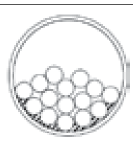


Fig. 5—RH_g measurement.

1. Mark 1 ft (0.30 m) sections for cut on each side of port for RH_g measurement on PVC pipe of specimens.
2. Cut the top half semicircular portion of PVC pipe at the specified locations with saw blade or rotozip as needed.
3. Remove PVC to access grout.
4. Darker gray section in Fig. 6 shows the location for grout sample collection in each 1 ft (0.30 m) long cut section. For 100PC grout, use circular saw and chisel to gather samples. For 15PC and 5PC, collect samples using hack saw and chisel.
5. Collect samples from different locations over the height of cross section, shown in Table 2, if possible. Note the position of the grout sample in cross section.
6. Immediately place the grout sample in an aluminum foil container and measure mass.
7. Place the grout sample in oven until mass has stabilized. Follow ASTM C566-13 and ASTM D2216-10 to measure moisture content (MC) of grout samples.
8. Compute moisture content based on the change in mass after oven-drying.

Table 2—Sample locations over height of cross section

Grout section	Section label
	Top
	Bottom
	Below the strands

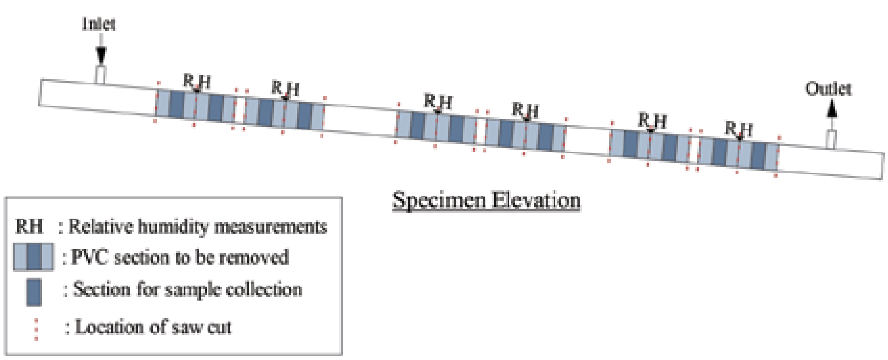


Fig. 6—Markup for dissection.

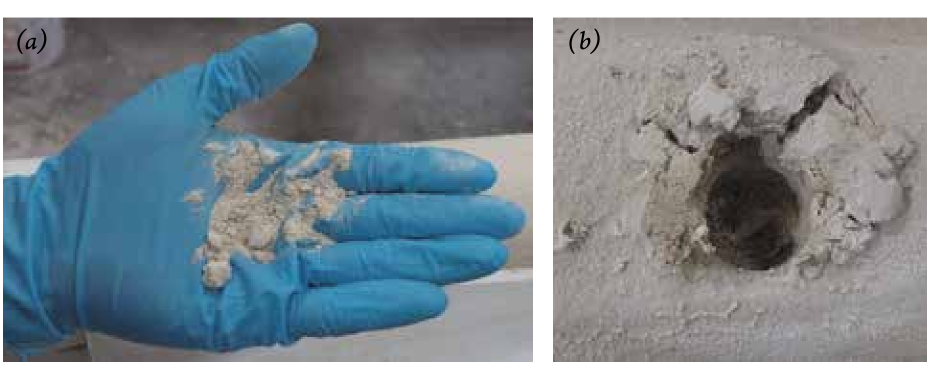


Fig. 7—Soft grout in Specimen ISG: (a) dried; and (b) wet.

Figure 6 shows the sampling locations for grout in Specimens ISG and TSG relative to the RH port where RH_g was measured. Grout samples were collected during dissection, and immediately weighed prior to placing them in oven to determine their moisture content.

RESULTS AND DISCUSSION

Visual inspection after dissection

As mentioned previously, drying and control ISG specimens were fabricated with layers of 5PC and 15PC grout (Fig. 3). By means of visual inspection after dissection, the grout in the drying specimen was deemed dried, while the grout in the control specimen was wet. In this context, soft grout is considered dry when it can easily crumble into individual particles or dust (Fig. 7(a)) and moisture is not obviously present. Wet grout was moldable like wet clayey sand (Fig. 7(b)) and left a moisture residue on fingers after handling. In the drying specimen, shrinkage cracks were present on the surface, but the control specimen had no visual indication of shrinkage cracks.

Specimen TSG consisted of soft grout (5PC) sandwiched between normal grout (100PC) (Fig. 3) and was determined to be dry based on visual observations. Additionally, soft and normal grout in drying specimens had shrinkage cracks indicating removal of moisture (Fig. 8).

Corrosion findings

During dissection, sampling, and inspection of specimens, the prestressing strands were uncovered and systematically evaluated visually for the presence of corrosion. During visual evaluation, corroded strands were found predominantly in drying specimens (Fig. 9). However, corrosion was preferential on the peripheral strands of the tendon. The location of corrosion found on the specimen is shown in Fig. 10.

The corrosion process was likely promoted by carbonation of grout through exposure to drying air. Carbonation is a chemical reaction between portlandite ($Ca(OH)_2$) in the cement matrix and with carbon dioxide (CO_2), resulting in formation of calcite ($CaCO_3$) and depletion of hydroxyl ions (OH^{-1}) (Zhou et al. 2014). The depletion in hydroxyl ions lowers the pore water pH from above 12.5 to below 9.0. At pH below 11.0, the passive layer on steel becomes unstable and corrosion occurs if sufficient water and oxygen is present (Heiyantuduwa et al. 2006). In the case of drying specimens, carbon dioxide and oxygen were supplied by the drying air, and soft grout had sufficient chemically unbonded water for causing corrosion.

Although unconfirmed experimentally, it was hypothesized that a macrocell formed in the drying specimens at the locations where the corrosion was most severe. The macrocell was probably driven by the difference in physical and chemical properties between the two grouts at the interface (Fig. 11). In Fig. 11, the physical difference between layers was due to lower porosity in the top layer than in 5PC grout layer, whereas the chemical difference was due to difference in proportions of cement and filler (dolomite limestone) in the mixture design of different layers.

The difference in porosity between the layers resulted in slower drying rates in the top layer than the bottom 5PC layer. Differential drying may have caused moisture gradient between the two grout layers, which caused 5PC grout to draw moisture from the top layer. At the same time, the dried pores in 5PC allowed oxygen from air to reach the strands. Therefore, corrosion-driving forces including oxygen and moisture were available in the corrosion macrocell along with carbonated grout, resulting in local corrosion observed in drying specimens (Fig. 12).

The drying TSG specimen had worse corrosion conditions than the drying ISG specimen probably due to greater hydraulic gradient and strand corrosion potential difference between dried 100PC and 5PC grout layers than between dried 15PC and 5PC layers. Figures 14 and 15 clearly show the dried TSG specimen had higher hydraulic gradient than the dried ISG specimen. Therefore, the dried TSG specimen (Fig. 12(b)) had worse corrosion than the dried ISG specimen (Fig. 12(a)).

On the other hand, control specimens had no or less corrosion than drying specimens. Corrosion in control

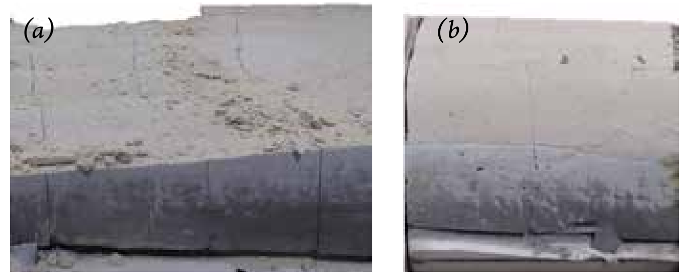


Fig. 8—Shrinkage cracks in drying specimen TSG: (a) normal grout; and (b) soft grout.

Fig. 9—In-place corroded strands near Port C drying TSG specimen.

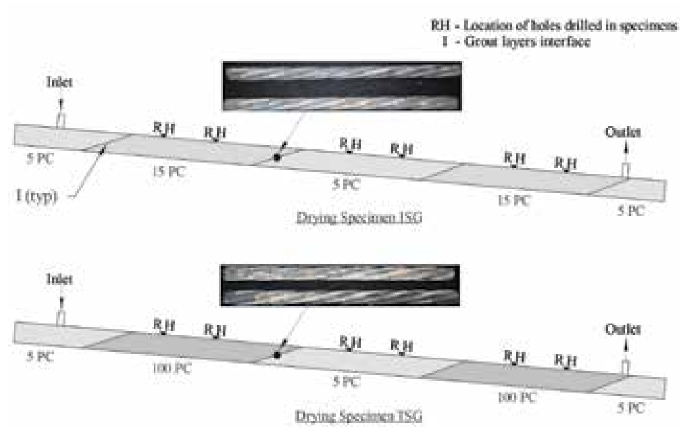


Fig. 10—Location of corroded strands in drying specimens.

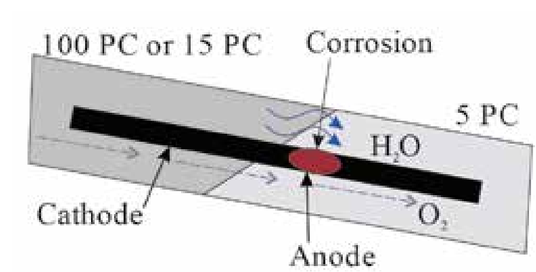
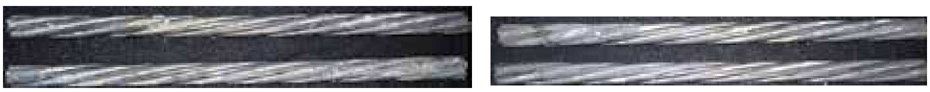


Fig. 11—Macrocell formation on peripheral strands of tendon.

(a) (b)

Fig. 12—Corroded strands near Port C of: (a) drying ISG specimen; and (b) drying TSG specimen.



(a) (b)

Fig. 13—Corroded strands near Port C of: (a) control ISG specimen; and (b) control TSG specimen.

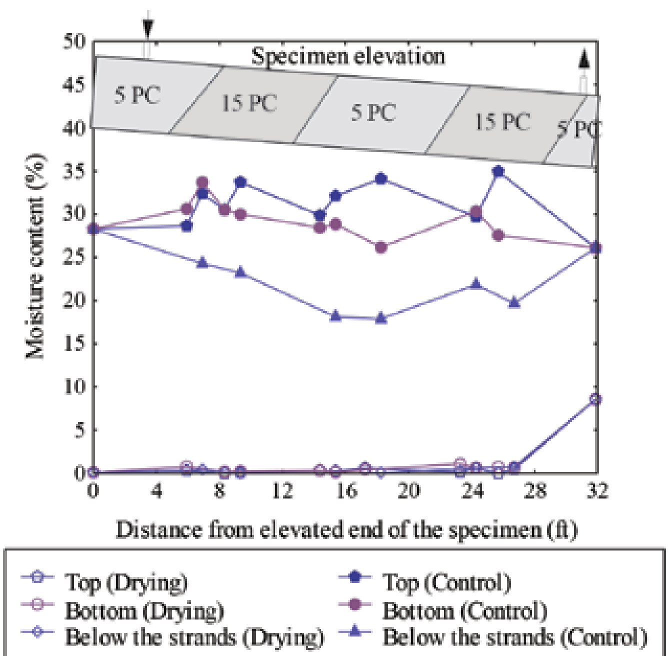


Fig. 14—Comparison of moisture content for drying and control ISG specimens.

specimens was suspected due to presence of bleed water, dissolved oxygen, and varying physical (porosity) and chemical (pH) properties of grout along the length of specimens. However, no drying air was present to carbonate the grout and wet pores probably reduced the diffusion of oxygen, resulting in slower corrosion rate in control specimens than in drying specimens. Thus, little or no corrosion was found on dissection of control specimens (Fig. 13).

Moisture content

Grout samples were collected during specimen dissection to determine their moisture content. ASTM C566-13 and ASTM D2216-10 were followed to measure MC of grout samples. Samples of grout, weighing in the range of 30 to 550 g, were collected during dissection and oven-dried overnight at 110°C. Preliminary tests indicated that sample weight equilibrated in less than 24 hours. Weight lost due to oven drying was used to compute grout MC at different locations along the specimen.

Figure 14 shows a graphical representation of the MC measurements plotted as a function of their location in the ISG specimen for both the control (solid markers) and drying specimens (hollow markers). Moisture content in the drying specimen was negligible (<1% by mass) compared to that measured in the control specimens, with the exception of the measurement taken at the lower end of the slope. Thus, it can be concluded that the drying technique was effective in removing almost all moisture from soft grout present in the drying specimen between the air inlet and outlet.

Figure 14 shows that the MC of 5PC grout, present upstream of inlet in drying specimen was negligible (<1%); however, the MC measurement at the low end of the slope was close to 10%, indicating that grout beyond outlet was dried but its MC was not as low as grout along rest of the specimen length. This likely occurred because the section of the specimen beyond the outlet was unable to completely drain water during drying.

Figure 15 shows moisture content measurements plotted as a function of their location in Specimen TSG for both the control (hollow markers) and drying specimens (solid markers). Figure 15 shows that in the undried control specimen, 100PC normal grout layer had lower moisture content than the adjacent 5PC soft grout layer even though the water to solids ratio was the same. This was because normal grout had more cement content, resulting in higher degree of hydration and higher consumption of water than soft grout. On the other hand, in a dried specimen, dried normal grout layer had higher moisture content than dried soft grout. This was probsably due to the less porous nature of the 100PC, which restricted the removal of moisture compared to the relatively porous soft grout.

In general, moisture content of both 5PC and 100PC decreased considerably after drying. Moisture content in the central 5PC layer in drying specimen was negligible (<1%) compared to the control specimen. These results in Specimen TSG are similar to that of Specimen ISG, indicating that the airflow through the hardened normal grout layers was sufficient to dry the trapped layer of 5PC grout.

The final dried moisture content of the 100PC grout layers, however, was between 5 and 15% and was unlikely to decrease notably with further drying. Further, past studies (Randell et al. 2015) have shown that normal grout has moisture content values varying from 16 to 22%, which is more than the dried 100PC grout moisture content.

Soft grout present upstream of the air inlet had negligible moisture content (<1%), but soft grout downstream of the air outlet had approximately 8% moisture content. Similar to Specimen ISG, this indicated that soft grout beyond the air outlet was not able to completely drain bleed water during drying and did not completely dry.

In conclusion, Specimen TSG was considered dry because soft grout between the inlet and outlet had negligible moisture content, and the moisture content in dried 100PC was less than normal grout. Note that even though 100PC grout had less porosity than 5PC grout, it did not obstruct drying of trapped 5PC grout.

Relative humidity analysis

RH measurements of drying air (ΔRH_d) and grout (RH_g) were recorded while drying was performed. These readings were analyzed to monitor the progress of drying and to determine if the grout moisture content could be calibrated to RH readings.

Figure 16 shows the difference between RH of drying air measured at inlet and outlet of drying specimens (ΔRH_d) over the entire drying period for both specimens.

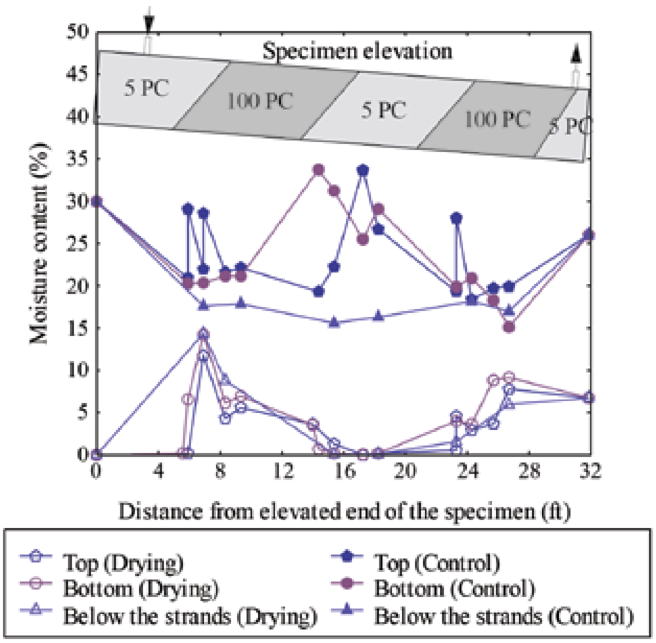


Fig. 15—Comparison of moisture content for drying and control TSG specimens.

Note that negative ΔRH_d data are not shown in the graph. Positive ΔRH_d designates an increase in RH of drying air, which indicated that the grout was continuing to dry, whereas negative ΔRH_d indicated that drying air deposited moisture in the grout. These brief periods of negative ΔRH were due to equipment malfunctioning, which allowed drying air with up to 20% RH to be pumped through the specimen. Ideally, grout will be considered dried when there will be no more free moisture that can be removed from grout and ΔRH_d approaches zero.

In general, ΔRH_d decreased with time, which represented gradual drying of grout. After approximately 50 days, ΔRH_d decreased notably faster for the ISG specimen than for the TSG specimen. This is thought to be due to the presence of low-porosity normal grout (100PC), which provided more obstruction to the airflow in the TSG specimen than in the ISG specimen.

Based on criterion of $\Delta RH_d \approx 0\%$, the ISG specimen was considered dried in approximately 110 to 120 days (gray shaded area in Fig. 16). During this period, ΔRH_d was within a range of 0 to 5%. Similarly, the TSG specimen was considered dried in approximately 140 to 150 days (blue shaded area in Fig. 16), and ΔRH_d was within a range of 0 to 20%. For both specimens, ΔRH_d increased over the period between 130 and 160 days. This is thought to be due to equipment malfunctioning and drying system shutdown, which allowed dried grout to absorb moisture through leaks in the specimens.

Companion measurements of grout RH measured in probe ports drilled into specimens (RH_g) were made during the drying process. RH_g was basically RH of air measured with probes placed inside ports drilled into the grout. The

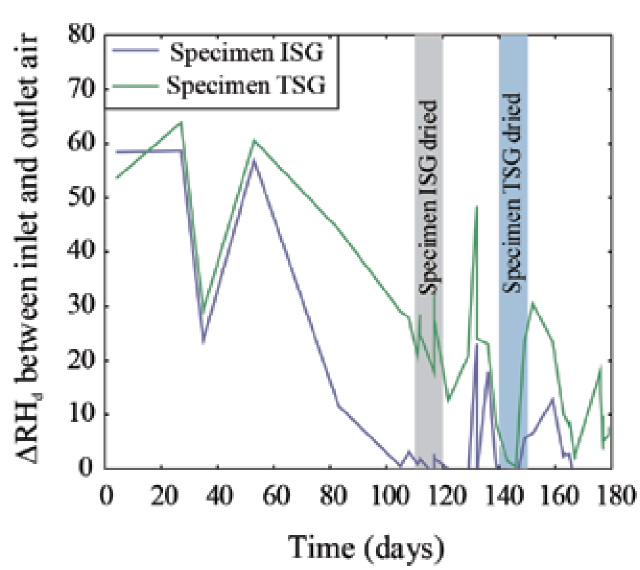


Fig. 16—ΔRH_d versus time.

air in these ports was influenced by the moisture content of the surrounding grout. As previously mentioned, each specimen had six ports with two ports drilled in each grout layer (Fig. 5). Figure 17 shows RH_g readings variation measured inside ports over the drying period for Specimens ISG and TSG. Similar to ΔRH_d between inlet and outlet air readings, the RH_g values decreased with time indicating drying of grout. However, TSG specimen ports were observed to have higher RH_g than ISG specimen ports near the end of the drying period. This was thought to happen due to presence of normal grout in the TSG specimen, which did not dry as much as soft grout and influenced RH_g of air in all ports. RH_g readings for dried soft grout (5PC and 15PC) ranged from 15 to 40% RH for temperatures between 15 and 35°C. On the other hand, RH_g readings for dried hard grout (100PC) varied over a wider range of 30 to 70% for the same temperature range.

Dryness check

Dryness checks were performed using the procedure described in drying process chapter for ΔRH_d readings to check if significant free moisture remained in the specimens. Dryness checks were performed several times after 89 days of drying. Table 3 shows interpretation of dryness check based on difference between the initial RH measured immediately after restarting the drying system (ΔRH_{di}) and RH measurement after 2 hours of restarting the drying system (ΔRH_{df}).

Dryness checks were performed on ISG and TSG specimens on days 89, 117, and 167 (Fig. 18). On day 89, ΔRH_{df} was less than ΔRH_{di} for Specimen ISG and TSG, indicating both specimens were not dry. On day 117, for Specimen ISG, ΔRH_{df} was equal to ΔRH_{di} (+5% tolerance), which indicated grout in ISG was dried. On the other hand, for Specimen TSG on the same day, the difference between ΔRH_{df} and ΔRH_{di} was greater than 5% RH, indicating grout in TSG was on the verge of drying. On day 167, ΔRH_{df} was equal to ΔRH_{di} (+5% tolerance) for both specimens, indicating grout was dried. To check repeatability of dryness check on Specimen TSG, a dryness check was performed on TSG on day 179, which again showed that grout was dried. Specimens ISG and TSG, after dissection on day 177 and day 182, respectively, consisted of dried soft grout. Therefore, the dryness check was helpful to determine if significant free moisture remained in the specimens.

SUMMARY AND CONCLUSIONS

In the present research, drying of grout was evaluated as an alternative to rehabilitation of tendons contaminated with soft grout. Two types of specimens with low-relaxation prestressing strands and multiple layers of different types of grout filled in a PVC pipe to represent a mockup tendon were constructed and dried. Drying involved passing of dehumidified air from one end of tendon specimens and removing moisture from another end. This technique

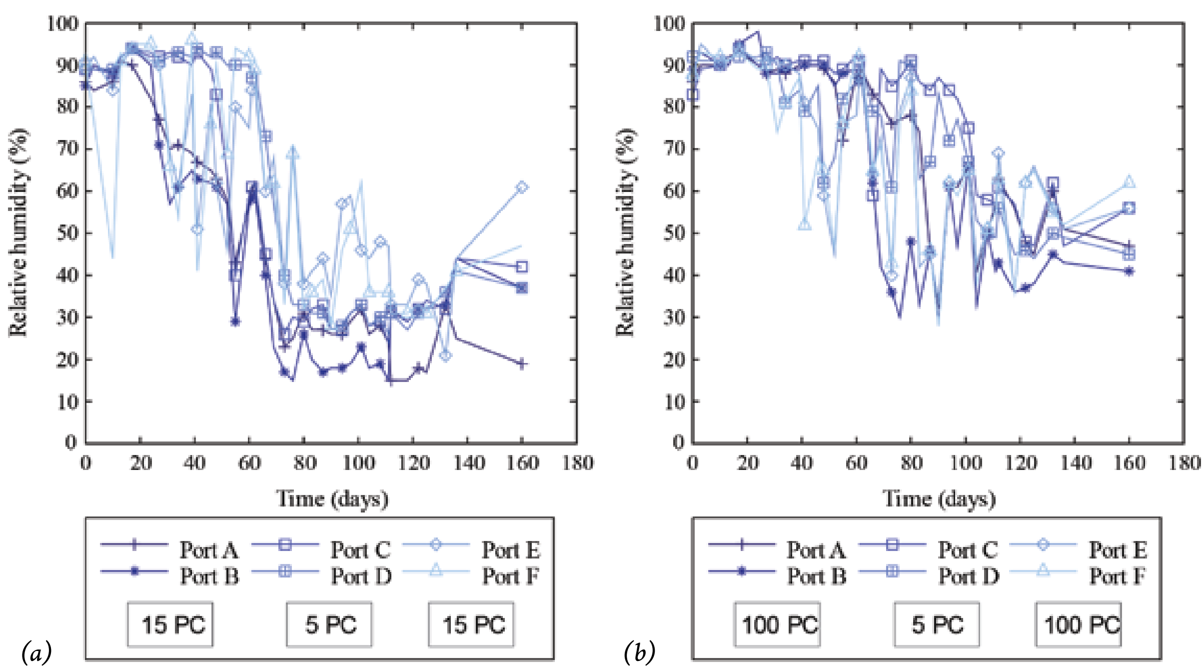


Fig. 17—RH_g readings versus time: (a) ISG specimen; and (b) TSG specimen.

required drilling only two holes for inlet and outlet of air and thus was a nondestructive method of rehabilitation. Only relative humidity measurements of drying air at inlet and outlet (ΔRH_d) were required to predict if soft grout dried. After performing drying on mockup tendon specimens, soft grout was found to be dried and have moisture content of less than 5%. However, leaks in tendons and presence of normal grout reduced the speed of drying, and the rate of drying was not predictable. Based on this research, the following conclusions were drawn:

Grout consistency

- Moisture content measurements on dried layers of 5PC and 15PC grout were consistently below 1%, which indicated that drying had effectively removed moisture from the soft grout. This was also true for the dried 5PC layers trapped between 100PC hardened grout
- Drying resulted in grout shrinkage, which was manifested by transverse, regularly spaced cracks in the grout. Dried soft grout was friable, porous, and not well-bonded to strands.
- Drying was much less effective at removing moisture at the end of the specimens outside of the air outlet ports.

ΔRH_d readings

- Specimen TSG had ΔRH_d readings higher than Specimen ISG during the end of drying period. This was likely caused by the large amount of moisture present at the end of the drying period in the 100PC grout of Specimen TSG.
- Based on the ΔRH_d readings, Specimen ISG dried in approximately 110 to 120 days and Specimen TSG in approximately 140 to 150 days. It is thought that the drying rate of Specimen TSG was reduced by the presence of the 100PC grout.
- Based on dryness check readings (ΔRH_{di} and ΔRH_{df}), the ISG specimen was found dried on day 117 and the TSG specimen was found dried on day 167.

Table 3—Interpretation of dryness check readings

Condition	Interpretation
$\Delta RH_{df} = \Delta RH_{di}$ (+5% tolerance)	Grout dried. Grout did not have moisture to release during drying shutdown.
$\Delta RH_{df} < \Delta RH_{di}$	Grout not dried. Grout released moisture during shutdown resulting in higher immediate ΔRH_{di} reading.
$(\Delta RH_{df} - \Delta RH_{di}) > 5\%$	Grout on verge of drying. During shutdown time, specimen did not release free moisture from grout. However, drying air could remove some trapped moisture couple hours after drying restart.

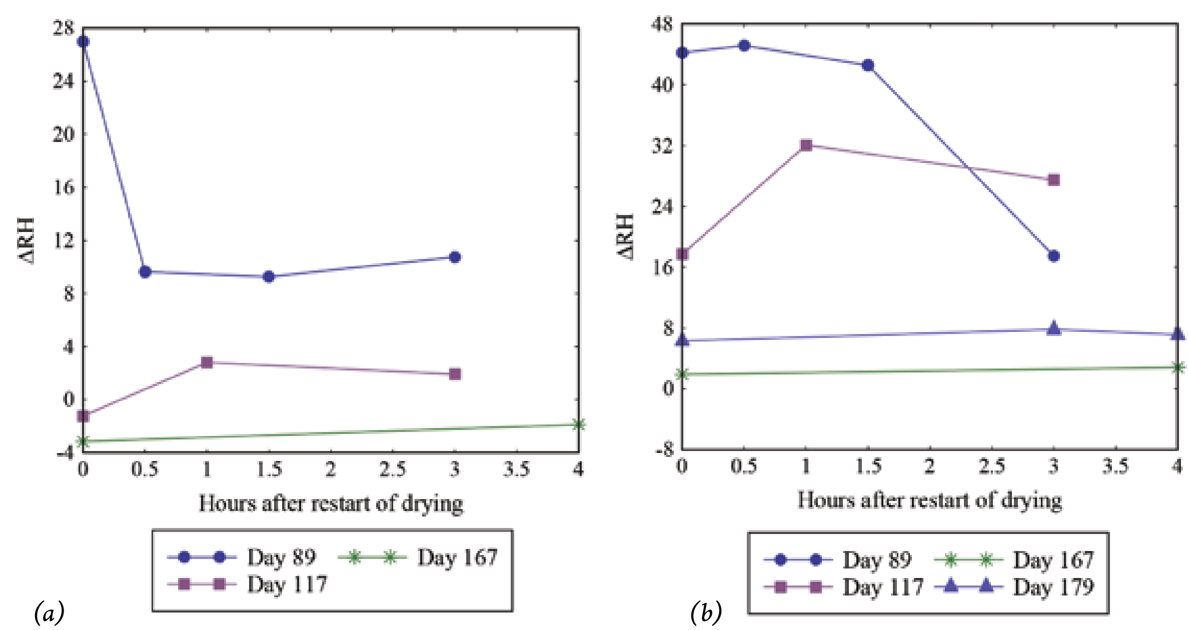


Fig. 18—Dryness checks for specimen: (a) ISG; and (b) TSG.

- Dryness check was helpful in determining if significant free moisture remained in the specimens.

RH_g readings

- RH_g readings for dried soft grout (5PC and 15PC) ranged from 15 to 40% RH for temperatures between 15 and 35°C. On the other hand, RH_g readings for dried hard grout (100PC) varied over a wider range of 30 to 70% for the same temperature range.

Strand corrosion

- Drying specimens exhibited strand corrosion in several locations, which did not occur in the control specimens.
- The porosity of dry grout, combined with the constant supply of air, provided the strands a direct access to a steady oxygen supply.
- Carbon dioxide in drying air was thought to carbonate the grout, which probably reduced pH below 11 and passive layer of strands became unstable.
- Sufficient moisture from bleed water of grout, along with lower pH and oxygen, was probably responsible for corrosion.

RECOMMENDATIONS

Although unconfirmed experimentally, it is hypothesized that a macrocell formed in the drying specimens at the locations where the corrosion was most severe. To prevent macrocell corrosion, use of inert gas is recommended, which will remove the supply of oxygen required for corrosion of steel. Nitrogen gas, which has been successfully used for drying unbonded strands (Velde 2002), is an example of inert gas that can be used for drying. Soft grout was found porous after drying and can allow oxygen and moisture to reach strands, resulting in corrosion. To prevent this, injection of corrosion inhibitor after drying is recommended. Additional studies are required to support the hypothesis of macrocell corrosion and carbonation occurring during drying.

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