Flexible filler mock-up injections of bridge post-tensioning tendons

Natassia R. Brenkus, Rahul Bhatia, Will A. Potter, and H. R. Hamilton III

- This paper presents the results of five mock-up injections of post-tensioning tendons with flexible filler material to assess standard grouting procedures for the use of flexible filler materials instead of cementitious products.
- Variables included the injection procedures (pumping equipment, flow rate, injection pressure, inlet/outlet location, and venting), the post-tensioning anchorage system, and the filler material.
- This work influenced the subsequent development of specifications for flexible filler injection procedures.

Cement grout is the most commonly used post-tensioning tendon filler material for internal and external bridge tendons in the United States. Inspections of these tendons have revealed some instances of corrosion and compromised tendon durability, including several cases of entire tendon rupture. These issues have prompted the exploration of alternatives to cementitious grout. Noncementitious, flexible filler materials—such as wax or grease—are an alternative class of fillers that result in unbonded tendon systems with constructibility and structural behavior implications. Flexible fillers have been employed to facilitate inspection, surveillance, and replacement of post-tensioning tendons, with the potential advantage of reducing maintenance, repairs, and costs over the service life of the bridge.

The use of grease and wax as post-tensioning tendon filler material in bridge applications has been increasing since the 1970s, most notably in France. Initially used to repair existing bridges, new designs incorporating unbonded tendons with flexible fillers became more common in the 1990s, with a focus on facilitating tendon inspection and replacement. Unbonded tendons with flexible filler materials are not typically used in U.S. bridges but have been used in other applications, such as nuclear containment structures, buildings, and parking structures.[1]

Objective

The objective of the work described herein was to investigate alternative tendon filler materials for use in post-tensioned bridges and to evaluate the compatibility of these materials with current injection equipment and post-tensioning hardware. This paper focuses on the investigation of modified grouting procedures for the injection of flexible fillers, which informed the subsequent development of flexible filler injection specifications. Additional work conducted as part of the larger experimental program included examination of the structural behavior of externally or internally unbonded post-tensioned beams. Several alternative filler materials, including wax and grease, were included in the testing program.

Experimental program

Five 19-strand, 200 ft (61 m) long nominally post-tensioned tendons were injected with heated flexible filler materials. Several procedural variables were examined in each of the injections (for example, flow rate, vent placement, and the use of vacuum assist). Duct serface and filler temperature and internal duct pressure of the filler material were monitored along the tendon length during pumping and immediately afterward.

Geometry

Each tendon profile was deviated over a 200 ft (61 m) length to simulate inclination angles and relative positioning of strands and duct found in two types of bridge construction: typical segmental box girders and drop-in I-girders. To achieve this, two profile types were incorporated into the mock-up. The profile of an external tendon was simulated at both ends of the setup length by a draped segment (approximately 30 ft [9 m]) and a straight segment (approximately 40 ft [12 m]). The parabolic profile (approximately 60 ft [18 m]) at midlength of the setup mimicked the internal tendon profile in an I-girder bridge with a drop-in segment (**Fig. 1** and **A1** [for appendix figures, go to www.pci.org/Brenkus_Appendix]) The tendon was nominally post-tensioned against the steel reaction frames. Deviation of the tendon was achieved through four concrete blocks.

Materials

Each tendon was composed of 19 Grade 270 (1860 MPa), 0.6 in. (15 mm) diameter prestressing strands; a smooth 4 in. (100 mm) diameter high-density polyethylene (HDPE) DR17 duct; a commercially available flexible filler material; and a post-tensioning anchorage system. Three different post-tensioning anchorage systems were used in the mock-up, representing three manufacturers. Clear pipe windows composed of 1/8 in. (3 mm) thick polycarbonate were positioned at several locations to allow visual observation of the injection process. A mechanical ductile iron coupler was used to connect the HDPE duct and polycarbonate tube (**Fig. A2**). Plastic inlet and venting tubes (typically used in grouting operations) were replaced with steel pipe and connections.

Four different commercially available flexible filler materials were used in the injections. All materials were delivered to the laboratory in 55 gal. (210 L) steel drums and were semisolid at ambient (laboratory) temperature (70°F to 80°F [21°C to 27°C]). Brenkus et al.[2] provides more information on the key material and performance properties.

Equipment

Equipment used in the first injection was a standard hopper-fed grout pump (**Fig. A3**) with a pumping capacity of 20 gal./min (76 L/min). The discharge line of the pump was connected to the inlet with a 1 in. (25 mm) diameter hose.

Subsequent injections (injections 2 through 5) used a heated centrifugal pump with a variable-frequency electric drive (**Fig. A4**). For each injection, the pump housing was heated to 250°F (120°C). The cast iron pump had 2 in. (50 mm) diameter national pipe thread (NPT) intake and discharge ports. At maximum speed, the discharge rate was 100 gal./min

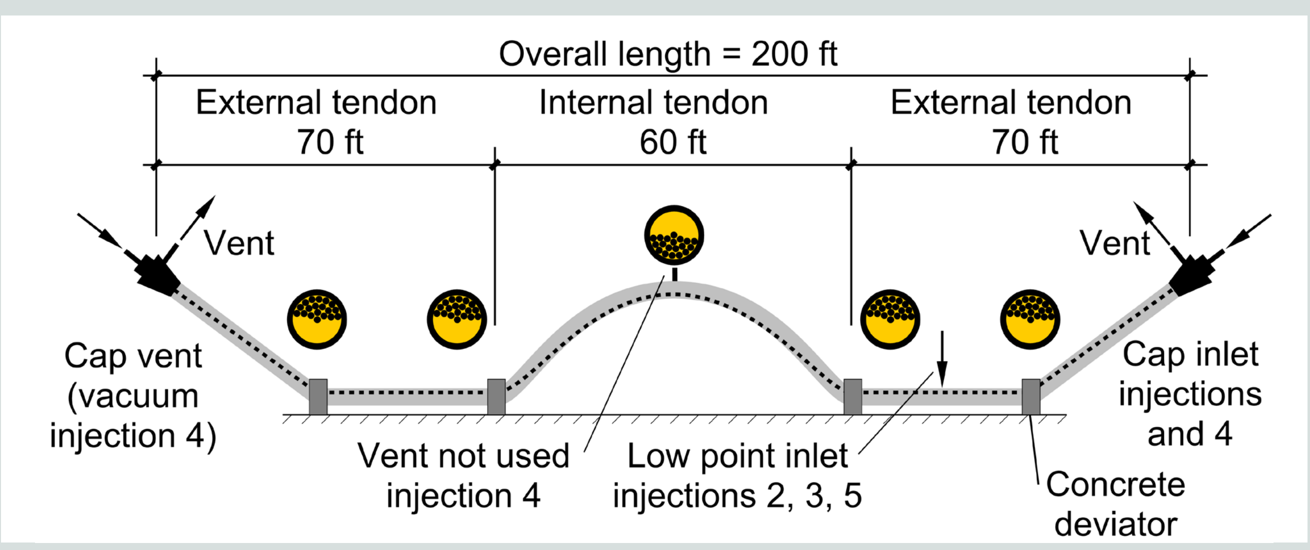


Figure 1. Tendon profile. Note: 1 ft = 0.305 m.

(380 L/min) at a pressure of 75 psi (520 kPa) (at a liquid viscosity of 20 cP [20 mPa-s]).

A high-capacity vacuum pump was used in conjunction with the centrifugal pump for the vacuum-assisted injection (injection 4, **Fig. A5**). The vacuum pump was capable of pulling a near-complete vacuum (29.98 in. [761.5 mm] of mercury).

Planning and safety

As with any grouting procedure, communication and planning are essential for a successful injection using flexible filler. Unlike cementitious grouting, the use of flexible filler materials involves heated materials and a shorter injection time schedule because the filler material cools and congeals as it approaches ambient temperature. Component testing (not reported in this paper) was conducted before the full-sized injection, both to familiarize the personnel with the equipment and procedures and to assess the compatibility of the components with the new procedure. In general, the selected pipes and fittings performed without leaking, though in one case deformation of the HDPE duct under prolonged exposure to heated filler material (continuously exposed to greater than 200°F [93°C] filler for more than 8 minutes) at high injection pressures (above 100 psi [700 kPa]) was observed. As a result, the injection pressures for the fill-sized injections were limited to 75 psi (520 kPa).

Several precaustions were taken prior to each injections. The equipment to be used was checked and moved into position. Pumps and hoses were cleaned and cleared to prevent clogs. This was important when performing several injections with the same hoses and equipment. The filler materials were stored indoors, and ingress of water was prevented. Air-pressure and vacuum tests were performed to ensure tendon integrity. The ducts and tendons were protected from the entrance of water and were verified to be both dry and free of contaminants. Personnel were familiarized with the pumping equipment. All personnel involved were educated on potential scenarios during the injection (that is, minor and major leaks). All personnel involved were required to wear personal protective equipment, including hand and eye protection, as well as protective coveralls.

Pressure and vacuum testing (before injection)

Before injection, each tendon was subjected to an air pressure test to ensure that the tendon was properly sealed. Each tendon was pressurized to 50 psi (340 kPa), and the retained pressure was monitored. To pass inspection, the tendon was required to lose not more than 15 psi (100 kPa) over a 1-minute period. The tendon was also required to pass a vacuum test. Each tendon was subjected to approximately 90% vacuum and sealed, and the vacuum was monitored to ensure a loss of no more than 10% over a 1-minute period.

Injection and dissection

Approximately 24 hours before injection, the barrels were heated to a target temperature of approximately 220°F to 240°F

Table 1. Injection parameters

Injection	Special consideration	Pumping direction	Filler material*	Pumping equipment	Temperature at start, °F	Pumping duration, minutes	Average injection rate, ft/min	Number of vents
1	Hopper-fed grout pump	Cap to cap	Petroleum-based corrosion preventative	Hopper-fed grout pump	230	5.4	49	4
2	Fast injection	Inlet at low point	Microcrystalline wax with additive	Preheated centrifugal pump	230	3.5	75	5
3	Typical grouting procedure	Inlet at low point	Blend of microcrystalline wax, mineral oils, and additives	Preheated centrifugal pump	225	5.3	62	5
4	Vacuum-assisted	Cap to cap	Petrolatum compound	Preheated centrifugal pump and vacuum	230	4.0	100	0
5	Slow injection	Inlet at low point	Petrolatum compound	Preheated centrifugal pump	236	15.5	21.5	5

Note: 1 ft = 0.305 m; °C = (°F - 32)/1.8.

* Description provided by manufacturer. Brenkus et al. 2017.

(104°C to 116°C) using strap heaters wrapped around the outer surface of the barrel. Insulation blankets were used to improve the heating efficiency. The filler was stirred regularly to ensure even distribution of heat in the barrel and to prevent clogging of the barrel drain, which was located at the base.

Once the filler achieved the target temperature, it was transferred to the injection barrels (a pair of barrels in parallel, feeding the injection pump) using an air-driven transfer pump. Barrel heaters and insulation blankets were also wrapped around the injection barrels to maintain temperature during injection. The outside air temperature at the injection site was between 60°F and 80°F (16°C and 27°C).

The injection procedures were varied to investigate the effects of the injection method. **Table 1** gives a summary of the test variables. The target flow velocity during the injection was 50 ft/min (15 m/min) when the inlet was at the anchorage and 80 ft/min (24 m/min) when the inlet was on the duct (or 40 ft/min [12 m/min] in each direction). The target pumping pressure was a maximum of 75 psi (520 kPa). For the vacuum-assisted injection, the target vacuum was 28 in. (710 mm) of mercury. Table 1 gives the average injection rates as determined from the time-temperature plots based on the assumption that the sudden increase in temperature indicates the time of arrival of the filler.

Injection 1 was conducted with a hopper-fed grout pump. Injections 2 through 5 were conducted with a heated centrifugal pump. After preheating the pump to approximately 250°F (120°C), the filler was injected either through the injection port at the anchorage plate or through a pipe saddle mounted to the duct. **Figure A6** illustrates how the filling proceeded, depending on the inlet location:

- Injection 1 was injected through the anchorage plate, with the fill proceeding end to end.
- Injection 2 was conducted to observe the effects of injecting the filler material as quickly as possible. The inlet was at the low point.
- Injection 3 simulated a typical grouting procedure using a centrifugal pump. The injection point was at a low point, and a venting procedure was used to evacuate the entrapped air.
- Injection 4 simulated an end-to-end injection with a centrifugal pump with vacuum assist. This procedure has been adopted in Europe and, subsequent to this investigation, in Florida.
- Injection 5 was conducted as slowly as possible to investigate the clogging potential. The injection pump was operated at its lowest setting, with the inlet at the low point.

On the day following each injection, short lengths of the tendons were dissected at critical locations to examine the filler material's coverage of the prestressing strand and to inspect for voids.

Instrumentation

Figure 2 shows the locations of pressure transducers and ther-

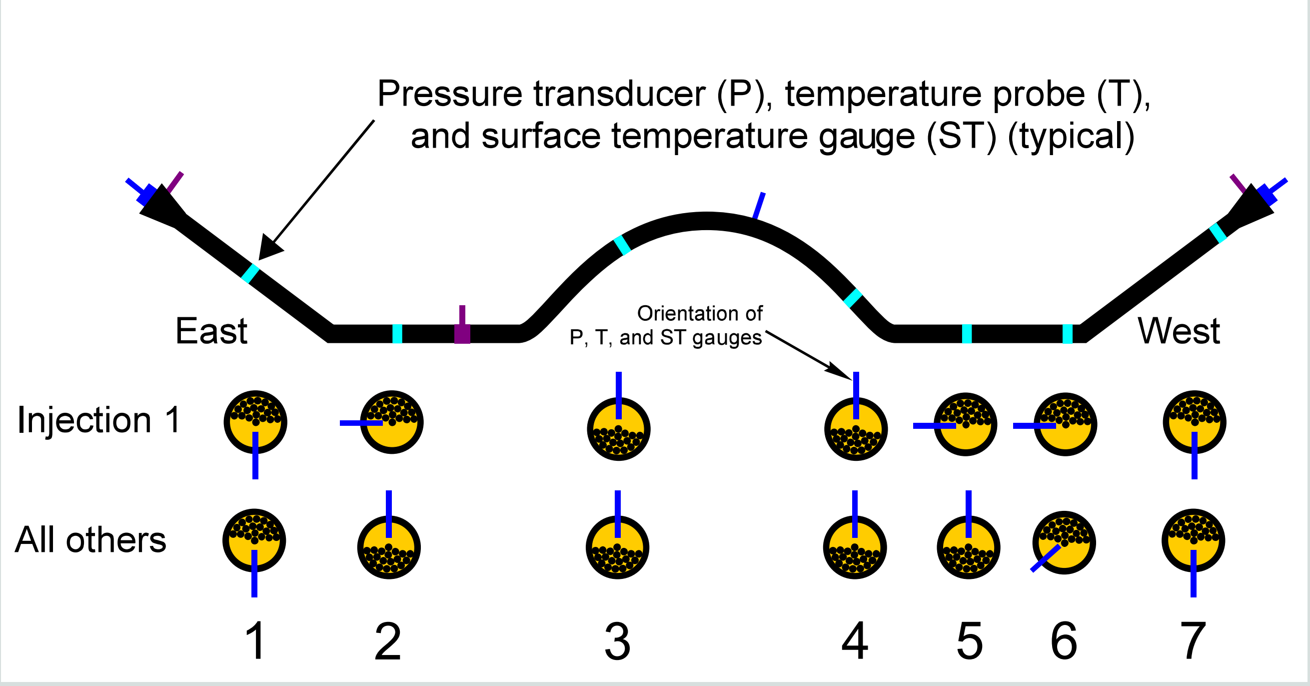


Figure 2. Instrumentation locations along duct.

mocouples along the length of the tendon. Also shown is the thermocouple orientation within the cross section. Locations were measured from the face of the anchor where the grout cap was fixed. Seven pressure transducers and seven internal thermocouples were installed on each specimen. In addition, seven surface-mounted (strap) thermocouples were installed adjacent to the probe thermocouples. The probe thermocouples were used to measure the temperature of the filler inside the duct. The surface-mounted thermocouples were used to measure the outside temperature of the HDPE duct.

The probe thermocouples and pressure transducers were oriented to avoid contact with the strand bundle to minimize the effect of the strands on their measurements **(Fig. 2)**. For injection 1 (hopper-fed grout pump, injected cap to cap), the instruments in the draped profile (P1, T1, ST1, P7, T7, and ST7) were installed at the bottom, those in the straight profile (P2, P5, P6, T2, T5, T6, ST2, ST5, and ST6) were installed on the side (at 90 degrees), and those in the parabolic profile (P3, P4, T3, T4, ST3, and ST4) were installed at the top of the duct. For subsequent injections, the orientation of the thermocouples (T2 and T5) and surface-mounted thermocouples (ST2 and ST5) were adjusted to the top, while T6 and ST6 were adjusted to the diagonal (Fig. 2). Pipe saddles were used to mount pressure transducers and the probe thermocouples on the duct. Surface-mounted thermocouples were placed with hook-and-loop fastener cuffs. **Table 2** gives the distances from the east anchor to each gauge measured along the ground.

Thermocouples Filler and duct surface temperatures were measured during and after the injection procedure. Probe thermocouples were used to measure internal filler temperature, while surface-mounted thermocouples were used to measure the surface temperature of the duct. Both types were monitored during and after injection. Type K thermocouple probes were chosen to measure the filler temperature inside the duct. The selection was based on an anticipated injection temperature of approximately 220°F (104°C). A compression fitting was used to obtain a pressure-tight seal around the probe at its point of insertion, and the probes were oriented in the duct to avoid direct contact with the prestressing strand. Flexible-cuff Type K probes were used to measure the surface temperature of the HDPE duct. Thermocouples and surface probes were connected to the data acquisition station with Type K thermocouple wires. Temperature data were recorded at 10 Hz during injection.

Table 2. Distance from the face of the east anchor to gauges

Location	Distance to pressure gauge, ft	Distance to temperature gauge, ft
1	14	16
2	44	46
3	80	82
4	122	124
5	144	146
6	164	166
7	182	184

Note: Figure 2 shows instrumentation locations. 1 ft = 0.305 m.

Table 3. Comparison of theoretical and injected filler volumes

Injection	Theoretical volume, gal.	Injected volume, gal.	Difference, %
1	96.4	91.38	(5.21)
2	96.4	95.76	(0.66)
3	96.4	98.75	2.44
4	96.4	93.46	(3.05)
5	96.4	94.64	(1.82)

Note: Numbers in parentheses are negative. 1 gal. = 3.785 L.

Pressure gauges Pressure transducers were used to measure the pressure inside the duct during and after injection. They were selected based on a maximum pressure of 75 psi (520 kPa) and an anticipated temperature of 220°F (104°C). Pressure transducers with an operating temperature from -65°F to 250°F (-54°C to 120°C) and operating pressure of up to 300 psi (2100 kPa) were used. Transducers were installed on the duct using a pipe saddle **(Fig. A7)**.

Results

Filler volume

The rate of injection of the flexible fillers was monitored to confirm the volume input and compare it with the theoretical volume of the duct **(Table 3)**. The filler volume was determined by deducting the volume of filler collected in buckets (vent discharge) from the volume of filler taken from the supply barrels. The theoretical volume of the pliable filler in the tendon was 96.4 gal. (365 L), assuming 10% volume loss during injection and change in volume due to temperature. In most cases, the volume injected into the duct was slightly smaller than the theoretical fill volume. The actual injected volume of filler material was within approximately 5% of the theoretical volume.

Visual inspection

The tendon was inspected approximately 24 hours after injection. Eleven inspection ports were made by cutting into the duct to inspect the relative fill of the filler material, cover of the strands, and presence of voids, if any. Each inspection port opening was cut on the top half of the HDPE duct and was approximately 1 to 2 ft (0.3 to 0.6 m) long. Clear pipe windows, vents, and caps were also inspected for relative fill.

Figure 3. Anchor cap inspection (injection 4).

Figure 4. Inspection of duct fill (injection 4).

Figure 5: Clear window at top of profile (injection 4).

Fig. A8 and **A9** show the locations of the inspection ports along the tendon length.

In general, each inspection revealed good coverage of the strands. Voids, when present, were located toward the top of the duct or anchorage cap and did not reveal the strand. **Figure 3** shows an example anchorage cap. In all cases, the anchorage caps were nearly, if not completely, full, with all wedges and strand tails completely covered by filler material. **Figure 4** shows a duct dissection: the top quarter of the duct was cut with a rotary saw and the duct pried open. The removed section of HDPE is shown at the top of the photo. The rest of the tendon is shown at the bottom. Visual inspection of this dissection found the prestressing strands to be covered. Although post-injection inspection revealed some air entrapped in the tendon duct in some cases, the prestressing strands and anchorage hardware inside the cap appeared to be covered by the filler material. **Figure 5** shows clear window C3, which is located at the top of the parabolic profile of injection 4. A small air bubble is visible, and the strands are coated by the filler material. In some cases, longitudinal cracks in the filler material were observed along the clear windows. The strands remained well-covered in these instances. The clear windows and couplers may have caused some flow disruption and local voids due to the thermal changes and inner diameter transitions between components. Additional photographs of the dissections can be found in the Florida Department of Transportation report (FDOT).[2] FDOT specifications provide guidance for void repair procedures.[3]

Temperature and pressure

Internal temperature **Figure 6** shows the temperature of the wax inside the duct over time for each of the five specimens. Figure 2 shows the temperature probe positions. In general, the sudden increases in temperature indicate the times at which the front of the filler reached the instrumentation. For instance, in the injection 1 specimen, which was injected end to end, the filler arrived at the temperature probes in sequential order: T1, T2, T3, T4, T5, T6, and T7. In specimens injected from the low point, the filler flowed in opposing directions, away from the injection point, and the arrival times (as interpreted from the sudden rise in measured temperature) are therefore less intuitive, though similarly revealed.

The peak temperature measured by a particular gauge does not necessarily correspond with the arrival time, suggesting that the flow was turbulent and that the filler material filled the duct unevenly. Gauge T1 from injection 1, for example, was the first location to register increased temperature but did not measure the maximum temperature until after the filler had reached all gauge locations, approximately 4.5 minutes after the injection started. This suggests that although probe T1 (nearest the inlet) experienced a temperature increase at the initial arrival of the hot filler, a backflow of the filler material occurred after the material reached the far probe (T7).

After initial contact with each thermocouple probe, temperatures generally decreased rapidly as the heat was transferred to the prestressing strands. The rate of temperature decrease slowed once equilibrium was attained between the flexible filler and the strands. The measured temperature decrease of subsequent temperature probes illustrates the cooling of the filler along the tendon length. Thermocouples in the parabolic profile (T3 and T4) had a slower rate of temperature decrease and typically settled at a higher temperature than the in other thermocouples. This is attributed to their orientation in the top of the duct at the high point of the profile, clear of the strand bundle. Thermocouples in the straight profile were oriented at 90 degrees from vertical, located near the strand bundle. The proximity of the probe to the strand bundle in these locations accelerated the rate of temperature decrease.

Surface temperature The surface temperature of the HDPE duct was measured at seven locations (**Fig. 7**) and exhibited a similar trend at all measurement locations and for all injections. At the start of the injection, measured

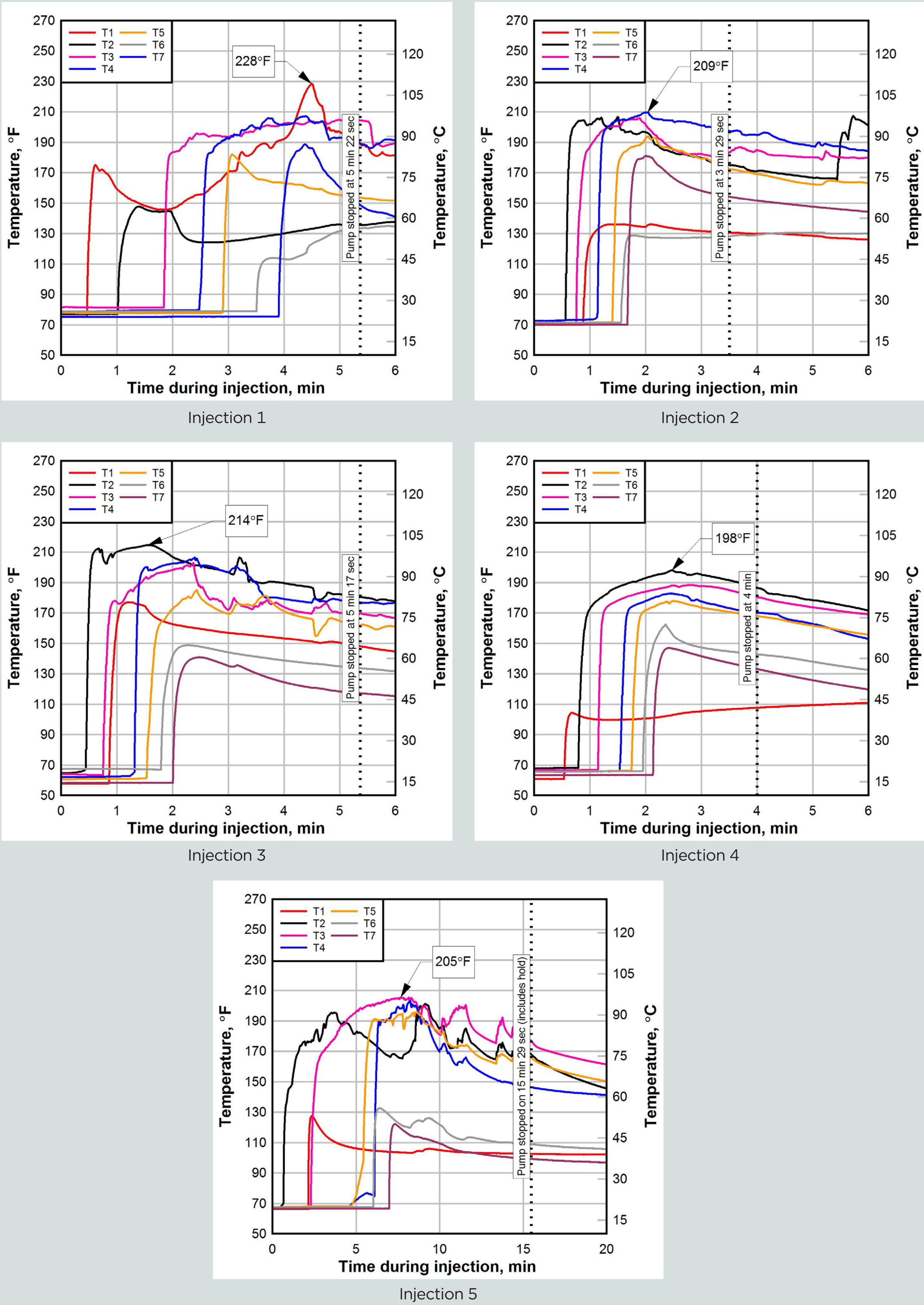
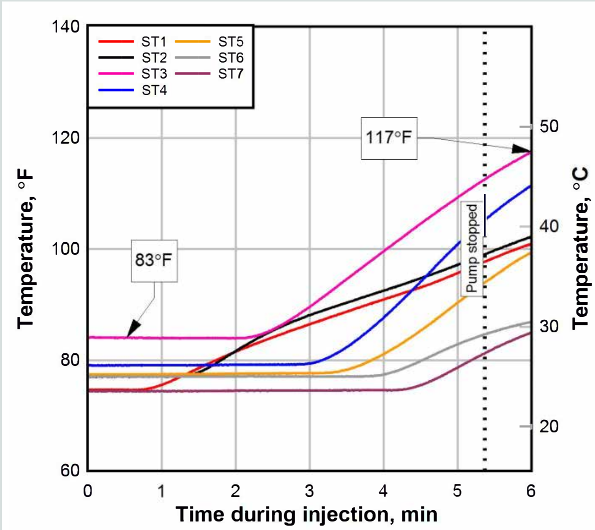
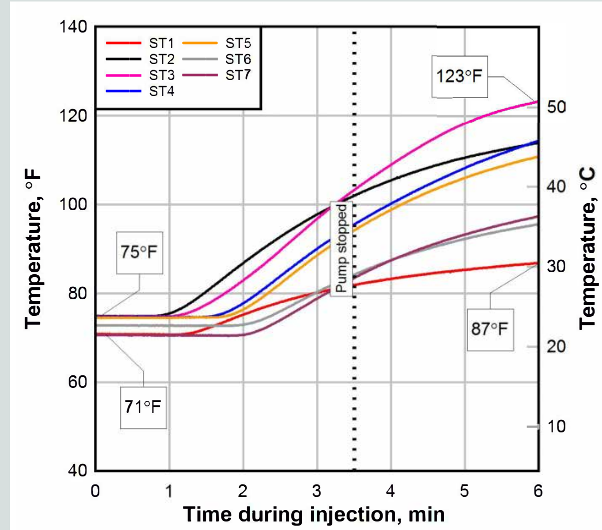


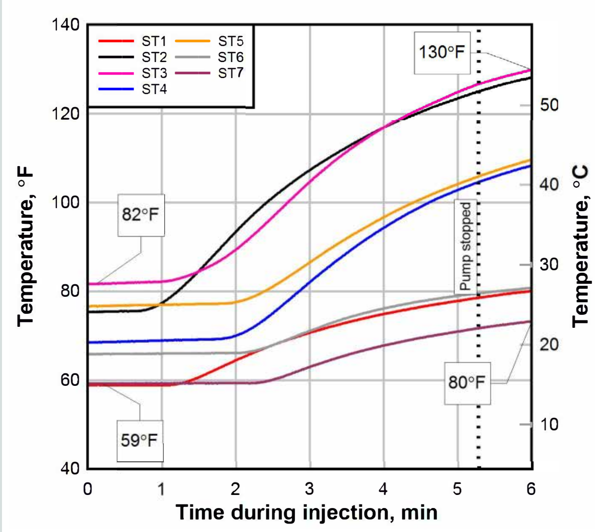
Figure 6. Filler temperature during injection. Note: °C = (°F - 32)/1.8.



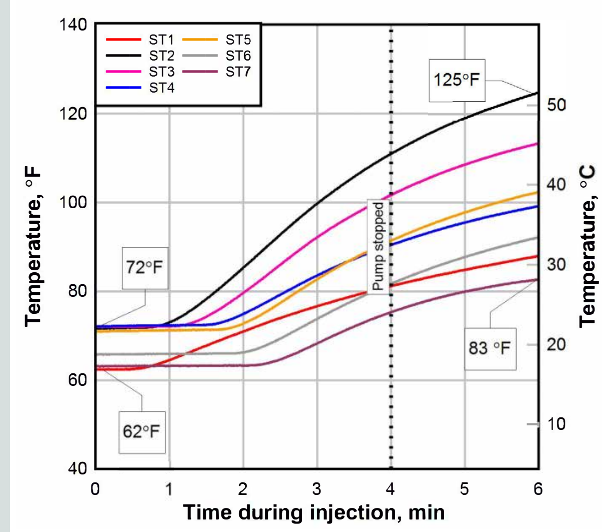
Injection 1



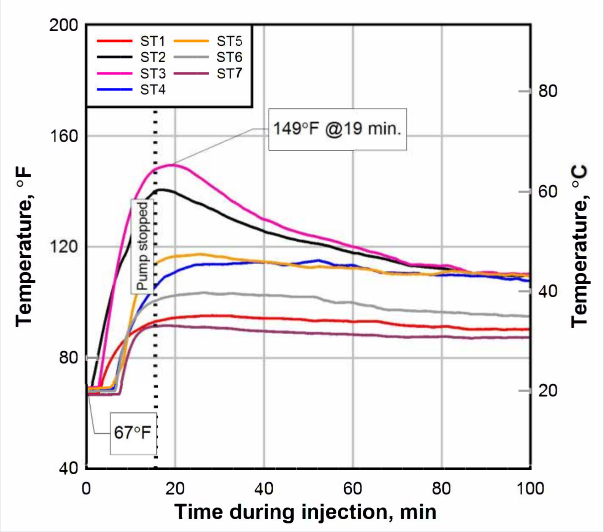
Injection 2



Injection 3



Injection 4



Injection 5

Figure 7. High-density polyethylene surface temperature during injection. Note: °C = (°F - 32)/1.8.

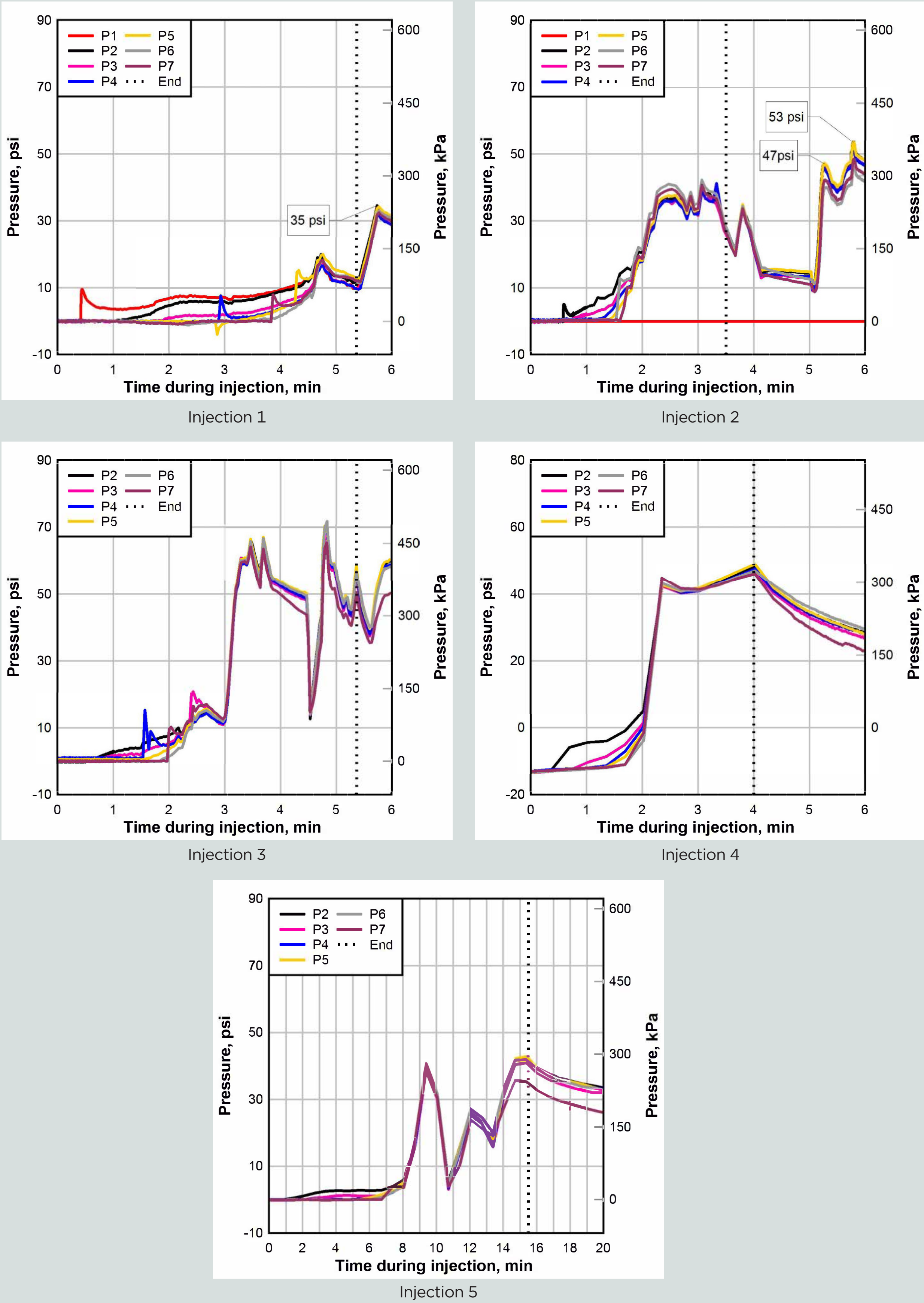


Figure 8. Internal duct pressure during injection. Note: 1 psi = 6.895 kPa.

surface temperatures were near the ambient air temperature and immediately started rising as the filler passed the probe. Temperatures plateaued at varying temperatures, depending on the orientation and location of the surface-mounted thermocouples. In general, surface temperatures measured on the bottom of the duct (ST1, ST6, and ST7) were lower than the surface temperatures at other locations. ST3 and ST4 showed the highest temperatures because they were installed at the top of the duct and had the highest elevation among the surface-mounted thermocouples.

Pressure The internal pressure of the duct was measured at seven locations **(Fig. 8)**. Maximum internal pressure for the duct was limited to 75 psi (520 kPa). The plots indicate that there was little variation in the pressure readings among the individual pressure gauges (P1 through P7 measured approximately the same internal pressure) along the length of the duct during the post-injection hold period.

During injection, the internal duct pressure was 10 to 20 psi (70 to 140 kPa) for injection 1 (using the hopper-fed grout pump) and 40 to 70 psi (280 to 480 kPa) for injections 2 through 5 (using the centrifugal pump). These differences were attributed to the pumping equipment, selected injection point, and pumping and venting technique, not to the filler material or post-tensioning hardware.

Similarly, the duct hold pressure varied. The hold pressure was 34 psi (230 kPa) for injection 1 and 40 to 50 psi (280 to 340 kPa) for injections 2 through 5, again due to variation in technique and equipment. Gauge P1 malfunctioned during injections 2 through 5.

Figure 8 illustrates the internal duct pressure during injection 4, which was accomplished with vacuum assist. The plot also indicates pressure buildup in the tendon once the filler crossed the P7 location. During injection, the vacuum in the tendon was -13.5 psi (93.1 kPa) and the hold pressure was approximately 45 psi (310 kPa).

Comparison with typical grout injection procedures

The injection of flexible filler presents some key differences compared with typical grout injection:

- A modified safety protocol and additional personal protective equipment is required to work with the heated filler material.
- A method of heating and circulating the filler material close to the injection site is required.
- If vacuum assist is used, a vacuum test must be performed.
- Elimination of active vents and the use of vacuum assist reduce the number of personnel stationed along the tendon length during the injection, as well as the amount of filler waste.
- The lower viscosity of the heated filler material may require lower injection pressures.

There are also several similarities:

- Air pressure testing is similar to that performed for grout injections.
- The duct and tendon must be dry (not damp) before the start of the operation.
- Materials must be stored properly on-site, away from moisture.
- Equipment and hoses must be cleaned thoroughly to prevent clogging.
- Clear communication and planning is critical to a successful, safe injection.

Conclusion

Four commercially available, alternative filler materials were selected and injected into deviated 200 ft (61 m) mock-up post-tensioning tendons to investigate the constructibility and nuances of handling and injecting flexible fillers. The tendons were composed of 19 prestressing strands with 0.6 in. (15 mm) diameter, which were prestressed (approximately 1 kip/strand [4 kN/strand]) to mimic the relative positioning of the strands and duct as they would be in field conditions. Temperature and pressure were measured during and after injection to assess the procedure and the filler behavior. Injection rates and venting procedures were varied among the five mock-up injections, primarily to determine the most suitable injection approach. Post-injection inspection of the interior of the tendons assessed the relative fill of the tendon and the presence of voids. Several conclusions can be made:

- The vacuum-assisted injection procedure minimized observable voids and material waste, as well as reduced the personnel required, making this the preferred method later adopted in the FDOT specifications.
- Despite the variation of procedures and materials, voids were localized, usually minor, and in no cases exposed the strands or anchorages. These voids are thought to be the result of the venting procedures and not a function of the post-tensioning system or individual filler products used.
- In all cases, all strands in the tendon were well coated with filler material.

- From a procedural standpoint, no significant differences were found to suggest that one flexible filler material or post-tensioning system is preferable to another.

- Injection of post-tensioning tendons can be successfully accomplished through slight modifications to the currently prescribed grouting procedures.

Subsequent development of a simplified heat transfer model was validated against the experimental work described herein to compute the decrease in temperature of the moving filler front during injection as it cools while interacting with the surrounding strands and duct. The developed model provides a tool for the determination of injectable tendon lengths and required pressures for various conditions.[4] Subsequent vacuum-assisted injections of flexible filler material in concrete beam specimens further demonstrated the effectiveness of the FDOT-adopted procedure.[2] Further research is needed, including investigation of the effects of extreme temperatures on injections of flexible filler at a local level and the effect of voids on strand integrity.

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Abstract

This paper presents the results of five mock-up injections of post-tensioning tendons with flexible filler material. The objective of the mock-up injections was to assess standard grout injection procedures for use of flexible filler materials instead of cementitious products. The focus was on developing an understanding of the procedural aspects and injection equipment of the injection. Each 200 ft (61 m) long tendon had a deviated profile to simulate strand and duct placements and inclination angles found in typical segmental box girders and internal tendons of drop-in spans (parabolic). Each tendon was composed of 19 prestressing strands with 0.6 in. (15 mm) diameters (with nominal pretensioning of approximately 1 kip/strand [4 kN/strand] to achieve the desired profile), a smooth high-density polyethylene duct, a commercially available flexible filler material, and a post-tensioning anchorage system. Variables included the injection procedures (pumping equipment, flow rate, injection pressure, inlet/outlet location, and venting), the post-tensioning anchorage system, and the filler material. Internal duct pressure and surface temperature, as well as filler material temperature, were measured during and shortly after injection. Despite procedural variations and the use of various filler materials, all prestressing strands in every mock-up injection were well coated with filler material, as observed in next-day dissection of the tendons. This work influenced the subsequent development of specifications for flexible filler injection procedures.

Keywords

Flexible filler, injection, post-tensioning, tendons.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

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