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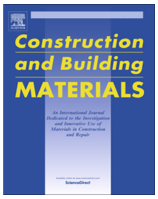

A thermal analysis of flexible filler injection for unbonded post-tensioning tendons

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HIGHLIGHTS

- Heat transfer model is presented to compute the rate of cooling of PT tendon fillers.
- Multiple experiments were conducted with varying injection parameters and fillers.
- Sensitivity of flexible filler temperature to various injection parameters is studied.
- Critical guidance for avoiding flow clogging and tendon constructability is provided.
- Recommendations are made for selecting injection parameters for unbonded tendons.

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ABSTRACT

Grout is widely used in bonded post-tensioned bridge construction as an anti-corrosive material for protecting the steel strands. Several occurrences of tendon failures in U.S. bridges, however, have led to an interest in unbonded tendons where a flexible filler, such as wax, grease, or gel, is injected into the tendon duct instead of cement grout. In general, the consistency of these flexible fillers in ambient temperature falls within the realm of semi-solids and, thus, they are not readily injectable without preheating. A major concern with flexible filler injection is, therefore, maintaining an adequately elevated filler temperature to keep the material's viscosity sufficiently low for complete filling of the duct and to avoid a blockage that might result in a burst pipe or duct. This paper presents a simplified heat transfer model that computes the decrease in temperature of the moving filler front during injection as it cools while interacting with the surrounding strands and duct. The proposed model has been validated by multiple mockup experiments conducted with different filler materials and injection rates. A comprehensive parametric study has been conducted to determine the sensitivity of the filler front temperature to several practical factors, such as effective strand surface area, tendon length, injection rate, ambient temperature, injection temperature, and number of strands in a tendon system. The required minimum injection pressure for different flow velocities and tendon lengths has also been determined. The experimental results confirm the model's applicability to a wide range of tendon lengths and strand patterns, and its usefulness in determining tendon constructability.

1. Introduction

Post-tensioning (PT) tendons can be either bonded or unbonded, categorized based on tendon's contact with the surrounding concrete. After installation and stressing of the tendon, the space in the duct is typically filled with cementitious grout. Grout provides both bond and corrosion protection to the prestressing steel; tendons surrounded by grout are referred to as bonded tendons. Alternatively, though much less common in the U.S. than in Europe for multi-strand tendons, the duct space can be filled with a non-cementitious material, such as petroleum wax, grease, or gel, which provides corrosion protection without bond; tendons using these filler materials are referred to as unbonded tendons.

In the U.S., unbonded PT tendons are most commonly found in office and residential buildings, parking structures, and nuclear reactor containments [1,2]. In Europe, however, unbonded tendons

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are also utilized in silos, pedestrian bridges, and major highway bridges [3]. Bonded post-tensioning is more common in U.S. bridges because it offers several advantages over unbonded post-tensioning, such as higher ultimate strength, greater structural redundancy, and the requirement for less reinforcing steel, allowing a more efficient design. However, a series of corrosion-induced tendon failures have occurred in bonded systems over the past few decades [4], resulting in a heightened interest in using unbonded tendons. Unlike the grout in bonded construction, which hardens once cured, the flexible filler injected into the unbonded tendon duct does not transfer bond. The use of flexible fillers in lieu of cement grout, therefore, not only makes maintenance and repair (e.g., replacement of corroded strands) easier but also presents a unique opportunity to monitor the deteriorating tendons [5–11].

Using an injection pump, the flexible fillers are typically injected into the tendon either through the anchor cap located at one end (Fig. 1) or through a pipe saddle attached to the duct. These fillers are typically semi-solid at ambient temperature and, therefore, are not readily pumpable. To allow the fillers flow into the duct, the container barrels are heated with barrel heaters attached to their outer surface. After preheating the pump and ensuring that all the vents and valves are in appropriate orientation, the pump is started to begin injection. As the filler is injected, it flows through the duct and strand bundle, which are initially at ambient temperature conditions. If the tendon is long, sufficient heat transfer may occur from the hot filler to the strands and duct, causing the filler front (fore end of the flowing filler) to drop temperature and increase viscosity. This increased viscosity may lead to a blockage that generates excessive pressure in the duct system, resulting in cessation of injection and possible damage to the duct and other injection equipment.

A significant concern with flexible filler injection is, therefore, the increase of filler viscosity during cooling as the filler hardening may render it unpumpable. Consequently, it is imperative that the filler maintains a sufficiently elevated temperature to ensure low viscosity during the entire duration of injection. The low filler viscosity ensures complete filling of the duct and the spaces between and around the individual prestressing strands. Achieving these desired results requires that the injection must, therefore, proceed as quickly as possible; the injection rate should be set as high as possible, but without causing undue system pressure or introducing turbulence. Consequently, having a sound knowledge of the change of filler temperature during the pumping process is critically important for successful injection operation. This emerging area of research, however, has received little attention until now, and to the authors' knowledge, no published work addressing this issue is currently available in the literature.

This paper focuses on developing a heat transfer model based on energy balance principle to compute the change in flexible filler temperature during injection. After validating the model with multiple experiments, an extensive sensitivity analysis was performed to obtain practically useful relationships between filler front temperature and effective strand surface area, tendon length, injection rate, ambient temperature, injection temperature, and strand pattern. In addition, pressure losses for different flow velocities and tendon lengths were estimated, which can be used when determining the injection locations and discharge points.

2. Development of heat transfer model for flexible filler injection

A thermal model has been developed to compute the decrease in filler temperature as it moves away from the injection port. Based on conservation of energy, the model aims to estimate the difference in bulk temperature, which represents energy average conditions [12], between two locations along the tendon length (Fig. 2). The model primarily considers forced-convection heat transfer between filler, strands, and duct, and does not take into account the portion of energy transfer through conduction or radiation. These assumptions have been considered reasonable for filler injection given the high-speed nature of injection process, which typically ranges 40–100 ft/min (12.2–20.5 m/min) [1]. In addition, the model assumes the filler flow to be laminar, although some flow turbulence is expected due to the presence of prestressing strand bundle inside the duct and the deviated profile of tendons commonly encountered in practice. Considering a tendon

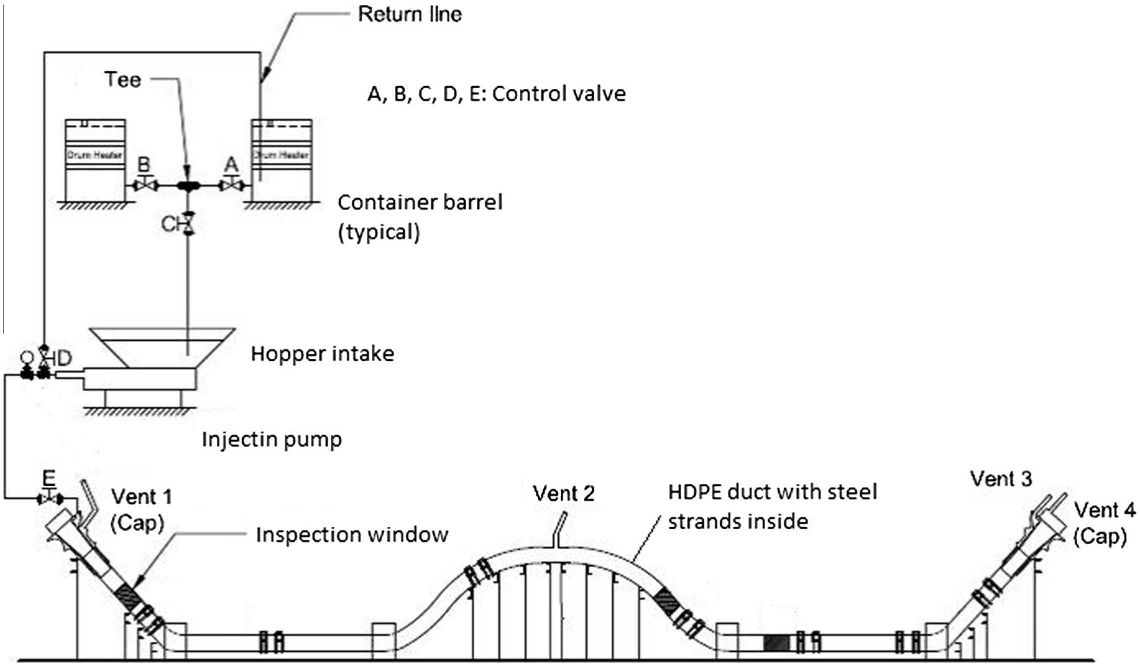

Fig. 1. Schematic of flexible filler injection process.