

Review on the Determination of Sulfate Ion Concentrations in Deficient Post-Tensioned Grouts

Rutambara Sonawane,
Samanbar Permeh,
and Kingsley Lau
Florida International University
10555 W. Flagler St., Miami, FL 33174

Ron Simmons
and Matthew Duncan
State Material Office
Florida Department of Transportation
5007 N.E 39th Ave. Gainesville, FL 32609

ABSTRACT

Severe corrosion of steel strand in post-tensioned tendons developed in several bridges in Florida and Virginia in the 1990s and recently in the 2010s. The corrosion that developed in the 2010s was associated with segregated grout that was characterized by elevated sulfate concentrations and alkaline pore water pH. Recent specifications by the Florida Department of Transportation include sulfate measurements. However, the characteristics of the grout can be significantly different depending on the level of grout deficiency. The paper reviews different methods to sample the pore water of physically deficient grout to measure the free sulfate ion concentration.

Keywords: Grout, Post-Tension, Corrosion, Pore water, Sulfate

INTRODUCTION

The prestress construction technology has certain advantages in construction and economy and has been widely utilized for highway bridges in the last several decades. In bonded post-tensioned systems, the high-strength steel strand is tensioned within tendon ducts after placement of the concrete structural elements, and the ducts are then filled with cementitious material called grout. The grout pore water has an alkaline pH that allows the steel to passivate and protects the embedded steel from active corrosion. Although there has been overall good use of post-tensioned (PT) bridge constructions in last three decades, various challenges with the application of PT have been documented, especially regarding to corrosion.

PT construction has been a significant part of the American infrastructure for more than 50 years. Bridges utilizing neat grouts had material deficiencies, notably in the form of grout voids and bleed water that led to corrosion of the steel strand. The Niles Channel Bridge (18 years of service), Mid-Bay Bridge (7 years of service), and the Sunshine Skyway Bridge (20 years of service) are some of the examples of PT bridges with severe strand corrosion relating to grout deficiencies.¹⁻² The westbound span of the James B. Edwards Bridge in South Carolina was closed in May 2018³ and the Roosevelt Bridge in Florida was closed in June 2020⁴ for some time due to the corrosion of post-tensioned tendons.

More recent grout material specifications in the 2000s required new bridge construction to use pre-packaged thixotropic grouts with non-bleed characteristics to mitigate the development of the corrosion that developed in neat grouts. However, some corrosion failures continued in Florida and were related to the formation of segregated grout even when using thixotropic grouts. Notably, the Ringling Bridge had tendon failures after only 8 years of service due to corrosion.⁵ More than 10% of the external post tensioned tendons (that were filled with a prepackaged thixotropic grout) needed to be replaced. The corrosion that developed in the Ringling Bridge in Florida in 2011 was not directly associated with grout voids, bleed water, carbonation, and chlorides but rather with the physically and chemically deficient grout.⁵⁻¹¹ The total chloride content in the deficient grout was low to moderate but below levels conventionally attributed to corrosion initiation and the pH of the segregated grout was typically greater than 12. Rather, the deficient grout had high moisture content and elevated sulfate concentrations measured as high as 10,000 ppm.⁵⁻⁶

Laboratory research showed that the early presence of sulfate ions in saturated calcium hydroxide solutions (pH 12.6) can impair the development of steel passivation.¹²⁻¹⁴ On these tests of steel strand in segregated grout with elevated sulfate concentrations, the strands exhibited corrosion. Furthermore, it was shown that the concentration of sulfate ions can be accumulated in the deficient grout without external sources¹⁴⁻¹⁷ These observations indicated that there is a need to address the level of sulfate ions in segregated grout.

Test methods to assess the chemical deficiency of segregated grout have only just started to be implemented. Notably, there is consideration to assess to the robustness of grout materials to segregate by implementing higher levels of mix water in grout testing. This paper reviews some of the efforts to assess grout segregation and the level of sulfate-ion accumulation.

CAUSES OF DEFICIENT GROUT

Defects in the PT duct and improper detailing at joints and vents may lead to water and air intrusion and recharge. At these locations, the excessive presence of entrapped water may create regions of deficient grout by overwatering during the curing stage or by allowing the intrusion of external chemical contaminants such as chlorides.¹⁸ Access to atmospheric carbon dioxide may allow for localized grout carbonation to occur.

Moreover, proper grout mixing, batching, and pumping are critical to ensure appropriate grout quality for protection from corrosion. Incomplete or improper grouting and entrapped air can cause voids to form within the PT ducts. Interstitial spaces in between the braided wires of the steel strand may not be filled with the grout and may affect the transport of the grout, water, and air such as by capillary action to further exacerbate the development of grout bleeding and segregation. Increased pressure due to the grout mass within the grout column of vertical tendons or tendons with a vertical rise can cause more grout deficiencies where segregation of grout components of various densities can form. Modified inclined tube test and inverted tee test showed that vertical deviations allowed for grout and water displacement to create regions of grout deficiencies with elevated moisture^{14,19} and sulfate content¹⁶. Research by Hamilton¹⁹ and Permehe et al.¹⁴ indicated that excess mix water allowed for some grout materials to have significant segregation at high elevation points. Hamilton described the adverse effect of grout pre-hydration on grout quality.¹⁹ In the Ringling Bridge, the tendon failures coincided with the segregated grout found at high tendon elevations (although some steel corrosion in similar segregated grout was found at some low elevation locations as well), and the segregated grout was differentiated from hardened grout by its high water content, low cement content, and the difference in the accumulation of filler material and silica fume.⁵

REVIEW OF METHODS TO ASSESS DEFICIENT GROUT

Grout Cylinders

Grouts from various test conditions (15-20% excess mix water) were made and formed in standard 4-inch diameter molds to differentiate the extent of grout segregation. Grout material from the segregated layers was sampled and tested by Perme et al.¹⁴⁻¹⁵. These test samples identified higher sulfate levels in the upper segregated layers. However, differentiation of the segregated layers was not easily identifiable or sampled. The most segregated grout often formed a thin layer of physically deficient grout less than 1 cm. Examples of cast cylinders with the grout exhibiting stratified layers are shown in Figure 1.

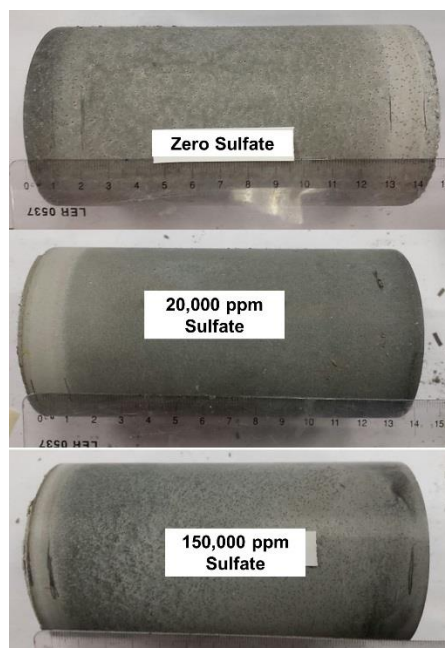


Figure 1: Example of stratified grout from cylinder molds.¹⁴

Modified Inclined Tube Test

The modified inclined tube test (MIT) is a large-scale laboratory mockup test that includes pumping grout within a duct with a vertical incline to assess grout bleeding and segregation. A 4-inch diameter, 15-ft long PVC pipe (tube) is placed at a 30-degree incline. Grout is pumped upwards from the lower elevation into the tube. During the pumping, the valves at the outlet and inlet are closed sequentially to prevent material loss and to ensure full encapsulation. An example of the MIT is shown in Figure 2. Testing by Hamilton¹⁹ introduced 15% excess mix water and assessed the level of grout deficiency by measuring the moisture content of the grout sampled from locations at the top of the tube. Testing by Perme et al.¹⁶ also introduced 15% excess water but compared the chloride and sulfate levels of the grout from the upper and lower elevations. It also monitored corrosion of steel corrosion probes placed along the length of the tube. Those research efforts showed that this test setup can promote the formation of a deficient grout (>20% moisture and >0.001g/g sulfate) at the upper elevation of the tendon.



Figure 2: Example of the modified incline tube test.

Inverted Tee Test

The inverted tee test was developed by Permeh et al.^{14, 20-21} as a small laboratory test to promote water displacement such as in the MIT. The test specimens consisted of a PVC tee ($2 \times 2 \times 1\frac{1}{2}$ " ϕ , 4 $\frac{3}{4}$ "length) filled with grout, mixed with 20% excess water and varying concentration of chloride and sulfate additions. The large change in surface area from the tee body to the tee header allowed for a compact accumulation of moisture where the grout material could be differentiated. The chloride and sulfate levels were found to be transported with the displaced water to the deficient grout in the tee header. The corrosion activity of steel probes in the tee header was differentiated from steel probes in the tee body¹⁶.



Figure 3: Example of deficient grout in the INT.

Grout Bleed Test

ASTM⁽¹⁾ C940²² describes a wick-induced bleed test, (also outlined in PTI⁽²⁾ M55²³ section 4.4.8). Test specimens for this test consist of a transparent tube, seven-wire steel strand, and dry grout/cement ingredients with water. Transparent tubes are positioned vertically and filled with the dry ingredients mixed with the water in the tube to a height of 1000 mm high and a 1000 mm length of a seven-wire steel strand is then inserted. The top level of the grout is marked as the initial grout volume. Separation of water from the solid phase indicates the level of bleed water formation and is expressed as the percent of the initial grout volume.

¹ ASTM International (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959

² Post-Tensioning Institute (PTI), 38800 Country Club Dr., Farmington Hills, MI 48331