Development of Deficient Grout and Corrosion due to Water and Solute Transport

Rutambara Sonawane, Samanbar Permeh, and Kingsley Lau

Civil and Environmental Engineering, Florida International University,

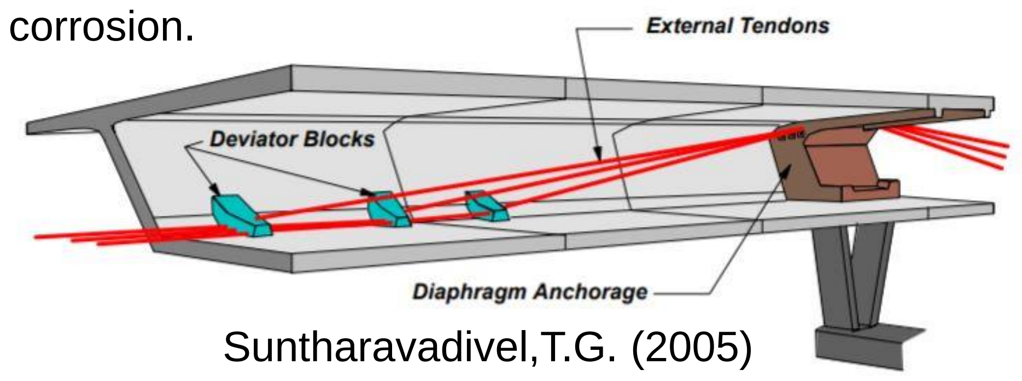
Miami, FL-33174

Abstract

Prestressed concrete has been used all over the world for bridge construction, but severe corrosion of steel strand in post-tensioned tendons has been documented. Recently, the corrosion was associated with physically and chemically deficient segregated grout with elevated moisture and concentrations of aggressive chemical species that allowed for early aggressive corrosion to develop. The transport of moisture and ionic species was thought to be related to capillary transport through the braided steel wires, but other transport mechanisms within the tendon duct may be possible as well. The grout mass pressure within grout column increases the hydrostatic pressure in the system. Vertical elevation of the grout with hydrostatic pressure of grout mass may elevate the moisture content at higher elevations. The paper reviews the results of lab and field testing characterizing deficient grouts and the various transport mechanisms that can be form in post-tensioned tendons, including modeling efforts of unsaturated flow and solute transport using HYDRUS-1D.

Introduction

- Prestressed concrete has been widely used for highway bridges.
- Post-tensioning – Strand tensioned after placing of the concrete.
- Ducts are filled with cementitious material called as grout that protects steel from corrosion.



Suntharavadivel,T.G. (2005)

- ➢ Consequent revisions in the grout material and construction specifications as bridges failures documented due to corrosion.

History

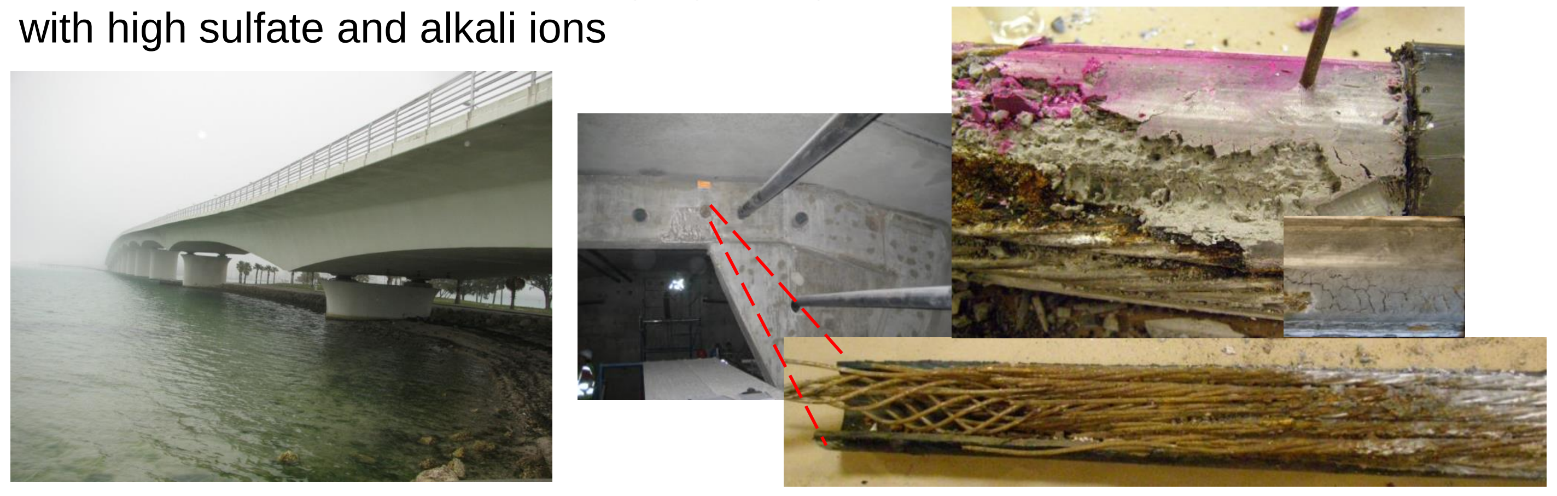
Bleed Water and Grout Void

- Prior to 1990s, corrosion attributed due to moisture and chloride ion penetration.
- After 1990s, corrosion attributed to improper duct filling with voids due to development of grout bleed water.
- In early 2000s, thixotropic grouts were developed but isolated corrosion cases of tendon were observed.

The Ringling Bridge

- Tendon failure after only 8 years of service due to corrosion and more than 10% external tendons were replaced.
- Investigation of the cause of unexpected failure of post-tensioned tendons utilizing updated thixotropic grout products.
- Corrosion mechanism not fully explained by chloride and carbonation induced corrosion, bleed water, and voids

➢Corrosion was related with segregated grout characterized as a moisture-rich with high sulfate and alkali ions

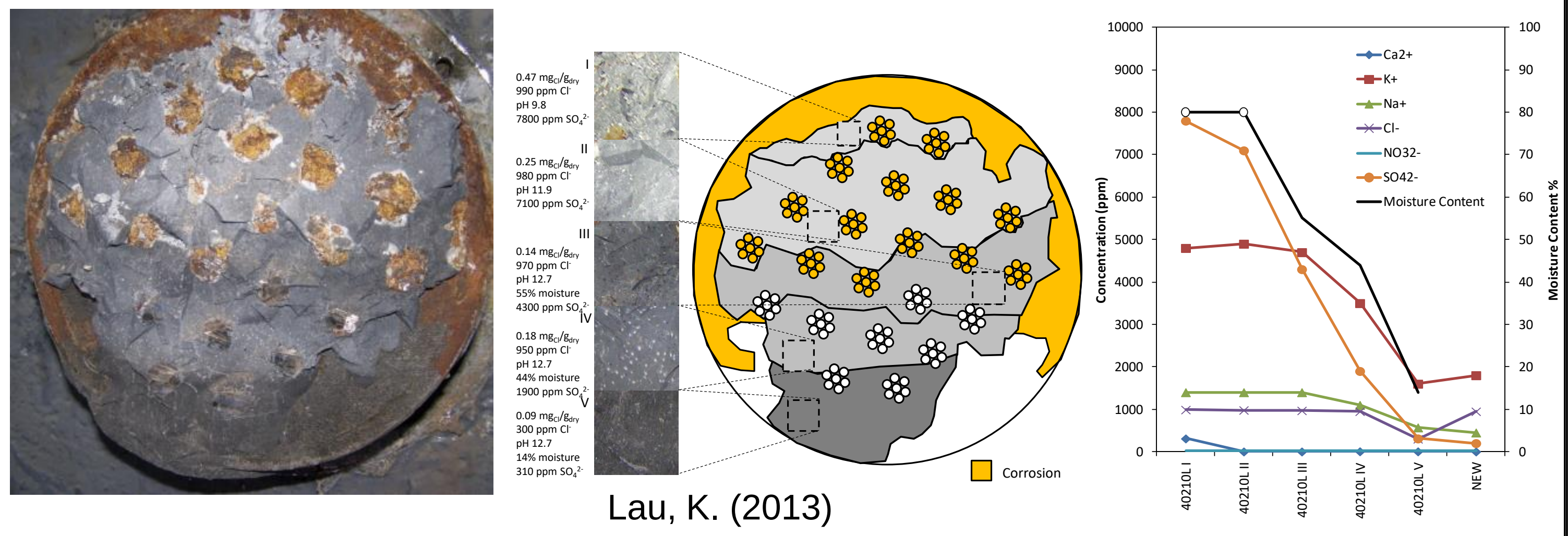


Lau, K. (2016)

Background

- As per previous research of Hamilton and Permeh et al., excess mix water allow grout material to segregate at high elevation points.
- Soft Grouts

Observed segregated grout had high sulfate ion in saturated calcium hydroxide solutions. Sulfate ion concentration, low chloride high moisture content and pH.



Lau, K. (2013)

Lab Testing

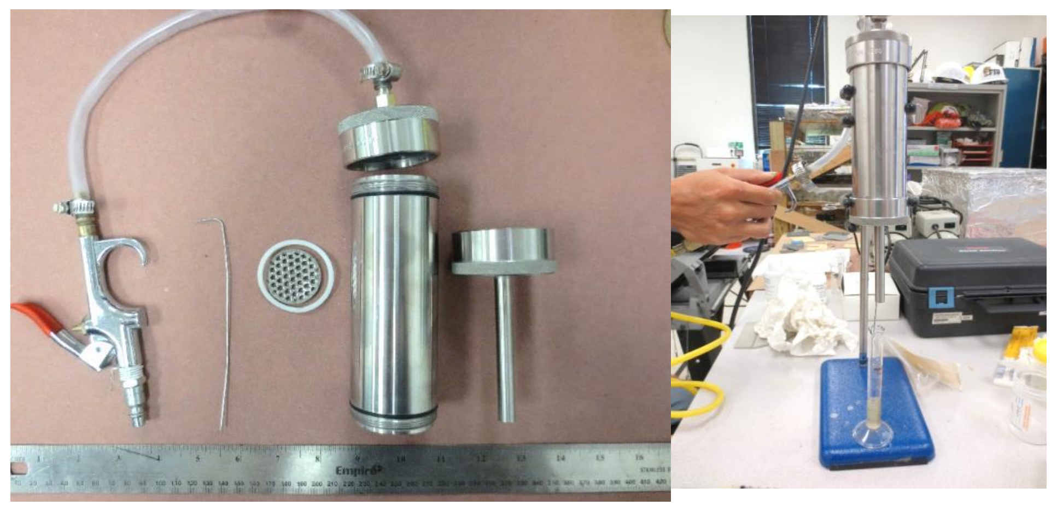
Modified Incline Tube (MIT) Test

- This is a large-scale laboratory mockup test.
- This test includes pumping grout within a duct with a vertical incline to assess grout bleeding and segregation.
- Research by Permeh et al. 2016 showed that this test setup can promote the formation of a deficient grout at the upper elevation of the tendon.

Permeh, S. (2016)

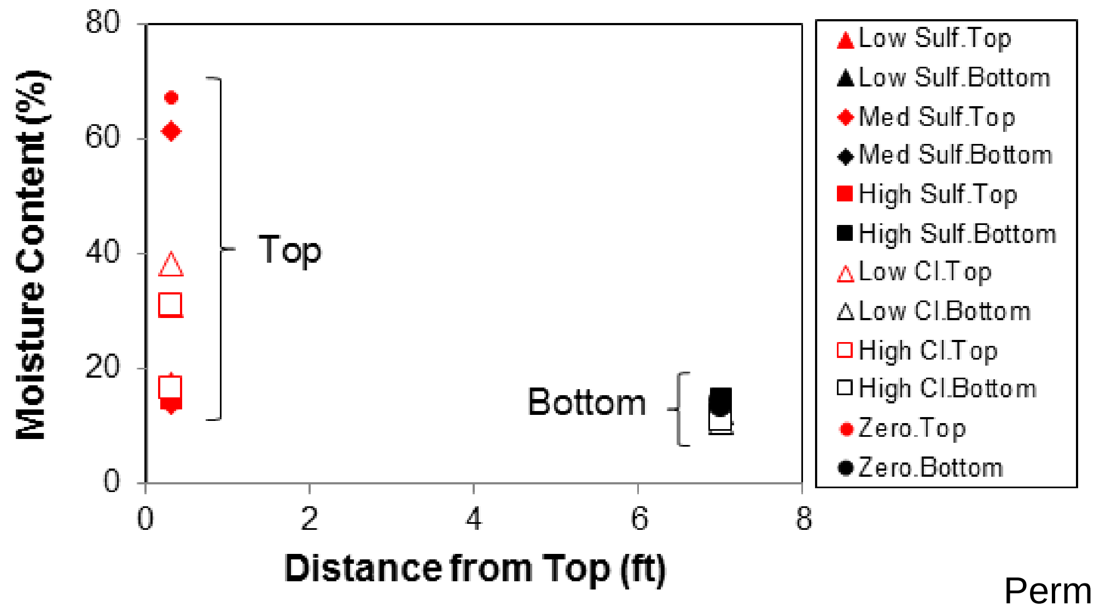
Schupack Bleed Water Test

- Grout bleed test is an effective and practical way of testing grout mixes for bleed resistance.
- Modified Schupack pressure bleed test conducted to extract grout solution. Excess mix water (20%) and pressure 100 psi tested.



Moisture and Sulfate Ion Content (MIT)

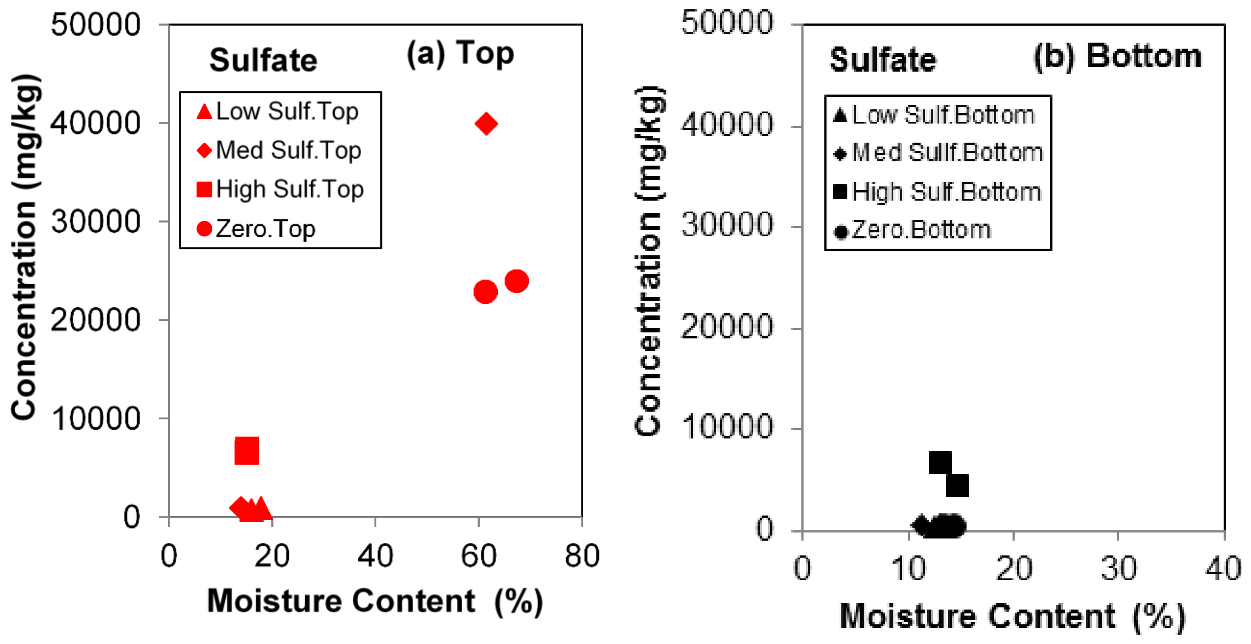
- Results from the modified incline tube testing by Permeh et. al, 2021 showed that the moisture content was higher at the upper elevations of the test specimen.
- Correspondingly, the sulfate ion concentrations were elevated in those locations with higher moisture content.



Moisture Content

Permeh, S. (2021)

- Moisture mobility caused by compression during grout hydration significantly increased the upward mobility of water in tendons which also resulted in upward mobilization of ions.
- Permeh et al., 2021 posited that the moisture mobility caused by compression and grout hydration increases the ion mobilization by advective transport (upward mobility of water in tendon).

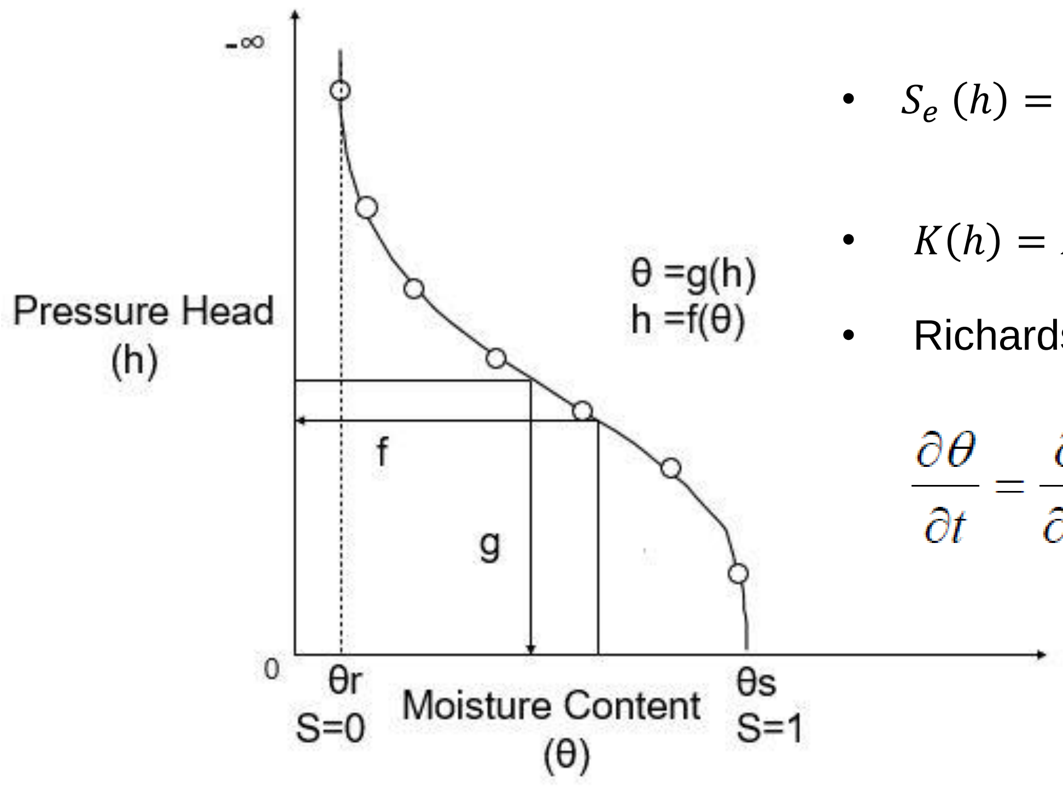


Sulfate Content

Permeh, S. (2021)

Transport in Porous Media and Introduction to HYDRUS-1D

- Linear finite element model
- Numerically solves Richards' equation for saturated and unsaturated flow
- Numerically solves advection-dispersion equations for solute transport
- Moisture content vs pressure head curve is used in the Hydrus solution of the Richards equation to solve for the transient pressure, water content evolution, and the unsaturated flow in a porous medium subject to boundary conditions.
- The unsaturated medium hydraulic properties are described with the equation of van Genuchten (1980) in the HYDRUS code.
- Van Genuchten-Mualem equation for hydraulic parameters:



Water Retention Curve

- $S_e\,(h) = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = (1+|\alpha h|^n)^{-m}$
- $K(h) = K_s S_e^{0.5}[1-\left(1-S_e^{\frac{1}{m}}\right)^m]^2$
- Richards Equation

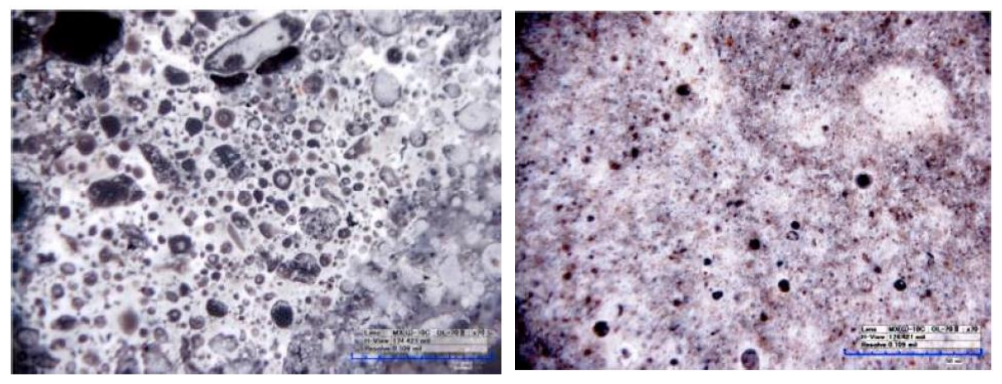
$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x}+\cos\alpha\right)\right] - S$$

Where,

- Se = Degree of saturation
- K_s = Saturated hydraulic conductivity;
- K(h) = Unsaturated hydraulic conductivity;
- (θ_r) = Residual water content;
- (θ_s) = Saturated water content;
- α, n, and m are derived from the graph (water retention functions).

Related factors in segregated grout.

- Variable water content ranging from saturated to non-saturated conditions.
  - Hardened Grout 20%
  - Segregated Grout up to 85%
- Variable grout porosity (hardened grout vs deficient grout).
  - Hardened grout ~20%
  - Segregated grout has lower cement content.



Wet plastic grout

Hardened grout

Micrographs contrasting wet, plastic grout to hardened grout.

Permeh, S. (2016)

- As per Schupack (2002), grout in a taller duct will experience larger hydrostatic pressures.
- These factors can affect the water retention characteristics of the grout.
- Ionic transport was posited to be facilitated by the transport of water.

Future Work

- Implementation of modeling using Hydrus-1D to consider deficient grout characteristics in progress to identify possible transport mechanism for water and sulfate ion accumulation.

References

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