Transportation Consortium of South-Central States (Tran-SET)

Modeling Sulfate Attack in Modern Concrete for Building Sustainable and Resilient Infrastructure

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Developing a reliable approach to analyzing the external sulfate attack in concrete structures

External sulfate attack is known to be the most widespread and common form of chemical degradation of concrete infrastructure and requires extensive rehabilitation within a few years of construction. In spite of numerous studies done in this field, damage due to sulfate attack is still not fully understood because of its complex mechanism and varied effects induced by different sulfate solutions. While experimental investigations indicate expansion as a damage parameter, softening of the concrete surface and mass loss due to spalling are widely considered in the field. Moreover, the accelerated experiments lack credibility due to their inherent limitations associated with the changing pH, and the unrealistically high concentration of sulfate ions and temperatures. Existing models account for expansion of concrete and crystallization pressure developed by expansive crystal growth due to long-term exposure, but do not consider the osmotic suction effect caused by the spatial gradient of the solute concentration in the pore solution. In this work, poroelastic theory has been applied to demonstrate the effect of osmotic suction on the crack initiating tensile stresses in concrete exposed to sulfate solutions. It has been found that high instantaneous tensile tangential stress can be developed at the concrete surface when the specimen is exposed to sulfate solution. This stress can be attributed to the strain differential and pressure gradient caused by the osmotic suction.

Problem Statement

Sulfate attack (as shown in Figure 1) is known to be the most widespread form of chemical degradation of concrete that appears in regions where concrete is exposed to soil or water containing sulfates. External sulfate attack has led to numerous studies, both experimental and theoretical, due to its complicated nature. Experimental determination of concrete susceptibility to sulfate attack involves long-term immersion of concrete specimens in sulfate solution. While these tests that require months to perform and manifest damage in the form of large expansion, field investigations indicate evidence of high stresses at surface leading to cracks or softening and disintegration of the cement matrix. The alternative recommended accelerated tests do not mimic the field conditions.

Figure 1. Concrete structure damaged by sulfate attack.

Little data are available for modern materials for which increasing substitution of cement is utilized to reduce energy consumption and environmental emission. For example, cement with low tricalcium aluminate, as prescribed by the design code to withstand damage caused by the sodium sulfate solution, may prove detrimental when exposed to magnesium sulfate or sulfuric acid.

Therefore, a mechanistic-based fundamental model is required to account for the effect of the variability in raw materials and sulfate-bearing solutions on the damage propensity by sulfate attack. A mechanistic model will allow engineers to understand the underlying mechanism (both expansion and spalling) dictating the damage evolution process by sulfate and guide them to develop new binding materials and build economic and durable infrastructure.

Summary

The diffusion of external sulfate ions triggers degradation of material immersed in sulfate solution through the pore network of concrete located in the geologic environment rich with sulfate ions. The diffused sulfate ions then react with the hydrated and unhydrated cement matrix components and form expansive agents, which expand upon precipitation. However, in field structures, mass loss due to surface spalling is also observed. A fundamental understanding of such damaging process that can accurately explain expansion and spalling is critical for building durable infrastructure resilient to aggressive agents.

Due to the complex nature of sulfate attack and varied effects caused by different sulfate bearing solutions, several models were developed in the past. However, none of these models account for the osmotic suction effect caused by the gradient in the salt concentration in the pore solution. The osmotic suction is defined as the difference in pressures exerted by solutes on either side of a semi-permeable membrane due to the spatial gradient in the solute concentration. The objective of this project is to assess the effect of osmotic suction on the stress and strains developed in concrete exposed to sulfate deformation.

The proposed work utilizes poroelasticity to develop a coupled linear elastic model that accounts for the difference in pore pressure driven by the gradient in solute concentration. A cylindrical concrete specimen saturated with pure water is assumed to subject to sulfate solution of a given concentration.

Findings

The simulated pore pressure, bulk strain, tangential stresses are plotted in Figure 2. As the specimen contains no solute in the pore solution, a sudden exposure to the salt solution creates a spatial gradient in the solute concentration. As a result, high osmotic suction is developed at the boundary which draws solvent molecules (water) from the specimen center to surface. Since concrete is a weakly permeable material, water takes a long time to drain to the surface to equilibrate with the boundary pressure. As a result, boundary contracts more than the center that exhibits higher pressure than the surface (Figure 2a). This differential strain across the radial position develops instantaneous high tensile tangential stresses at the boundary as shown in Figure 2b.

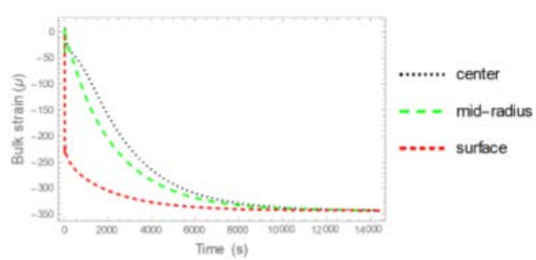

Figure 2a. Bulk strain pressure in a cylindrical concrete specimen exposed to 6% Na2SO4 solution.

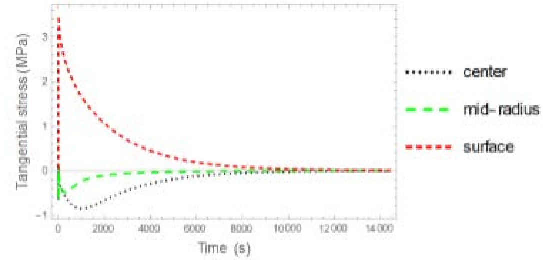

Figure 2b. Tangential stress developed in a cylindrical concrete specimen exposed to 6% Na2SO4 solution

This high stress has a potential to create micro-cracks in the surface, which may exacerbate the problem when the expansive agents are precipitated in the pore network accompanied by the diffusion of sulfate ions and may lead to flaking of materials. It is expected that the osmotic suction plays an important role in the deformation of concrete exposed to sulfate solution.

Impacts

This research project incorporates a new mechanism, the osmotic suction effect, to demonstrate short-term damage mechanism in concrete surface exposed to sulfate solution. It is shown that the osmotic suction can cause significant pressure gradient and high tensile stress at the surface within a few hours of exposure. This modeling approach is novel to the transportation research community and can be applied to other durability problems including salt damage caused by wetting and drying cycles, alkali-silica reaction, and salt scaling caused by freezing and thawing cycles. It is expected that incorporation of the osmotic suction in the modeling approach will help engineers understand the complex damaging mechanism of sulfate attack and other distresses of concrete induced by salt solutions.

Tran-SET

Tran-SET is Region 6's University Transportation Center. It is a collaborative partnership between 11 institutions (see below) across 5 states (AR, LA, NM, OK, and TX). Tran-SET is led by Louisiana State University. It was established in late November 2016 "to address the accelerated deterioration of transportation infrastructure through the development, evaluation, and implementation of cutting-edge technologies, novel materials, and innovative construction management processes".

Learn More

For more information about Tran-SET, please visit our website, LinkedIn, Twitter, Facebook, and YouTube pages. Also, please feel free to contact Mr. Christopher Melson (Tran-SET Program Manager) directly at transet@lsu.edu.

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