

March/April 2009

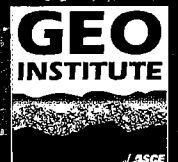
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Heave Distress Problems in Chemically-Treated Sulfate-Laden Materials

By Anand J. Puppala, Ph.D., P.E., M.ASCE and Amy Cerato, Ph.D., P.E., M.ASCE

Expansive unsaturated soils, found in every state, cover one-fourth of the United States. These soils undergo large amounts of heaving and shrinking due to seasonal moisture changes. These movements lead to cracking and buckling of the infrastructure built on the expansive soils and result in billions of dollars of damage annually. A recent study showed the cost of damage to homes due to expansive soil was approximately \$13 billion per year.

Although not life-threatening or cataclysmic as compared to other natural events, expansive soils are certainly a natural hazard. And with the exception of Hurricane Katrina, which caused about \$25 billion in damage, expansive soil damage exceeds the average annual damage caused by floods, hurricanes, earthquakes, and tornados combined. Surprisingly, expansive soils are frequently overlooked as a major problem because they often take years to cause extensive damage. In reality however, expansive soils are a widespread and costly natural hazard.

Currently, the most economical and accepted method of stabilizing expansive soils used as fill is to add lime to the soils before compaction. This method reduces the soil's plasticity and its ability to undergo volume change when wetted or dried. Lime stabilization increases the soil's bearing strength and permeability, reduces potential volume changes and the maximum density, and results in a stronger compacted soil mixture that will react less, or not at all, to changing moisture conditions.

However, a problem has been observed with lime stabilization of soils that contain soluble sulfates. Sulfate-bearing, cohesive soils are found in several states in the U.S., in particular throughout the southwestern and western states. The primary source of soil sulfates is gypsum, a common rock-forming

mineral classified as an evaporite that forms as a precipitate from lakes and sea water. When calcium-based stabilizers (i.e., lime, cement kiln dust, or fly ash) are added to sulfate-bearing soils, reactions cause the volume change potential to increase, creating a soil mixture that is more expansive than the soil alone.

The combination of sulfates in the soil, calcium in the stabilizer, aluminum in the clay structure, and water create calcium-aluminate-sulfate-hydrate minerals, such as ettringite. Ettringite is a mineral that holds large amounts of water in its structure, and has the potential to swell 250 percent.

Sulfate Heaving Mechanisms

Sulfates are present in natural soils in various forms such as gypsum or calcium sulfate, sodium sulfate, and magnesium sulfate. Each sulfate-type mineral has a different solubility level, which implies that the reactivity of sulfates in

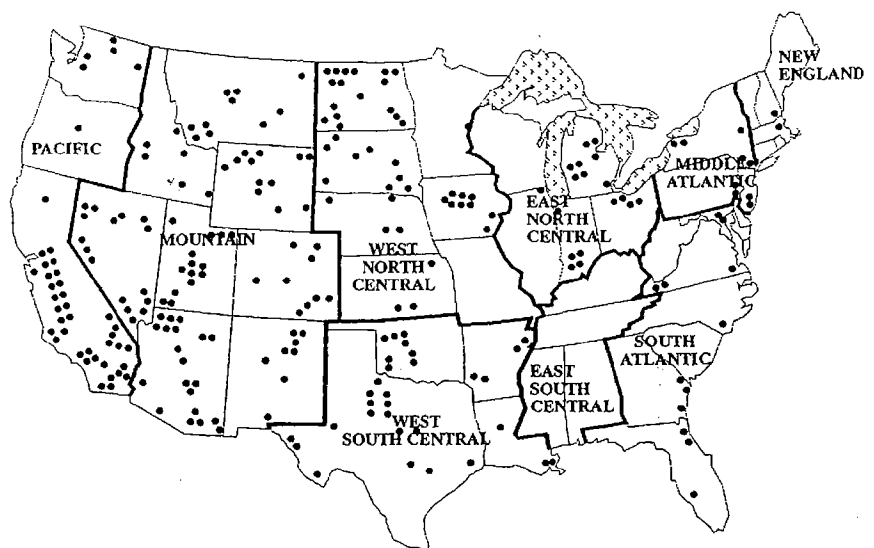


Figure 1. Locations of sulfate-bearing soils (gypsum mines) in the U.S. (Kota et al., 1996)

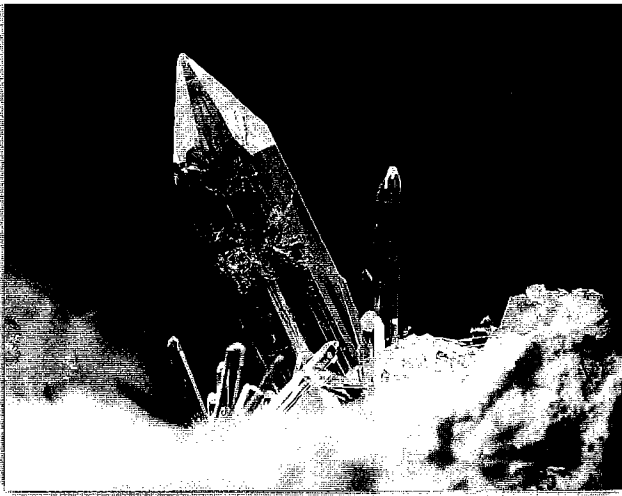


Figure 2. Ettringite crystal.

soils depends on their solubility and the amount of moisture present. Gypsum is the most common sulfate mineral in soils because of its relatively low solubility level (2.6 gm/L) when compared to both sodium sulfate (408 gm/L) and magnesium sulfate (260 gm/L).

When sulfate-rich soils are treated with calcium-based stabilizers, the sulfates in the soils will react with the alumina (possibly in amorphous structure) liberated from the clay particles and the calcium component from the stabilizers to form a combination series of calcium-aluminum-sulfate hydrate compounds. These compounds will lead to the formation of ettringite crystals, which can expand to two or three times their original size when subject to hydration.

Once the ettringite crystal is formed, it continues to grow in almost pure form. The minerals will also expand due to continuous crystalline material growth. Both hydration reactions and crystal growth will result in a significant amount of heaving (reportedly up to 250 percent) in sulfate-rich soils.

When the temperature of the soil-water system reaches less than 15°C with an abundance of soluble carbonate content present, ettringite is transformed by a series of intermediate reactions to thaumasite. This transformation in mineral structure occurs by isostructural substitution of silica for alumina and carbonate for sulfate. A thaumasite crystal is very

expansive when exposed to hydration, and its expansion potential is much higher than that of ettringite.

Overall, the resulting amount of heaving phenomena is primarily a function of the quantity of ettringite formed, the crystal morphology and size, restraint of the system, and ion accessibility. All of these depend on different environmental conditions including pH conditions, the presence of soluble sulfates and carbonates, and water.

Damage Caused by Sulfate-Induced Heave

There are many documented cases of sulfate-induced heave causing damage to infrastructure throughout the U.S. that have resulted in poor performance and considerable reduction in the design life of the affected critical infrastructure.

Waste materials such as phosphogypsum and other sulfate wastes are sometimes used as base and subbase materials to support pavements. These wastes leach sulfate ions, which can increase the sulfate levels in soils. Sulfates can also occur in soils from the construction water used in the projects. Such sulfate levels could potentially lead to heaving when calcium stabilizers are used to stabilize these types of soils. Distress problems are also observed at sites where recycled concrete pavements are used as bases.

Many states, including Kansas, Oklahoma, Nevada, Arizona, New Jersey, Texas, Colorado, and California, have reported structures distressed by sulfate-induced heave. Repair and maintenance costs of heave-distressed problems on earth structures and pavements are reported to be several millions



Figure 3a: Sulfate heave distress on Stewart Avenue in Las Vegas, NV (Hunter, 1988).



Figure 3b. Sulfate heave in pavement section in Joe Pool Lake Area (Courtesy: Les Perrin, US Army Corps of Engineers, Fort Worth District).

of dollars per year; the City of Las Vegas spent close to \$2.7 million to repair and maintain the pavements damaged by sulfate-induced heave in the late 1980s.

Threshold Sulfate Levels

One important answer that is often sought by practitioners is at what soil sulfate level will sulfate heave be a concern. These levels are reported to range between 1,500 ppm and 5,000 ppm, and in some cases close to 10,000 ppm for different types of chemical treatments. Establishment of such levels based on the database of various case studies is not appropriate, as the soil composition and environmental conditions are different in each case study, and findings or observations from one particular study may not be valid at other locations. However, studies are ongoing to determine sulfate threshold levels based on mineralogy and geological depositional environments.

Using the same type and amount of stabilizer at one construction site may not be adequate at another site with the same soil classification

One recent study sponsored by the National Science Foundation showed that the problematic levels vary for cement and lime treatments and their dosage levels. Figure 4 shows various treated soil specimens that were cured prior to strength testing. The specimen on the far right experienced severe heaving during curing, with clearly visible bulging. Based on swell strain magnitudes measured, the problematic sulfate levels varied between 1,000 ppm for soil-cement treatments to 2,000 ppm for lime treatments. Each specimen with different sulfate levels was stabilized with ordinary Portland cement.

Summary

Sulfate-induced heave in lime-stabilized soils is a serious problem that can cause costly infrastructure damage if not addressed. Sulfate-induced heave encompasses complicated chemical reactions within the soil and seems to be depositionally and geologically dependent, making it difficult to determine one threshold level across the country. Soil sulfate tests are being reviewed and modified to enable engineers to accurately test for the presence of sulfates to determine if alternative chemical or mechanical stabilizers are necessary, or if the soil should be removed and replaced.

Current alternatives to lime stabilization in sulfate-bearing soils used in practice include low-calcium fly ash or cement-kiln dust, but questions still remain on how much of these stabilizers is necessary to achieve the correct strength and stiffness in subgrade soils. Using the same type and amount of stabilizer at one construction site may not be adequate at another site with the same soil classification. Studies are being conducted to determine the reasons behind this difference in behavior and to determine other soil parameters that may indicate the variability in behavior. In addition to fly ash and cement kiln dust as alternative stabilizers, a few other recycled materials are being tested, such as Plasti-soil™ and shredded tire rubber, that may prove viable as stabilizers, either alone or with a mixture of a waste chemical.

Many of these stabilizers have shown great promise in bench and field-scale experiments; however, more work must be done to fully understand the strength and stiffness characteristics in a variety of stabilized soils before they can be widely adopted. With improved soil-sulfate testing capabilities and alternative non-calcium based stabilizers, sulfate-induced heave problems affecting our infrastructure should be avoidable.



Figure 3c. Sulfate heave in cross-section of Highway 412 in Woodward, OK (Courtesy: Dr. Jim Nevels, Oklahoma Department of Transportation).

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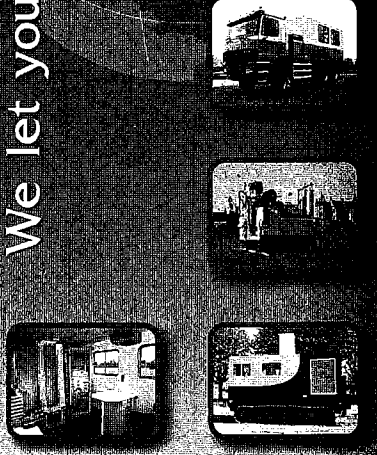
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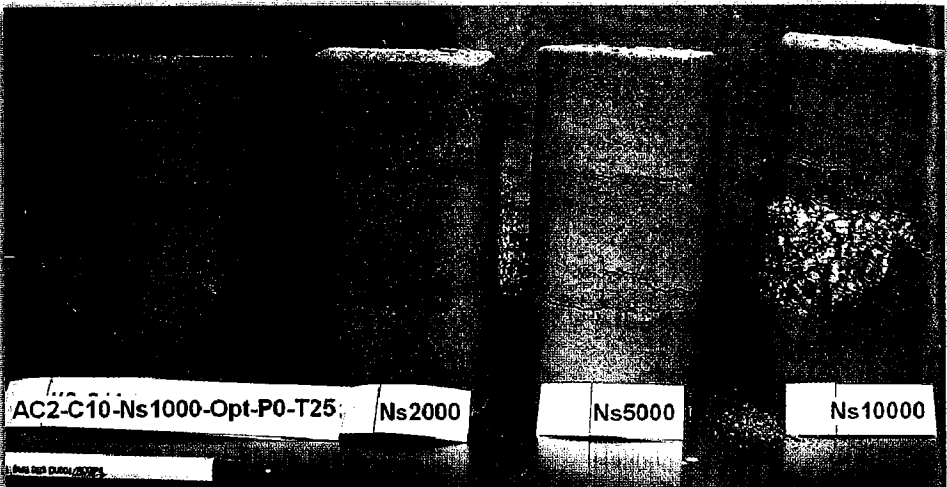


Figure 4. Cement-treated soil samples at different sulfate levels after curing.

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