SOIL STABILIZATION IN HIGH SULFATE SOILS
Summary Findings

CONSORTIUM FOR EDUCATION AND RESEARCH IN GEOENGINEERING PRACTICE

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Background

Sulfate-rich soils treated with calcium-based stabilizers are subjected to sulfate induced heave due to ettringite formation. Several researchers have studied the conditions favoring ettringite formation and proposed guidelines to reduce the risk. The CERGEP members requested a literature review addressing sulfate induced heave due to ettringite formation in soils treated with a calcium-based stabilizers.

What the Researcher did:

Information collected from a review of existing knowledge was completed covering the work of state agencies, federal agencies, global agencies, university research, and private contractor research. This information was summarized in a report. The reference is:

Akula P., Little N.-D., 2020, Soil Stabilization in High Sulfate Soils", CERGEP Report No.12 – SI/US units, Civil engineering, Texas A&M University.

What the Researcher Found:

Ettringite formation

For 1 mole of ettringite to form, 6 moles of Ca^{2+}, 2 moles of Al^{3+}, 12 moles of OH^- and 26 mole of water is required. In soils with high soluble sulfates when lime or similar pozzolanic materials are added to clayey soils, the pH raises and causes partial dissolution of alumina (Al^{3+}) and silica from oxyhydroxides and phyllosilicates minerals. During this process, the Ca^{2+} from lime can react with the dissolved Al^{3+} and ${SO_4}^{2-}$ ions in the presence of water to form ettringite (Equations 1 to 4)

$$\mathrm{Ca(OH)_2} \longrightarrow \mathrm{Ca^{2+}} + 2\,\mathrm{(OH)^-} \tag{1}$$

$$\underset{\text{Sulfate Source}}{\mathrm{CaSO_4 \cdot 2\,H_2O}} \longrightarrow \mathrm{Ca^{2+}} + \mathrm{(SO_4)^{2-}} + \mathrm{Water} \tag{2}$$

$$\underset{\text{Phyllosilicates}}{\mathrm{Al_2Si_2O_5(OH)_4}} \xrightarrow{\mathrm{OH^-}} \mathrm{Soluble\,Alumina} + \mathrm{Soluble\,Silica} \tag{3}$$

$$\mathrm{Ca^{2+}} + \mathrm{Soluble\,Alumina} + \mathrm{{SO_4}^{2-}} + \mathrm{H_2O} \longrightarrow \mathrm{Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26\,H_2O} \tag{4}$$

Sulfate induced heave due to ettringite formation is a complex geochemical and geophysical process and it depends on the following factors factor:

Mineralogy
The formation of ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26\text{-}32\,H_2O$), a calcium-alumino-sulfate mineral in a sulfate-rich soil is dependent on the release of alumina from clays. Minerals such as kaolinite, montmorrillonite and illite, which are predominant in Texas and various parts of the U.S, provide a nominal source of alumia for ettringite formation.

Stabilizer
Popular calcium-based stabilizers include lime and cement. Both stabilizers form strength enhancing pozzolanic products. The rate of reaction to form pozzolanic products is higher in cement as compared to lime. The hydration rate for lime treated soils can vary depending on the mineralogical composition of the soil. It can range from months to a couple years after hydration but in sulfate-rich soils, the mechanism and rate of ettringite are similar. Contrary to the common belief, the use of sulfate resistant cement such as Type V cement does not provide a significant advantage in reducing sulfate induced heave.

Sources of sulfates
Sulfates in soils are usually found in steams and concentrated pockets. Typically, sulfate ions are made available by dissolution from sulfur rich soil minerals such as pyrite, marcasite, gypsum and, anhydrite. In Texas, pyrite and gypsum are the most common sources for sulfate.

Solubility of sulfates
The percentage of dissolved SO_4 in soil can be calculated stoichiometrically. For example, one molecule of gypsum has a mass of 172g and contains 96g of SO_4. If we mix 100g of soil containing 0.3% gypsum with 100g of water, and 5% lime, (CaO), only 1/5th of the sulfates can be solubilized with the mixing/ compaction water.

$$\frac{2.58g\,gypsum}{100g\,soil} * \frac{1mol\,gypsum}{172g\,gypsum} * \frac{96g\,\mathrm{SO_4}}{1mol\,gypsum} * \frac{25g\,\mathrm{H_2O}}{100g\,\mathrm{H_2O}} = \frac{0.036g\,\mathrm{SO_4}}{100g\,soil} = 0.036\%\,\mathrm{SO_4}$$

Variability and Mobility of sulfates
Hydrological processes can influence the variability and redistribution of sulfates in soil. Subsurface runoff and ground water mobility through the soil can transport SO_4 ions. When the water evaporates, dissolved salts with SO_4 precipitates. A higher concentration of sulfates is generally observed in subsurface layers that are permeable, where the processes of moisture infiltration and evaporation and transpiration reach a state of general equilibrium and deposit a higher concentration of sulfates at a specific depth within the pedagogical profile of the soil.

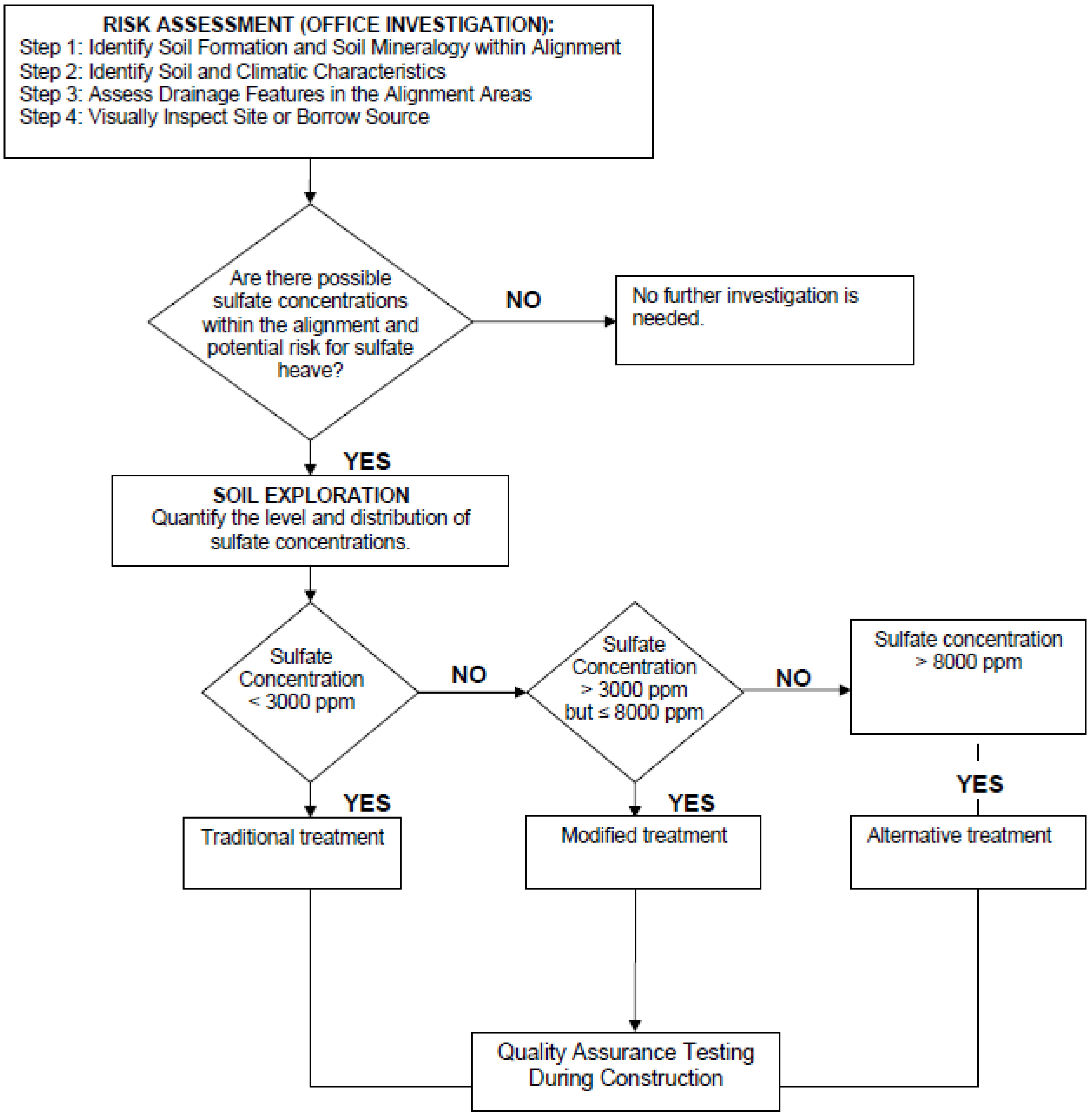
Case studies: Sulfate induced heave

Table 1: Case studies on sulfate induce heave

Project	Soil type	Clay sized fraction(%)	Lime(L)/ Cement(C) (%)	Sulfate content (ppm)	Comments
Stewart Avenue, Nevada	Clay (Non-expansive)	10-55	4.5%(L)	43,500	6 months
Lloyd Park, Texas	Clay (Expansive)	3-18	5%(L)	2,000–9,000	Immediately
Auxiliary Runway, Texas	Clay	-	6-9%(L)	14,000–25,000	2 months
Cedar State Park, Texas	Clay (Expansive)	-	6%(L)	21,200	2 months
Laughlin AFB Runway	Clay (Expansive)	34–63	-(L)	14,000-25,000	Moderate
Denver International Airport, Colorado	Clay (Expansive)	-	-	2,775	NA
SH-118 and SH-161, Texas	Clay	-	4%(C)	>12,000	6 to 18 months
Dallas, Texas	Clay	-	6%-9%(L)	233-18,000	Varies
WES Lab study	Clay (Expansive)	-	-(L)	5,000–12,000	Moderate to severe
Dallas–Fort Worth International Airport, Texas	Clay	-	5%(L)	320– 13,000	3 months
Holloman AFB Taxiway	Clay(Non-expansive)	33-56	-(C)	High	Severe
U.S.82, Texas	-	-	6%(L)	100-27800	Immediately
Georgia Road	Clay (Expansive)	6-13	C	NA	Moderate
Baylor Creek Bridge, Texas	Fine	-	5%(L)	6800-35000	Severe
Pavements in Frisco, Texas	Clay	-	6-8%(L)	500-5000	1 month
Shopping complex, Mississippi	Clay	-	6-80%(L)	100-30,000	Severe(12 months)

Recommendations

Pre-design inspection and treatment methodology play a critical role in determine the risk of sulfate attack. The following flowchart can be used for treating sulfate-rich soils.



Traditional treatment (Soluble Sulfate $\leq$ 3000 ppm)
Regular mix design and construction practices can be implement, but a minimum 24 hours of mellowing is recommended.

Modified treatment (3000 $<$Soluble Sulfate $\leq$ 8000 ppm)

- Single lime application
- Mellowing
- Additional moisture

Alternative treatment (Soluble Sulfate $<$ 8000 ppm)

- No treatment for soils with low swell potential.
- Remove and replace sulfate soils.
- Blending in non-plastic soils.