Guidelines for Treatment of Sulfate-Rich Soils and Bases in Pavement Structures

Construction Division
Materials & Pavements Section
Geotechnical, Soils & Aggregates Branch

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Section 1

Disclaimer

The Texas Department of Transportation, in conjunction with the Texas Transportation Institute, has developed this document to serve as guidance for TxDOT personnel for soil and base treatment in sulfate-rich areas. The information and guidance provided herein reflects the authors' knowledge and experience and may not reflect the views of others. Although much research has been conducted on the subject of the treatment of sulfate-bearing soils and bases during the past several decades, materials, design, and construction techniques are continuing to evolve. This document will likewise evolve.

Direct questions regarding these guidelines to the Geotechnical, Soils, and Aggregates Branch of the Construction Division at 512-506-5907.

Chapter 2
Sulfate Induced Heave

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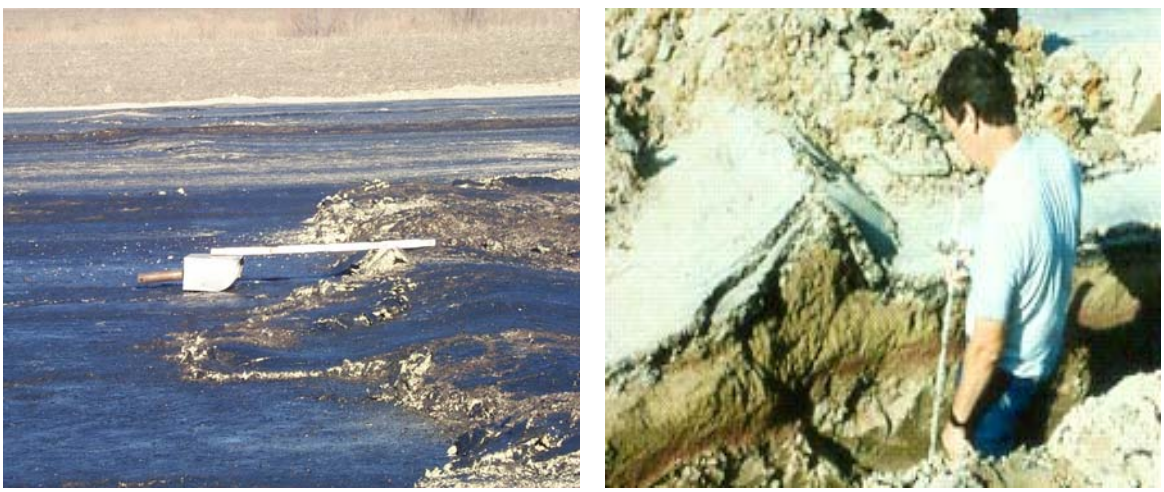
Section 1

Introduction

In general, the use of calcium-based additives (lime, cement, and Class CS fly ash) to treat soils and bases has been performed with success over many years. Over the past 20 years, a phenomenon has surfaced in which many subgrade soils treated with calcium-based additives experience heaving problems due to the chemical reactions with sulfate and/or sulfide minerals and calcium-modified soils, as illustrated in Figure 1. Field observations indicate that the reactions can be very rapid and occur overnight following a single rainfall event. In other cases the reaction is delayed and may take years for the problem to manifest itself in terms of excessive pavement roughness. Research has revealed the rate of the reaction is due to the particle size of the sulfate crystals (finer grained sulfates = faster reaction) and the amount of water present in the system (more water = faster reaction). Sulfate-induced heave has surfaced around the state as well as the country. Texas has experienced heave problems with treated soils containing high sulfate concentrations before completion of construction, as seen in Figure 1(a). Sources of sulfates often occur in seams and stratified pockets, and many of the cases investigated in Texas revealed sulfate problems in small, localized areas, as seen in Figure 1(b). It is not uncommon to have one or two sulfate-induced heaves that are several stations apart on the same project.



(a) (b)

Figure 1: (a) U.S. 67 near Waxahachie during construction, showing vertical heaves generated by lime treatment of sulfate-rich soils (Harris, Scullion, Sebesta, 2004); (b) Illustrates a Localized Heave (Petry, 1992)

Detrimental soil properties, such as shrink-swell and low shear strength, still need to be addressed despite the presence of sulfates. This document will provide guidance on:

- basic mechanisms and causes of sulfate heave,
- risk assessment for sulfate heave potential within an alignment, prior to design,
- use of additives and construction techniques for sulfate levels and prevailing conditions within project alignment, and
- establishing quality management practices for treatment of sulfate-rich soils.

Section 2

Sulfate Induced Heave Chemical Reactions

Sulfate heave is initiated when calcium based additives are used to treat subgrade soils that contain sulfate/sulfide minerals. Research has determined that the cause of heaving is due to the formation of minerals that contain large amounts of water in their structure and reach expansions approximately twice their volume. This mineral is called ettringite. Ettringite is formed when clay minerals, which contain alumina and silica, combine with sulfate minerals, water, and calcium. Calcium-containing additives raise the pH of the system to above 12, which causes dissolution of clay minerals and releases aluminum and silica into the system. Water may be supplied from a number of sources. It may be supplied during the treatment process, occur as precipitation after treatment, or be supplied from the groundwater or adjacent reservoirs. Sulfur is supplied from the sulfide and/or sulfate bearing soils or water. The result of this reaction is the generation of crystals that can expand approximately 2 to 2.5 times their original volume. This expansion is the cause of swell in the treated soil and the pavement structure.

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Treating Subgrade Soils with Sulfates

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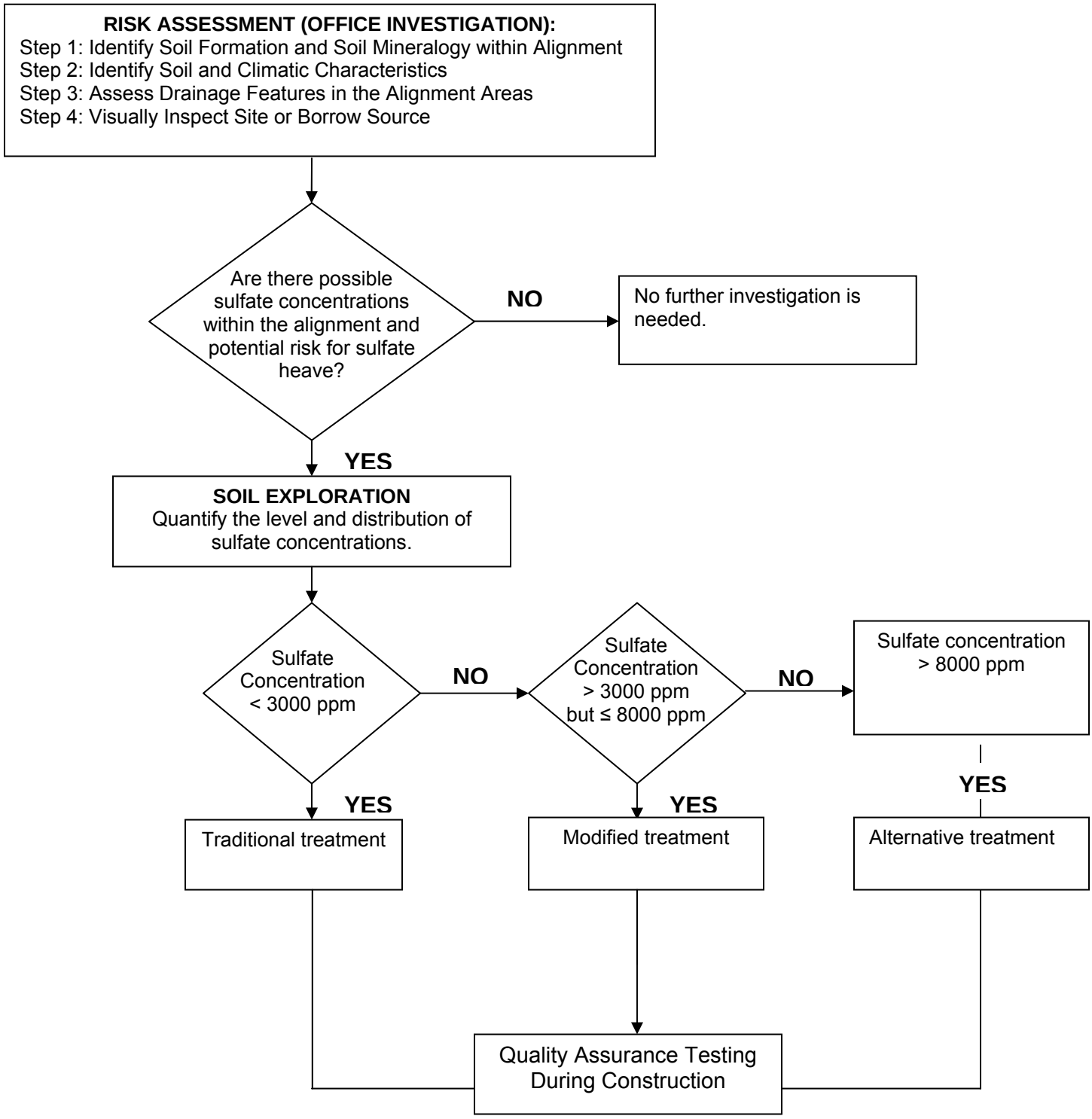
Section 1
Methodology



Section 2

Risk Assessment

Sulfate detection prior to specifying and constructing calcium treated soils is the only means of prevention of sulfate-induced heave. The following is a method to estimate the potential risk for sulfate heave on a project. The goal of the risk assessment process is to reveal potential problem areas within a project. If there is a probable risk for sulfate induced heave within the project, the appropriate level of exploration, testing, and controls can be applied to the project.

Step 1: Identify Soil Formation and Soil Mineralogy within Alignment

The first step in detection is determining the soil formations within the limits of the proposed construction project. Research and forensics data have revealed certain soil formations have a higher probability to possess significant sulfate sources, like gypsum, than others. For example, some of the most severe heaves identified from the Dallas/Fort Worth area to the border counties of Laredo are associated with the Eagle Ford formation, as shown in Figure 2. This formation approximately parallels Interstate 35. Other areas with high sulfate concentrations have been identified around Texas. Counties known to have problematic sulfate concentrations are identified in gold in Figure 2. This map offers a general overview of potential areas with known sulfate heave potential.

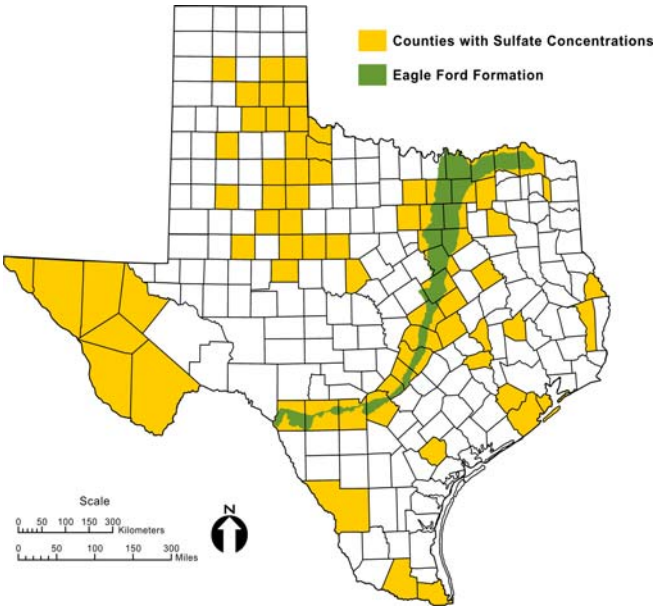


Figure 2: Texas counties with measurable sulfate concentrations (>100 ppm).

Maps from the Bureau of Economic Geology from the University of Texas offer information and assistance in determining the soil formations and mineralogy within the project. The first step is to overlay the alignment of the project on the appropriate Bureau of Economic Geology county map, and identify the soil formations that overlap the alignment of the roadway, as seen in Figure 3.

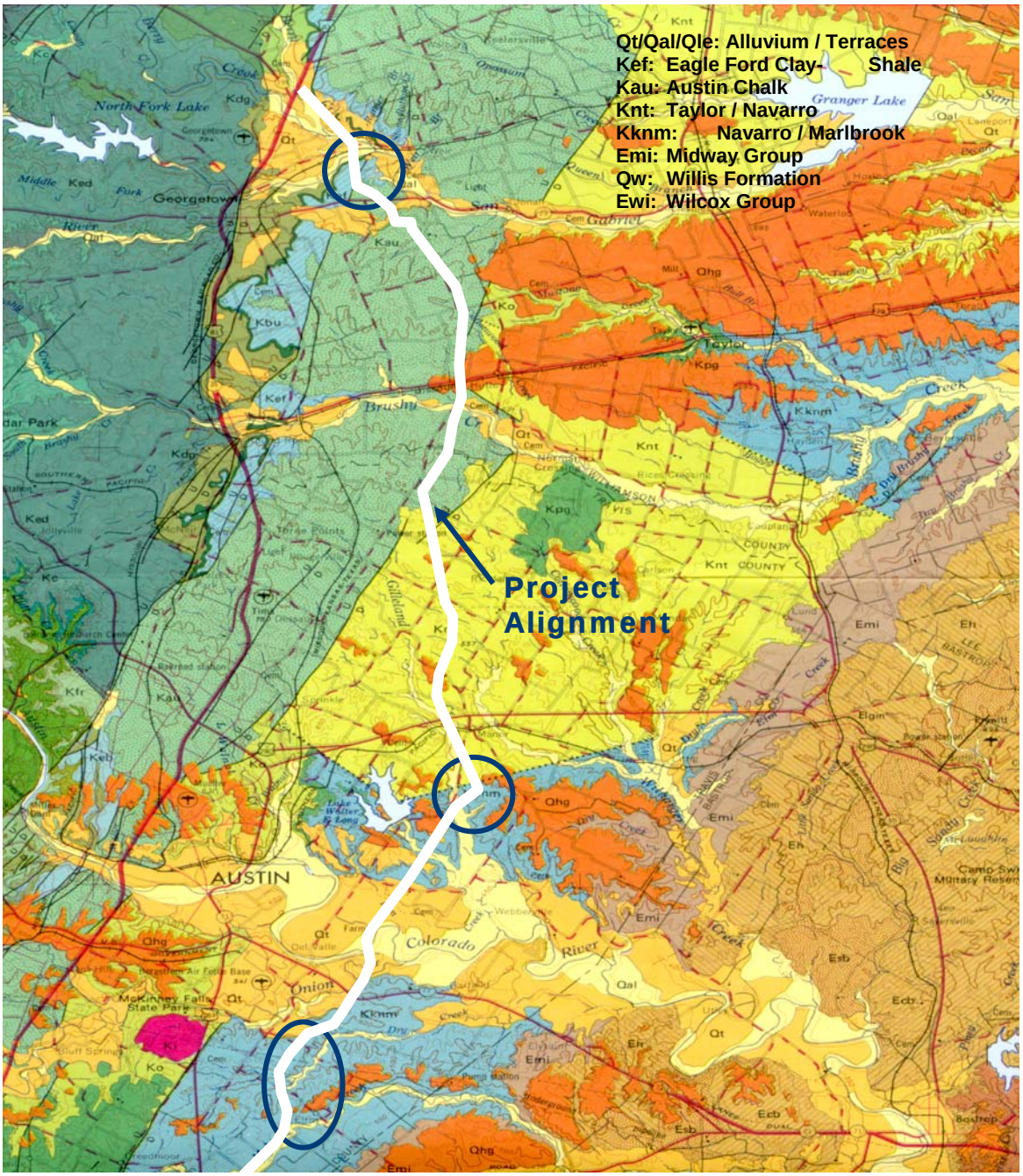


Figure 3: Illustration of a project alignment overlaid on a Bureau of Economic Geology county map.

Once the soil formations within the project alignment are identified, investigate the mineralogical composition of the soil formations. This information is found in the index information booklet that accompanies the geological atlas maps, as seen in Figure 4. The parent rock formation descriptions in the index of these maps provide insight into the mineralogy present in the rock and the soil. The following minerals can be potential sources of sulfate/sulfide minerals:

- Alunite
- Bassinite
- Kainite
- Kierserite
- Mirabilite
- Thenardite
- Arcanite
- Jarosite
- Barite
- Antlerite
- Angelesite
- Pyrite
- Pyritic
- Marcasite
- Marcasitic
- Gypsum
- Gypsiferous
- Selenite
- Selenitic
- Satin spar
- Alabaster
- Anhydrite
- Anhydritic

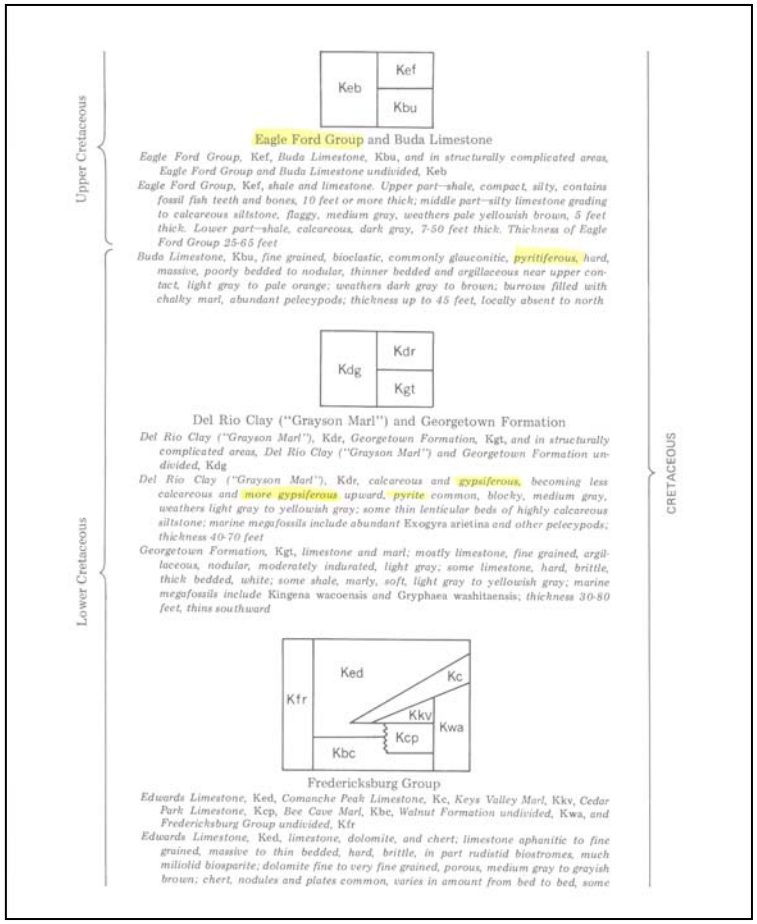


Figure 4: Illustration of the mineralogical index booklet of the geological maps.

Another source of information to identify the potential for sulfate concentrations within an alignment is GIS maps. These maps contain historical laboratory test data obtained from testing performed on previous projects and soil investigations. Unlike the county maps, these maps illustrate the sulfate concentrations on the actual highway and within the limits the data represents, as seen in Figure 5. Higher concentrations may exist within the colored areas representing tested areas due to the variability of the sulfate concentrations. In addition, sulfate concentrations may exist in areas in which the map does not show evidence from laboratory testing. Treatment and construction decisions should not be based solely on the information in these maps. Rather, the maps are meant to provide an indication of the possibility of sulfates in a certain area.

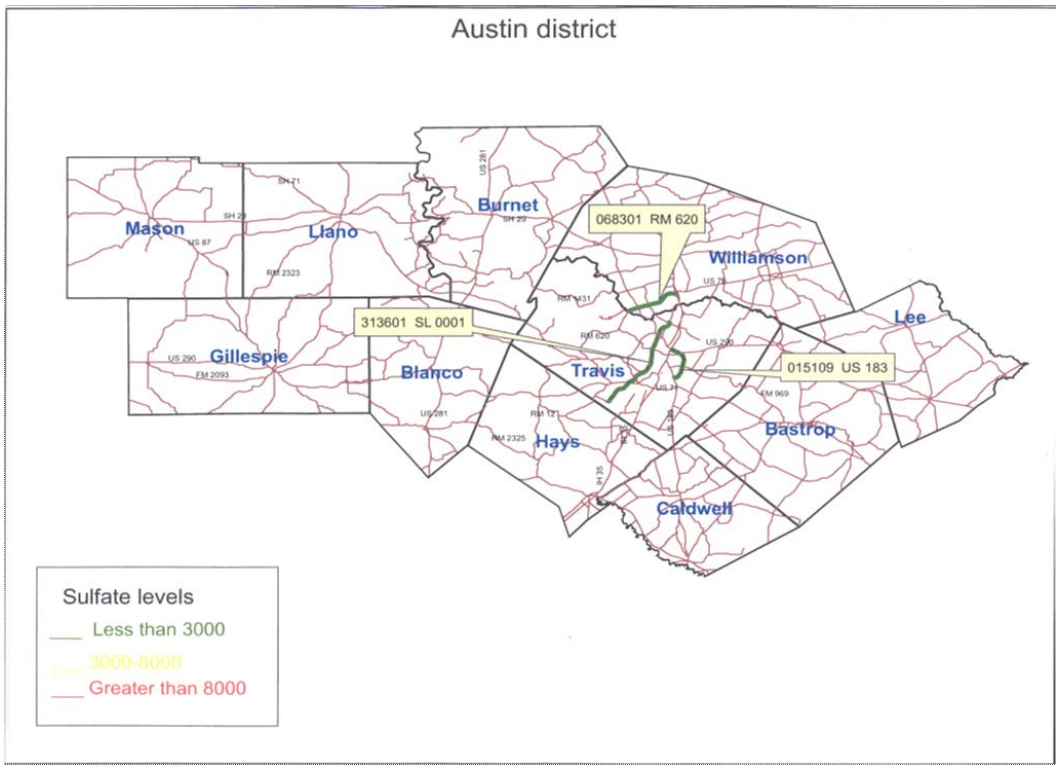


Figure 5: GIS maps of sulfate concentrations on existing roadways.

Step 2: Identify Soil and Climatic Characteristics

Climatic Impact

In order for the formation of ettringite and sulfate heave to occur, the reaction requires access to water. Climatic areas with high annual rainfall and humid conditions contribute to the potential for sulfate formation and in turn, sulfate induced heave. Water can gain access to sulfate minerals through ditches (seepage) and openings in the surface such as cracks or permeable layers in pavement structures. High annual rainfall also raises the water table and transports dissolved sulfates from underlying parent formations, especially in soils with high suction properties (clays). The transported sulfates can then come into contact with calcium treated soils through hydraulic transport or capillary action.

Soil Classification

The classification of the soil can also provide another tool in assessing the potential risk for sulfate outcrops. Soil with low hydraulic conductivities and high capillary or suction properties are prone to serve as reservoirs for growing and storing sulfate bearing minerals. Soil properties like low permeability and high capillarity are typically associated with clays and shales. In soils with low permeability, water cannot readily flow through the soil. Sulfates are not easily dissolved and transported to streams or other areas of lower hydraulic potential. With the high capillary action common in these types of soils, the soil suction can draw water from deeper strata that contain sulfates or sulfides and cause them to oxidize in the upper strata. The end result is that sulfate stagnates in these clay or shale layers, causing high concentrations of sulfate bearing minerals to develop. In addition, during dry conditions, clays and shales can form a network of desiccation cracks and faults into which water can migrate. When they dry out, sulfate crystalline formations remain, as seen in Figure 6.

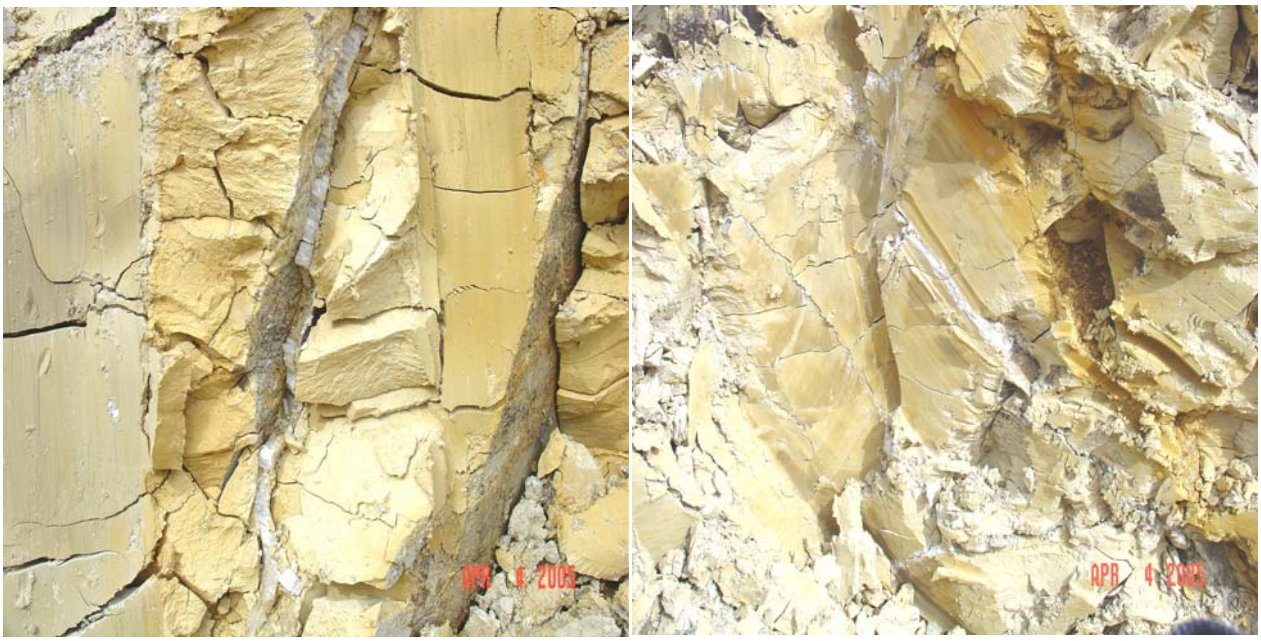


Figure 6: Sulfate crystalline formations in desiccated clay.

High sulfate concentrations can exist in soils such as gravels, sands, and/or silts. Typically this occurs in arid regions such as western regions of Texas. If a calcium-based additive is used to modify a granular material, the risk for sulfate heave is still present.

Step 3: Assess Drainage Features in the Aligning Areas

The availability of water is critical for the formation of ettringite. A project's topographical characteristics must be evaluated for low lying areas, especially in cuts. These low lying areas can accumulate large amounts of water and when combined with calcium-based treatments, may create a high risk for sulfate heave.

In addition, terrain with rolling hills or a project with several slopes can also contribute to the accumulation and availability of water. During drying cycles, sulfates can become apparent on the surface in the form of powdery, white efflorescence. These sulfates can be transported into desiccation cracks in clays or washed down slopes into calcium-treated layers in roadways, as seen in Figure 7.

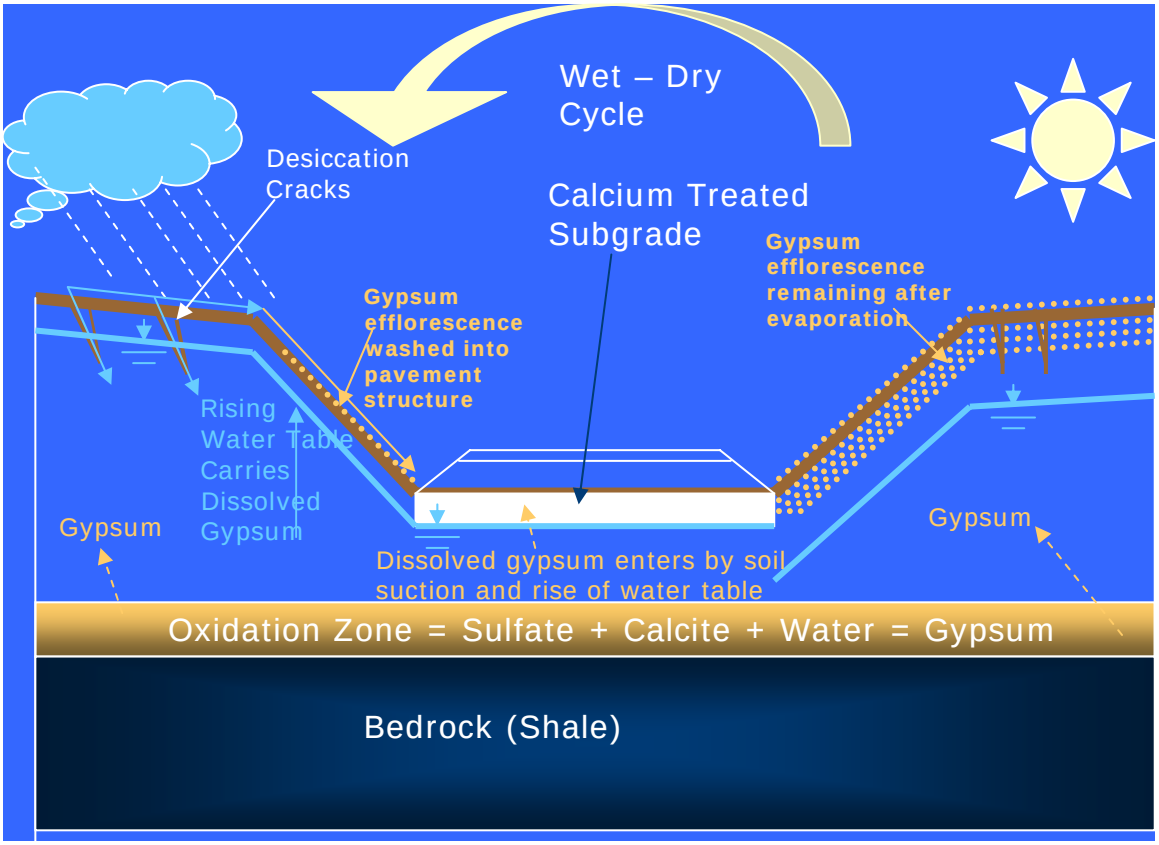


Figure 7: Illustration of the effect of low-lying areas and slopes on the transport of sulfates and water accumulation.

Step 4: Visual Inspection of Site or Borrow Source

Field detection of sulfates is crucial in the pre-design phase of a project. If any of the previous steps reveal possible risk of sulfates in the alignment of the roadway, perform a visual inspection of the site and potential borrow sources that may be used as select fill. Sulfate bearing crystals, like gypsum, can vary in size. These crystals can grow to a size readily visible to the eye, as seen in Figure 8(a) or they can be microscopic, as seen in Figure 8(b). In fact, gypsum crystals larger than softballs have been found in parts of Texas.

Figure 8: (a) Large grain gypsum crystals (b) Small grain gypsum crystals

Large grain-size gypsum crystals can be visually seen as sparkling, diamond-like crystals on natural or constructed slopes, in excavated areas, or naturally occurring on the surface, as seen in Figure 9(a). Small grain-size gypsum crystals can be visually detected as powdery, white efflorescence during dry seasons on the surface of the ground, as seen on Figure 9(b).

Figure 9: (a) Illustration of large grain gypsum crystals on a natural slope (b) Illustration of fine grain present on the surface through efflorescence.

Chapter 4
Pre-Design Soil Investigation

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Section 1

Requirements and Procedures

If there is an apparent risk for sulfate heave in the alignment of a project, a soil investigation is required prior to design. Requirements and procedures for these investigations are described below. The objective of this investigation is to identify and quantify the levels and distribution of sulfate concentrations within the alignment. The concentrations determined from the investigation will assist materials and pavements engineers in selecting the appropriate treatment type, additive levels, and construction techniques.

For pre-design investigation, schedule a drilling and soil investigation. Refer to the "Soil Investigation" section of the Pavement Design Manual for the details. Sulfate testing must be added to the schedule of testing recommended in the "Soil Investigation" section.

The minimum recommended frequency for drilling and logging test holes for areas with potential sulfates is every 500 feet, on alternating sides of the width of the roadbed. In cut sections, drill the test hole to a depth which corresponds to the final grade elevation of the subgrade of the proposed pavement. For example, if a section requires a 10 foot cut to meet the subgrade elevation, the driller must drill 10 feet to the proposed subgrade elevation before capturing soil samples for sulfate testing. Take samples at the final grade elevation and at least 7-10 feet below the final grade elevation. It is recommended that soil samples be taken at one-foot intervals.

Perform Part II of Tex-145-E, to determine the concentration of sulfate for each sample. Once the concentrations are determined, illustrate the level and distribution of sulfate concentration along the alignment of the project as seen in Figure 10.

Quantifying the sulfate levels and distribution will assist the materials and pavements engineer in determining where alternative material and pavement designs need to be performed. It is recommended that material designs and construction technique options be made for the highest concentrations measured in the alignment. The distribution will provide the areas and depths requiring alternative material and pavement designs. The more testing performed, the more precisely the limits can be defined for certain treatment techniques. For example, in Figure 10, from STA 0+00 to 16+00, traditional treatment can be implemented; from STA 16+00 to 34+00, alternative treatment is required; from STA 34+00 to 56+00, modified treatment can be utilized. Defining each area that requires specific treatments promotes more efficient and effective use of resources and money. Refer to the next section to determine the treatment types and construction techniques required for varying concentrations.

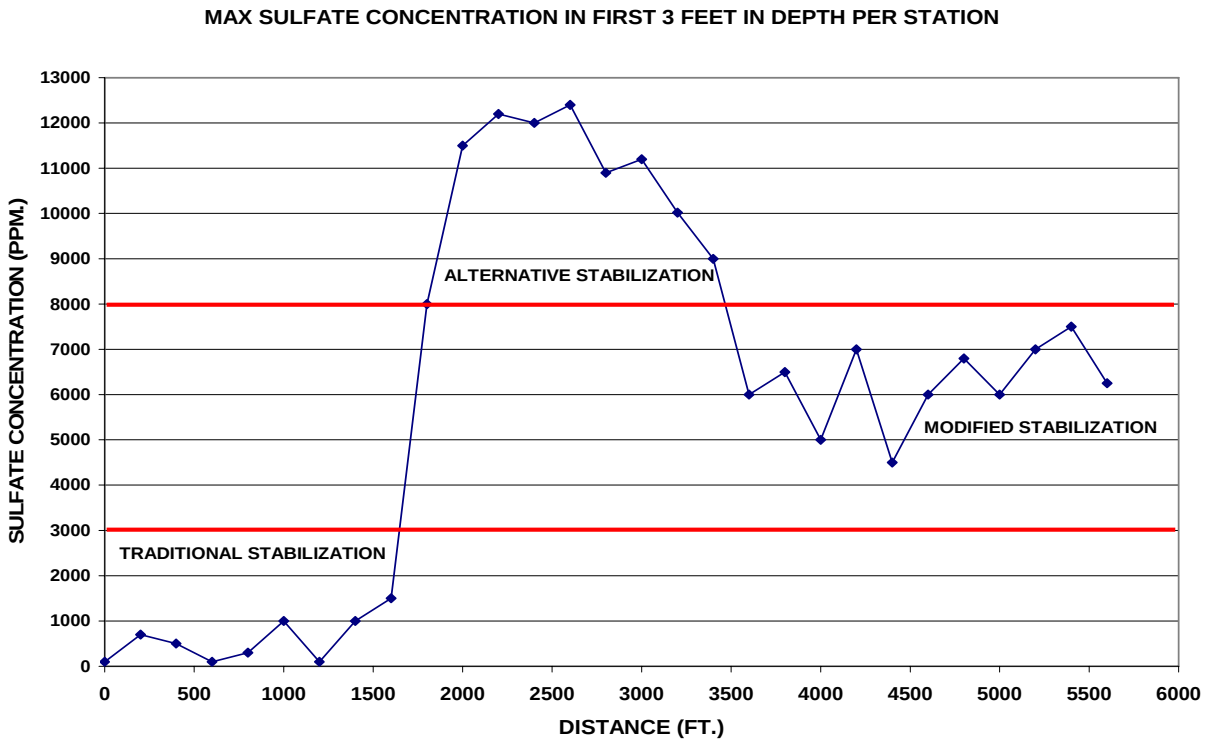

Figure 10: Distribution of sulfate concentrations along an alignment.

Chapter 5
Guidelines for Treatment of Sulfate Soils

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Section 1

Overview

Sulfates can occur in any type of soil regardless of the texture or plasticity. Therefore, sulfate-induced heave can occur in spite of the soil type. Typically, there is a higher probability for sulfates to occur in soils with high plasticity due to its high suction properties and ability to retain moisture containing soluble sulfates. Sulfates can also exist in granular soils, especially in arid regions or in strata that experience little water migration. Regardless of the soil type, due diligence is required in treating areas at risk. The following guidelines address all types of aggregate-soils.

Section 2

Moderately to Highly Expansive Soils (PI > 15)

The purpose of treatment of expansive soils is typically to mitigate swell potential. Soils with low hydraulic conductivities and high capillary or suction properties are prone to serve as reservoirs for growing and storing sulfate bearing minerals. Research Project 4240 has determined the critical levels and conditions for successful lime treatment of expansive, sulfate-rich soils. Treatment with cement and Class CS fly ash in expansive, sulfate-rich soils has not yet been researched. The following flowchart provides a treatment decision tree based on sulfate levels.

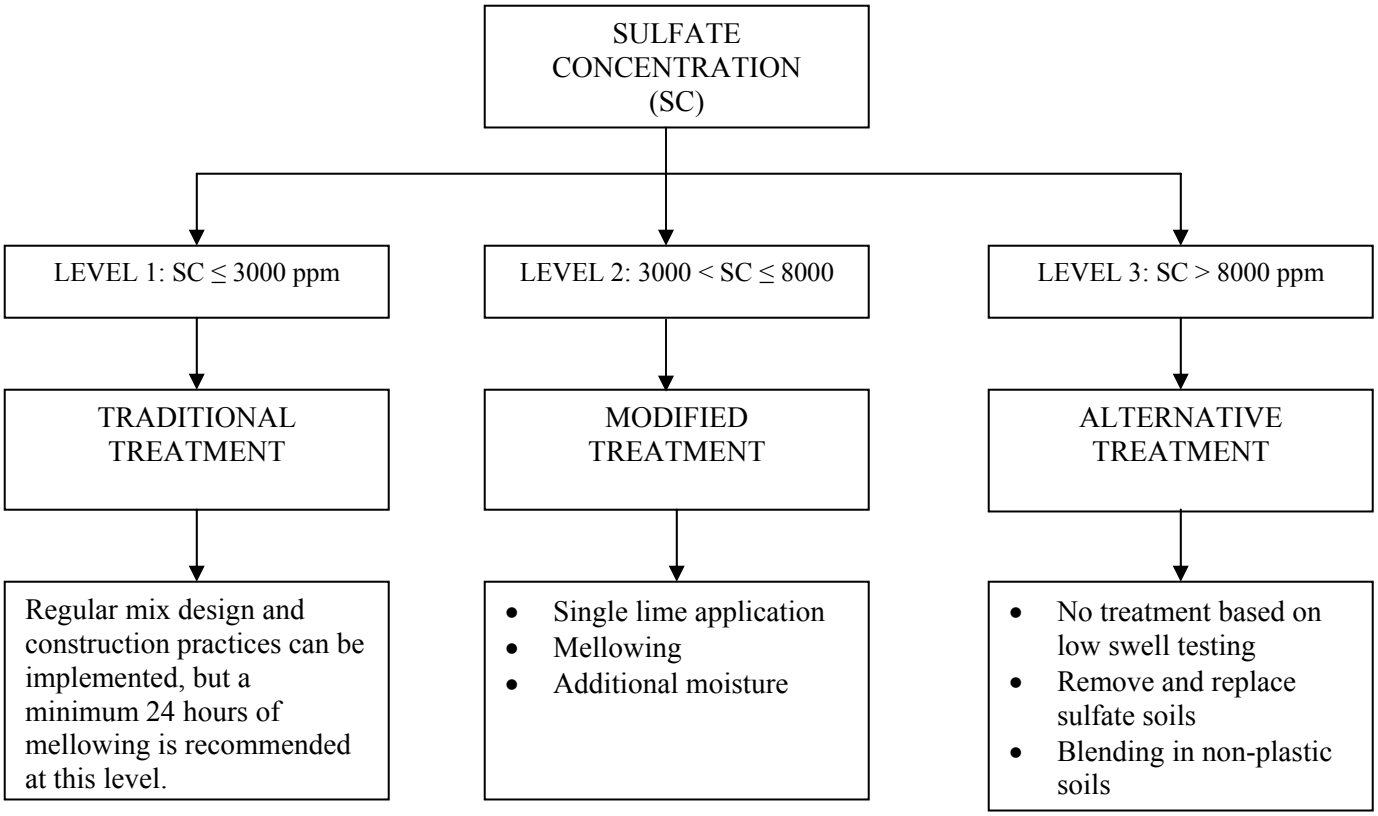

Figure 11: Decision tree to determine type of treatment for varying sulfate contents.

Level 1: Traditional Treatment (SC ≤ 3000 ppm)

Research and field experience have shown soils with sulfate levels of 3000 ppm or less pose low potential for sulfate heave. Standard construction and mix design practices, as specified in applicable items in TxDOT's 2004 Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges, can be utilized to treat with sulfate concentrations below 3000 ppm. Sulfate reaction still occurs in these types of soils, but with adequate mixing and moisture, the effects are typically not detrimental.

Level 2: Modified Treatment (3000 ppm < SC ≤ 8000 ppm)

Research and some cursory field data has shown that soils with PI >15 and sulfate levels greater than 3000 ppm but less than or equal to 8000 ppm can be successfully treated with lime. Since research to date has only produced data using lime as an additive, the following recommendations are **for lime treatment only.** Use of other additives is not recommended without first performing extensive laboratory testing. The following modified construction methods must be followed to ensure the prevention and mitigation of sulfate heave:

Material Mix Design

Perform the mix design (Tex-121-E) as required by the specification to determine the optimum lime content, but use a representative sample of soil with the most representative sulfate concentration. An inherent amount of lime will be consumed by the sulfate reaction, so the lime content must be designed for the specific soil and representative concentration of sulfate. The amount of mellowing time and moisture content required for a specific soil can be estimated during the mix design process. Once the optimal lime content is determined, multiple samples, at varying moisture contents above optimum moisture, can be mixed at the design lime content. The sulfate reduction of the mixes can be monitored and determined over time using Tex-145-E, Part II. Once the sulfate level falls below 3000 ppm, record the amount of time and moisture content required to achieve this concentration at the most rapid rate. This amount of time and moisture content can be used in the field as controls for mellowing time and moisture content. For example, in Figure 12, the sample with 24% moisture and the full 6% lime content reached a concentration below 3000 ppm faster than the other samples. It took about 1.9 days to reach 3000 ppm, but round up the time to 2 days for practicality.

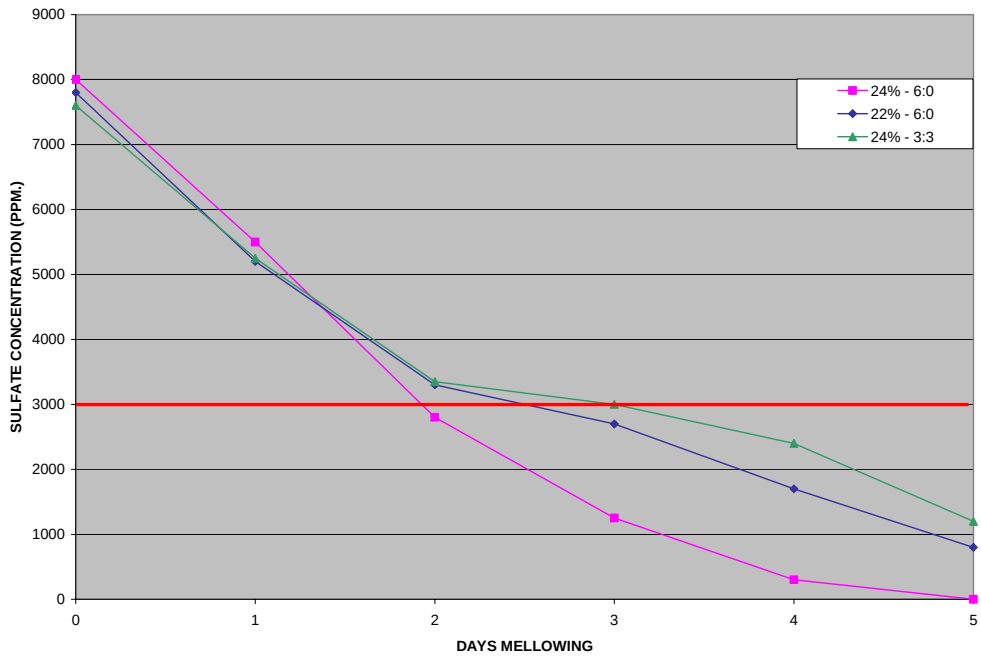

Figure 12: Determination of the optimum moisture content and minimum amount of time required to lower the sulfate content to 3000 ppm.

Application and Mixing

Apply the total lime content in one application. Thorough mixing is critical as this will promote complete and rapid reaction between the soil, sulfates, and water. Use of mixers with in-line water application or application of lime in slurry form is recommended to achieve thorough mixing. Light compaction will help seal the soil-lime mixture during mellowing and reduce lime oxidation. After mellowing, remix the soil-lime and perform final placement and compaction.

Mellowing and Moisture Control

Mellowing is the process of allowing the lime treated soil to remain in an uncompacted state for a period of time in order for the lime to react with the clay particles and sulfates. As the sulfate level increases, the corresponding reaction time required to lower the concentration of sulfates to a tolerable level (< 3000 ppm.) also increases. This reaction requires adequate moisture to initiate and complete the reaction between the sulfate, soil and lime. Additional moisture can assist in driving down the mellowing time and increasing the rate of reaction. But if water is added for this purpose, one must account for the time and effort to rework the material in order to lower the moisture content of the mellowed material to the optimum moisture for compaction. Use the estimated mellowing time and moisture content determined from the mix design. The mellowing period can be translated to the construction specifications and operations of the project. Ensure the moisture content is maintained by sprinkling the mixture regularly to prevent excessive evaporation. Approximate moisture content can be measured with a nuclear density gauge. Since calcium affects nuclear density moisture content, a correction factor must be applied. The most certain manner to control the

moisture content is to perform an oven-dry moisture content (Tex-103-E) on a sample of the mixture.

Always consider that the mellowing time and moisture content determined from laboratory testing is performed in a system protected from environment and construction conditions found in the field. Issues, like uniformity of mixing, coverage, and evaporation, cannot be simulated in laboratory testing. Engineering judgment must be exercised when specifying mellowing time and moisture content.

Level 3: Alternative Treatment (SC > 8000 ppm)

The recommendations for soils with sulfate concentrations above 8000 ppm are as follows:

Remove and Replace

Remove and replace the sulfate-rich soils with select fill.

Blend in Low Sulfate Materials

For soils with a PI between 15 and 35, blending in non-plastic, granular material such as sand or aggregate, can effectively reduce the plasticity and swell. If this option is chosen, the gradation of the granular material must meet the requirements in Table 1. Determine the potential vertical rise of the mixture in accordance with Tex-124-E potential vertical rise (pvr) with varying amounts of the proposed granular material blended into the sulfate-rich material. Select the amount of granular material that reduces the pvr to one inch or less, which equates to a volumetric swell of approximately 6% or less. Use Tex-117-E to verify that strength requirements are met.

Table 1: Gradation Requirements of Added Material (minimum % passing)

Sieve Size	Base	Subgrade
1-3/4 in.	100	100
3/4 in.	85	85
No. 4	--	60

No Treatment

If the pvr is one inch or less and the strength is adequate or can be addressed by increasing the thickness of the base, hotmix asphalt concrete, or concrete layers, no treatment is recommended. The use of a geogrid can aid in obtaining density on layers acting as ‘working platforms’ or may add some structural capacity to the subgrade, but this will not address the swelling potential of the soil, if it is an issue. Enforce strict mixing and moisture-density requirements and increase frequency of density control testing to ensure uniformity and stability.

Alternative Additives

Alternative mitigation methods and products such as ground granulated blast furnace slag (GGBFS) and lime/fly ash blends are being researched in Research Project 4240. Laboratory data obtained to date indicates promising results in reducing the swell potential of expansive soils with sulfates. Test sections are currently being constructed to obtain field validation.

Section 3

Minimally Expansive Soils or Bases (PI ≤ 15)

Soils in arid regions or in strata with small amounts of water migration can allow sulfates to accumulate. The following are guidelines for calcium-based additives for low plasticity or non-plastic soils and bases.

Sulfate Concentration ≤ 3000 ppm

Research and field experience have shown soils and bases with sulfate levels of 3000 ppm or less pose low potential for sulfate heave. Standard construction and mix design practices, as specified by the appropriate item in TxDOT's 2004 Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges, can be utilized in calcium treated soils or bases with sulfate concentrations below 3000 ppm. Sulfate reaction still occurs in these types of soils, but with adequate mixing and moisture, the effects are typically not detrimental.

Sulfate Concentration > 3000 ppm

Calcium-based additives are often used in low plasticity and non-plastic materials to increase strength properties, reduce moisture susceptibility or treat physically unstable, graded soils and bases. Failures have been documented in Texas due to sulfate heave in low plastic soils treated with calcium-based modifiers. Alternatives to using calcium-based additives and still achieving improved engineering properties are as listed:

- Add non-plastic materials like sand or aggregate to achieve the desired strength or physical stability required.
- Re-analyze the pavement design to determine if structural capacity can be achieved without stabilizing the sulfate-containing material. If material stability is a problem, it may have to be enhanced by mechanical methods such as fabric or geogrid.
- Remove and replace existing material or select another source of material if new material is being is brought to the project site. This is the best method to prevent sulfate-induced heave for these types of materials.

Techniques like mellowing and moisture treatment, as discussed in the previous section for plastic soils, can be attempted but only on soils or bases with less than 8000 ppm. The soil or base material being treated must have the ability to be mixed with the calcium additive multiple times and have adequate time for the ettringite formation to occur in an uncompacted state. Once this is achieved, the mixture can be reworked, shaped, and compacted.

Chapter 6
Quality Assurance Testing During Construction

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Section 1

Detecting Sulfates in Soils

TxDOT research project 4240 has developed rapid field tests to detect sulfates in soils. These test methods provide a means for detecting concentrations on the roadway during rough and final grading as well as verification of the concentrations measured during soil exploration and used for mix design.

- Level I, Tex-146-E
  - Tex-146-E is a field method to measure soil conductivity.
  - Conductivity is an indicator of the presence of salts and can be used as a screening tool to identify potential sulfate problem areas on a project.
  - Research has found that soil with a conductivity greater than 238 micro-siemens at a 1:20 soil/water dilution ratio indicates the possibility of the presence of sulfates. If conductivities greater than 200 micro-siemens are detected, begin Level II testing.
- Level II, Tex-145-E
  - Tex-145-E is a laboratory method that will accurately quantify the portion of the conductivity results that are attributed by sulfates rather than by other salts.
  - Part I is used for quality control during construction. The total sulfate concentration up to 8000 ppm is determined by Part I.
  - Sulfate concentrations in excess of 8000 ppm require extensive time to measure and if desired, can be determined by using Part II. Part II should always be used during the pre-design, soil exploration phase in order to select the proper treatment techniques and identify treatment limits. Multiple treatment techniques may be required within the project limits.

The minimum recommended frequency for sulfate screening during construction is once per each 500 feet on alternating sides for the entire width of the roadbed and for the full depth of treatment. The more frequent the testing, the greater the accuracy will be in locating and mapping sulfate concentrations on a project. Colorimeter testing will only need to be performed in response to high results from conductivity testing. If the risk assessment and pre-design soil investigation performed prior to the project's letting indicated all sulfate concentrations in existing materials within the project limits were less than or equal to 3000 ppm, minimum sampling frequencies can be reduced.

Once a location with an undesirable sulfate concentration is identified, increase the testing frequency in proximity to the location until the boundaries of the sulfates are identified. Sulfate concentrations can occur in seams and pockets. Method of treatment, construction technique and additive percentages may need to be adjusted during construction in response to varying sulfate levels. Refer to the "Guidelines for Treatment of Sulfate Soils" chapter of this document for recommended methods of treatment and construction.

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