

**Ettringite Formation in Lime-Treated Soils: Establishing Thermodynamic Foundations for Engineering Practice**

DALLAS N. LITTLE (*Corresponding Author*)

Professor, Department of Civil Engineering,  
603E CE/TTI Building, Texas A&M University, College Station, Texas 77843-3135  
Phone: (979) 845-9963, Fax: (979) 845-0278, E-mail: d-little@tamu.edu

BRUCE HERBERT

Associate Professor, Department of Geology and Geophysics,  
309 M.T. Halbouty, Texas A&M University, College Station, Texas 77843-3115  
Phone: (979) 845-2405, E-mail: herbert@geo.tamu.edu

And

SACHIN N. KUNAGALLI

Graduate Assistant Research, Texas Transportation Institute  
501B CE/TTI Building, Texas A&M University, College Station, Texas 77843-3135  
Phone: (979) 458-4148, Fax: (979) 845-1701, E-mail: sachinkn@yahoo.com

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## **ABSTRACT**

The use of calcium-based stabilizers such as calcium oxide (lime) in sulfate-bearing clay soils has historically lead to distress due to the formation of a mineral called ettringite and possibly thaumasite. In trying to control the damage associated with such occurrences, engineers have attempted to determine a threshold value of soluble sulfates, a quantity that is relatively easy and quick to measure, at which significant ettringite growth and, therefore, structural distress occurs. This is indeed a complex problem related not only to soil composition but also construction methods, availability of water, ion migration, and whether the expansive mineral growth can be accommodated by void structure. Unfortunately, experience alone and “rules-of-thumb” based on experience is not sufficient to deal with this complex issue. This paper describes how thermodynamic geochemical models of the lime treated soil can be used as a first step toward establishing problematic threshold levels of soluble sulfates for a specific soil. A foundation for the model development is presented, and two different soils are compared to illustrate their very different sensitivities to ettringite growth upon the addition of hydrated lime. Since the model predicts ettringite growth based upon site-specific properties, the paper also shows how the model can be used to assess the potential amelioration effects of soluble silica.

## ETTRINGITE FORMATION IN STABILIZED SOILS

### Sulfate-Induced Heave

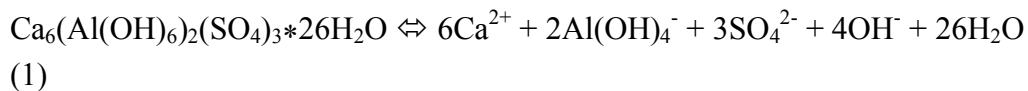
The hydrous sulfate mineral, ettringite ( $\text{Ca}_6(\text{Al}(\text{OH})_6)_2(\text{SO}_4)_3 \cdot 26\text{H}_2\text{O}$ ), has been implicated in sulfate attack on cement and concrete, as well as stabilized soils [1, 2, 3]. Ettringite is a hydrous calcium aluminosulfate mineral that precipitates in environments with high pH and high sulfate activity [4]. Ettringite often forms when a calcium-based stabilizer is added to sulfate-bearing clay soils [5, 6, 7, 8]. Ettringite, which tends to form very small ( $\mu\text{m}$ ), fibrous crystals [9], damages the soil structure through mineral expansion during precipitation. To make the matter even more complex, a second mineral, thaumasite may develop through the isostructural transformation of ettringite at temperatures below about  $15^\circ\text{C}$  in the presence of soluble silica and carbonate. The result of the formation of ettringite can be considerable expansion, while the formation of thaumasite will result in a loss of strength and is normally preceded by the formation of ettringite [1, 3, 10, 11, 12].

The amount of damage due to ettringite formation depends on a number of factors including: (i) the thermodynamic favorability of ettringite precipitation in specific soils, (ii) the quantity of limiting reactants that stoichiometrically control the mass of ettringite formed, (iii) the migration of water, sulfate and other ions that support continued ettringite nucleation, (iv) the strength of the pozzolanic or cementitious matrix, and (v) the spatial arrangement of the ettringite crystals in the soil matrix. Ettringite can grow in void spaces that accommodate their growth without substantial expansion or within a dense matrix such that the soil matrix cannot accommodate crystal growth.

### Geochemistry of Ettringite

The ettringite mineral group has a general mineral formula of  $(\text{Ca}_6(\text{X}(\text{OH})_6)_2(\text{Y})_3 \cdot 26\text{H}_2\text{O})$ , where X is a trivalent metal such as  $\text{Al}^{3+}$ ,  $\text{Fe}^{3+}$ , or  $\text{Cr}^{3+}$  and Y is an oxyanion such as  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{SeO}_4^{2-}$ , or  $\text{CrO}_4^{2-}$  [4, 13, 14]. Minerals with alternative substitutions of other ions, such as  $\text{B}(\text{OH})_4^-$  and  $\text{AsO}_4^{3-}$ , are possible but not common in most surface environments. The one exception is thaumasite ( $\text{Ca}_3(\text{Si}(\text{OH})_6)(\text{CO}_3)(\text{SO}_4) \cdot 12\text{H}_2\text{O}$ ), a silicon-bearing member of the ettringite mineral group [13], which can form a solid solution with ettringite [15, 16].

Dissolution-precipitation reactions control the stability of ettringite in lime-treated soils. The solubility of ettringite can be written as a dissolution reaction:



Ettringite precipitates in highly alkaline solutions with high activities of Ca,  $\text{SO}_4^{2-}$  and Al. These reactants exhibit strong spatial variation at a variety of scales due to variation in their content with the geologic parent material and migration within the soil column [17]. Additional geochemical controls on ettringite stability include temperature and dissolved  $\text{CO}_2$  and  $\text{H}_2\text{O}$  activities [18]. The kinetics of ettringite precipitation-dissolution is fast, precipitation-dissolution achieves steady state in approximately 150 hours at pH 11.5 [18].

### **Thermodynamic Modeling of Ettringite Formation at Stewart Avenue**

Early attempts at predicting ettringite and thaumasite formation used geochemical models based upon thermodynamics [19, 20]. In his 1989 Ph.D. dissertation, Dal Hunter [21] assessed the relative stability of ettringite to other sulfate minerals prone to develop in sulfate-bearing clay soils stabilized with calcium oxide (CaO) or calcium hydroxide (Ca(OH)<sub>2</sub>). Some of the highlights of Hunter's findings are:

1. Slight increases in the activity of calcium, a rise in the pH, or an increase in the activity of aluminum favors the precipitation of ettringite in sulfate-bearing clay soil amended with lime.
2. The stability field of ettringite increased as the activity of aluminum increased, and the activity of aluminum increased from approximately  $10^{-6}$  to  $10^{-3}$  when lime and adequate water was added to the soil system.
3. An increase in the activity of calcium and/or sulfate drives the reaction into the stability field of ettringite.

Although most of Hunter's research simulated the Stewart Avenue soils (Las Vegas, NV) with simple geochemical models of only three minerals: gypsum, ettringite, and portlandite (Ca(OH)<sub>2</sub>); his results were very instructive. Hunter (21) predicted, for his simplified system and at a pH of about 12.3, that ettringite was thermodynamically more stable than gypsum at soluble sulfate contents as low as 15 parts per million (ppm). However, Hunter [21] raised his estimates of the amount of soluble sulfates needed to cause damage based on swell observations. Using stoichiometrics, he correlated observed swell with the mass of material, sulfate, calcium oxide, aluminum, and water required to support the observed volume increase. He adjusted the total volume increase, based on observed swell and density measurements, to account for volume change due to crystal growth as well as the concomitant void development associated with the growing minerals. Based on his observations from soils at Stewart Avenue, Hunter suggested a threshold limit of 5,000 ppm for soluble sulfates for damage by ettringite formation in flexible pavements. This accounts for the fact that some of the swell due to mineral growth can be accommodated in the void structure of the soil.

### **Thermodynamic Modeling of Ettringite Formation in Texas Soils**

Lonestar Infrastructure (LSI) is coordinating the design and building of a toll road between Seguin, Texas, east of San Antonio along IH-10, and Georgetown, Texas, east of Austin (Fig. 1). This toll road is intended to by-pass a congested portion of one of the nation's most heavily truck-trafficked highways. The preliminary design for SH-130 is a continually reinforced Portland cement concrete mainline with asphalt concrete frontage roads along the 94-mile corridor. Because of the expansive clay soils in the corridor, chemical stabilization of the subgrade soils is necessary both as a construction expedient and to provide structural support for the asphalt pavements.

The rocks and unconsolidated sediments underlying the SH 130 corridor are generally composed of sedimentary rocks and reworked sediments deposited in fluvial, deltaic-near shore, and shallow marine environments [22]. Most of the soils and sediments that compose the SH 130 corridor have high contents of amorphous silica and clay minerals, major sources of Si and Al, carbonate, providing both Ca and CO<sub>3</sub><sup>2-</sup>, and sulfur bearing minerals. The two major geologic sources of SO<sub>4</sub><sup>2-</sup> in the SH 130 corridor are sediments that contain significant pyrite (FeS<sub>2</sub>),

especially those deposited in near-shore environments, such as marls, shales or carbonates that contain high levels of clay minerals, and sediments that contain significant evaporite deposits. The sulfur in pyrite is oxidized to  $\text{SO}_4^{2-}$ , while evaporates contain significant amounts of gypsum ( $\text{Ca SO}_4$ ) and other sulfate-containing minerals that release sulfate through dissolution.

In order to minimize the risk of sulfate-induced heave in lime and cement-treated subgrade soils along the SH 130 corridor, a research project conducted by Texas Transportation Institute (TTI) at Texas A&M University established a protocol to: (i) screen for potentially problematic soils based on GIS mapping of the corridor, which accounts for geology, pedology, and topography; (ii) establish spatial heterogeneity of sulfate levels through the characterization of terrain conductivity using electromagnetics (EM31, Geonic Ltd.), and (iii) evaluate the risk of swelling based on thermodynamic modeling and stoichiometric analysis of the lime-treated soils. One objective of this paper is to compare thermodynamic model predictions of ettringite formation in lime-treated soils to current understanding based upon engineering practice and experience.

## **THERMODYNAMIC MODELING OF ETTRINGITE PRECIPITATION**

While engineering experience and "rules of thumb" can offer important guidance on potential ettringite formation, more quantitative estimates of ettringite formation under a wide variety of conditions are needed. Precipitation-dissolution of ettringite in soils and sediments can be predicted using thermodynamics [20, 23], with the quality of the predictions being dependent on the degree to which the system of interest matches model assumptions and the reliability and internal consistency of the associated thermodynamic database [2].

The use of geochemical models to simulate physical and chemical processes in subsurface systems entails the formulation of a conceptual model of the subsurface system, the development of mathematical relationships describing the processes occurring in the system, and the numerical solutions to these equations [24, 25, 26, 27, 28]. In all cases, the conceptualization of a subsurface system is a matter of simplification since we never completely understand these systems due to the lack of characterization information. In large part, successful geochemical modeling is dependent on the interpretation of modeling results in terms of the assessed accuracy of the subsurface conceptualization.

In most cases, the application of geochemical speciation models to subsurface environments requires an assumption that structure does not influence geochemical processes and the system is a well-mixed, closed (energy, but not matter, can move in and out of the system) system. This defines the ideal conceptualized system for geochemical speciation modeling. In the ideal case, the aqueous and gaseous phases are in intimate contact with the solid phases; transport processes, such as advection and diffusion, do not limit geochemical reactions; microbial catalysis is not explicitly modeled; and the system has an infinite amount of time to achieve equilibrium [29]. Soils and groundwaters only approximate this ideal case.

Geochemical model validation is important if model results are used to support engineering decisions [30, 31]. The validity of geochemical models predicting ettringite formation in lime-treated soils is dependent on the quality of the thermodynamic database; the soil characterization data, and the match between soil system characteristics and assumptions inherent in thermodynamic-based models including assumptions of equilibrium; validity of the

activity coefficient models as a function of the system ionic strength; the types of system components and geochemical processes included in the model; and solid phase ideality.

We can assess the impact of many of the common thermodynamic assumptions incorporated in geochemical modeling factors on model validity. Because the kinetics of ettringite and associated calcium and sulfate mineral formation is relatively rapid, the assumption of local equilibrium is likely appropriate in most cases [18, 32, 33]. This is not necessarily true for many associated minerals that contain aluminum and silica; therefore careful evaluation of the appropriate aluminum and silicate phases to be included in the model is needed. Likewise, most geochemical models used to predict ettringite formation ignore other geochemical processes besides precipitation-dissolution. A pressing need it to assess this assumption for a range of soils.

The thermodynamic constants for ettringite have been carefully evaluated, so the quality of the thermodynamic database for this mineral is likely appropriate [4, 18]. This assumption may not be correct for the other complex mineral phases that result from pozzolanic reactions in lime-treated soils [26]. The assumption of ettringite ideality, so the solid phase activity can be set to one, is likely reasonable except when ettringite forms a solid solution due to the high concentrations of associated metals or anions that substitute in the crystal including  $\text{Fe}^{3+}$ ,  $\text{Cr}^{3+}$ ,  $\text{CO}_3^{2-}$ ,  $\text{SeO}_4^{2-}$ , or  $\text{CrO}_4^{2-}$  [4, 13, 14]. In this case, special models of solid-phase activity coefficient models that account for the effects of the solid solution on the solid phase activity coefficient need to be used [34].

## **HYPOTHESIS FOR EMPLOYING THERMODYNAMIC MODELING**

The hypothesis of this research is that the stability or phase diagram can be used to identify the thermodynamically stable phases that will develop when calcium oxide, hydrated lime, or other calcium containing cementitious or pozzolanic stabilizers are added to sulfate-bearing clays. Furthermore, the stability model or phase diagram is useful in that it may help define a site-specific threshold level where soluble sulfates become problematic because significant levels of expansive minerals develop at the threshold level. The hypothesis is that different soils have different threshold levels of soluble sulfates; and, therefore, phase diagrams can be used to define this threshold level and thus help define the specification level.

An additional hypothesis is that the stability of phase diagram can be used to assess the impact of additives to the soil system being evaluated. For example, a long standing approach to mitigate sulfate reactions in lime stabilized soils is to add pozzolans such as fly ash, ground, granulated blast furnace slag [35], or other forms of soluble silica. The fundamental premise is that the soluble silica will force the reaction into some other stability field other than ettringite and prevent deleterious expansion. The stability model would thus become a valuable assessment tool or virtual experiment to assess the impact of a selected type and amount of additive.

## **IDENTIFYING THRESHOLD LEVELS OF SOLUBLE SULFATES BASED ON ENGINEERING EXPERIENCE**

Petry [7] correctly points out that a major problem preventing a clear identification of a threshold soluble sulfate level above which damage can be expected is the method of partitioning soluble sulfates from the soil. Since sulfate has a finite solubility, the amount of sulfates partitioned depends on the amount of water used to partition. Petry suggests a 10:1 water-to-soil solution to partition. Based on this approach, which is now routinely used in Texas Method Tex 620-J, Petry suggests that sulfate levels above about 2,000 ppm or 0.2 percent have the potential to induce damage due to swelling, and that sulfate levels above about 10,000 ppm or 1 percent induce severe damage. Hunter [21] also suggested 10,000 ppm threshold as a standard for severe distress potential, but warns that much lower soluble sulfate levels can lead to severe damage, especially when one considers an open system where sulfate ions can migrate to ettringite nucleation sites and “feed” the growth of this potentially expansive mineral.

Mitchell and Dermatas [36] identified soluble sulfate contents as low as 3,000 ppm that lead to the formation of ettringite, and this is supported by Perrin’s [37] study of swelling soils in the Joe Pool Lake areas south of Fort Worth, Texas, in the Eagle Ford formation. Laboratory work by McCallister and Tidwell [38] identified levels of risk based on soluble sulfate content. They suggested that sulfate levels between 100 to 5,000 ppm pose a low to moderate threat; levels between 5,000 ppm and 12,000 ppm pose a moderate to serious threat, and levels above 12,000 ppm pose a very high risk of damage. Little, et al., [39] suggested similar levels based on field observations and laboratory testing. Rollings et al. [40] provides an extensive review of the literature regarding risk and measured levels of soluble sulfates, and their work was used as a key document in this review of procedures. Harris et al. [8] substantiated a threshold level of soluble sulfates related to significant distress based on extensive laboratory testing. They also identified that the fineness of the sulfates affects the reactivity of the sulfates and hence the potential for damage and must be considered.

In 2001, Orange County, California [41] evaluated the impact of soluble sulfates on swell potential in three soils from the area. Sulfate levels of 0, 5,000, 8,000, and 14,000 ppm (plus or minus 500 ppm) were collected and tested from each soil type with 4 percent CaO and 4 percent CaO plus 8 percent fly ash. None of the soils with soluble sulfate levels below 14,000 ppm exhibited significant swell during a 60-day period. The pH levels of these soils dropped below 10 during the period of testing, which may indicate that a strong pozzolanic reaction used up the reagents before or instead of forming ettringite.

During the construction of the Denver International Airport, CTL/Thompson, Inc., [42] the Quality Assurance Manager for geotechnical operations, tested approximately 40 samples of lime treated claystone soils. They initially used a threshold soluble sulfate level of 3,000 ppm, but based on the testing felt confident to raise the allowable sulfate content to 8,000 ppm. However a close look at the CTL/Thompson data revealed that below about 3,000 ppm swell was essentially non-existent and a small rise in swell began at about 3,000 ppm.

Clearly, the threshold level associated with damage is a variable “call” when based on experience. Some of this variation is due to the definition of distress (e.g., level of swell associated with damage, whether based on lab or field evidence, duration of evaluation, etc.). However, it is probable that a significant portion of the variability is due to soil chemistry, ion activity, and thus the impact of the level of sulfates at which ettringite formation is

thermodynamically favorable in the soil-lime mixture. Based on experience, one sees a general trend that soils that are highly pozzolanically reactive, e.g., Orange County, California, soils require greater levels of soluble sulfates to trigger ettringite grow compared to less reactive clays.

## **APPLICATION OF THERMODYNAMIC MODELS TO EVALUATE ETTRINGITE PRECIPITATION IN FRISCO SOIL (EAGLE FORD FORMATION) AND PARMER-SH 290 SOIL (TAYLOR FORMATION)**

### **Description of Soils**

To illustrate the utility of the stability models to differentiate sensitivity to ettringite formation in lime-treated soils based on sulfate content, consider two different soils. The first is a soil from Frisco, Texas. This soil comes from an area notorious for damage due to ettringite formation in lime-treated soils in the region. This soil comes from the Eagle Ford formation, which is described by Goss et al [43] to be highly susceptible to ettringite precipitation due to high pyretic content, and pedological effects that promote high sulfate levels. The second soil is from a location along the SH 130 corridor near the intersection of Parmer Lane and US 290 in Austin. Pertinent properties of both soils are described in Table 1. The SH 130 soil comes from the Taylor formation and contains variable levels of soluble sulfates. While damage due to ettringite formation is documented in this area, it is much less common than in the Eagle Ford formation.

### **Model Approach**

Two very different approaches were used to develop stability models for the soil systems studied: a reaction path approach and a predominance approach. In the former, the reactive ions were extracted at a pH of 7 and then reactive minerals were selected based on the chemical analysis of the soil in question. The minerals selected (based on experience) as reactive were allowed to react to completion. This is a very conservative approach. The second approach, predominance, considers the aqueous chemistry of the system. The first step is to extract the ions in a pH 12 environment, since this environment exists when lime is added. We assumed that we were able to quantify all ion concentrations in the extract. In this approach a selected percentage of lime, CaO, was allowed to react in this aqueous environment to completion of the reaction. The major limitation of this method is the possibility that minerals may precipitate from solution before these measurements can be made or that the time is not sufficient to allow complete reaction. The major limitation of the reaction path model is that it is not likely that selected reactive minerals will completely react. Thus, the reaction path method is probably overly conservative. The authors are studying these effects more thoroughly.

At this point, the authors believe that the predominance method best simulates actual conditions. The authors have observed that stability models based on the predominance approach demonstrate that as soluble sulfate content is reduced, the ettringite field is diminished and that as the level of soluble silica increases, the ettringite stability field is diminished. These observations are very important because one expects a threshold level of sulfates to be required to trigger ettringite formation, and the authors know from experience that adding sources of soluble silica can interrupt the formation of ettringite.



## **Initial Model Parameters**

Initial model parameters used in the development of the thermodynamic models are presented in Table 2.

## **DISCUSSION OF RESULTS AND PRACTICAL APPLICATIONS**

Figures 2 through 5 compare the two different soils: the soil from the SH-130 corridor that lies in the Taylor geological formation, and the soil from near Frisco, Texas, that lies in the Eagle Ford formation. These two soils have different mineralogies as reflected in Tables 1. Based on the previous description of thermodynamic modeling, one would expect these two soils to react differently when treated with CaO.

The initial condition for each soil was based on chemical speciation calculations, which are in turn based on measured ion concentrations. At this point total activities of calcium, aluminum, sulfate, and silica were calculated by the computer program REACT. These parameters are shown Table 2. The soluble sulfate level was held constant for each soil at 3,000 ppm, Figures 2 and 3, and at 10,000 ppm, Figures 4 and 5, during the development of the thermodynamic phase diagrams.

The important trend shown in these figures is that at a soluble sulfate concentration of 3,000 ppm the locus of pH and log activity of sulfate is positioned well below the ettringite stability field for the (US 290) Taylor Formation soil, but the locus is well within the ettringite stability field for the (Frisco) Eagle Ford formation soil. This demonstrates the utility of the phase diagram in the engineering application of soil treatment with CaO (lime). Geotechnical and pavement engineers responsible for soil treatment and stabilization have relied on experience to establish “rules of thumb” regarding threshold levels of sulfates leading significant damage. The stability of phase diagram offers a scientifically sound and unbiased approach to at least begin to establish a reasonable threshold level for a give soil.

Figures 6 and 7 show the results of mass-balance calculations. In the development of these figures, the same ion concentrations measured and used in the thermodynamic model development were again used in a simulated mass-balance reaction with kaolinite, smectite, muscovite, goethite, and CaO. Kaolinite, smectite, muscovite, and goethite were quantified using x-ray diffraction (XRD).

The practical implication of Figures 6 and 7 are in line with those of Figures 2 through 5, which is that ettringite begins to form at a much lower level of soluble sulfates in the Eagle Ford Formation soil (approximately 3,000 ppm) than in the Taylor Formation soil (approximately 10,000 ppm). This once again substantiates the very important impact of mineralogy on the potential for ettringite to form and the threshold levels of sulfate that trigger its growth.

Silica-rich additives such as granulated blast furnace slag (GBFS) and fly ash have been successfully used [35] to stop the development of ettringite or to at least alter the form of the ettringite crystal in order to arrest expansion. Figures 8 and 9 compare two soils from the SH 130 corridor (Taylor formation). Each soil contains 20,000 ppm soluble sulfates. In Figure 8, 5 percent calcium oxide was added to increase the pH to approximately 12.4. This pushes the locus

of pH and log activity of sulfate ions into the ettringite equilibrium polygon. Figure 9 represents the identical soil system with the same level of soluble sulfates and the same lime addition. However, in Figure 9 the activity of soluble silica is changed from  $-7.64$  (Figure 8) to  $-5.46$  in Figure 9. The result is that the locus of pH and log activity of sulfate ions resides in the Prehnite mineral equilibrium polygon due to the higher soluble silica content. This demonstrates how the stability model can be used to assess the effect of using additives to change energetics and prevent the formation of ettringite.

## **VALIDATION OF STABILITY MODELS**

The stability models were validated in two ways: by comparing solution extracts with predictions from the stability models and by preparing specimens representative of the models and monitoring ettringite growth in these samples. In the latter approach, actual soil samples of the exact type modeled were allowed to react with lime for 60-days in a controlled and moist environment. The lime-soil mixtures were monitored for swell and tested using differential scanning calorimetry (DSC) to assess whether or not ettringite developed. The phase diagrams predicted that ettringite would not form even at low to moderate soluble sulfate contents, below about 10,000 ppm, and this was validated by DSC analysis. High soluble sulfate contents, above about 10,000 ppm plotted on the stability boundary line, and DSC failed to confirm ettringite development. On the other hand, phase diagrams predicted ettringite formation in the Frisco soils, and this was validated by the DSC scans.

## **CONCLUSIONS**

Experience alone is not sufficient to determine a threshold level of soluble sulfates that leads to destructive expansion due to the formation of ettringite. Many factors influence the manifestation of distress as discussed. However, one of the most important is the thermodynamic favorability of ettringite precipitation in a specific soil. The thermodynamic stability model or phase diagram provides a first step toward establishing threshold levels of soluble sulfates for specific soils. The model is highly sensitive to chemical composition and ion activities and provides the additional capability of being able to assess the impact of additives used to shift the reaction from ettringite to some other innocuous mineral. An example of this is the popular solution to add a source of soluble silica, such as fly ash or ground, granulated blast furnace slag.

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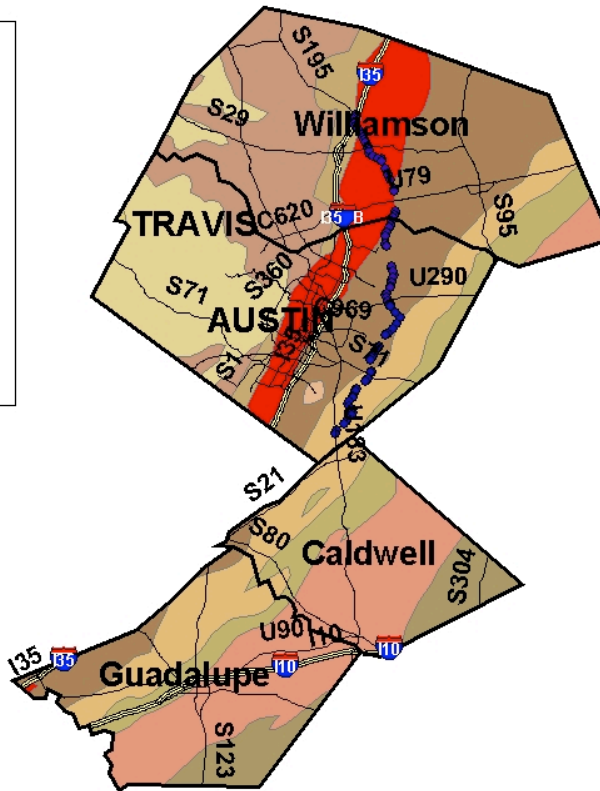
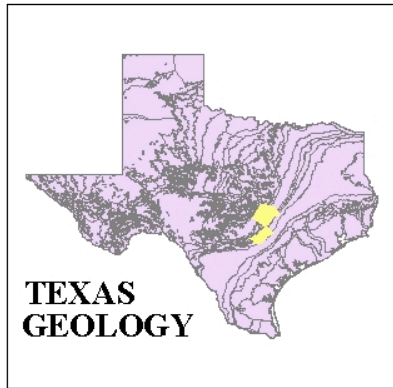
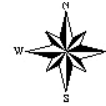
**Table 1 Comparison of Frisco (Eagle Ford Formation) and Parmer-US 290 (Taylor Formation) Soils**

	<b>Eagle Ford Formation</b>	<b>Taylor Formation</b>
<b>Geology</b>	Tan to brown in color. montmorillonitic shale with high shrink-swell potential	Tan to brown in color. High shrink-swell potential
<b>Mineralogy</b>	38 - 88% clay About 50% clay are smectites High swell potential, compressibility, and creep deformation	40 - 60% clay Smectites, mica, kaolinite, calcite  High swell potential
<b>Atterberg Limits</b>	LL = 39 - 140 PI = 16 - 113 CaCo <sub>3</sub> = 2 - 39% Water Content = 4 - 25%	LL = 30 - 120 PI = 10 - 100 CaCo <sub>3</sub> = ~50% Water Content = 18 - 28%
<b>Unified Classification</b>	Inorganic clay with high plasticity (CH)	Clayey Sand (SC), Fat Clay (CH), Lean Clay (CL)
<b>Chemical Analysis</b>	Magnesium = 53 mg/kg Potassium = 158 mg/kg Aluminum = 5 mg/kg Calcium = 3640 mg/kg Sulfate = 35000 mg/kg Silicon = 33 mg/kg Iron = 5 mg/kg Chloride = 18 mg/kg	Magnesium = 30 mg/kg Potassium = 50 mg/kg Aluminum = 3 mg/kg Calcium = 100 mg/kg Sulfate = 30000 mg/kg Silicon = 55 mg/kg Iron = 10 mg/kg Chloride = 50 mg/kg



**Table 2 Initial “Act” Model Parameters**

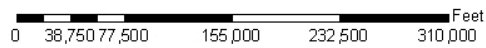
	Water Activity	pH	Temperature (°C)	Pressure (bar)	Log Activity			
					Al(OH) <sub>4</sub> <sup>-</sup>	SiO <sub>2</sub>	Ca <sup>2+</sup>	SO <sub>4</sub> <sup>2-</sup>
Frisco Soil SO <sub>4</sub> = 3,000 ppm	1	12	25	1.013	-3.864	-5.887	-1.663	-1.6603
Parmer US 290 Intersection Taylor Formation SO <sub>4</sub> = 3,000 ppm	1	12	25	1.013	-3.267	-6.514	-3.154	-1.8784
Frisco Soil SO <sub>4</sub> = 10,000 ppm	1	12	25	1.013	-3.871	-5.706	-1.847	-1.2139
Parmer US 290 Intersection Taylor Formation SO <sub>4</sub> = 10,000 ppm	1	12	25	1.013	-4.578	-7.305	-2.64	-1.4283
Natural Silica activity of Soil	1	12	25	1.013	-4.553	-7.46	-2.467	-1.6363
Influence of Silica Indicating Decrease in Ettringite Precipitation Potential	1	12	25	1.013	-4.553	-5.46	-2.467	-1.6363



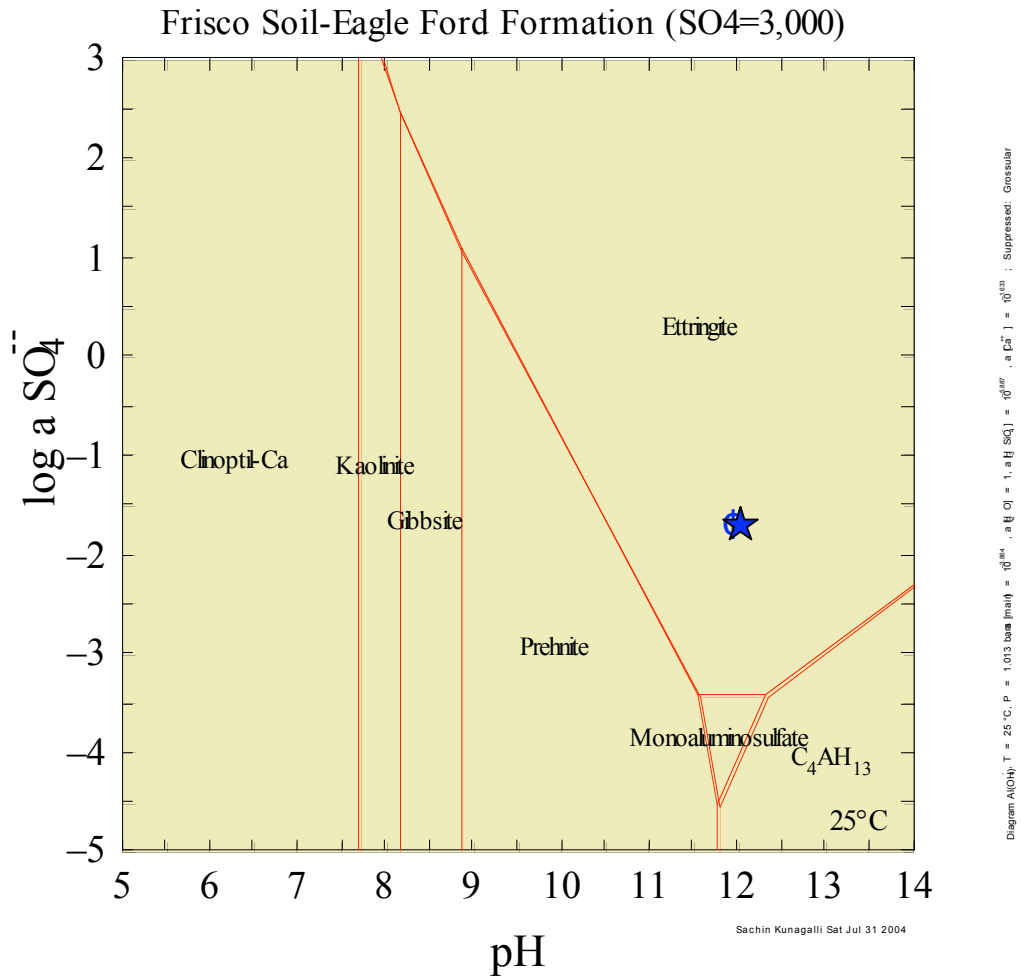
### Legend

- Major Roads
- SH130 Baseline-1
- SH130 Baseline-2
- Major Roads
- Rock Types**
- Atokan and Morrowan Series
- Austin and Eagle Ford Groups
- Cretaceous intrusive rocks
- Eocene Claiborne Group
- Eocene Wilcox Group
- Fredericksburg Group
- Navarro Group
- Paleocene
- Taylor Group
- Trinity group
- Washita Group
- interstates

## Geology of the Area

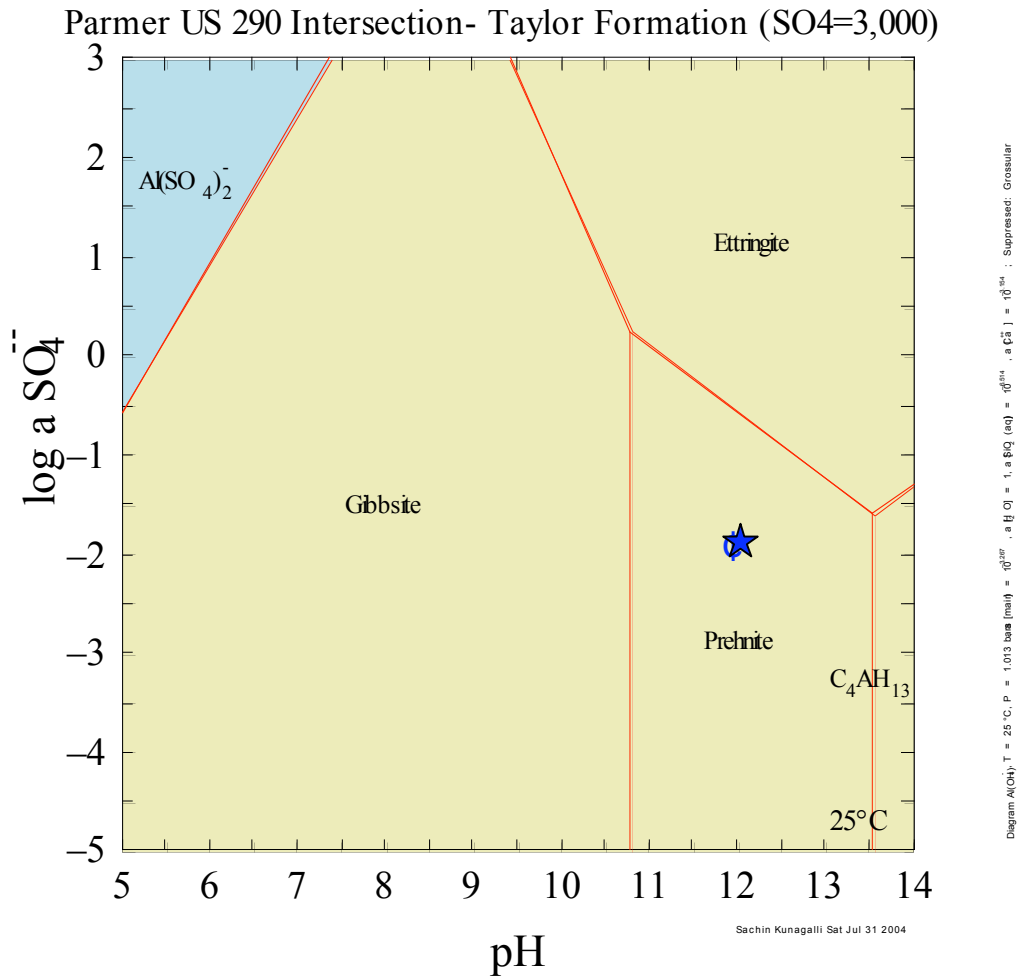


**Figure 1** Location of SH 130 Toll Way in the Austin-San Antonio corridor



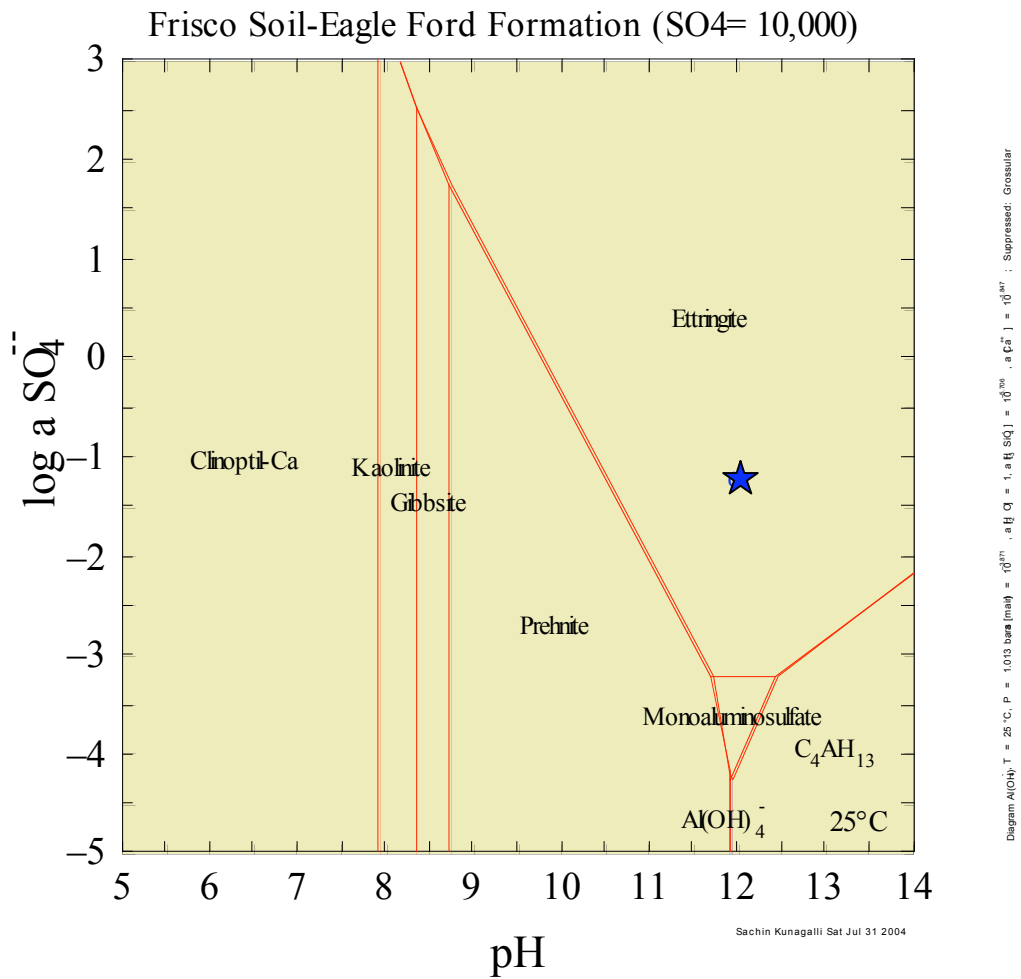
**Figure 2 Phase Diagram for Frisco Soil (Eagle Ford Formation) with Soluble Sulfate Concentration of 3,000 ppm**

Note: Star represents the locus of pH and log activity of Sulfate for the condition being considered.



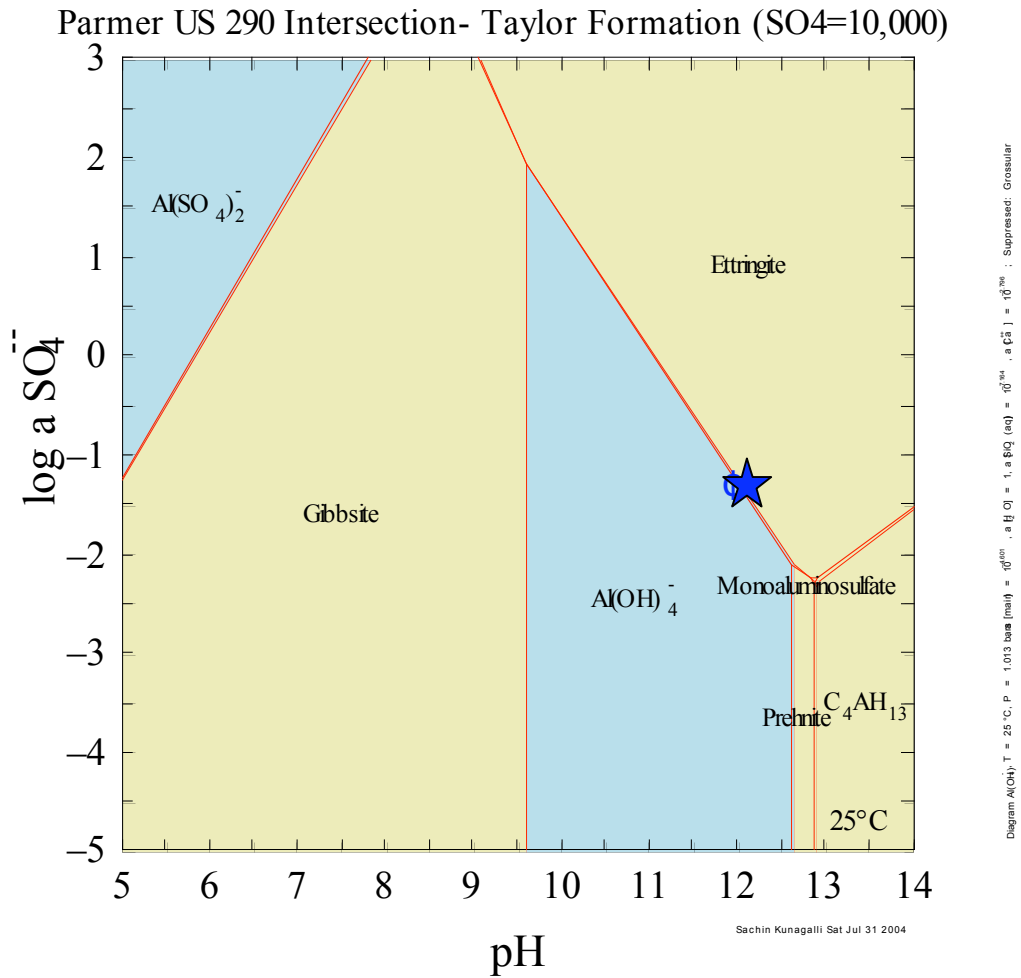
**Figure 3 Phase Diagram for Parmer US 290 Intersection (Taylor Formation) with Soluble Sulfate Concentration of 3,000 ppm**

Note: Star represents the locus of pH and log activity of Sulfate for the condition being considered.



**Figure 4 Phase Diagram for Frisco Soil (Eagle Ford Formation) with Soluble Sulfate Concentration of 10,000 ppm**

Note: Star represents the locus of pH and log activity of Sulfate for the condition being considered.



**Figure 5 Phase Diagram for Parmer US 290 Intersection (Taylor Formation) with Soluble Sulfate Concentration of 10,000 ppm**

Note: Star represents the locus of pH and log activity of Sulfate for the condition being considered.

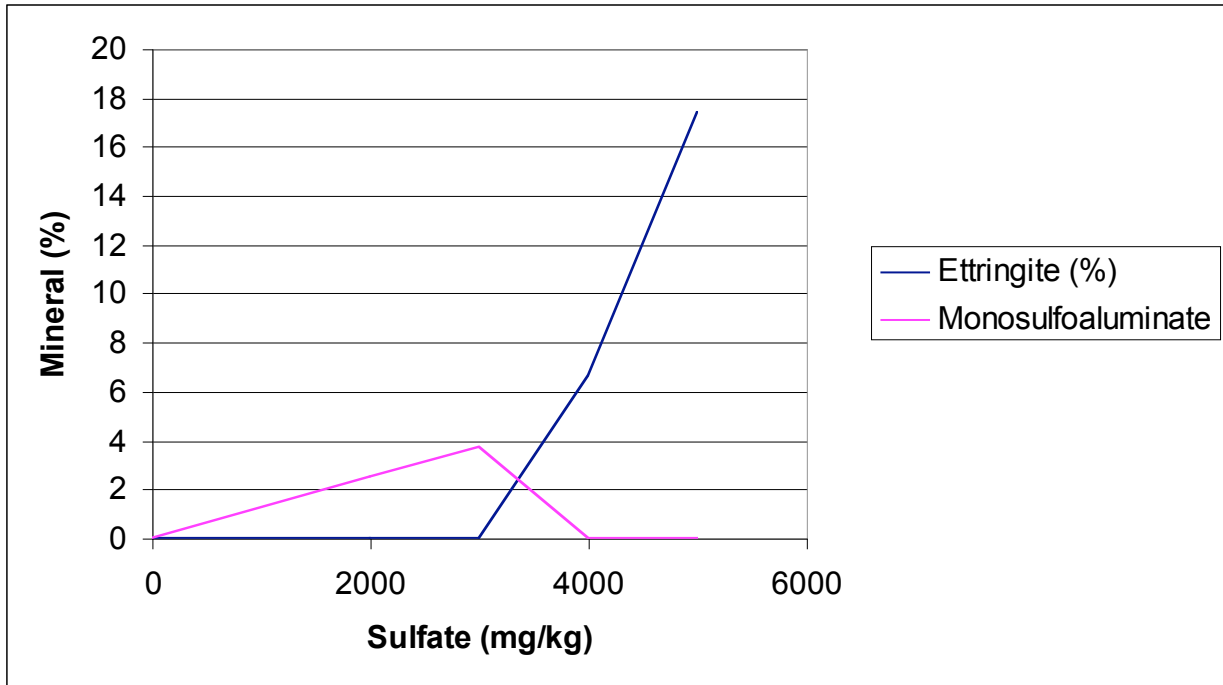
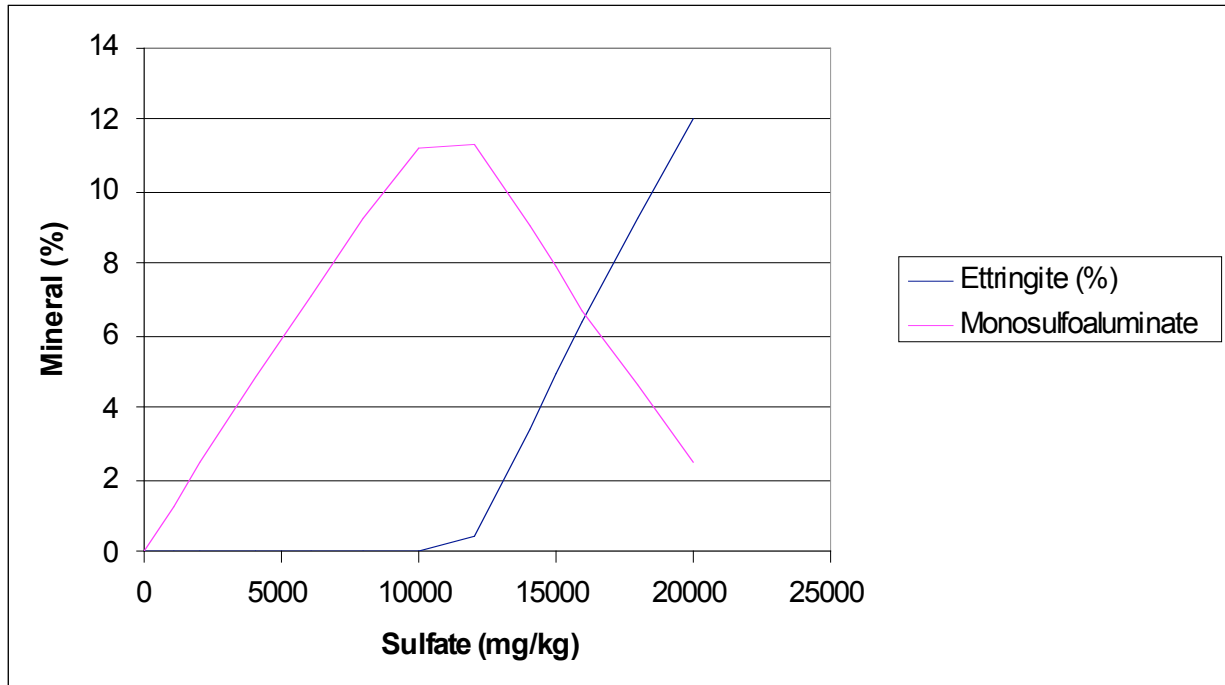
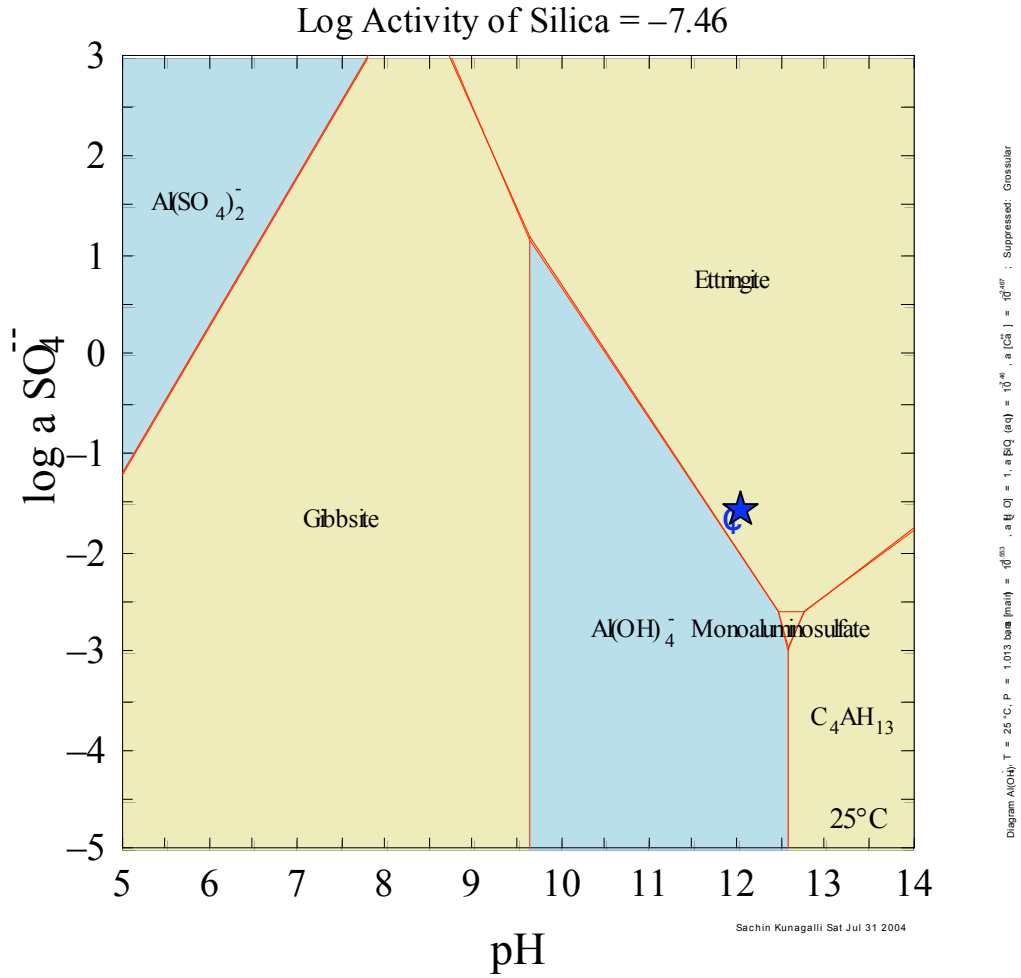


Figure 6 Minerals Precipitation Threshold in Frisco Soil (Eagle Ford Formation)



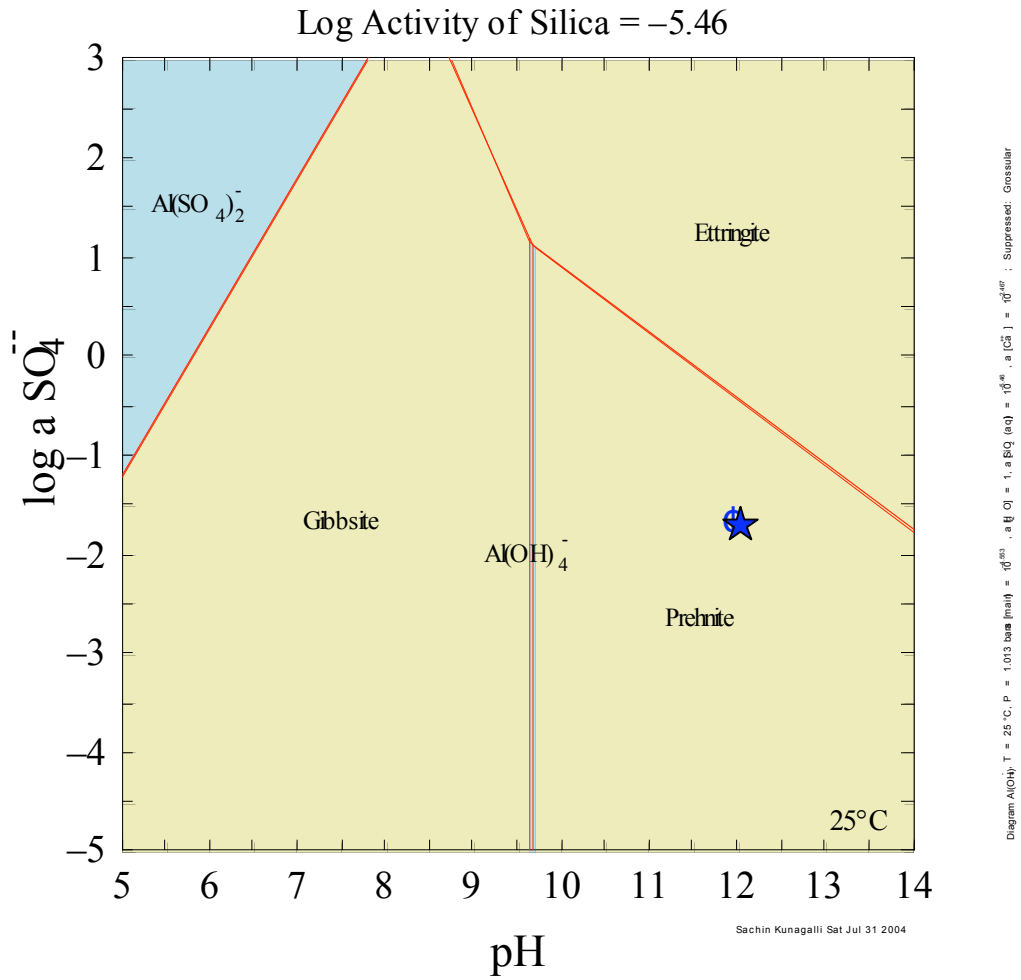
**Figure 7 Minerals Precipitation Threshold in Parmer-US 290 Intersection (Taylor Formation)**





**Figure 8 Impact of Silica Activity on US 290 (Taylor Formation Soil) – Lower Silica Activity**

Note: Star represents the locus of pH and log activity of Sulfate for the condition being considered.



**Figure 9 Impact of Silica Activity on US 290 (Taylor Formation Soil) – High Silica Activity**

Note: Star represents the locus of pH and log activity of Sulfate for the condition being considered.