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16. Abstract <p>Highways in Texas are now constructed much more rapidly than they were 20 years ago. During this same time period, there has also been an increase in the number of pavement failures in Texas attributed to a phenomenon called sulfate-induced heave. As part of Research Project 0-4240, a database of pavement failures due to sulfate-induced heave problems was developed. The researchers traveled across the state in search of pavement failures due to sulfate stabilization problems with calcium-based stabilizers. All of the projects discussed in this report were verified by the researchers as being caused by sulfate-induced heave.</p> <p>This report details eight case studies located in nine counties spread across the state of Texas. Many failures that had previously been attributed to improper stabilization of expansive subgrades can now be classified as sulfate heave problems. Comments from the Texas Department of Transportation (TxDOT) inspectors and construction engineers like “roller coaster roads” and “diamonds sparkling on the hillside” were commonly applied to these areas. Geologic maps, available in a Geographic Information Systems (GIS) format, indicated the presence of sulfates on 75% of the projects discussed in this report.</p> <p>Two alternatives to lime and cement were evaluated on three soils containing sulfates in excess of 20,000 ppm. An acid stabilizer showed improvement in strength but did not reduce swell over the long term. A mixture of ground granulated blast furnace slag and lime increased strength and reduced swell in all high sulfate soils tested.</p>					
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DISCLAIMER

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The United States Government and the state of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1

INTRODUCTION

Highways in Texas are now constructed much more rapidly than they were 20 years ago. During this same time period, there has also been an increase in the number of pavement failures due to a phenomenon called sulfate-induced heave. Many researchers have investigated the causes of sulfate heave, and they concluded that four ingredients are necessary for heaving to occur.^{1, 2, 3, 4, 5, 6} The ingredients include: (1) clay minerals (aluminate source), (2) lime or cement (calcium-based stabilizers), (3) sulfate or sulfide minerals or ions, and (4) copious amounts of water.

As part of Research Project 0-4240, researchers identified techniques for stabilizing sulfate-rich soils (sulfate concentrations above 7000 parts per million [ppm]) that did not produce the large heaves generated by lime and cement stabilization. The researchers went to many parts of the state evaluating roads with characteristics indicative of sulfate heave. The phrase most often used to describe such roads is a roller coaster. The Texas Department of Transportation (TxDOT) also evaluated many more roads with these same characteristics.

[Figure 1](#) shows all of the counties in Texas that have been identified as bearing sulfates in yellow; the green areas are the Eagle Ford Formation, which is a sulfate-bearing rock formation that has caused many sulfate heave problems for TxDOT. Counties highlighted in orange are where sulfate heave projects have been identified and repaired by one of two methods: first, some kind of chemical treatment has been added to mitigate the sulfate reactions on some roads, and second, the stabilized material is removed and replaced with a select material.

In the pages that follow, projects in which the researchers were directly involved will be discussed in some detail, and other projects evaluated by TxDOT will contain a brief discussion.

As shown in [Figure 1](#), this report describes projects located in nine counties spread across the state of Texas. These projects are located in vastly different climatic regions as well as varying soil types with one common denominator being sulfates.

Chapter 3 evaluates soils from four projects in great detail: it provides a template for designing a subgrade stabilization project in high sulfate soils. Three of these projects contained sulfate concentrations in excess of 20,000 ppm, and the fourth project contained approximately 5000 ppm sulfates.

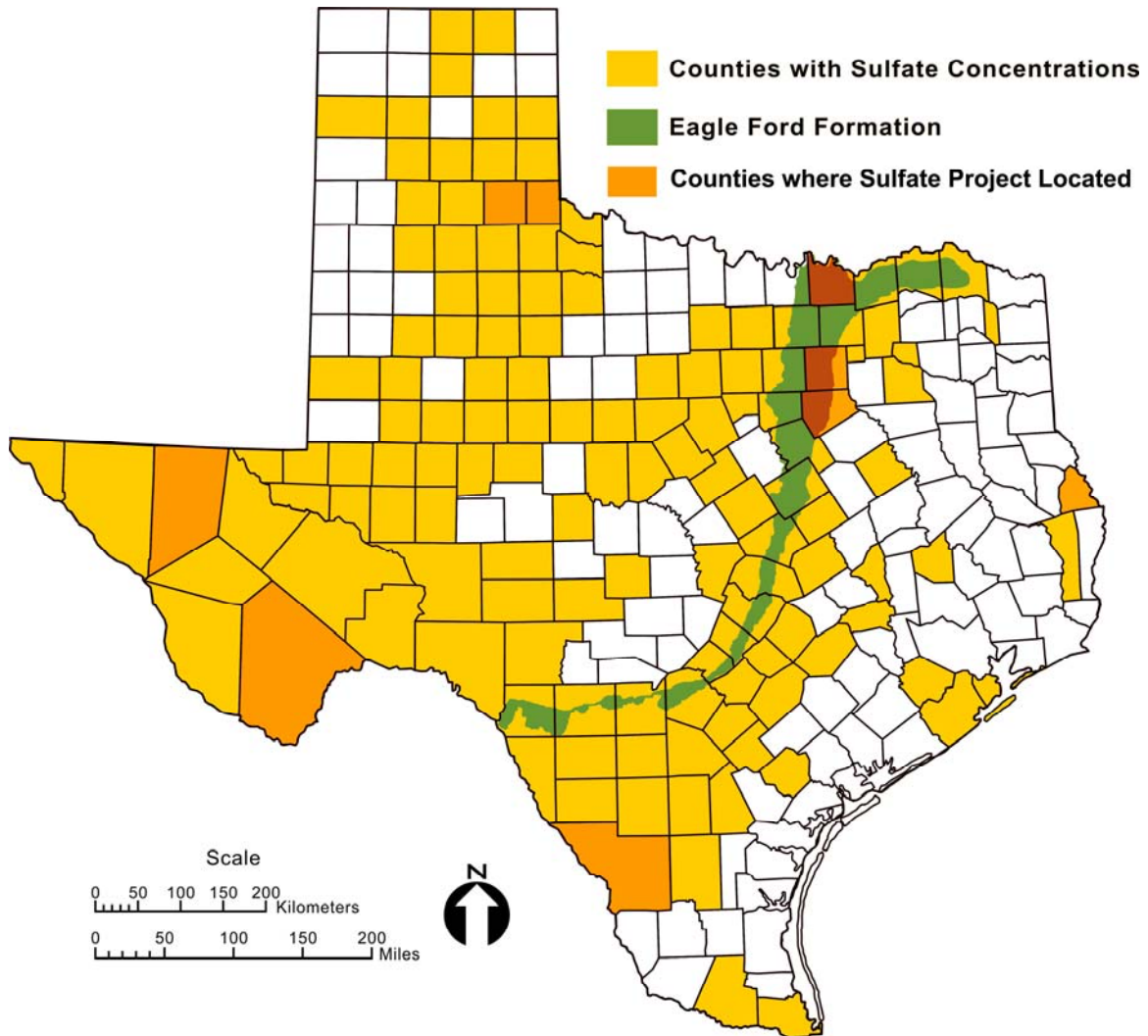


Figure 1. Map of Texas Shows the Counties of Sulfate Remediation Projects (in orange) Discussed in this Report.

CHAPTER 2

DISCUSSION OF FIELD SITES

The discussion of the projects starts in the east and proceeds to the western part of the state. The problem is discussed followed, by the remediation options. This list is only a partial representation of projects in Texas where sulfate heave has been documented.

SABINE COUNTY, FM 201

The first project is located in the Lufkin District in Sabine County (East Texas). It is FM 201, located approximately 5 miles south of Pineland. The paved highway ended approximately 3.3 miles east of U.S. 96, at which point the road changed to gravel. This project was an extension of FM 201 to the east ([Figure 2](#)).



Figure 2. Extension of FM 201 East from US 96.

The original paved highway was very bumpy or wavy; TxDOT engineers assumed that the bumps were due to poor stabilization of the expansive soils. The Geologic Atlas of Texas proved to be of no use in this particular case. This highway is

constructed on the Eocene Yazoo Formation. The geologic description of the Yazoo is clay, sandy, interbeds of silt and glauconitic sand with marine megafossils. There is no mention of sulfur-bearing minerals in this geologic unit. Evidence of sulfate heave on the original highway consisted of humps in the road (roller coaster), as well as gypsum crystals in the drainage ditches (Figure 3). Cores were taken on the tops of some of the humps, and the stabilized subgrade was examined. Ettringite (an expansive sulfate) was identified in some of the stabilized subgrade samples.



Figure 3. White Crystals below the Mechanical Pencil are Gypsum Crystals in Drainage Ditches on FM 201.

The ettringite in the stabilized layer and gypsum crystals found on the job site (Figure 3) suggested that sulfate-induced heave caused the rough road on FM 201. For the new construction, TxDOT decided to remove the existing subgrade and replace it with 2 feet of select fill (Plasticity Index [PI] = 20 to 25). Portland cement was mixed with the select fill and allowed to mellow for 2 to 5 days before compacting at 3% to 5%

above optimum moisture. The contractor had difficulty bringing the soil back to optimum moisture, so it was compacted 3% to 5% above optimum moisture at 95% density.

GRAYSON COUNTY, US 82

TxDOT (Dar-Hao Chen) contacted TTI about a failure on a new construction site in the Paris District. There was unexplained heaving of a lime-treated subgrade soil on the east side of the project (Figure 4). The west side had not been treated yet.



Figure 4. Heaved Area on the Eastbound Side of US 82 Near Sherman, Texas.

TTI advised TxDOT personnel (Dar-Hao Chen and John Bilyeu) how to sample the site to determine the cause of heaving and how to determine the extent of the problem area. TxDOT collected samples and returned a portion of them to the materials laboratory at TTI.

TxDOT personnel delivered 16 samples (Figure 5) to TTI to answer the following questions. 1) What caused the heaving in the pavement on US 82? 2) If the problem is sulfate heave, then what is the extent of the sulfates? 3) What can be done to prevent this from happening again?

A geologic map of the area was consulted to determine what rock formation in which the US 82 construction site was located (Figure 6). The area in blue is the Eagle Ford Formation, which is known to be sulfate bearing. The red and pink squares represent locations where samples were collected.

Representative samples (Figure 7) were taken from each bag delivered to TTI and allowed to air-dry overnight. Five grams of material was taken from each sample and mixed with 100 mL of double-distilled water on a mechanical shaker. The conductivity and pH of each sample were measured at different time intervals with an Accumet AR50 pH/Conductivity meter. These samples were not pulverized.



Figure 7. Representative Samples Taken from Each Bag That TxDOT Delivered to TTI.

After high conductivity measurements revealed possible problem areas, four samples (Table 1) were selected for analysis with a JEOL 6400 scanning electron microscope (SEM) located on the Texas A&M University campus. The SEM is equipped with a Princeton Gammatech energy dispersive spectrometer (EDS), which gives qualitative measurements of elemental composition. Each sample was placed on a round 30 mm diameter aluminum stub and coated with a gold/palladium alloy to make the

sample conductive. The samples were then analyzed at an accelerating voltage of 15kV and 15 mm working distance.

Following conductivity measurements and SEM analysis, six samples were tested with a colorimeter for soluble sulfate content. This was accomplished by filtering the water from the conductivity measurements through Whatman #42 filter paper and placing 10 mL of the filtrate in the colorimeter vial. A barium chloride tablet was placed in the solution and dissolved by crushing with a glass stirring rod. This created a cloudy precipitate that was quantified by a light beam traveling through the vial to a light meter on the other side. The amount of light detected by the meter decreased as the concentration of sulfate increased allowing the sulfate concentration to be determined.

Results

Conductivity measurements were high for samples taken from the eastern side of the project, and they were low on the western side (Table 1). Samples E-1T and E-1B were taken from the top of the raw subgrade and from 41 inches below the top, respectively. There was a six-fold increase in conductivity with an increase in depth, and the sulfate content increased by more than six-fold. This is exactly as expected because the more soluble gypsum is washed from the near surface to greater depth during the rainy season.

Samples taken from the west side of the project had very low conductivities. This should correlate with low soluble sulfate contents. Two samples from the west side were analyzed by colorimetry and revealed zero and 100 mg/L sulfate (Table 1).

A valuable approach is to monitor conductivity over time to determine how quickly sulfates react with lime. Figure 8 shows a graph of conductivity over a time period of approximately 24 hours for an unpulverized soil sample. It is evident from this graph that there is a range of grain sizes because samples on the east side have a fairly high initial conductivity reading. The conductivity increases over time, indicating dissolution of coarser grained constituents. Coarse-grained samples take longer to dissolve, so the conductivity increases more slowly as these crystals dissolve.

Table 1. Summary of Analyses Performed on US 82 Samples.

Sample Name	Max Cond. (μS)	pH	SEM Analysis	Colorimetry (SO_4^{-2} mg/L)
E-0	1880	10.97		10,400
E-1T	657	8.60	Yes	4,160
E-1B	3480	8.27	Yes	27,840
E-1 LTSa	1170	11.09	Yes	5,120
W-0	221	9.08		
W-1	224	9.02		
W-2	230	8.77		
W-3	120	8.93		
W-4	101	8.98		
W-5	90.1	8.99		100
W-6	89.8	9.01		
W-7	90.2	8.96		
W-8	92.2	9.01		
W-9	91.5	9.10		
W-9m	87.8	9.10		0
E-1 LTSb	2310	10.41	Yes	

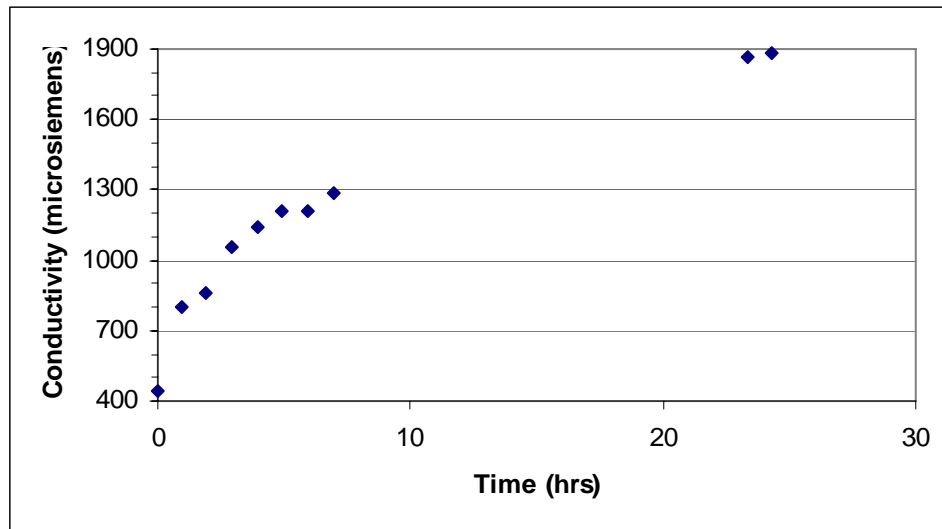


Figure 8. Conductivity Measurements for Sample E-0 Shows How Sulfate Grain Size Affects Readings.

Figure 9 shows some gypsum crystals removed from Sample E-1B. These crystals increase to more than a centimeter across. Crystals several centimeters in size

have been observed from this formation. The crystals have a muddy appearance because they grew in the soil, and some of the soil is trapped in the crystal structure.

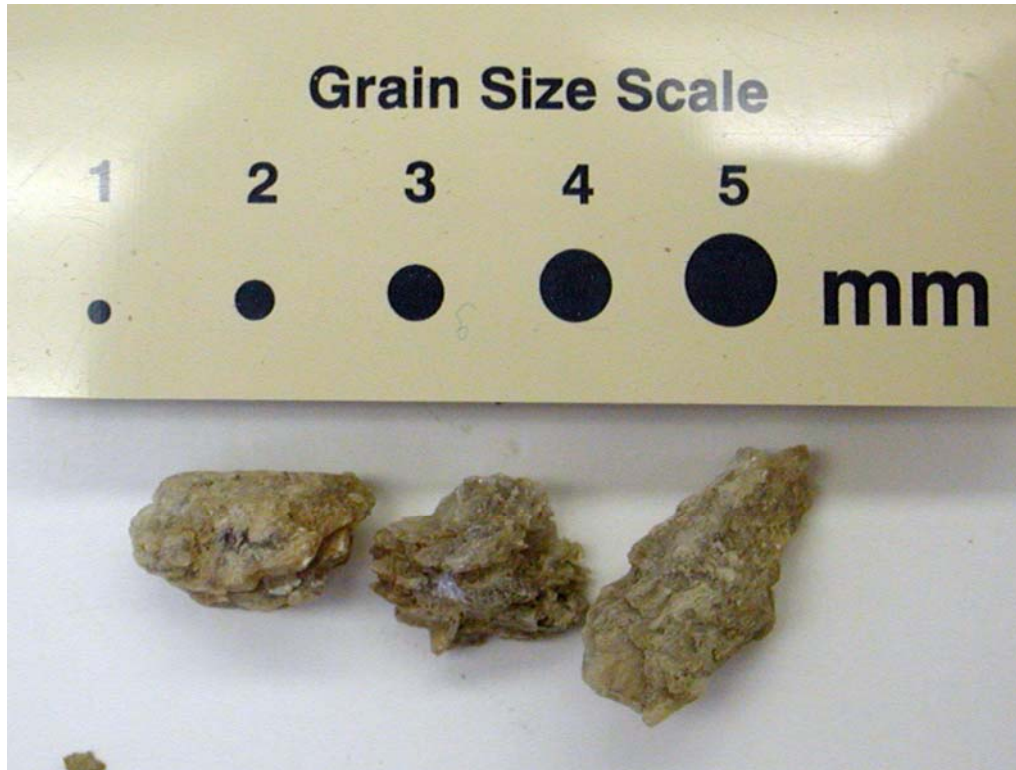


Figure 9. Individual Gypsum Crystals Extracted from Sample E-1B.

Scanning electron microscopy was used to examine samples for deleterious reaction products. Two lime-treated samples and two raw subgrade samples were analyzed. It is obvious from comparing images from the stabilized and unstabilized samples that lime reacted with gypsum to form ettringite (Figures 10-14) in the stabilized material. Figure 10A shows the absence of calcium (Ca) in this untreated sample. Figure 10B is an untreated subgrade sample that shows unaltered smectite crystallites in a subparallel arrangement due to compaction.

Figures 11A and 11B are from the untreated subgrade as well. The EDS pattern is of the gypsum crystals in Figure 11B. Note the absence of aluminum (Al). Figure 11B shows small gypsum crystals (~50 μm) that were observed in some of the untreated samples.

All of the untreated samples show an absence of the long acicular crystals observed in [Figure 12A](#). [Figure 12B](#) was taken at about the same magnification as 12A and shows the marked contrast between the treated and untreated samples. There are abundant long, fibrous crystals in the lime-treated subgrade that are absent in the untreated samples. This crystal morphology is typical of ettringite. The EDS pattern in [Figure 13A](#) confirms that the long, fibrous crystals are indeed ettringite.

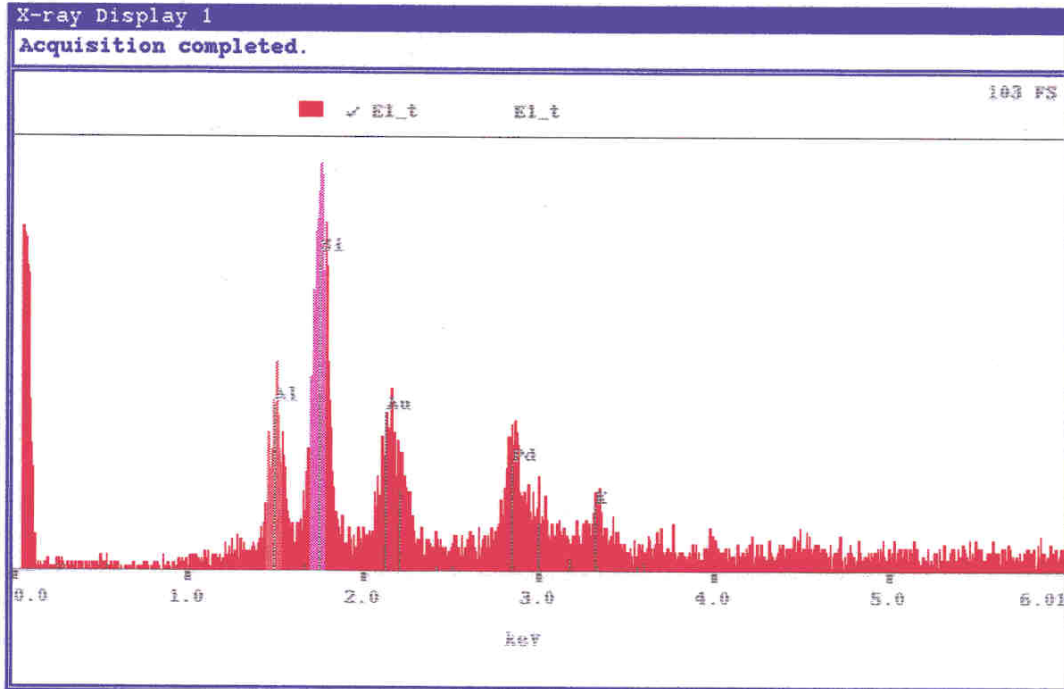


Figure 10A. EDS Pattern from Sample E-1T Which Is an Untreated Subgrade Sample. (These elements are typical of smectite and other clay minerals from image 10B. Note absence of calcium.)



Figure 10B. SEM Image of Natural Clay Rich Soil. (The crinkly masses are smectite grains. Note the absence of long needle-shaped crystals.)

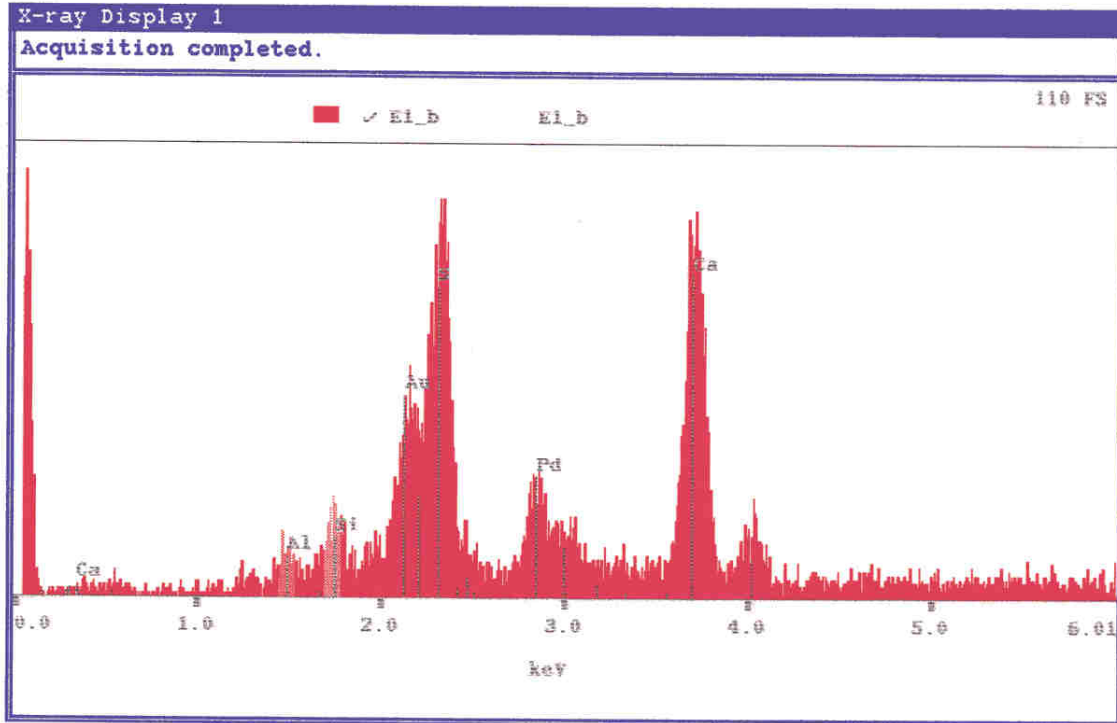


Figure 11A. EDS Pattern of Gypsum Crystals Shown in 11B.
 (Note the ratio of the calcium to sulfur peaks and the absence of an aluminum peak.)



Figure 11B. SEM Image from Sample E-1B Showing Gypsum Crystals in the Untreated Subgrade.

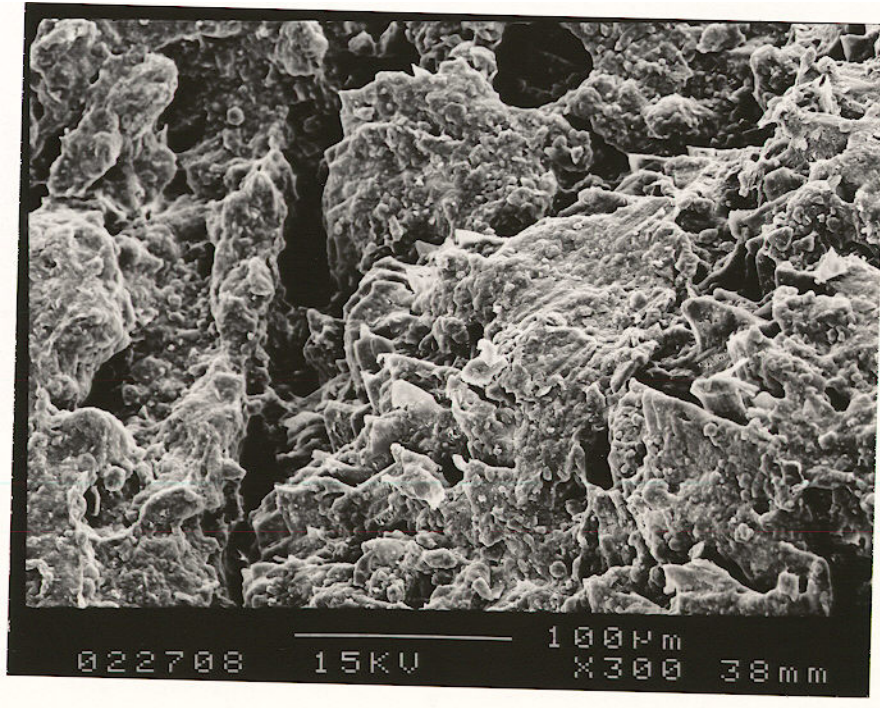


Figure 12A. SEM Image Illustrates What the Untreated Soil Looks Like.
(Note absence of reaction products.)

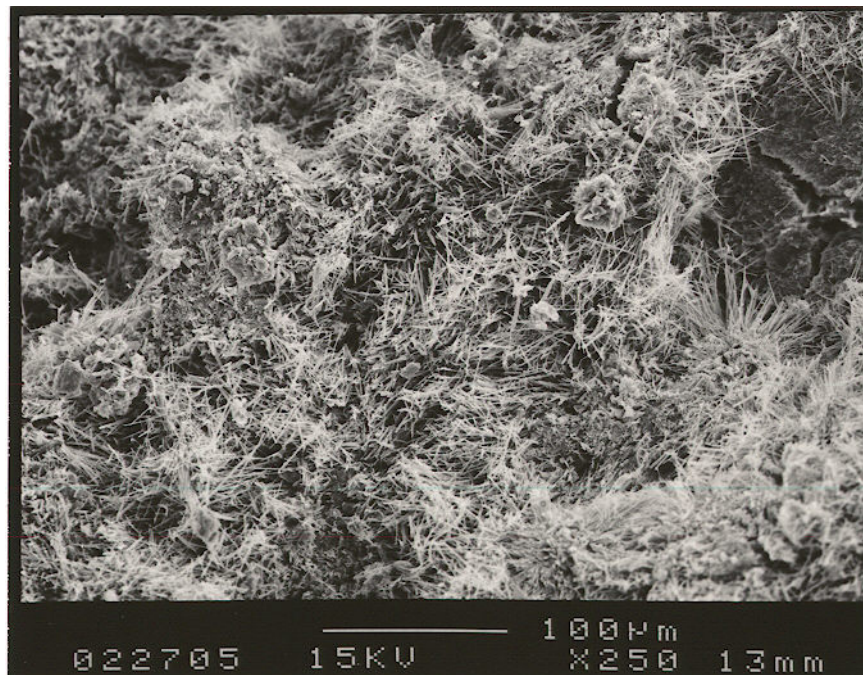


Figure 12B. SEM Image from Sample E-1 LTSa Showing What the Lime Treated Subgrade Samples Look Like. (Note the abundant long needle-like crystals everywhere.)

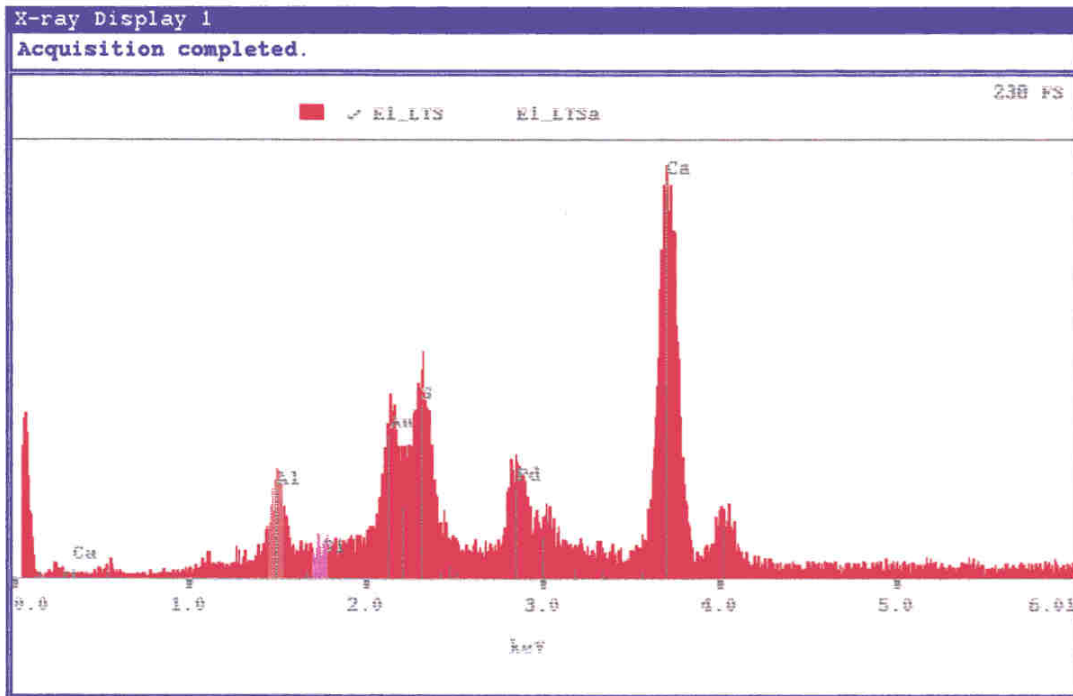


Figure 13A. EDS Pattern from the SEM Image Below.
(Note the high calcium peak and the sulfur and aluminum peaks. This pattern is typical of ettringite.)



Figure 13B. SEM Image from Sample E-1 LTSa Shows Acicular Prismatic Crystals Which Are Typical of Ettringite. (This is an expansive reaction product of lime and gypsum.)

OBSERVATIONS

The following observations are based on the conductivity, SEM, and direct sulfate measurements (colorimetry) made at TTI.

- The formation of ettringite can be blamed for the heaving observed on US 82 in the Paris District.
- From the samples analyzed at TTI, the sulfate problem appears to be concentrated on the eastern side of the project.
- TxDOT needs to be careful if there is any **cut and fill work because sulfates tend to be more concentrated at depth** in the soil profile, which is evident from samples taken from site E-1.
- There is a need to analyze for sulfides in this particular case since sections are being cut, because the Eagle Ford Formation is rich in pyrite at depth. Pyrite is the ultimate source of the gypsum crystals observed in the soils developed in the Eagle Ford Formation.⁶

Grayson County, US 82 Revisited

Following the initial laboratory investigation of soils from US 82, delivered to TTI by Dr. Dar-Hao Chen and John Bilyeu, more questions were generated than answers. Researchers determined that TTI would go to the site and perform extensive field testing for soluble sulfates and collect samples for laboratory analysis.

Questions were raised about the extent of the high sulfate areas, and if high sulfate concentrations were encountered at other places along the project, how should they be handled? The following testing plan was devised to address these questions.

Testing Plan

Conductivity measurements were made in two parallel passes separated by 12 feet, with measurements taken at intervals of 100 feet in the westbound direction of US 82 (Figure 14). Samples were not collected east of US 69 because that is where the lime stabilized subgrade heaved (Figure 15). Due to the cut and fill operations, samples were not collected in areas where earthwork was not complete, because sulfates could be

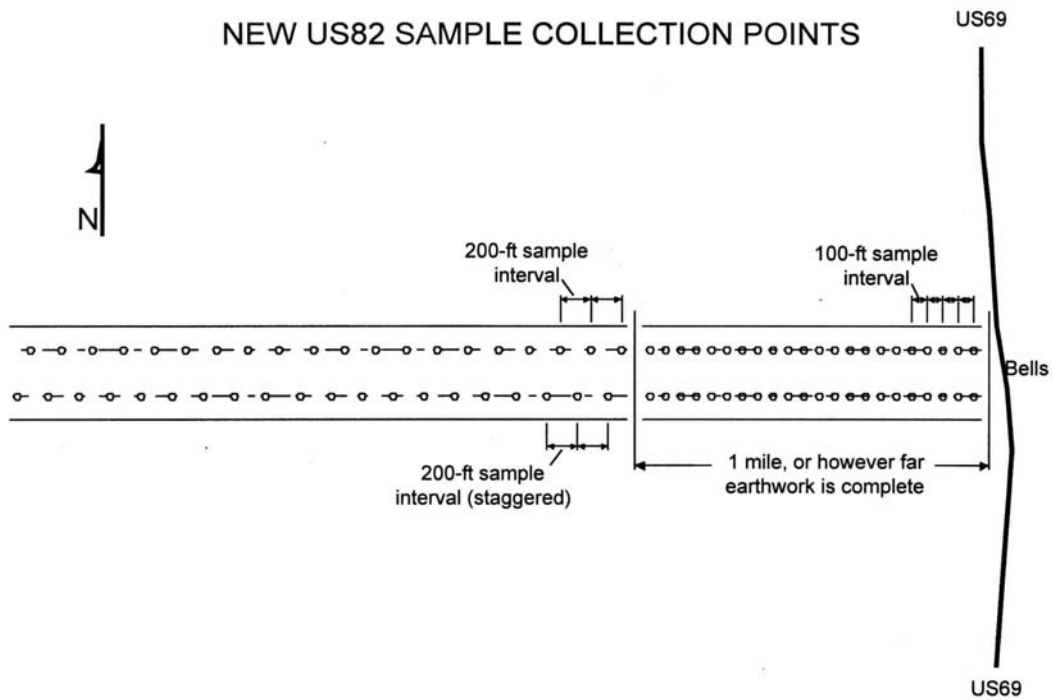


Figure 14. Sample Collection Sites along US 82. Samples Were Only Collected along the First Mile of the Project. (Map courtesy Dar-Hao Chen of TxDOT)



Figure 15. Trench Cut along Heaved Section of US 82.

brought in from adjacent hills as fill in low-lying areas. The sample spacing was planned because the sulfate tends to run in seams that may not be very large, so it was decided to use 100 feet of spacing between measurements in hopes of detecting possible sulfate seams (Figure 16).

Sulfate concentrations were determined using colorimetry for samples with elevated conductivity readings following the conductivity measurements taken in the field and taken again 10 hours later. The later measurements all show higher conductivities, but some are much higher, indicating higher sulfate concentrations. Samples were then chosen for laboratory testing based upon the sulfate test results.



Figure 16. Veins of Gypsum (pen) Filling Fractures in Eagle Ford Formation along US 82.

RESULTS

Conductivity measurements were taken at 102 stations as illustrated in [Figure 14](#). Based on the initial and final conductivity measurements (time = 0, 10 hrs.), 12 locations were chosen to collect samples for extended laboratory testing ([Table 2](#)).

The acetone test, a quick field test, detects the presence of sulfates above a concentration of approximately 2000 ppm using a dilution ratio of 1:20 (soil:water). If a lower dilution ratio were used, then lower concentrations of sulfates could be detected. Conductivity measurements were made at the 1:20 dilution ratio, and the solution was filtered and centrifuged to obtain a clear supernatant to analyze for sulfate concentrations using colorimetry and the acetone test (results presented in [Table 2](#)).

Table 2. Results of Soluble Sulfate Analyses from Two Commercial Laboratories and Three Quick Field Tests.

Sample Name	Lab 1 Sulfates (ppm)	Lab 2 Sulfates (ppm)	Acetone sulfates detected	Colorimeter Sulfates (mg/L)	Initial Cond. (µS) time = 0	Final Cond. (µS) time = 10 hrs.
*1596R	0	330	ND	0	40	55
*1597R	0	90	ND	0	40	59
*1603L	0	260	ND	160	40	53
*1612R	515	150	ND	0	40	94
*1612L	502	150	ND	180	40	61
*1613R	2125	1100	ND	1800	50	219
*1613L	1669	1900	Ppt.	3960	20	178
*1614R	807	380	ND	780	30	217
*1614L	704	470	ND	760	20	152
*1615R	529	100	ND	100	30	76
*1615L	638	230	ND	100	30	68
*1635L	1025	810	Ppt.	>4000	50	403

**Sulfides were not detected in any of the samples tested in the laboratory.*

ND is not detected; Ppt. is precipitate.

DISCUSSION/INTERPRETATION

- The sulfate concentrations on the part of the project analyzed by TTI ([Figure 14](#)) are apparently low with a couple of exceptions where higher concentrations of gypsum were detected.
- The conductivity test did an excellent job of detecting the higher sulfate soils.

- As illustrated in [Figure 16](#), and from the field testing, these sulfate seams can be quite localized.
- The researchers recommend stabilization with lime on the western section that has been tested because the sulfate concentrations are low enough to stabilize with lime. However, they need to continue sulfate testing as areas are filled to grade and prior to stabilization on the remainder of the project.

TxDOT lime stabilized the western section of the project since the testing performed at TTI showed low sulfate concentrations. There have not been any problems reported from this section. A new section was recently constructed where sulfate heave problems were again occurring. The researchers are not aware of any sulfate testing on the new construction site.

Dallas County, SH 161

The soil on this project is developed on the Eagle Ford Formation ([Figure 17](#)). Sulfate concentrations range from 21,000 to 27,000 ppm. This project is part of an interchange being constructed on SH 161 and SH 183.

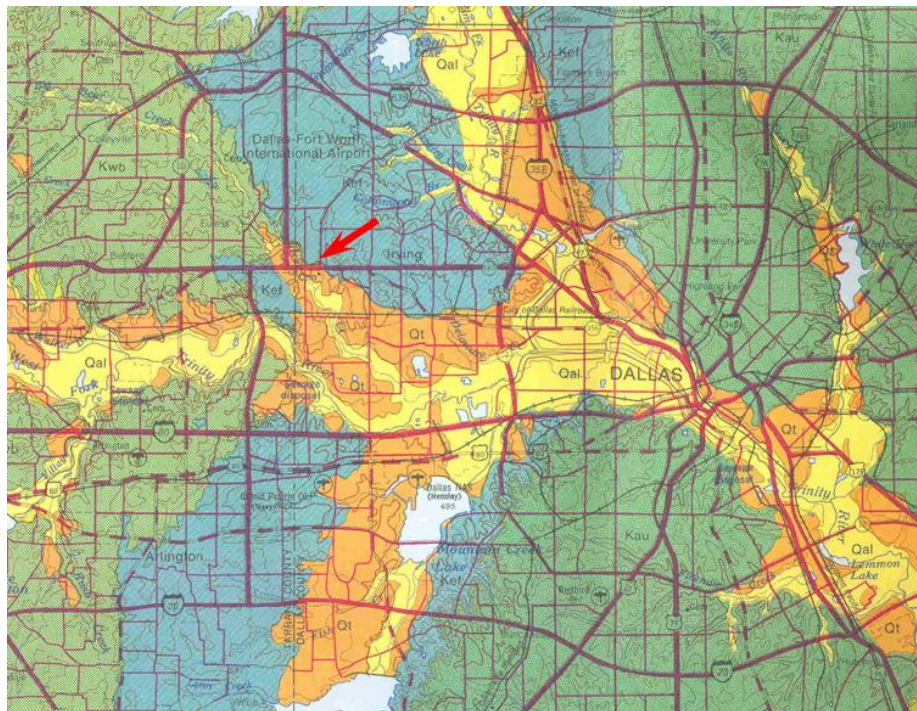


Figure 17. Portion of Geologic Atlas of Texas Showing SH 161 (red arrow) Located on the Eagle Ford Formation.

There was extensive preconstruction testing which revealed areas of high sulfates in this project. Maurice Pittman, P.E., of the Project Management Committee asked the researchers to test stabilizers identified in Research Project 0-4240 with soil from this construction site. Details of this testing are listed in [Chapter 3](#) of this report. Based on the testing that TTI did, TxDOT decided to stabilize the subgrade with a combination of lime and ground granulated blast furnace slag (GGBFS).

Ellis County, U.S. 67

TxDOT was expanding a two-lane highway (US 67) to four lanes on the western edge of Ellis County. TxDOT lime stabilized the subgrade with 10% to 11% lime and sealed it to cure. One evening while the subgrade was curing, it rained on the project. The morning after the rain storm, there were equally spaced ridges 10 to 12 inches high along the construction site ([Figure 18](#)). TTI was asked to determine what caused the heaves and answer five questions for TxDOT.



Figure 18. Vertical Heaves of Lime-Stabilized Subgrade on US 67 in Ellis County.

Question 1: What caused the initial swelling?

The Geologic Atlas of Texas may give a good indication of what minerals are in a soil. It shows the rock formations in an area. In this case, the widening project runs east-west, right across the Eagle Ford Formation (Figure 19, lower third of map), the same rock formation that caused problems on US 82. The red vertical line on Figure 19 marks the western boundary of the project, and the red arrow points in the direction of the project. The legend of the Eagle Ford (Kef) describes it as being *selenitic*. Selenite is another name for gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which supplies the sulfate needed for the heaves. Samples of the stabilized and unstabilized soil were collected for analysis at TTI. The following figures show evidence of ettringite formation in the lime-stabilized soil. The formation of ettringite generates a volume increase double its original volume.

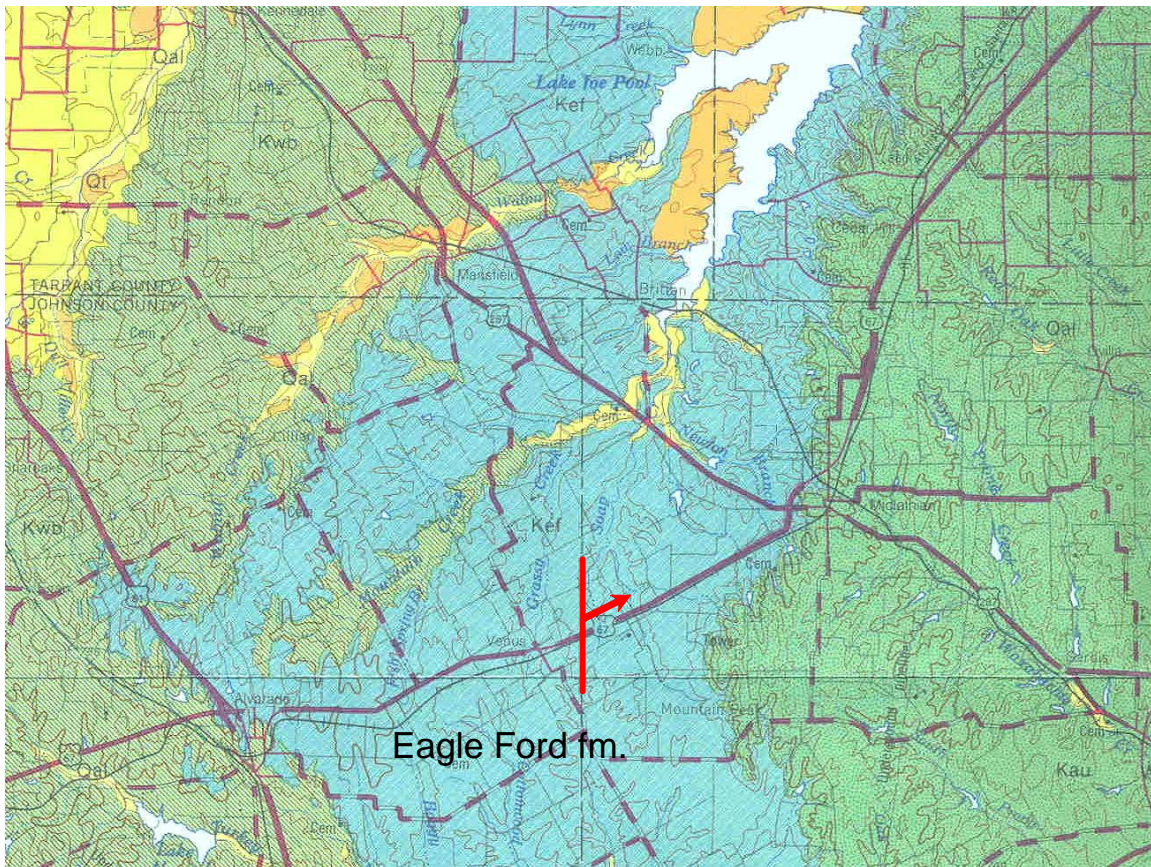


Figure 19. Portion of Geologic Atlas of Texas Showing US 67 West of Midlothian Passing through the Eagle Ford Formation (in blue).

Ettringite was identified in the lime-stabilized soil by X-ray diffraction and SEM analysis. The ettringite crystals are the white needle-like crystals shown in the image in [Figure 20A](#). The EDS attached to the SEM gives the elemental composition of the crystals. [Figure 20B](#) is an EDS pattern of the needle-like crystals, which confirms the presence of sulfur (S), aluminum (Al), and silicon (Si) in a concentration typical of ettringite. Gypsum crystals abound in the unstabilized soil as both large crystals in excess of 2 mm and as exceptionally small crystals less than 1 μm ([Figure 21A](#) and [B](#)).

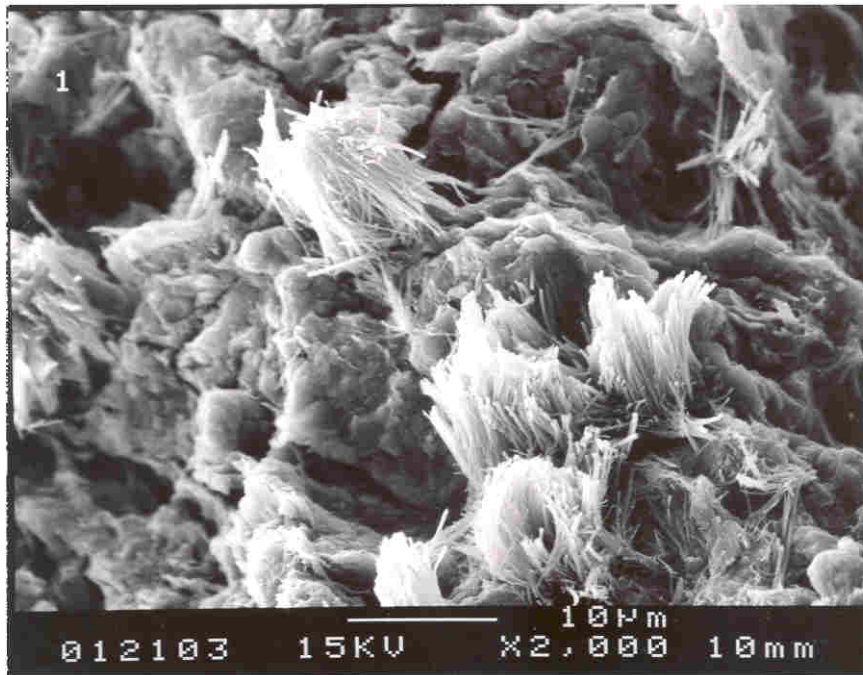


Figure 20A. SEM Image of Ettringite Crystals in Lime-Stabilized Subgrade.

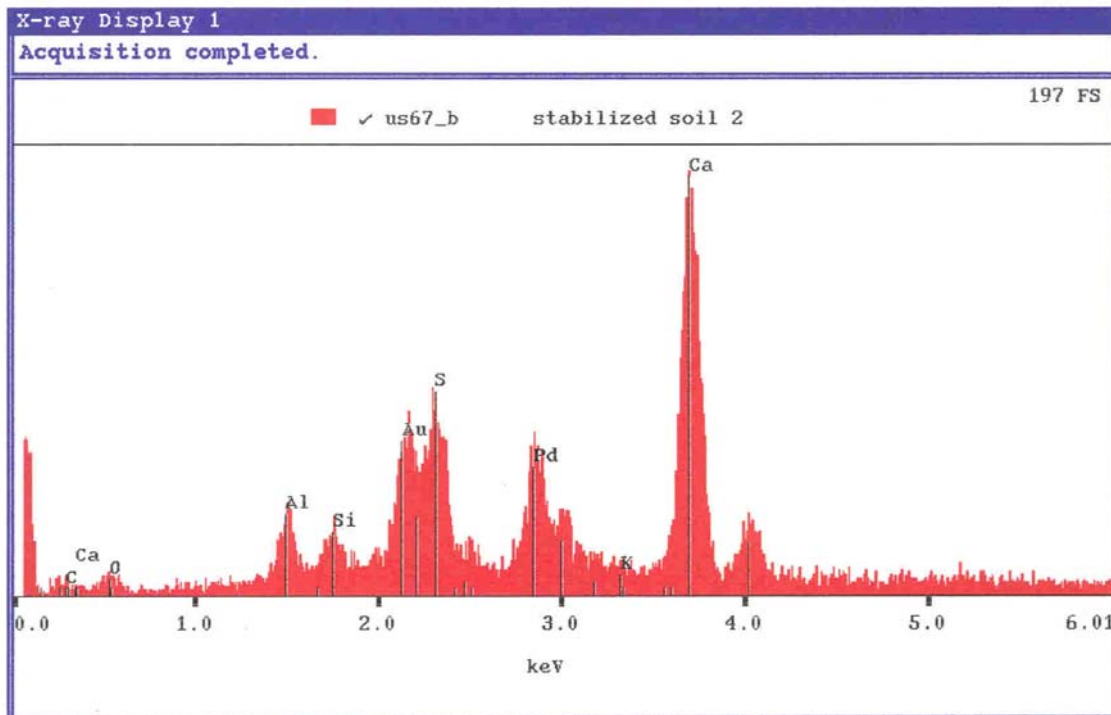


Figure 20B. EDS Pattern of Ettringite Crystals Shown in the SEM Image in 20A.

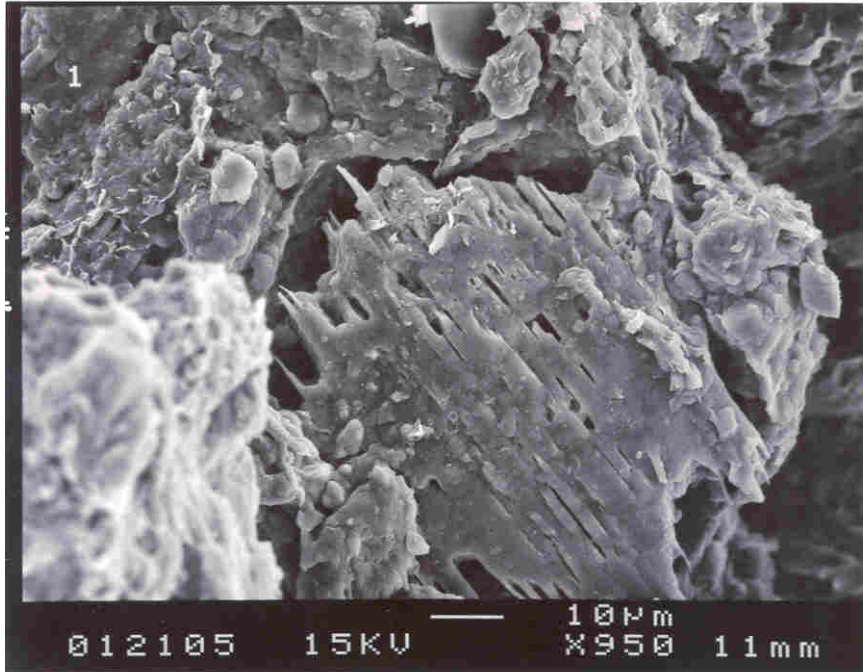


Figure 21A. SEM Image of a Gypsum Crystal in the Unstabilized Soil.

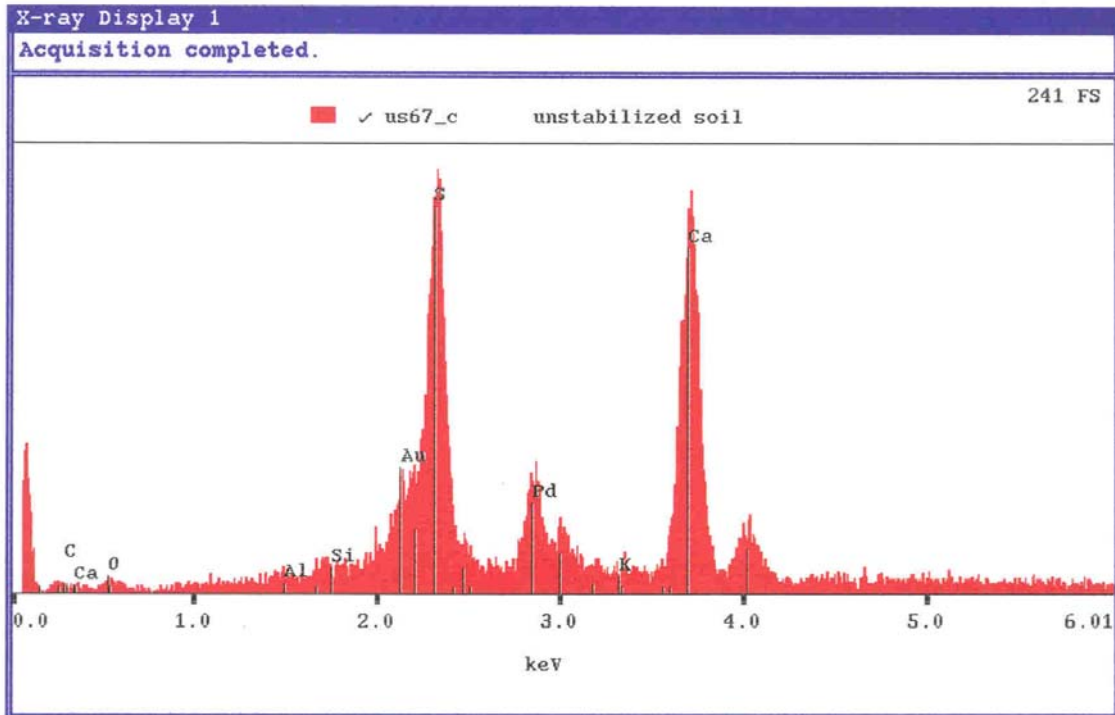


Figure 21B. EDS Pattern of the Gypsum Crystal Shown in SEM Image Above.

Question 2: Are the sulfates completely reacted in the lime-stabilized soil?

No, the gypsum is still present in the lime-treated soil. Large gypsum (up to 2 mm) crystals were observed in the lime-treated soil by visual inspection under a binocular microscope. X-ray diffraction of the lime-treated soil confirmed the presence of ettringite as well as unreacted gypsum. As discussed above, the gypsum crystals are large, and it appears that they were not all consumed in the original reaction with the lime.

The presence of sulfates was also confirmed by laboratory testing conducted on both the raw and treated soils (Table 3). In the raw soil, one sample had a total sulfate content of 32,500 ppm. The lime-stabilized material even had sulfate concentrations up to 12,900 ppm available for reaction. A consequence of having the unreacted gypsum in the stabilized material is the possibility of forming more deleterious products with further chemical stabilization.

Table 3. Soil Samples from US 67 Showing Sulfate Concentrations.

Sample Name	Sulfate Sulfur in parts per million
Unstabilized-1	32,500
Unstabilized-2	29,200
Unstabilized-3	26,000
Unstabilized-4	23,400
Stabilized-1	11,300
Stabilized-2	12,900

Question 3: Will double treatment be effective?

This is a tough question to answer. If all of the sulfate is removed from the system and if water is restricted from the stabilized layer, then restabilizing the material may work. These soils are extremely variable in mineralogical composition. For example, one may look at a sample which contains 20,000 ppm sulfate and determine that the stabilizer (lime) completely neutralized all of the sulfate. However, the next sample may contain 50,000 ppm sulfate. This may leave a large percentage of unreacted sulfate

which will be available for further reaction if the material is restabilized using calcium-based stabilizers.

Question 4: What to do now?

The safest thing is to remove all of the sulfate-bearing soil from the site and replace it with a material free of sulfates or sulfides. The existing lime-stabilized material still has about 1% unreacted gypsum, which could cause the swelling problem to recur.

Question 5: Could problematic soils be identified prior to lime stabilization?

Yes, the Geologic Atlas of Texas is a valuable resource for identifying potential sulfate problems prior to construction, when the project is still in the planning stages. Most of the sulfate heave problems researchers have encountered in the field may have been avoided if the Geologic Atlas of Texas were consulted. However, there have also been cases where sulfates were identified in the field but not identified on the geologic maps.

Another technique is to visually look for the sulfates when the soil is being moved on a project. Look for sparkling crystals and a white powder in the drainage ditches.

The final step is to measure for sulfates along a project. There are two tests that can be run. The first, conductivity (TxDOT Test Method TEX-146-E), is a quick screening tool to identify high salt concentrations. The second test takes longer (approximately 30 minutes) to perform, but it measures actual sulfate content in ppm. This sulfate measuring device is a colorimeter, and TxDOT Test Method TEX-145-E was developed using this device.

Webb County, FM 3338

René Soto, the Laredo District Laboratory Supervisor, contacted TTI and discussed potential construction sites to include as high sulfate test sections for Research Project 0-4240. In order to get the site constructed prior to the August 2005 research project deadline, only one FM road widening construction project was considered.

FM 3338 is an 8 mile widening project (Figure 22) that had sulfate contents measured below 2000 ppm across the entire project initially and was scheduled to be lime

stabilized. But the laboratory performed proctor tests and measured soil samples for sulfates a second time. They found a short section where the sulfates measured in excess of 40,000 ppm.



Figure 22. FM 3338 is an 8-Mile Long Widening Project in the Laredo District.

Researchers Pat Harris and Stephen Sebesta selected three sites, in the zone with high sulfate contents, to collect soil samples to return to the laboratory for measuring sulfate concentrations and to mold test specimens with stabilizers that have shown promise in high sulfate soils.

Quick conductivity tests were performed at stations to verify high sulfate levels before samples were acquired to depths of 8 to 12 inches with an auger:

- Station 103 - conductivity > 900 μS collected 4 bags of soil;
- Station 107 - conductivity > 1000 μS collected 4 bags of soil; and
- Station 113 - conductivity > 800 μS collected 4 bags of soil.

A quick study of the field site revealed small gypsum crystals and efflorescence of gypsum (Figure 23) on the embankment and in the drainage ditch adjacent to the widening project.



Figure 23. Mechanical Pencil Points to Small Gypsum Crystal.
(Note also the white patches.)

A review of the Laredo Sheet (Figure 24) from the Geologic Atlas of Texas at a scale of 1:250,000 showed that the FM 3338 project (red arrow) is on the El Pico Clay Formation (Eep, left hand side of map), which is *gypsiferous* as explained in the legend. Gypsiferous is another name for gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which illustrates how important these maps can be in locating areas with potential sulfate problems.

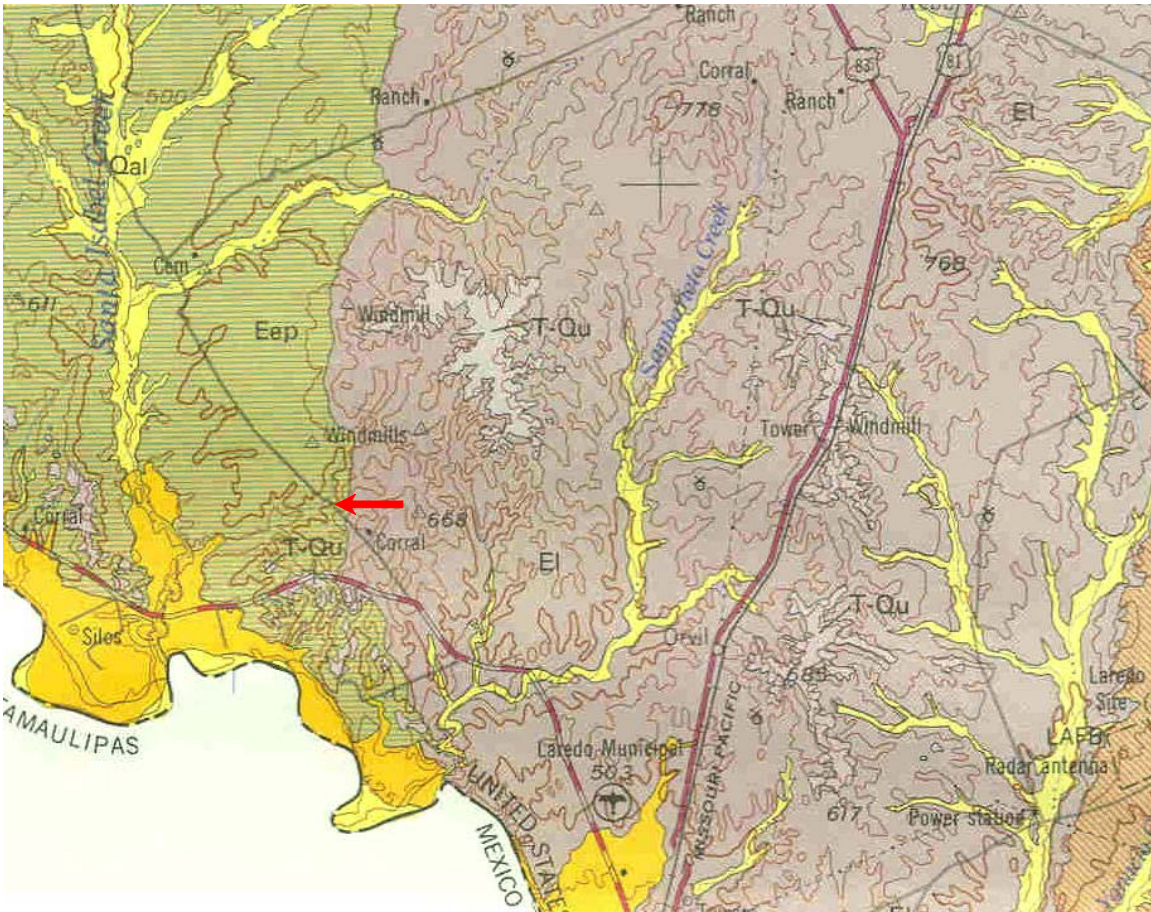


Figure 24. Geologic Atlas of Texas Showing FM 3338 Passing through the El Pico Clay (Eep) Which is Gypsiferous.

Based on three-dimensional (3-D) swell and strength testing of the high sulfate soils from FM 3338 in Laredo, the decision was made to change the stabilizer from lime to a mixture of GGBFS and lime only in areas where high sulfates were detected. Lime was used to stabilize parts of the project where sulfates were less than 3000 ppm. There is a more detailed account of the procedures used to select the stabilizers for FM 3338 in [Chapter 3](#) and [Appendix B](#).

Childress County, US 287

The Materials and Pavements Section of TxDOT evaluated the cause of extensive longitudinal cracking and severe roughness (swells) near Baylor Creek Bridge on US 287 in western Childress County ([Figure 25](#)). Both the northbound and southbound lanes were reconstructed approximately 5 years ago. There were 9 inches of lime-treated

subgrade (3 % wt.) in the reconstructed section. About 2 years after the reconstruction, the section near Baylor Creek developed extensive fatigue cracking in the right wheel paths and longitudinal edge cracking on the shoulders. The northbound lanes were milled and inlayed in this section approximately 2 years ago. [Figure 25](#) shows what the section looks like today.



Figure 25. Longitudinal Cracks on Shoulder and Swell (solid white line marking the shoulder) near Baylor Creek on US 287. (Image courtesy of Zhiming Si)

[Figure 26](#) is a portion of the Plainview Sheet of the Geologic Atlas of Texas, and it shows the limits of the premature failure (white lines across road) on US 287. The solid blue portion of the map labeled Pwh consists of the Cloud Chief Gypsum and Whitehorse Sandstone units deposited in the Permian period. A geologic description of these rocks includes interbedded sandstone, shale, gypsum, and dolomite. The sandstone is described as fine-grained orange to orange-brown quartz. The gypsum is white to gray and pink up to 20 feet thick. The term *gypsum* in the name of the unit should raise a red flag regarding sulfates in the soil.

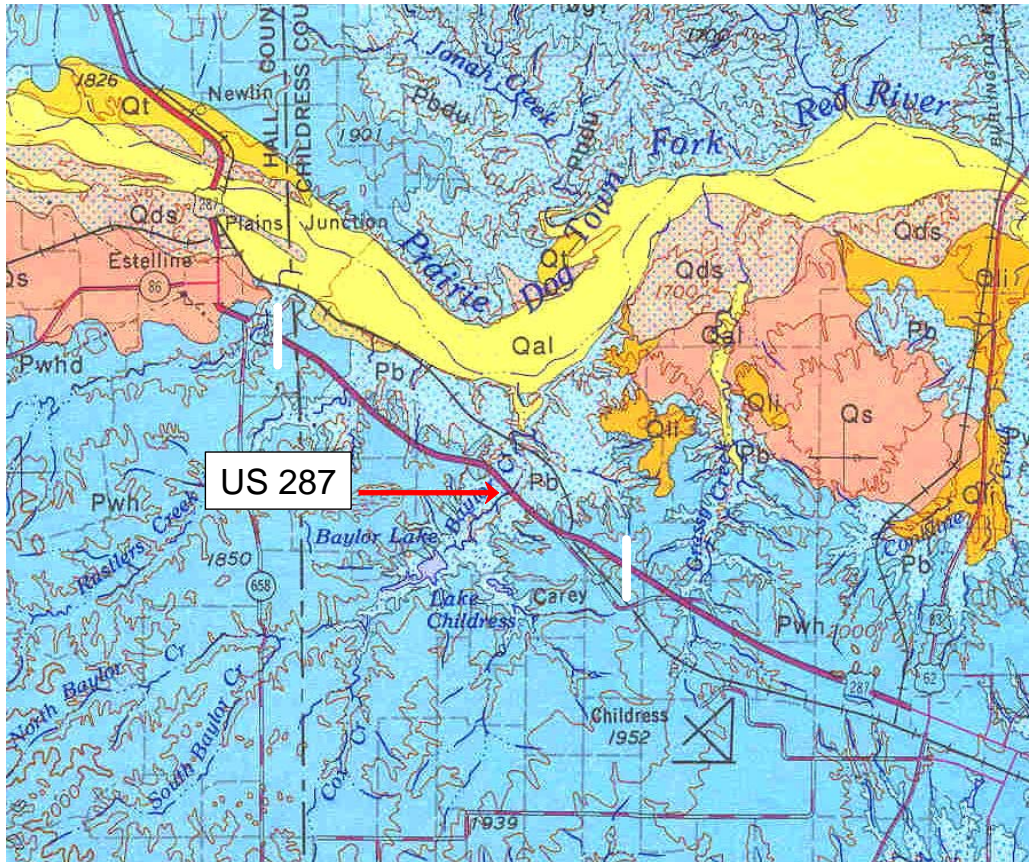


Figure 26. Geologic Map Showing Limits of US 287 Reconstruction (white bars) Project where Premature Failure Occurred.

Analysis of the Plainview Sheet shows US 287 in the vicinity of Baylor Creek (Figure 26, red arrow) is constructed on rocks of the Blaine Formation (Pb, light blue stippled). The description of the Blaine Formation in the legend states “shale, siltstone, sandstone, gypsum, and dolomite interbedded.” Figure 27 is from a ditch adjacent to the northbound outside shoulder of US 287 south of the Baylor Creek Bridge. The rocks exposed in the ditch illustrate the interbedded nature of the gypsum with the shale, siltstone, and dolomite. An interbed is defined as a bed, typically thin, of one kind of rock material occurring between or alternating with beds of another kind.⁷

The cause of the repeated failure on US 287 is sulfate-induced heave generated from the lime reacting with the gypsum present in the underlying rocks (Figures 26 and 27). TxDOT tested different stabilizer options with this soil and determined that a combination of lime and fly ash was the best option for this high sulfate soil.



Figure 27. Gypsum Interbedded with Shale, Siltstone, and Dolomite near Baylor Creek along US 287. (Image courtesy of Zhiming Si)

TxDOT made four recommendations addressing the problems on US 287. The first recommendation was that the existing soil be removed and replaced with a select fill. Secondly, they suggested reworking the existing subgrade with a lime and fly ash combination. The third recommendation was to use a mechanical stabilizer like Geogrid® in lieu of chemical stabilization. The last option was to mill the surface and apply a thin overlay and apply compost to the shoulders to stabilize moisture movement.

Brewster County, SH 118 from Alpine to Study Butte

The El Paso District is about to start a rehabilitation project on SH 118, south of the town of Alpine. TTI researchers accompanied TxDOT Materials and Tests personnel to the highway to test for sulfates. Lime stabilization is typically not used in this part of the state because there are very few problems with high PI expansive soils. However, they commonly use cement to stabilize culverts against erosion from the ephemeral streams in the area.

Just south of Alpine, a white powdery substance was observed in the drainage ditches on the side of the highway (Figure 28). This material is characteristic of gypsum that precipitates from groundwater that evaporates at the surface (efflorescence).



Figure 28. Efflorescence Observed on SH 118 South of Alpine.

Farther south on SH 118, 3 miles north of the intersection with SH 170, more evidence of potential problems with sulfates surfaced. In the hills adjacent to the highway, sunlight was observed reflecting off crystals (Figure 29). Upon closer inspection, researchers suspicions were confirmed and gypsum crystals ranging in size

from less than 1 mm to several centimeters were observed (Figure 30). The description given in the Geologic Atlas of Texas did not mention gypsum or any other sulfur-bearing minerals; this is a case where observation of the surrounding countryside led to the discovery of the gypsum and consultation with published geologic maps may give one a false sense of security.



Figure 29. Aguja Formation Showing a Zone in the Center of the Image with White Spots. (Note: This is the Gypsum Shining in the Sunlight.)

Tests were performed in the field, and sulfates were identified on SH 118. The researchers recommended to TxDOT personnel that they perform more extensive sulfate testing on the highway before the rehabilitation project begins. If they stabilize the subgrade, then they will need to develop a stabilization design prior to construction. Some possible stabilizers include combinations of fly ash plus lime and ground granulated blast furnace slag plus lime.



Figure 30. Image of Multiple Gypsum Crystals Observed on the Right-of-Way Adjacent to the Sparkling Hills in [Figure 29](#).

Culberson County, SH 54

The El Paso District also asked for an appraisal of culverts installed on SH 54 north of Van Horn and south of Guadalupe Mountains National Park. TxDOT had installed corrugated culverts with concrete headwalls; the area around the culverts was backfilled with cement-stabilized sand. The cement was used to prevent the sand from washing out during flash flood events.

The road rises over the culverts and falls on the other side. The headwalls were cracked, and the culverts were often deformed ([Figure 31](#)). TxDOT wanted to know what was causing the problems.



Figure 31. Expansion of Cement-Treated Backfill on SH 54 North of Van Horn.

A review of the Van Horn-El Paso Sheet of the Geologic Atlas of Texas showed that most of this highway sits on Quaternary lacustrine and fluvial deposits of clay, silt, sand, and gypsum in bolsons (Figure 32). Lacustrine means lake deposits and fluvial means river or stream deposits. A bolson is a term applied in desert regions where there is an extensive, flat basin with drainage flowing into it from the surrounding mountains.

The geologic map again indicates gypsum in the rocks. The sand used in the backfill was full of gypsum, which reacted with the cement to form ettringite. The ettringite caused expansion, which deformed the culverts and broke the headwalls. TxDOT replaced the deformed culverts and used an untreated backfill around the culverts.

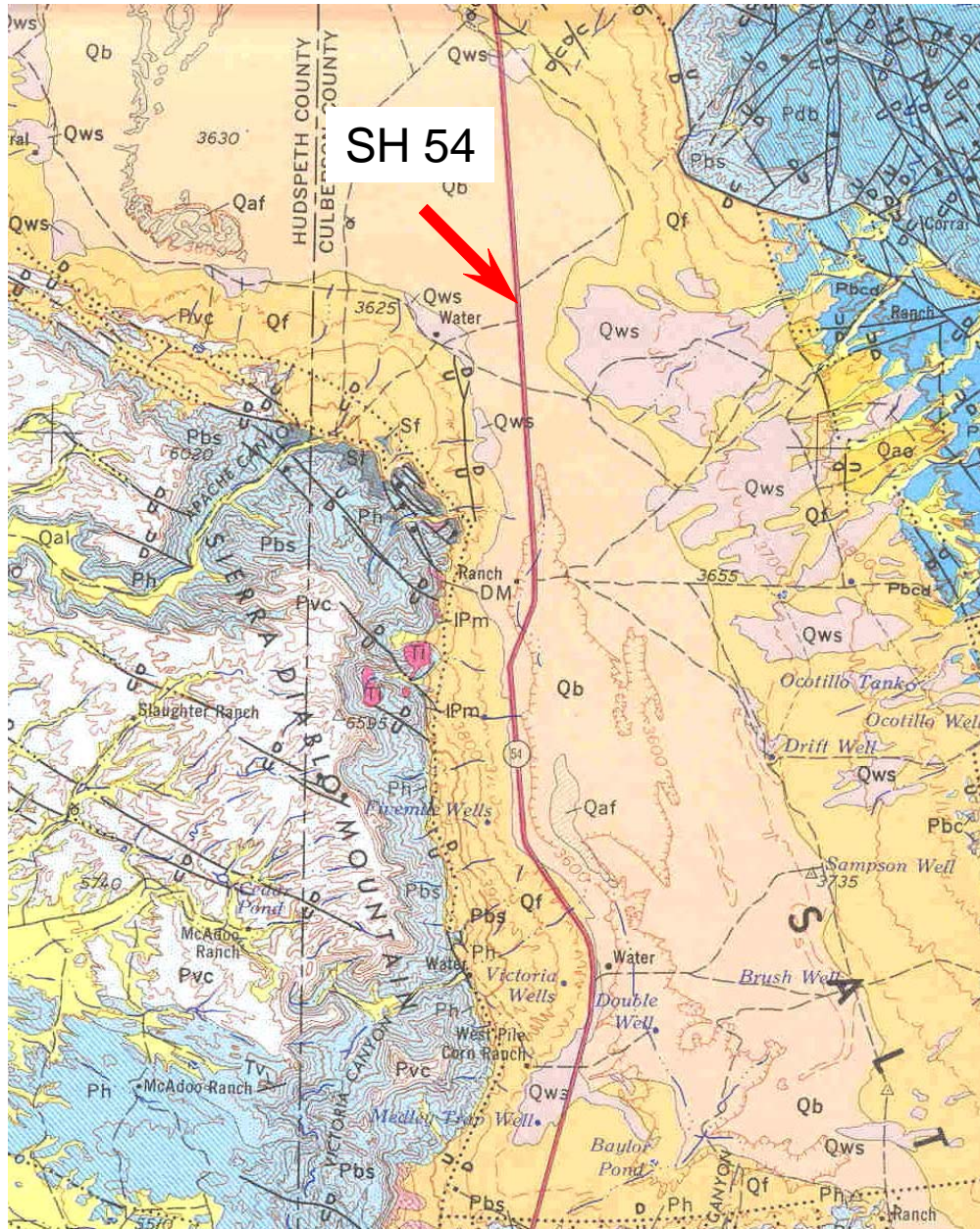


Figure 32. Geologic Map of SH 54 Showing That the Highway Is Constructed on Quaternary Bolson (Qb) Deposits.

CHAPTER 3

FIELD TESTING OF ALTERNATIVE STABILIZERS IN HIGH SULFATE SOILS

INTRODUCTION

The Texas Department of Transportation has seen an increase in pavement failures over the last 20 years resulting from sulfate-induced heave. As part of Research Project 0-4240, researchers identified two stabilizers as being effective in stabilizing a moderate PI soil with sulfate concentrations in excess of 7000 ppm.

This portion of the research evaluated how well these stabilizers worked in natural soils with high sulfates from different parts of Texas. Three soils with PIs ranging from 14 to 29, from two distinct climatic regions (Dallas and Laredo) with sulfate contents ranging from 20,000 to 30,000 ppm were examined. One soil, from the Dallas District, with a sulfate content of approximately 5000 ppm was also evaluated.

METHODS

Based on the results obtained with the soil from College Station, Texas, the ClayStar 7 (henceforth referred to as ClayStar) and GGBFS plus lime were tested on three soils from around Texas having naturally high concentrations of sulfates. These soils were selected from TxDOT projects currently or soon to be constructed and would provide the researchers an opportunity to test the stabilizers in the field if favorable results were observed with the soils in the laboratory. Three of the soils were from the Dallas District (SH 161, SH 183, and US 287) and one from the Laredo District (FM 3338).

Soil Processing

The soil was received in unsealed bags, which made it difficult to assess the original field moisture of the soil. Also, due to time constraints to complete the testing before construction started, the soil was dried in a 140°F (60°C) oven and then pulverized to pass a #4 sieve as outlined in American Society for Testing and Materials (ASTM) D 698.

Soil Properties

Table 4 summarizes the engineering properties of the three soils. For all properties tested during this research project, refer to Appendix A.

Table 4. Engineering and Chemical Properties of Test Section Soils.

TEST	FM 3338 STA103	FM 3338 STA107	SH 161	SH 183	US 287
PI (ASTM D 4318)	14	16	25	29	41
Liquid Limit	31	33	52	48	41
Plastic Limit	17	17	26	19	30
pH	7.9	7.8	7.6	7.7	6.1
SO ₄ content (ppm); 1:20 dilution ratio (TEX-145-E)	23,000- 26,000	20,000- 23,000	21,000- 27,000	20,000- 30,000	~5,000
Optimum lime (%) (ASTM D 6276)	7		6	6-7	5-6
Optimum moisture content (%) (ASTM D 698)	16.5		27	22	28
Dry density (pcf) (ASTM D 698)	109.5		91.5	101	88

At the optimum lime content determined by ASTM D 6276 (also referred to as Eades & Grim), the optimum moisture content and maximum density were determined by standard proctor (ASTM D 698). The optimum moisture content and maximum density of the ClayStar was determined by standard proctor (ASTM D 698) as well. The two stabilizers were tested for 3-D swell and unconfined compressive strength with each of the soils. The 3-D swell procedure is identical to the procedure outlined in the testing sequence of the Riverside Campus soil (Research Report 0-4240-3). The pH was determined using a saturated soil paste similar to that described in the United States Department of Agriculture (USDA) Soil Survey Laboratory Methods Manual, Nov. 2004 (method number 4F2 and 4C1a1a2). The PI was measured in accordance with ASTM D 4318. The unconfined compressive strength samples were molded with a compactive effort in accordance with TEX-114-E (equivalent to standard proctor ASTM D 698, but

with a 4 X 6 inch mold, requiring more soil). The samples molded to evaluate strength were cured according to the following curing regime:

- Claystar: 7-day air cure; 7-day air cure followed by a 4-hour soak; 7-day air cure followed by a 10-day capillary rise; and
- GGBFS plus lime: 7-day moist cure (in a sealed bag); 7-day moist cure followed by a 4-hour soak; 7-day moist cure followed by a 3-day dry back and then a 10-day capillary rise.

RESULTS

The results for each soil are discussed individually in the section that follows.

State Highway 161

The consequences of stabilizing this soil with lime were illustrated by the 6% lime sample swelling to just below 40%, about 4 times as much as the unstabilized soil (Figure 33). The 5% by weight GGBFS and 1% by weight lime combination showed a reduction in swell of almost 4% compared with the unstabilized sample. A combination of 4% GGBFS and 2% lime was also tested, but this showed an increase in swell compared to the unstabilized sample. ClayStar samples were tested after a 3-day dry back and another set of samples after a 7-day dry back. The 3-day dry back showed no improvement in swell compared to the control sample. The 7-day dry back showed a slight decrease in swell of <2%. The reason the 7-day dry back performed better than the 3-day dry back remains unclear. However, the committee felt that the 7-day dry back was excessive and would not be realistic in the field.

The addition of the ClayStar to the soil produced a great deal of effervescence (fizzing), due to the reaction of the acid with the carbonates in the soil. Because the stabilizer reacted with the carbonates, this soil needed additional applications of ClayStar to supply enough product to fulfill the stabilizing function. In light of this and the fact that the 3-day dry back using the ClayStar did not show any improvement in the swell, the researchers decided not to test this product any further with this particular soil.

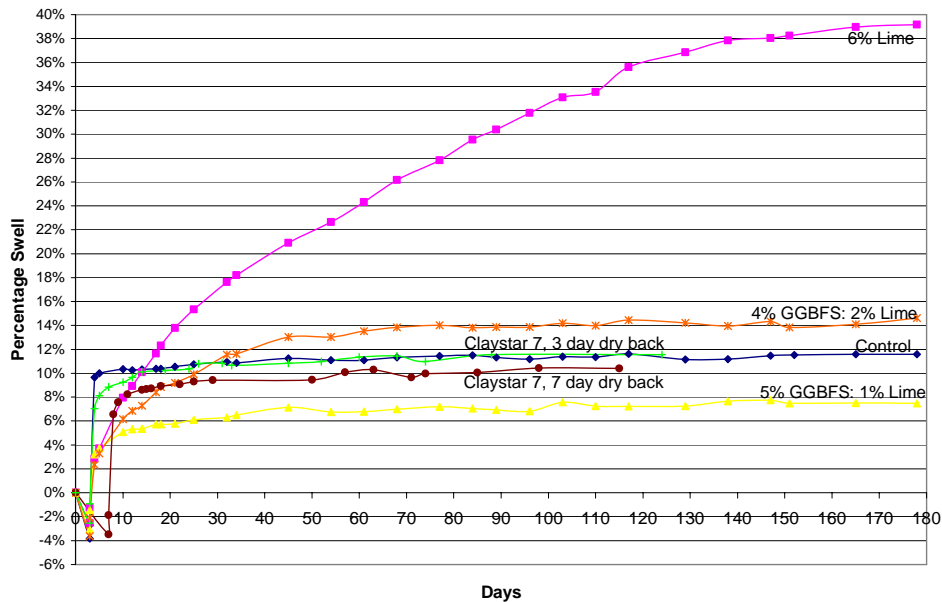


Figure 33. Three-Dimensional Swell Results for a High Sulfate Soil from SH 161.

Since the GGBFS and lime combination reduced swell in the SH 161 soil, the researchers wanted to know if it increased strength sufficiently to provide a working platform for construction. Figure 34 shows the unconfined compressive strength of the 5% GGBFS and 1% lime samples compared to the untreated samples. The stabilized samples show a significant improvement in strength (~50 to 60 psi) for the 7 day moist cure, the 4-hour soak, and the tube suction test (TST) compared to the control samples.

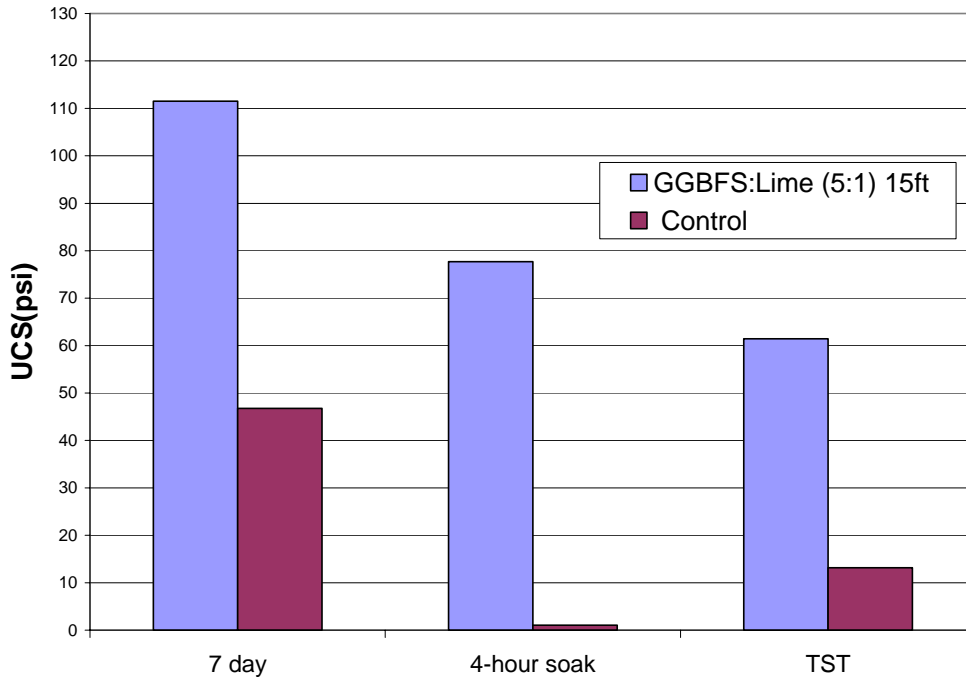


Figure 34. Unconfined Compressive Strength of Samples from SH 161.

The researchers wanted to see how the two treatment options affected the plasticity index and pH of the soil. As evident in [Table 5](#), the GGBFS and lime combination reduced PI significantly while the ClayStar produced a nominal reduction. The GGBFS and lime combination increased the pH to over 12.3, and the ClayStar reduced the pH slightly. The pH reduction for the ClayStar is not very great due to the carbonate minerals in the soil buffering the pH.

Table 5. Plasticity Index and pH Measurements for Soil from SH 161.

SH161	PI	pH
Soil only	25	7.6
+ ClayStar 7	23	7.1
+ 5% GGBFS, 1% Lime	13	12.3

State Highway 183

This soil contains 20,000 to 30,000 ppm sulfates as a result; the 3-D swell for the soil from this test section showed an increase in swell of 35% with the addition of 6%

lime (Figure 35). After the first 14 days, the Claystar looked like it would reduce swell but prolonged testing revealed more or less the same level of swell as the control sample without stabilizer.

The control samples appear to shrink slightly with time. There are two explanations for this shrinkage: 1) it is due to the cracking that resulted from the 3-day dry back where the sample expands, but the cracks subside as the sample is exposed to water during the swell test, and 2) some of the soil from the untreated samples started oozing out of the bladder and into the water bath as the test progressed, which also results in a decrease in volume.

The combination of GGBFS and lime provided some reduction in swell (6%) when compared to the control samples (Figure 35). However, the reduction in swell is quite significant when compared to the lime-stabilized samples.

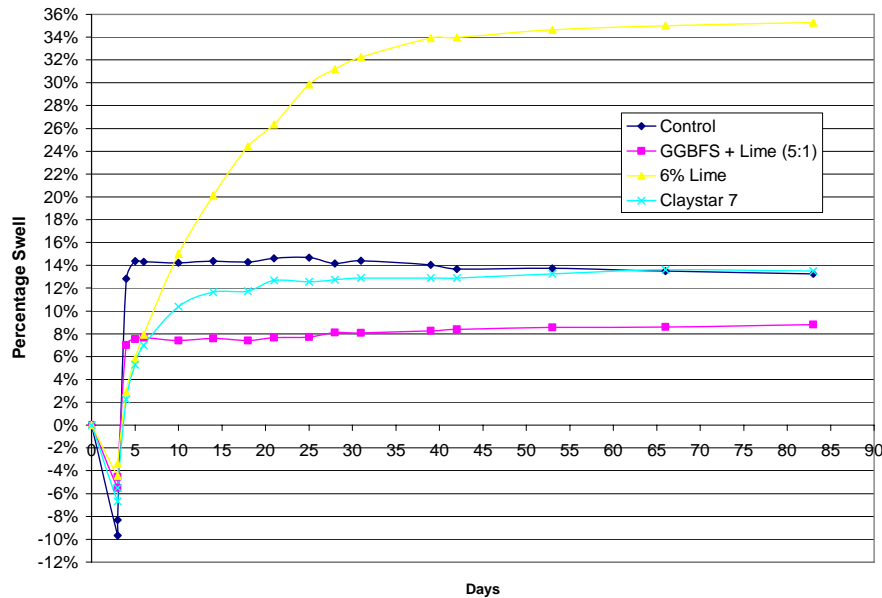


Figure 35. Three-Dimensional Swell of High Sulfate Soil from SH 183.

At the time the samples were molded for unconfined compressive strength testing, the ClayStar-treated samples looked as if they would reduce the swell. Therefore, samples were molded for measuring strength using both stabilizers. Both stabilizers showed some retained strength after the 10-day capillary rise. The GGBFS and lime combination yielded an unconfined compressive strength of 40 psi and the ClayStar

approximately 25 psi. The control samples subjected to the 10-day capillary rise for both the 7-day air cure and 7-day moist cure fell apart and, therefore, could not be tested (Figure 36). Photos of the various samples at the end of the 10-day capillary rise are shown in Figure 37. Untreated samples were not molded and tested with the 7-day air cure (vendor’s recommendation) because, based on previous experience, the researchers assumed the strength would be similar to the treated soil.

As expected, the 7-day air cure for the ClayStar samples is in a league of its own, and unrealistic.

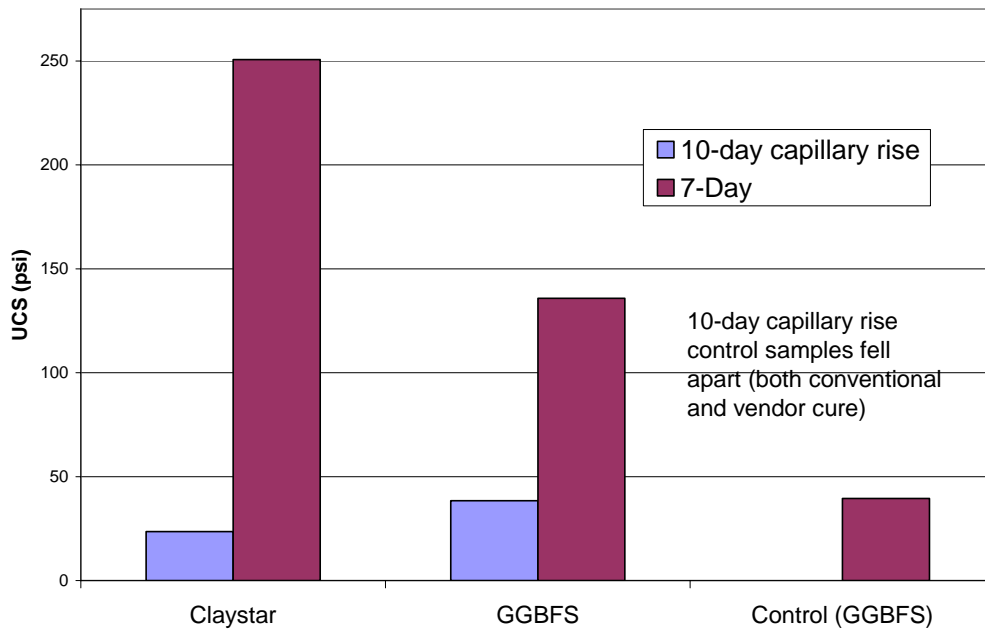


Figure 36. Unconfined Compressive Strength Results for High Sulfate Soils on SH 183.



Figure 37. Clockwise from Top Left: 5% GGBFS & 1% Lime, ClayStar, Control Cured as GGBFS: Lime, Control Cured as ClayStar (treated at completion of 10-day capillary rise and untreated fell apart after Day 1).

Since the untreated soil had a PI of 29, the researchers wanted to investigate the effect of increasing the lime content. This was to ensure that the PI would be reduced sufficiently to provide a working platform during construction. Samples were molded to test the 3-D swell and unconfined compressive strength following a 10-day capillary rise keeping the GGBFS content constant but increasing the lime content. Combinations of 5% GGBFS and 1%, 2% and 3% lime were tested. Table 6 shows how the PI is reduced and the pH is increased with higher concentrations of lime.

Table 6. PI and pH of Untreated Soil and Soil Treated with GGBFS and Increasing Amounts of Lime.

SH183	PI	pH
Control	29	7.7
+5% GGBFS, 1% Lime	19	11.6
+5% GGBFS, 2% Lime	18	12.3
+5% GGBFS, 3% Lime	15	12.4

For one set of samples, the GGBFS and lime was added simultaneously and molded. For another set of samples, a portion of the lime (1%) was added, left to cure for 6 hours followed by mixing the remaining lime (1% and 2%) and GGBFS into the sample. Figure 38 shows that the 5% GGBFS and 2% lime mixture, where 1% lime is

mixed in and cured for 6 hours followed by the remaining stabilizer, performs similar to the 5% GGBFS and 1% lime mixture where all of the stabilizer is added at once. This figure shows that addition of a small percentage of lime followed by mellowing for a short time before applying the rest of the stabilizer results in less swell. This technique may work well toward increasing the workability of high PI soils with high sulfate concentrations.

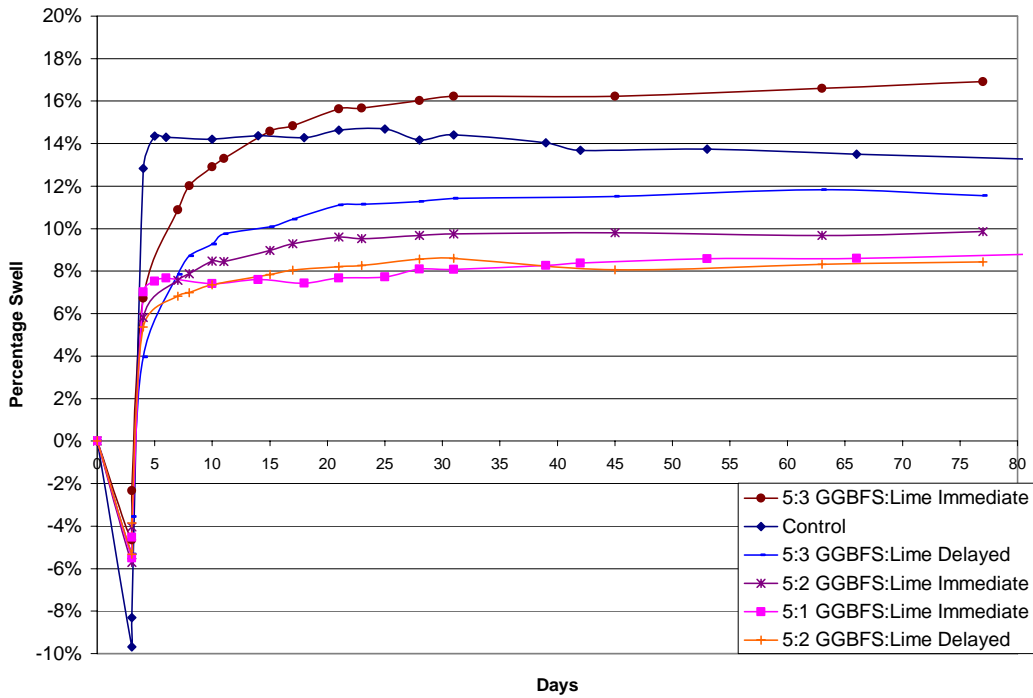


Figure 38. Three-Dimensional Swell of High Sulfate Soil on SH 183 with Increasing Lime Content.

Unconfined compressive strength measurements after a 10-day capillary rise were performed on the combinations of GGBFS with increasing lime contents from 1% to 3%. The strength measurements showed that there is no benefit to increasing the lime content if the goal is to increase the strength of the subgrade (Figure 39).

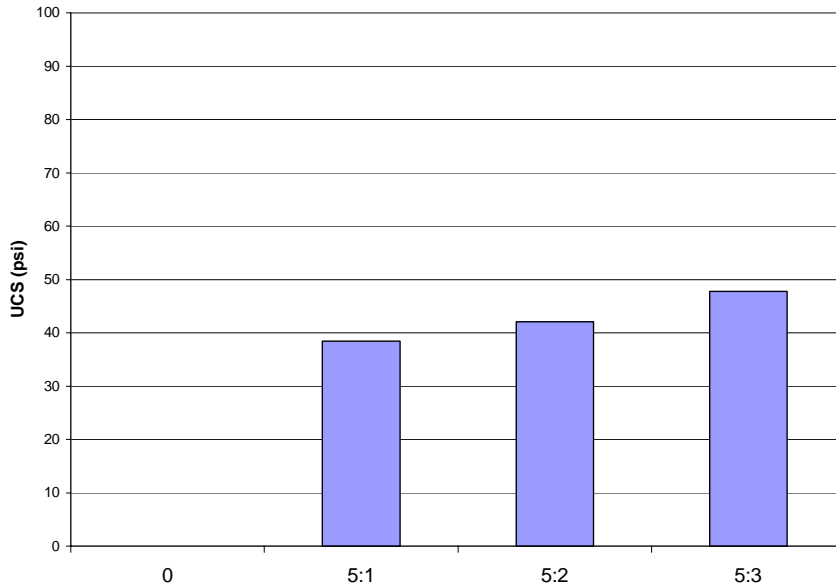


Figure 39. Unconfined Compressive Strength with Increased Lime Content Combinations. (5% GGBFS & 1% Lime; 5% GGBFS & 2% Lime; 5% GGBFS & 3% Lime.)

FM 3338

Soil was tested on two locations along FM 3338, at Stations, 103+00 and 107+00. Both of these stations contained sulfates in excess of 20,000 ppm. [Table 7](#) shows the effect of the two stabilizers on the PI and pH. Since this is a low PI material, the GGBFS and lime combination had little effect in reducing PI. The ClayStar does not appear to change PI. The GGBFS and lime combination did increase the pH to 12.3. The ClayStar decreased the pH more on SH 161 due to a lack of carbonate minerals in this soil.

Table 7. Plasticity Index and pH of Stations 103 and 107 on FM 3338 Treated and Untreated.

FM 3338						
	PI			pH		
	Soil only	GGBFS + Lime	ClayStar	Soil only	GGBFS + Lime	ClayStar
Station 103	14	11	13	7.9	12.3	6.3
Station 107	16	11	17	7.8	12.3	6.9

The 3-D swell results (Figure 40) indicated that like the two soils from the Dallas District, lime would not be a suitable choice of stabilizer for the Laredo soil (swell ranged from 25% to 36%). For both stations, the samples treated with ClayStar initially looked as if it would show a reduction in swell. However, after approximately 1.5 months the ClayStar samples swelled as much as the untreated samples.

The GGBFS and lime mixture produced very different swell results for the two stations. For Station 103, the GGBFS and lime swelled 2% more than the unstabilized soil, whereas for Station 107 the GGBFS and lime reduced the swell by about 5% over the unstabilized soil. Two factors that contributed to the odd swell results are: 1) the sulfate level of Station 103 (23,000 – 26,000 ppm) is higher than the sulfate content of Station 107 (20,000 – 23,000 ppm), and 2) there is about 5% more fine clay in the soil from Station 107, which increases the swell of the unstabilized soil (Appendix A). The gradation of the two samples was virtually the same (Appendix A). Figure 41 shows a magnification of the swell results between 1 and 10%.

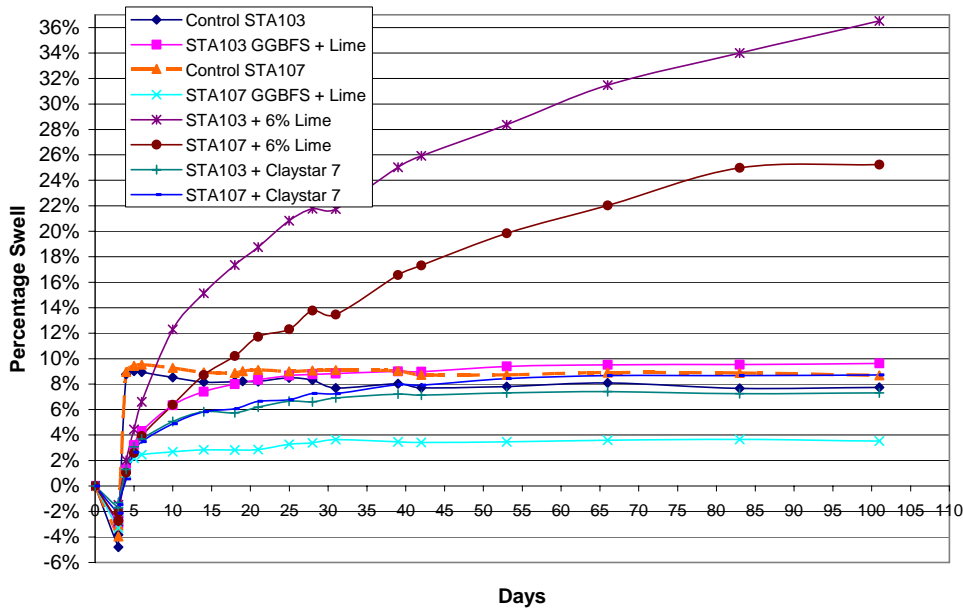


Figure 40. Three-Dimensional Swell for High Sulfate Soils on FM 3338 at Stations 103 and 107.

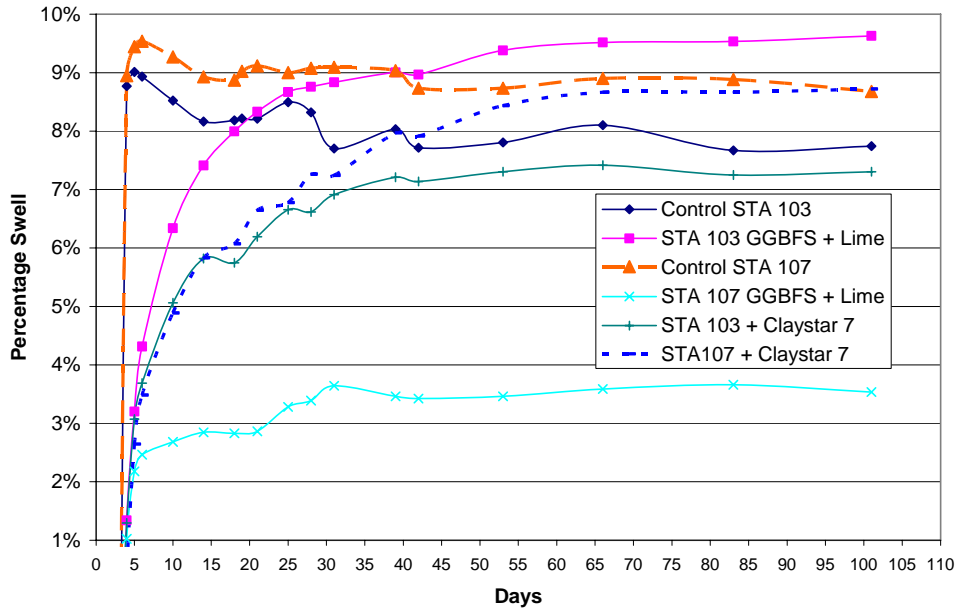


Figure 41. Expanded Scale of Three-Dimensional Swell on FM 3338.

Since the untreated soil already had a low PI and the 3-D swell results for the two stabilizers were mixed, the researchers concluded that the soil would be best left untreated. However, the unconfined compressive strength tests for Stations 103 and 107 show that there is a definite benefit in treating this soil with either of the stabilizers tested (Figure 42). The bar graph in Figure 42 illustrates the unconfined compressive strength of both stations after the 10-day capillary rise using the two treatments. The two sloping lines show the amount of moisture gained as a percentage of the molded weight after the 10-day capillary rise. The ClayStar had the lowest moisture gain with the GGBFS and control samples gaining progressively more moisture.

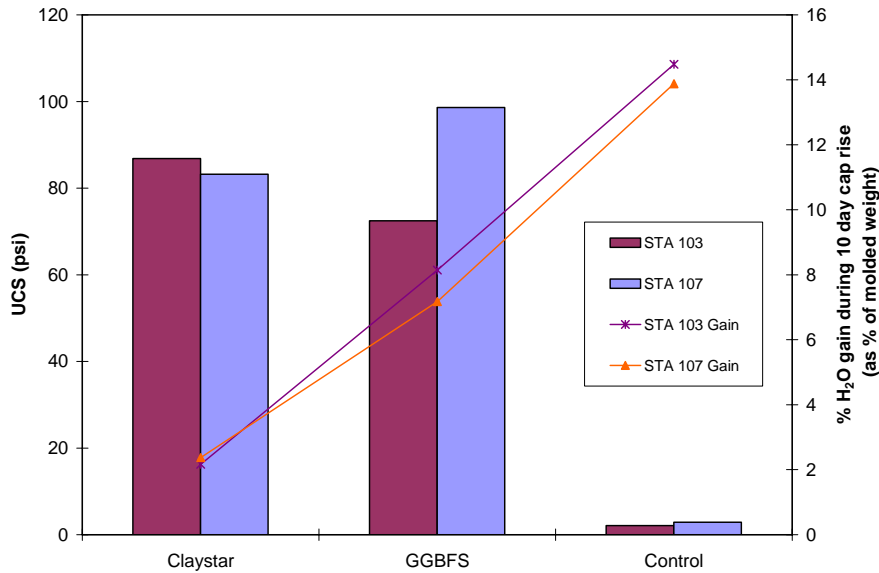


Figure 42. Unconfined Compressive Strength and Moisture Content Results for Stations 103 and 107 on FM 3338 Following the 10-day Capillary Rise.

The samples subjected to the 10-day capillary rise test were also evaluated with the dielectric test to determine the amount of moisture ingress. The dielectric measurements were taken to compare with the moisture determined by weight. The moisture gain determined by weighing the samples after the 10-day capillary rise test was confirmed by the dielectric measurements taken before and after the 10-day capillary rise (Table 8).

Table 8. Dielectric Values for FM 3338 before and after 10-day Capillary Rise.

Treatment	Dielectric Before	Dielectric After
ClayStar 7	9.46	17.27
GGBFS + Lime (5:1)	10.91	27.47
Control	12.12	35.99

Figure 43 shows the unconfined compressive strength of Station 107 on FM 3338 after curing. The GGBFS and lime combination was subjected to a 7-day moist cure in a sealed bag, similar to lime curing. The ClayStar samples were air cured for 7 days as prescribed by the vendor: untreated samples (Control [ClayStar]) were air cured for 7 days as well to compare with the ClayStar results.

The 7-day air cure for the ClayStar and Control (ClayStar) samples is, as was the case with SH 183, unrealistic. It is interesting to note that the 7-day unconfined compressive strength of ClayStar is almost 120 psi less than the 7-day air cure control samples. Researchers speculated that this could be due to the difference in the amount of water lost by the ClayStar versus the control samples. However, as indicated in Figure 42, there was very little difference between the amount of water lost by the ClayStar (8.71%) treated samples and the control (8.99%) samples. Another reason could be due to the way the ClayStar (especially the surfactant) alters the bonding between the clay particles.

The strength of the 7-day moist cure for the GGBFS and lime combination was significantly higher than the 7-day moist cure control samples (~140 psi). Since the 7-day curing was different for the two stabilizers, a direct comparison of the strength results could not be made. However, since all the treated materials were subjected to a 10-day capillary rise, a comparison of the strength after 10 days could be made. The strength results after the 10-day capillary rise showed an increase of between 70 and 100 psi above the untreated, which retained negligible strength (2 psi) in the case of the GGBFS-cured sample and no strength for the ClayStar-cured control because it fell apart before testing. The retained strength of the GGBFS samples was a little better than the ClayStar samples (Figure 43).

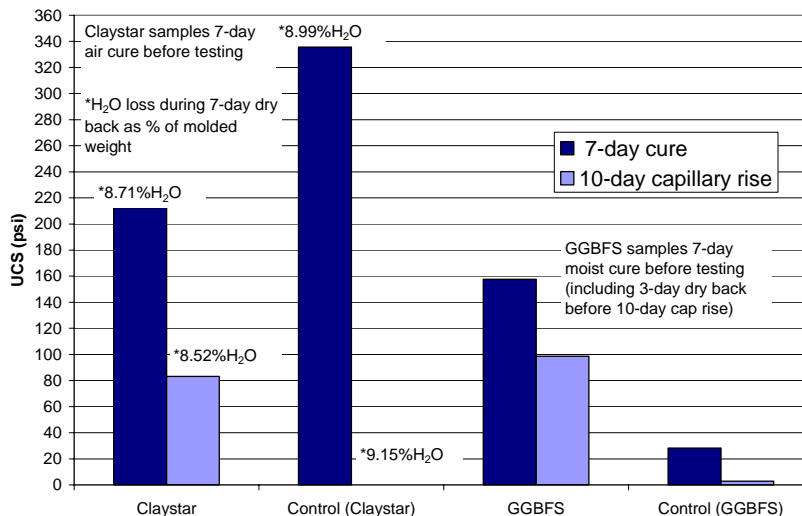


Figure 43. Unconfined Compressive Strength Testing of Station 107 on FM 3338.

US 287

TxDOT was concerned about a construction project on US 287 near the town of Midlothian in Ellis County. Material from this construction project was submitted to TTI for testing as another possible field test site. The untreated material had a PI of 41. TxDOT was concerned with the workability of such a high PI soil, so the researchers decided to start with evaluating the pH and PI of various combinations of GGBFS and lime. This is similar to the approach used in previous research by Hilt and Davidson using the plastic limit to identify the “lime fixation” point, where no further reduction in the PI is observed.⁸ The GGBFS additions were 5, 6 and 7%, combined with 1, 2 and 3% hydrated lime. The pH was determined using a saturated soil paste similar to that described in the USDA Soil Survey Laboratory Methods Manual, Nov. 2004 (method number 4F2 and 4C1a1a2). The PI was measured in accordance with ASTM D 4318. [Table 9](#) shows the effect of increasing amounts of GGBFS and lime on the PI. The combination of 5% GGBFS and 2% lime reduced PI enough to yield a workable platform (PI of approximately 15 to 20). [Table 10](#) shows that the pH does not reach saturation for lime until 3% lime is added to the soil.

Table 9. Variations in PI of US 287 Soil with Different Combinations of GGBFS and Lime.

		% Lime				
		0	1	2	3	6
% GGBFS	0	41	-	-	-	13
	5	47	27	17	15	-
	6	37	21	16	12	-
	7	32	23	16	11	-

Table 10. Variations in pH of US 287 Soil with Different Combinations of GGBFS and Lime.

		% Lime				
		0	1	2	3	6
% GGBFS	0	6.1	-	-	-	12.5
	5	10.1	11.4	12.1	12.4	-
	6	10.3	11.4	12.1	12.3	-
	7	10.7	11.7	12.2	12.3	-

For high PI soils, this relatively quick check enables testing to be concentrated on combinations of GGBFS or fly ash and lime, which also provide a satisfactory working platform during construction. Once adequate amounts of stabilizers have been identified, this procedure can be followed with 3-D swell and unconfined compressive strength testing. A combination of 5%, 6%, and 7% GGBFS with 2% lime was selected as a starting point for further testing. The pH of these combinations is above the point (~10.5) where previous research has indicated that silica and alumina solubility become relatively high, after which calcium can react with the siliceous and aluminous pozzolans to form cementitious compounds.^{1, 4, 8, 9, 10}

Since this material had a sulfate content of approximately 5,000 ppm and a high PI, it would have been a good candidate for mellowing with lime. 3-D swell results are presented in [Figure 44](#), which confirms the moderate sulfate levels because the 6% lime-treated samples showed similar amounts of swell as the GGBFS and lime mixtures.

This underscores two important points. First, double-check the sulfate content of the material received in the laboratory before conducting any further testing, even if it has been tested in the field. Second, it is important to sample the correct material in the field for lab testing to identify a successful stabilizer for a subgrade containing sulfates, especially when the proposed construction will entail cutting and filling.

The untreated sample appeared to shrink after it was placed in the water bath. As discussed previously for SH 183, the reason for this is two-fold, the 3-day dry back and subsequent exposure to water results in severe cracking of the sample, which results in an apparent rapid increase in volume, followed by a period of settlement as the cracks diminish and the sample deteriorates. Deterioration of the sample also results in some of the untreated sample oozing out of the bladder, which adds to the shrinking effect.

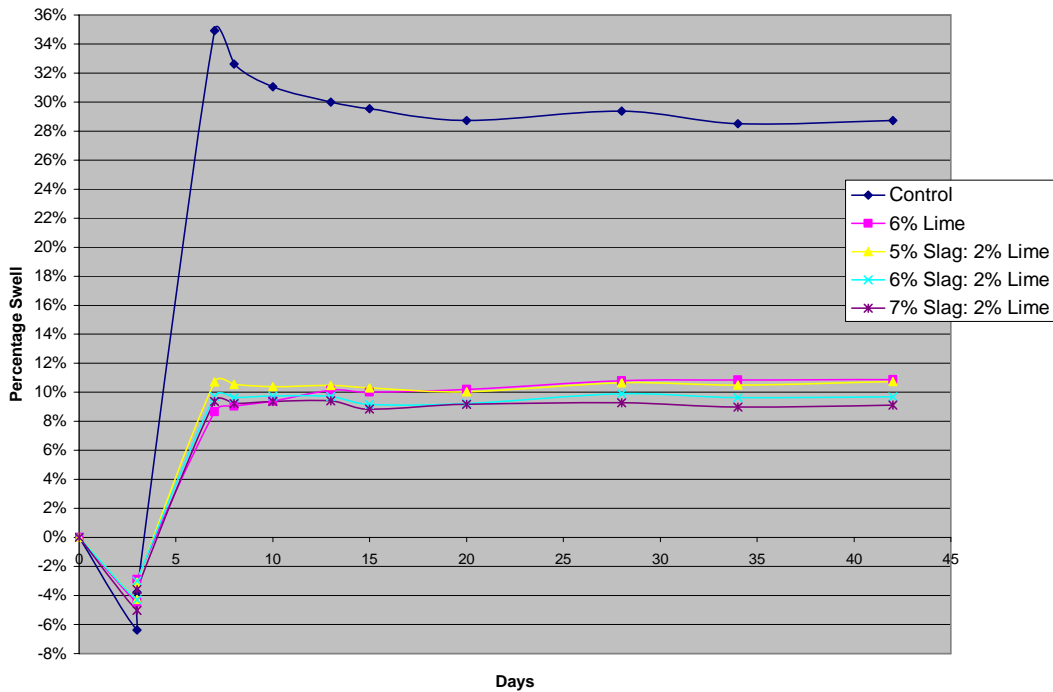


Figure 44. Three-Dimensional Swell of Soil from US 287 Containing 5000 ppm Sulfate.

DISCUSSION/INTERPRETATION

Testing of these four soils illustrates the value in subjecting a proposed stabilizer to a testing sequence aimed at evaluating how effective the stabilizer is when the soil contains high sulfates. In choosing a stabilizer, consideration should be given to the properties of the soil to be stabilized as well as the mechanism by which the proposed treatment reportedly achieves stabilization.

Subjecting the soil to a series of tests, including the PI of the treated and untreated soil, a 3-D swell test, and an unconfined compressive strength test, will determine whether the stabilizer is successful in meeting the requirements set for creating a working platform and/or a stabilized subgrade layer.

All soils are different, and the stabilizers evaluated in this research project all behave differently in these soils. It is imperative for nonstandard stabilizer suppliers to provide a mechanism by which their product stabilizes the soil. Some soils may respond well to that mechanism, and other soils may not. Below is a short explanation of some of the mechanisms proposed for the two stabilizers used in these samples.

Acid Stabilizers

Acid stabilizers like ClayStar perform very differently in various soil types. A researcher at Texas A&M University examined one acid stabilizer for a stabilization mechanism.¹¹ For a low pH soil like the College Station soil (no carbonates), the acid stabilizer reduces swell by formation of hydroxyl aluminum groups, which decreases the number of hydrated cations that can exist in the interlayer of clays.¹¹ With higher concentrations of the acid stabilizer, swelling was observed to increase.¹¹ This trend was explained by forming a new mineral, basaluminite, by removing the hydroxyl aluminum groups from the interlayer of the clays, which allows hydrated cations to enter the clays, resulting in an increase in swell.¹¹

The SH 161 soil has a high pH due to calcium carbonate nodules in the soil. The ClayStar did not show any benefit in this soil because the acid reacted with the carbonates instead of the clay minerals. Marquart (1995) made the same observations using an acid stabilizer in a high carbonate soil. He concluded that carbonates decrease the effectiveness of acid stabilizers by buffering the pH.¹¹ The acid first reacts with the carbonates, leaving little stabilizer available to alter the clay minerals.

The ClayStar initially looked good in swell tests on FM 3338 (Figures 40 and 41) but after about 45 days of swell testing, the ClayStar samples had expanded as much as the unstabilized soil. Researchers speculate that the effects of the ClayStar are not permanent.

Ground Granulated Blast Furnace Slag

There have been several studies in Europe evaluating the mechanisms that prevent sulfate heave when GGBFS is added as a stabilizer. One mechanism the Europeans suggest is that the calcium ion concentration is reduced by replacing lime with GGBFS, resulting in less calcium available for forming ettringite.¹² Based on thermodynamic stability diagrams, the Al/Si ratio was reported to be significant in reducing the stability field of ettringite.¹³ Little et al. (in press) stated that GGBFS reduces the stability field of ettringite by changing the Al/Si ratio. Other researchers have suggested that GGBFS alters the pH of the stabilized soil so ettringite will not form. Researchers monitored pH

as part of this investigation, but there was no significant difference in pH of the GGBFS samples and lime-stabilized samples.

There is still much work to be done in this area, but researchers note that the GGBFS and lime mixture reduced swell and increased strength on all high sulfate soils tested in Texas.

Evaluating the Economics of Non-Traditional Subgrade Treatments

Even with the existence of some promising approaches to treating high sulfate soils, using these treatments still may not be the best option due to economics. This section presents a format for evaluating the economic implications of using nontraditional treatments. First, the cost of replacing the high-sulfate material with select fill is estimated. Next, the cost of the treatment is compared to the cost of using select fill.

As of October 2005, the average cost of TxDOT Item 132 Type A embankment was \$9.63 per cubic yard (CY). Additionally, the average bid cost of Item 110 for Excavation of Roadway was \$4.76 per CY. Therefore, the total cost of removing and replacing the high sulfate material with select fill is \$14.39 per CY. Based upon this cost and the necessary depth of coverage to limit potential vertical rise (PVR) to common desired values of 1 inch or 1.5 inches, [Table 11](#) shows what the removal and replacement cost would be for varying soil PI. [Figure 45](#) shows this information graphically. Researchers assumed the maximum depth of coverage needed regardless of soil PI was 4 feet.

Table 11. Required Depth of Coverage for Common PVR Values and Corresponding Cost per Square Yard for Removal and Replacement.

Plastic Index	For 1.5 inch PVR		For 1 inch PVR	
	Depth of Coverage (in)	Cost per SY (\$)	Depth of Coverage (in)	Cost/SY (\$)
20	0	0.00	2	0.80
25	3	1.20	18	7.20
30	14	5.60	29	11.59
35	22	8.79	36	14.39
40	30	11.99	44	17.59
45	34	13.59	48	19.19
50	40	15.99	48	19.19
55	44	17.59	48	19.19
60	47	18.79	48	19.19
65	48	19.19	48	19.19

(Depth of Coverage data courtesy of Darlene Goehl, P.E.)

In order for a soil treatment to be justifiable economically, the total cost of treatment must cost less than the removal and replacement cost. Using [Figure 45](#), the cost of replacing the sulfate-laden material can be estimated. Next, the cost of the treatment is needed. As an example, on a proposed experimental section in the Laredo District, estimates for treatment with Claystar 7 were nearly \$220,000 just for the product to treat a 0.5-mile section 36 feet wide. This translates to over \$20 per SY of pavement, even before construction costs. This option clearly was not economically justifiable. On the same project, cost estimates for treating a 5000-foot section with GGBFS/lime were approximately \$144,000. This equates to approximately \$7.20 per SY of pavement. At this cost of treatment, the soil PI would have to be 25 or higher for the treatment to be economically justifiable. However, the soil PI did not exceed that value, and therefore, none of the alternative treatments were economical on the project.

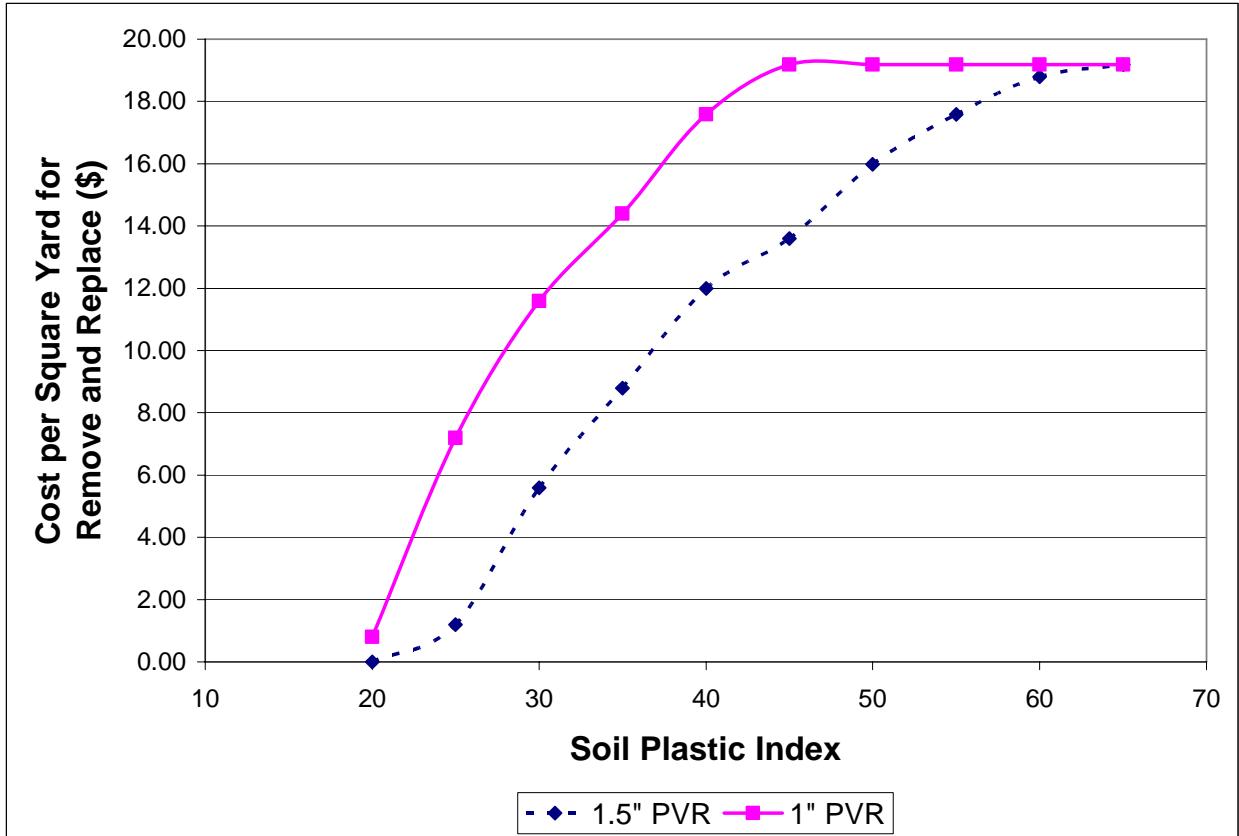


Figure 45. Cost of Removal and Replacement for Varying Soil PI.

Although in the example case presented no alternatives were economical, the analysis framework used can be applied to evaluate future projects. In projects with higher plasticity sulfate-bearing soils, nontraditional treatments have a better likelihood of being cost competitive.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on observations and work performed on test sites all around Texas over the last 4 years.

- The Geologic Atlas of Texas is an effective way to identify potential problem areas. The Geologic Atlas identified six of the eight projects (or 75%) discussed in this report as sulfate bearing.
- Sulfate-induced heave occurs with lime or cement stabilization.
- Sulfate-induced heave occurs in many different climates and soil types. All that is required are four ingredients: calcium-based stabilizer, clay minerals (aluminates), sulfate minerals, and water.
- Sulfate-induced heave continues until one of the four ingredients is depleted.
- The formation of ettringite can be blamed for the heaving observed on all of the projects in which the researchers have been involved.
- It may take years for the reactions to proceed to a point where heave is observed.
- Proper sampling is critical in determining sulfate contents in the field.
- Care should be taken if there is any cut and fill work because sulfates tend to be more concentrated at depth in the soil profile, which is evident from samples taken from Sherman, Texas.
- Sulfates can be concentrated at different depths depending upon the time of year and amount of precipitation.
- There is a need to analyze for sulfides in many parts of the state since sections are being cut, because the Eagle Ford Formation is rich in pyrite at depth. Pyrite is the ultimate source of the gypsum crystals observed in the soils developed in the Eagle Ford Formation.⁶
- The conductivity test does an excellent job of detecting the higher sulfate soils.
- As illustrated in Figures 16 and 27, and from the field testing, these sulfate seams can be quite localized.

- The researchers recommend stabilization with calcium-based stabilizers on sections that have been tested for sulfates and the sulfate concentrations are below 3000 ppm. However, TxDOT needs to test for sulfates as areas are filled to grade and prior to stabilization. If a small area has sulfate concentrations above 7000 ppm, then use an alternative like GGBFS and lime only to stabilize that small section.
- A combination of GGBFS and lime reduced swell and increased strength in all high sulfate soils tested.
- The expense of nonstandard stabilizers that showed improvement was too excessive. Soil Sement required too high of an application rate to be cost effective, and ClayStar 7 was too expensive.
- The acids did not reduce the PI over the unstabilized soil.
- Some of these stabilizers may work in certain soil types. For example, the acids may work in low pH soils, but are ineffective in high pH soils unless they are applied in very high concentrations which may make them uneconomical.
- Adding some of the lime to a soil and letting it mellow for a while before adding the rest of the lime and GGBFS allows for higher concentrations of lime to be used and still maintain acceptable swell reduction. This is crucial for high PI soils that need more lime for workability.
- Unconfined compressive strength is not really affected by higher concentrations of lime.

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APPENDIX A
TEST SITE PROPERTIES

SH 161

Optimum and molded moisture content and dry density

	Optimum Moisture Content (%) (ASTM D 698)	Dry Density (pcf) (ASTM D 698)	Molded Moisture Content (%)	Molded Dry Density (pcf)
Soil only	27	91.5	27	90
+ 6% Lime	28	88.5	28	90
ClayStar 7	Not tested	Not tested	Not tested	Not tested
GGBFS + Lime			28	90

SH 183

Optimum and molded moisture content and dry density

	Optimum Moisture Content (%) (ASTM D 698)	Dry Density (pcf) (ASTM D 698)	Molded Moisture Content (%)	Molded Dry Density (pcf)
Soil only	22	101	22	98
+ 6% Lime	23.4	96.5	23.4	98
ClayStar 7			22	98
GGBFS + Lime			23.4	98

FM 3338

Optimum and molded moisture content and dry density – Station 103

	Optimum Moisture Content (%) (ASTM D 698)	Dry Density (pcf) (ASTM D 698)	Molded Moisture Content (%)	Molded Dry Density (pcf)
Soil only	17	109.5	17	106.5
+ 6% Lime	19	103.5	19	106.5
ClayStar 7			17	106.5
GGBFS + Lime			19	106.5

Size Fractionation

Data for the less than 200 mesh fraction

	Station 103		Station 107		SH 161		SH 183	
	% of Total	% of Insoluble	% of Total	% of Insoluble	% of Total	% of Insoluble	% of Total	% of Insoluble
Sand (%)	27.14	30.48	17.38	20.79	0.29	0.81	5.48	6.35
Silt (%)	36.93	41.47	35.47	42.42	10.75	30.30	27.42	31.79
Coarse Clay** (%)	12.54	14.09	13.47	16.11	14.90	42.00	18.55	21.50
Fine Clay** (%)	12.44	13.97	17.29	20.68	9.54	26.89	34.80	40.35
Total (%)	89.05	100.00	83.62	100.00	35.47	100.00	86.25	100.00

**Coarse clay 2 – 0.2 μm ; Fine clay <0.2 μm

Chemical

	FM 3338 Sta103	FM 3338 Sta107	SH 161	SH 183
SO ₄ (ppm) 1:20 dilution ratio	23,000-26,000	20,000-23,000	21,000-27,000	20,000-30,000
Ca (ppm)	12,704	11,716	48,858	11,389
Mg (ppm)	323	144	185	335
Organic C %	0.363	0.494	1.462	0.55
Total C (ppm)	4,460	7,980	56,600	8,110

APPENDIX B

CONSTRUCTION SPECIFICATIONS

Project Number: C3532-2-8

Sheet: 7H

County: Webb

Control: 3532-02-008

Highway: FM 3338

Item 260 Lime Treatment for Materials Used as Subgrade (Road Mixed)

Lime treated subgrade shall be constructed and governed under the requirements in accordance to Item 260, unless directed otherwise. Subgrade treatment construction from STA 75+00 to STA 125+00 shall be governed by the following requirements.

When ground granulated blast furnace slag (GGBFS) is required, furnish GGBFS meeting the requirements of DMS-4620, "Ground Granulated Blast Furnace Slag." Apply ground granulated blast furnace slag at a rate of 5% of the dry weight of subgrade soil in conjunction with 1% lime. Once the subgrade is prepared and pulverized in accordance to the requirements in article 260.4, apply GGBFS and lime in accordance to the following construction methods for application, mixing, and compaction:

1. **Application of Ground Granulated Blast Furnace Slag (GGBFS).** Uniformly apply ground granulated blast furnace slag in dry form unless otherwise approved. Apply at the percentage as directed. Apply GGBFS only on that area where the mixing and compacting operations can be completed during the same working day. Do not use a motor grader to spread GGBFS.
For lime-slag treatment, begin lime application within 4 hours after the GGBFS mixing operation has been completed unless otherwise approved.
2. **Mixing of Ground Granulated Blast Furnace Slag.** Thoroughly mix the subgrade and GGBFS using approved equipment until a loose, homogeneous mixture is obtained. Sprinkle in accordance with Item 204, "Sprinkling," as

directed, to achieve adequate mixing and hydration moisture. Prevent formation of GGBFS balls.

3. **Application of Lime.** Once the GGBFS has been thoroughly mixed with the subgrade, uniformly apply lime using slurry placement as shown on the plans or as directed. Add lime at the percentage as directed. Apply lime only on an area where mixing can be completed during the same working day.

Provide slurry free of objectionable materials, at or above the approved minimum dry solids content, and with a uniform consistency that will allow ease of handling and uniform application. Deliver commercial lime slurry to the jobsite or prepare lime slurry at the jobsite or other approved location by using hydrated lime, as specified.

Distribute slurry uniformly by making successive passes over a measured section of roadway until the specified lime content is reached.

4. **Mixing of Lime.** Begin mixing immediately without allowing 1 hour to lapse after lime application. Thoroughly mix the subgrade-GGBFS and lime using approved equipment. Sprinkle the treated materials during the mixing, as directed, to achieve adequate hydration and proper moisture content.

Minimize dust and scattering by wind. Do not apply lime or ground granulated blast furnace slag when wind conditions, in the opinion of the Engineer, cause blowing lime or ground granulated blast furnace slag to become dangerous to traffic or objectionable to adjacent property owners.

During the interval between application and mixing, sections treated with hydrated lime and ground granulated blast furnace slag that have been exposed to the open air for a period of 6 hr or more, or that experience excessive loss due to washing or blowing, will not be accepted for payment.

After mixing and required curing, the Engineer will sample the mixture at roadway moisture and test in accordance with TEX-101-E, Part III, to determine compliance with the gradation requirements in [Table 1](#).

Table 1. Gradation Requirements Minimum % Passing.

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

Compact the mixture in one lift using density control unless otherwise shown on the plans. Complete compaction within 2 hours after the application of lime.

Sprinkle or aerate the treated material in accordance with Item 204, “Sprinkling,” to adjust the moisture content during compaction so that it is within 2.0 percentage points of optimum as determined by TEX-121-E. Determine the moisture content of the mixture at the beginning and during compaction in accordance with TEX-103-E. Adjust operations as required.

Compact to at least 95% of the maximum density determined in accordance with TEX-121-E. The Engineer will determine roadway density in accordance with Test Method TEX-115-E and will verify strength in accordance with TEX-121-E. Remove material that does not meet density requirements. Remove areas that lose required stability, compaction, or finish. Replace with lime-slag mixture and compact and test in accordance with density control methods.

Follow all requirements in Item 260 for finishing and reworking a section.

Lime-slag treatment will be measured by the square yard of the depth specified to the lines and grades shown on the plans.

Ground granulated blast furnace slag (GGBFS) will be measured by the ton of 2000 pounds. Hydrated or Commercial Lime (Slurry) will be measured in accordance to article 260.6, as specified in the plans.