

TECHNICAL MEMORANDUM
GUIDELINES FOR STABILIZATION OF SOILS
CONTAINING SULFATES

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TECHNICAL MEMORANDUM

GUIDELINES FOR STABILIZATION OF SOILS CONTAINING SULFATES

AUSTIN WHITE LIME, CHEMICAL LIME, TEXAS LIME

Purpose of This Technical Memorandum

This memorandum is prepared for members of the engineering and construction communities to establish a protocol for lime stabilization of clay soils containing soluble sulfates. It is critical to perform a thorough investigation of a site where sulfates have been identified so that a program can be devised to produce a strong, stabilized structural layer that will perform as expected for its entire design life. Any additional testing and analysis that is required can easily be justified considering the enormous expense of alternatives to lime stabilization which commonly include removal and replacement of the expansive clays or full-depth paving with an unnecessarily thick asphalt or concrete pavement section.

The memorandum presents a brief background explaining the scope of the problems associated with sulfate bearing soils when stabilized. This is followed by a practical explanation of the reactions which result in distress in sulfate soils stabilized with lime or with other calcium-based stabilizers. This practical discussion provides a basic level of understanding of the complex causes of sulfate-induced distress. This is necessary so that designers and builders will understand the reason for the protocol used in the stabilization of sulfate-bearing soils. Furthermore, this background will help to address questions posed regarding the need for more careful attention to testing, mix design, construction and quality control required when dealing with sulfate-bearing soils.

Background

In 1986 Jim Mitchell, professor of civil engineering at the University of California at Berkeley, presented a paper in the Terzaghi Lecture Series published by the American Society of Civil Engineers (ASCE). This paper addressed several interesting and rather unique geotechnical engineering problems. One of these problems was the Stewart Avenue pavement failure in Las Vegas, Nevada. The paper gained widespread notoriety because it was published by ASCE under the prestigious Terzaghi Lecture series and because it addressed unconventional and distinctive geotechnical engineering failures.

The Mitchell paper was followed by a paper by Dal Hunter also addressing the Stewart Avenue failure but with a more complete description of the chemical and mineralogical aspects. Sulfate induced problems in soils stabilized with calcium-based stabilizers such as lime, Portland cement and fly ash have been documented since the late 1950's. The mechanism has been studied by a number of highly qualified cement

chemists in an effort to understand and control sulfate attack on Portland cement concrete structures.

Basic Mechanisms of Reactions

An in-depth discussion of the complex reactions of sulfate-induced distress in stabilized soils is not within the scope of this technical memorandum. However, it is important for engineering and construction professionals to understand the fundamentals of sulfate-induced distress.

Basically four components are the culprits in sulfate-induced distress in stabilized soils: calcium, aluminum, water and sulfates. Together in the right combination these components will produce calcium-aluminate-sulfate-hydrate minerals with very large expansion potential, in some cases as high as 250%. One of these minerals is called ettringite. This mineral holds very large quantities of water within its structure. During the formation of ettringite very high swell pressures can develop, and very large volume increases can and do occur.

The formation of ettringite and similar troublesome minerals can be prevented by interrupting the supply of any one of the four components: calcium, aluminum, water or sulfate. When lime and water for construction are added to clay, the calcium is supplied by the lime, and the aluminum is released from the clay in the high pH system produced by lime and water. If the soil contains a high sulfate concentration in the form of gypsum, for example, all the ingredients with the exception of water are present for the formation of the expansive minerals. Using a low aluminate Portland cement (such as type V, sulfate-resistant cement) does not solve the problem because the source of the aluminum is not entirely the Portland cement but the soil.

There is no easy answer to the problem. Calcium is present when either lime or Portland cement are used for soil stabilization. Soils containing clay are rich with aluminum, a basic structural unit of clay. Water is necessary for compaction and for stabilization reactions and is present within pavement structures during their service life. Unfortunately, the sulfates usually cannot be efficiently or economically removed from the soil.

Factors Affecting the Reactions

A number of efforts have been made to control the reactions that result in the formation of the problematic expansive minerals. Some of these efforts have been successful, but others have not. Some are successful but economically impractical.

Presently, the best approach when dealing with lime stabilization of clay with a significant soluble sulfate content is to force the formation of the deleterious minerals

prior to compaction. If these minerals form during the mellowing period before placement and compaction, no damage will be done to the pavement. Fortunately, the expansive minerals do form relatively rapidly as long as the sulfates are soluble, the aluminum is released from the clay and adequate water is available for the formation of the minerals. The keys to success are to force the expansive mineral ettringite to form prior to placement and compaction of the pavement layer by providing adequate mellowing time (time delay between application of the stabilizer and compaction of the stabilized soil) and adequate water.

Adequate mellowing time may (practically) be as little as 24 hours or as much as 7-days, depending on the level of soluble sulfates in the soil. An adequate amount of water is typically 3 to 5 percentage points above the optimum needed to achieve maximum density during compaction. Excess water should be applied during the mellowing period, and plentiful amounts of water should be applied to the surface of the stabilized layer during curing.

Water is *the* most important component of the equation. Adequate water must be supplied throughout the stabilization construction process to force formation of the ettringite prior to compaction. The worst scenario would be to compact a lime-treated, sulfate-bearing clay with too little water. This is especially a problem if quicklime is used, and too little water is used to completely hydrate the quicklime. If this were the case, water entering the soil subsequent to compaction would cause development of expansive minerals in the compacted layer and produce very high and very disruptive expansive pressures. For this reason use of lime slurry is always recommended in stabilization of sulfate-bearing clays. Lime slurry provides the abundance of water and uniformity of hydration required to lower risk. In the event that slurry is unavailable, the soil should be kept at 5% over optimum during the mellowing period to solubilize the sulfates. Remember, quicklime was used at Stewart Avenue, and forensic studies showed inadequate water and poor construction techniques in many areas. The result was post-construction heave when water ultimately reached the quicklime causing hydration of the quicklime and the ensuing expansive chemical reactions.

Guidelines for Using Lime in Sulfate Bearing Soils

In an effort to assist you in recommending lime stabilization in sulfate-bearing clays, the following general recommendations are made.

Sulfate Levels Too Low to be of Concern

If the total level of soluble sulfates is below 0.3%, or 3,000 parts per million (ppm), by weight of soil, then lime stabilization should not be of significant concern. The potential for a harmful reaction is low. However, good mix design and construction practices should be followed as usual. If soluble sulfates are detectable at all, lime slurry

should be used, if possible, in lieu of dry lime and adequate water (optimum for compaction plus at least 3%) should be used for mixing.

Sulfate Levels of Moderate Risk

Total soluble sulfate levels of between 0.3% (3,000 ppm) and 0.5% (5,000 ppm) are of moderate concern. Generally, these sulfate levels do not result in harmful disruption, but on occasions have caused localized distress. Localized distress is often due to seams of higher sulfate concentration not detected in testing. The potential for some localized distress is a “fact of life” with sulfate levels in this range.

When encountering sulfate levels in the range of 0.3% to 0.5%, it is imperative to follow good mix design and good construction techniques explicitly. Special attention must be given to using excess water during mixing, mellowing and curing. Mixing water should be at least 3% to 5% above optimum for compaction. Lime slurry should be used in lieu of dry quicklime or hydrated lime.

The mellowing period should typically be at least 72-hours, but may need to be longer depending upon experience.

Sulfate Levels of Moderate to High Risk

Total soluble sulfate levels between 0.5% (5,000 ppm) and 0.8% (8,000 ppm) represent moderate to high risk. These soils can and have been successfully treated but require very close attention to construction technique. Generally, the same mix design and construction guidelines as described for soils containing sulfate levels between 0.3% and 0.5% should be followed. However, before treating these soils with lime laboratory testing to determine swell potential is recommended. This testing will not only establish the approximate amount of swell but also will help establish the required period of mellowing between mixing and compaction.

Sulfate Levels of High and Unacceptable Risk

Total soluble sulfate levels of greater than 0.8% (8,000 ppm) are generally of high risk to stabilize with lime. In certain situations, such soils have been successfully treated. However, the risk is generally too high for routine work. If such soils are to be treated, it should only be done following laboratory testing and by an experienced contractor, well-schooled in lime stabilization of high sulfate soils.

Treatment of such high sulfate soils requires lime slurry, mixing, mellowing, curing water contents of 3% to 5% above optimum for compaction and may require an extended mellowing period of longer than 72-hours. The required mellowing period may be as long as 7-days during which monitoring of density is recommended. Double application techniques (discussed below) may be effective in successfully treating high sulfate soils.

Soils with total soluble sulfate contents greater than 1.0% (10,000 ppm) generally are not suitable for lime stabilization because of the high risk of sulfate-induced disruption and failure. However, such concentrations often exist as seams on a project as opposed to being evenly distributed throughout a site. If the seams can be characterized using tools such as the field electrical conductivity test, detailed in Appendix C, then strategies such as removal or blending may be employed to diminish the sulfate concentrations.

Reducing Sulfates to an Acceptable Level

Evaluation of several projects that have experienced swelling problems related to elevated levels of sulfates suggests that it is seams of especially high concentration that contribute the most to pavement failures. If consistent (homogeneous) levels of sulfates exist throughout a project they can be dealt with using a variety of strategies. If, on the other hand, seams of unusually high concentrations are present they may migrate laterally as water enters the subgrade over the project's life to stable areas where, in the presence of water, calcium, and alumina ettringite may form. A practical difficulty in the field has been to identify the locations of sulfate seams so that they can be removed or diluted. A quick and easy test has been developed at the Texas Transportation Institute to reduce that problem by measuring the electrical conductivity of the soil. That test is described in more detail in Appendix C of this memorandum.

Seams containing high concentrations of sulfates are often localized on a project site. If they can be accurately characterized they may either be removed or dispersed throughout the project, diluting the total sulfate concentration to an acceptable level and homogeneity. An excellent example of sulfates being blended to a benign level occurred during the construction of the Denver International Airport. The sulfates on that project ranged higher than 3% in several areas. The high sulfates at the Denver International Airport were blended into lower sulfate areas to create a homogeneous soil throughout the project. The soil was then treated by pre-wetting and a progressive, or double, application of lime that included a mellowing period to allow ettringite to form prior to the final application of lime. The lime stabilization strategy was successful and stands as a testimonial to the marriage of sound engineering and quality construction practices.

Progressive (Double) Application of Lime

In certain situations a progressive (double) application of lime is effective in reducing heave potential and in providing successful long-term stabilization. Double mixing is obviously more expensive and, therefore, must be cost effective. Double mixing uses one-half the required lime initially. The soil, excess water and lime are then mixed followed by a mellowing period of from 72-hours to about 7-days. The purpose of the long mellowing period is to allow time for expansive reactions prior to compaction. Then

the second lime treatment is applied (the other half of the required lime is used). The lime-soil mixture is then compacted. Double treatment does not mean twice the amount of lime. It means that the same amount of lime is added in two increments. This technique should be thoroughly evaluated through laboratory testing of site-specific soils to establish appropriate lime application amounts, mellowing times, etc. before proceeding with field construction.

How to Get a “Handle” on Whether or Not Sulfates May Be of Concern

The only “fool proof” way to know whether or not sulfates will be a problem is to test the soil for sulfates. This is done by sampling the soil at enough locations and at the appropriate depths to reasonably assess the level and extent of sulfates.

Quantitative sulfate testing requires the extraction of sulfates from the soil. This is done by solubilizing the sulfates in water, followed by quantitative measurement. Since sulfate salts, such as gypsum (calcium sulfate), have specific levels of solubility, the amount of sulfate extracted from the soil is determined by the type of sulfates present and amount of water added. Therefore, 10 parts water to 1 part soil will result in more solubilized sulfates than 3 parts water to 1 part soil, especially at higher sulfate contents. Experience has shown that an extraction protocol using 10 parts water to 1 part soil is the best for evaluating potential problems resulting from sulfate reactions. This also allows better comparison with most of the test data developed in related research efforts to date. ***Note that the sulfate levels and associated treatment guidelines provided in this document are based on the 10 parts water to 1 part soil testing ratio and may not be applicable to other water:soil ratios.***

Sulfates soluble in water are measured in parts per million (ppm) and often expressed either in ppm or percent. 10,000 ppm are equivalent to 1.0%. Therefore, 3,000 ppm are equivalent to 0.3% and 5,000 ppm to 0.5%, etc. The soluble sulfate content should be reported on a ***dry soil basis*** to insure consistency of test results. Soluble sulfates should be extracted from the soil using 10 parts distilled water to 1 part soil. Test method Tex-620-J (appendix A) prepared by the Texas Department of Transportation is recommended. Any of several quantitative methods (barium precipitation, ion chromatography, etc.) may be effectively used to measure the water solubilized sulfates. Again, the important thing to remember is that the water:soil ratio used in preparation of the solution will control the amount of sulfates solubilized and measured by any of these methods, and that guidelines presented here are based on 10:1 extractions.

In testing for sulfates, it is important to remember that sulfates often are present in concentrated areas and may not be uniformly distributed. Seams or veins of sulfates are common. It is also important to realize that sulfates tend to concentrate at a certain depth below the surface of the soil. This depth of concentration is dependent on the climatic conditions of the area or region. In Texas, this depth is often three to six feet (about one to two meters) below the surface.

Sulfates typically are concentrated nearer the surface in drier, western regions. As we move eastward into wetter and more humid climates, the general rule is that sulfates, if present, tend to concentrate at lower depths.

Probably the most beneficial and reliable preliminary tool for assessing the presence and significance of sulfates within an area is the United States Department of Agriculture's County Soils Report. A report is available for every county in the United States and can be obtained from the Soil Conservation Service, a County Agent or the State land grant university. The soils report provides an abundance of engineering information conveniently tabulated. There is also a discussion of each soil series within the county and a discussion of the soil profile. This discussion will generally identify the presence of gypsum and other sulfate salts and the depth of significant concentrations, if any. This is an extremely valuable reconnaissance tool. Keep in mind that it is very important not only to identify the presence of sulfates but also the depth of occurrence. For example, a soil may be essentially sulfate free in the upper two or three feet (0.67 to 1.0 meters) but have sulfate concentrations at a depth of 6 feet (approximately 2 meters). In this case, sulfates would not be of concern during normal surface stabilization operations but could be of concern in cut and fill areas.

Required Testing and Frequency of Testing

The best approach in checking for sulfates is to ask the county agent where sulfates typically occur and at what depth to expect significant concentrations. It is also wise to buy or check out a County Soil Report. You can locate the construction job of interest to you on the aerial photographs of the county in the back of the report. From these photos the soil series in the area can be identified. Pertinent information on each soil series is presented in the discussion section and in the tabulated agricultural and engineering data for each soil.

If sulfates are present and identified in the County Soils Report, a field testing plan should be established with the geotechnical engineer. The frequency of testing depends on the level of sulfates present and the geological information for the region. If initial testing confirms the presence of sulfates in concentrations that may present problems, additional testing using the conductivity process may be warranted. The conductivity procedure and equipment are described in Appendix C.

If total soluble sulfate levels are above 0.5%, tests to determine the degree of expansion that may occur should be performed. These tests require monitoring the vertical and circumferential swell on compacted lime-soil cylinders (see appendix B). The cylinders are subjected to water by placing them on porous stones, surrounding them with absorptive towels and allowing the samples to take on water for at least 30 days or until swell levels off. The measured circumferential and vertical swells are then compared to criteria established by the engineer. If total soluble sulfate levels exceed 0.8%, this type of testing should be mandatory.

Addressing and Countering Inaccurate and Misleading Assertions

Probably the most common misconception is that ***lime is the only stabilizer that causes sulfate-induced heave***. The fact is that any calcium-based stabilizer has the potential to cause heave in sulfate-bearing soils. Not only lime but also Portland cement and type C fly ash are sources of calcium. In fact the Portland Cement Association (PCA) promotes the concept that lime results from the hydration of Portland cement and is available for soil stabilization. Many cases have been documented of sulfate-induced heave or damage in cement- and fly ash-stabilized soils. Indeed some fly ashes high in sulfates have been the source of the distress.

Another common assertion is that ***sulfate resistant Portland cement can be used to effectively stabilize sulfate-bearing clays without the fear of deleterious reactions***. This claim is not true. Sulfate resistant Portland cement was developed to resist the attack of sulfate-bearing water on concrete. Sulfate-bearing water will react with calcium and aluminum in the concrete to form the expansive ettringite mineral in the hardened concrete causing cracking and degradation of the concrete. Cement chemistry researchers found low-aluminum cement to be effective in reducing the expansive reaction. This is logical as one of the components of ettringite has been reduced - aluminum.

However, this approach does not work in soil stabilization because clay is a source of abundant quantities of aluminum. Therefore, using a low aluminum cement is a moot point.

An assertion of some credibility is that ***low calcium fly ashes will minimize heave potential***. The problem with this statement is that low calcium ashes are low in the component that is the key to stabilization of clay soils - available calcium. Low calcium fly ash is primarily a pozzolan - a finely divided source of silicates and aluminates that has the potential to develop cementitious properties in the presence of water and lime. Clay is also a pozzolan. Therefore, adding pozzolans to pozzolans without the key ingredient, calcium, is poor engineering judgement. In other words, adding low calcium ash to a clay may not induce heave, but neither is it an effective stabilizer of the clay.

APPENDIX A

TEXAS DEPARTMENT OF TRANSPORTATION

**TEST METHOD TEX-620-J
DETERMINING CHLORIDE AND SULFATE CONTENT IN SOILS**

**TEST METHOD TEX-619-J
ANALYSIS OF WATER FOR CHLORIDE AND SULFATE IONS**

DETERMINING CHLORIDE AND SULFATE CONTENT IN SOILS

This method describes how to determine the chloride and sulfate content in soil.

Apparatus

Balance, calibrated to weigh to nearest 0.1 g (0.004 oz.)

Balance, calibrated to weigh to nearest 0.0005 g (0.00002 oz.)

Sieves, U.S. Standard 4.75 mm (No. 4) and 425 μm (No. 40)

Pulverizer and Crusher

Oven, capable of maintaining a temperature of 60 ± 5 °C (140 ± 9 °F)

Beakers - 400 mL (13.5 oz.)

Stirring rod

Hot Plate

Funnels

Whatman #42 filter paper, 185 mm (7.4 in.) (round)

Wash bottle

Volumetric Flask - 500 mL (15 oz.)

Pipette.

Reagents

Dilute Silver Nitrate Solution

Sample Preparation

Step	Action
1	Obtain 300 g (10.5 oz.) representative sample when material top size is smaller than 4.75 mm (No. 4).
2	Pulverize the 300 g (10.5 oz.) to pass the 425 µm (No. 40) sieve.
3	Weigh to the nearest 0.1 g (0.004 oz.)
4	If material top size is larger than 4.75 mm (No. 4) , obtain approximately 3000 g (105 oz.) representative sample and crush/grind to pass the 4.75 mm (No. 4) sieve.
5	Obtain 300 g (10.5 oz.) representative sample of the minus 4.75 mm (No. 4) material.
6	Pulverize the 300 g (10.5 oz.) to pass the 425µm (No. 40) sieve.
7	Weigh to the nearest 0.1 g (0.004 oz.).
8	Dry the sample in a 60 ± 5 °C (140 ± 9 °F) oven and cool to 25 ± 3 °C (77 ± 5°F) in a desiccator to constant weight.

Procedure

Step	Action
1	Weigh 30 g (1.05 oz.) of the sample material into a 400 mL (14 oz.) tall form beaker and add 300 mL (10.5 oz.) of deionized water.
2	Place the beaker on a hot plate and heat to near boiling for 24 hours.
3	Stir the sample into solution occasionally throughout the 24 hours and keep the beaker covered with a watch glass.
4	At the end of the 24 hour digestion period filter the sample through a No. 42 Whatman filter and wash with hot water until filtrate is free of chlorides. NOTE: Test the filtrate for chloride by adding 1 to 2 drops of filtrate from the funnel to a dilute silver nitrate solution. Any turbidity indicates chlorides present.
5	Pipette an Aliquot from the filtrate and determine the sulfate and chloride content according to Tex-619-J.
6	Calculate the sulfate and chloride contents: $\text{Cl} = \frac{\text{Normality AgNO}_3 \times 3.5453 \times \text{mL of AgNO}_3 \times \text{Aliquot} \times 10000}{\text{Sample Weight}} = \text{ppm}$ $\text{SO}_4 = \frac{41.15 \times \text{Wt. of Residue} \times \text{Aliquot} \times 10000}{\text{Sample Weight}} = \text{ppm}$

ANALYSIS OF WATER FOR CHLORIDE AND SULFATE IONS

This method covers the calculation of chloride and sulfate ions in water to determine its suitability for concrete, sprinkling or similar uses. Interferences and methods of treating them may be found in ASTM D512 (Method B) for chloride and ASTM D516 (Method A) for sulfate.

Apparatus

Muffle furnace, 427 to 593 °C (800 to 1,100 °F)
Oven, 100 °C (212 °F)
Balance, analytical
Magnetic stirrer
Desiccator
Hot Plate
Meeker burner
Filter papers, No. 2 and No. 42 Whatman or equals
pH paper, range 8 to 9
Platinum crucible
Volumetric flask 500 mL (15 oz.)
Beaker, 200 mL (6 oz.) tall form
Beaker, 250 mL (7.5 oz.)
Buret, 50 mL (1.5 oz.)
Graduated cylinder, 25 mL (0.75 oz.)
Filter Funnel
Wash Bottle.

Reagents

All reagents must be ACS reagent grade. Use deionized or distilled water to prepare solutions.

Silver Nitrate Solution, 0.1 Normal. Standardize against a sodium chloride solution of known concentration

Potassium Chromate Indicator Solution. Dissolve 50 g (1.75 oz.) of potassium chromate (K_2CrO_4) in 100 mL (3 oz.) of water

Nitric Acid (1 + 19). Mix 1 volume of concentrated nitric acid (70% by wt) with 19 volumes of water

Sodium Hydroxide Solution (1 g/l). Dissolve 1 g (0.03 oz.) of sodium hydroxide (NaOH, pellet form) in water and dilute to 100 mL (3 oz.)

Barium Chloride Solution, 10%. Dissolve 10 g (0.03 oz.) of barium chloride ($BaCl_2 \cdot 2H_2O$) in 90 mL (2.7 oz.) of water

Hydrochloric Acid. Concentrated hydrochloric acid (HCL) (37% by wt.)

Procedure

Sample Preparation

Step	Action
1	Filter 500 mL (15 oz.) of the as-received water sample into a 500 mL (15 oz.) volumetric flask using a No. 2 Whatman filter paper.
2	Weigh 50 g (1.75 oz.), to the nearest milligram, of the filtered sample into a 200 mL (6 oz.) tall bottom beaker.
3	Adjust the sample pH to between 8 and 9 using nitric acid or sodium hydroxide solution.
4	Add 11 drops of the potassium chromate indicator and titrate using the silver nitrate solution in a 25 mL (0.75 oz.) buret.
5	The end-point is reached when a brick-red color persists throughout the sample.
6	Determine the chloride ion concentration (weight percent) as follows: $\% \text{ Chloride} = 3.545 \text{ VN/S}$ <p>Where: V = mL of silver nitrate solution N = normality of silver nitrate solution S = sample weight, grams (ounces)</p>

Procedure (continued)

- Sulfate Ion Determination

Step	Action
1	Weigh 80 g (2.8 oz.), to the nearest milligram, of the filtered sample into a 250 mL (7.5 oz.) beaker.
2	Add 10 mL (0.34 oz.) of concentrated hydrochloric acid to the sample.
3	Heat to near boiling.
4	Add 25 mL (0.75 oz.) of barium chloride solution and heat again for 10 minutes.
5	Remove from the hot plate and let cool for 15 minutes.
6	Filter through a No. 42 filter paper and wash the precipitate with hot water until the washings are free of chlorides, as indicated by testing the washings with silver nitrate.
7	Place the filter paper and precipitate in a weighed platinum crucible and dry in a 100 °C (212°F) oven for 1 hour.
8	Remove crucible from oven and slowly char the paper to a white ash using a Meeker burner.
9	Place the crucible and residue into the muffle furnace for 1 hour.
10	Cool in a desiccator and weigh.
11	Determine the concentration of sulfate: $\% \text{ Sulfate} = 41.15 R/S$ Where: R = residue weight, grams (ounces) S = sample weight, grams (ounces)

APPENDIX B

SIMPLIFIED SWELL TEST

Materials Required

1. Compaction mold and compaction equipment to meet ASTM D 698 or D 1557.
2. Calipers to measure vertical height and diametral width of the compacted sample.
3. Porous stone, water reservoir and absorbent fabric to transmit water to soil.

Testing Procedure

1. Compact two replicate samples at 100% and 95% of the required compaction energies (i.e., ASTM D 698 or ASTM D 1557 or Tex-113a).
2. Immediately after compaction, place the sample on a porous stone in a water reservoir with the water level even with the top of the porous stone.
3. Place a absorbent fabric around the circumference of the samples with the bottom 25-mm of the fabric below the top of the water reservoir so that the fabric can “wick” water to the circumference of the sample. The samples are placed in a 25°C temperature environment for 7-days. Vertical height and diametral dimensions are recorded at the end of each day. Six diametral measurements are made: two at 25-mm below the surface, two at the mid-height and two at 25-mm above the base. The diametral dimensions are recorded at approximately 90° from one another. Measure the vertical height at two random points.
4. After 7-days the samples are carefully placed in a 12°C (plus or minus one degree) temperature room for an additional 21-days or until swell stops.

Calculations and Presentation of Data

1. Calculate the average of the diametral dimension measurements (average of six) after sample fabrication and the average of the vertical height after sample fabrication. Use these values as datum values.
2. Calculate average diametral and vertical measurements at the end of each day. Calculate the percentage of change in diametral measurement as the ratio of the average diametral measurement divided by the diametral datum multiplied by 100%. Calculate the percentage change in vertical measurement as the ratio of the average vertical height divided to the vertical height datum multiplied by 100%.
3. Plot the data as % diametral and vertical dimension (ordinate) change versus time (abscissa) for a 28-day period or until swell ceases to occur.

APPENDIX C

Electrical Conductivity Test

This test was developed at the Texas Transportation Institute (TTI) by Sanet Bredenkamp and Robert L. Lytton. It is described in detail in Research Report 1994-5, **Reduction of Sulfate Swell in Expansive Clay Subgrade in the Dallas District**. The report sets forth a method by which sulfate content in the soil as well as its probable expansion can be estimated using the conductivity test. That method remains to be confirmed through comprehensive field tests at this time and is not included here. The **Electrical Conductivity Test** can, however, identify the presence of soluble salts in the soil rapidly and simply. The salts that are identified may or may not be sulfates, so additional tests need to be run to assess both the type of salt and the level of concentration. Because the test is inexpensive and quick it may be used to identify the boundaries of high sulfate seams to assist in formulating a strategy for dealing with them. The following procedures are taken directly from the report which is available from the National Technical Information Service (NTIS - www.ntis.gov). The reference number is PB96-136007INZ.

Materials Required

1. Wide mouth plastic containers with water-proof lids.
2. Distilled water.
3. Battery driven digital scale that can measure up to 500g.
4. Hand held conductivity meter.
5. Calibration solutions for the conductivity meter.

Note: according to the Bredenkamp/Lytton Report the cost of materials is less than \$600.

Testing Procedure

1. Find the location where the sulfate test is to be performed and use an auger to obtain two small soil samples at approximately 10 and 20 cm below the soil surface. Only 5 grams of soil is needed to perform the test.
2. Weigh approximately 5 g of each soil sample into two separate plastic containers. If the soil is wet, break lumps apart and leave the soil to air-dry for 1 to 2 hours. Record the exact dry weight of the samples.
3. Add distilled water with a mass of exactly 20 times the dry weight of the soil sample to the dry sample. Tightly close the lid of the plastic container and shake vigorously until the soil dissolves and forms a homogeneous solution.
4. Calibrate the conductivity meter as described in the instruction manual accompanying the device.
5. Take conductivity measurements on each soil:water mixture and record the data in milli Siemens (mS). Note: $1 \text{ uS} = 0.001 \text{ mS}$. The experience of the authors of the study indicates that mixtures with a conductivity $> 8 \text{ mS}$ have a potential to cause a problem.