# ALTERNATIVE EXPLANATION OF “LIME-INDUCED HEAVE”

**Ronald F. Reed, P.E., M.ASCE**

Reed Engineering Group, Ltd., 2424 Stutz Drive, Suite 400, Dallas, Texas, 75235; e-mail: rreed@reed-engineering.com

## Abstract

Lime-induced heave is a process whereby calcium from lime chemically reacts with sulfates within the soil, producing expansive minerals which result in expansion of the limed layer causing surface heave. This paper presents a case study of subgrade heave and offers an alternative explanation of the mechanism causing heave other than development of expansive minerals. After final grading, the site was subject to heavy rainfall. Relatively uniformly-spaced ridges developed within the limed layer in less than four days. The study included physical inspection of the ridges, elevation surveys, field density and moisture content tests, Atterberg Limits, soluble sulfate tests, and x-ray diffraction. None of the characteristics generally attributed to development of heave-related minerals were observed. Approximately four months of dry weather preceded the heavy rainfall event. It is hypothesized that development of the observed ridges is associated with closing of shrinkage cracks in the native subgrade which resulted in lateral stress and shear failure within the stabilized layer.

## Introduction

Use of lime as a stabilizing agent for clayey soils has been extensively used throughout North Texas for over 60 years; however, in the mid to late 1980’s, concern was raised regarding lime-induced heave. Articles by Mitchell (1986) and Hunter (1988) identified subgrade conditions in Las Vegas where lime combined with high sulfates within the soil produced expansive minerals ettringite and thaumasite which lead to subgrade failure. Failures were characterized by both Mitchell (1986) and Hunter (1988) as post-compaction expansion of the limed layer, with corresponding gain in moisture, and loss of density and strength. Hunter (1986) also reported significant growth in visible mineral aggregates within portions of subgrade undergoing heave.

Within the City of Frisco, located north of Dallas, Texas, significant distress of streets and infrastructure has been experienced. Various studies were performed by the City, concluding that lime/sulfate-induced heave was at least partially responsible for the distress. Various engineering standards were then passed via ordinances to address this conclusion. The standards include use of double lime application, increased hydration time and excavation and replacement of soils with high soluble sulfate with alternative materials. Numerous other cities have subsequently adapted similar engineering standards to specifically address lime/sulfate-induced heave.

This paper reviews lime/sulfate-induced heave and documents conditions observed on differential heave of a pavement subgrade within the City of Midlothian, which is located south of Dallas, Texas. An alternative hypothesis for the observed movement is presented.

## Lime Stabilization Process

Hydrated lime is commonly used to stabilize clayey soils. The stabilization process is generally described by Little (1995) as two processes: 1) an initial cation exchange leading to a reduction in the absorbed water layer on the clay which results in flocculation; and 2) agglomeration of silt and clay-size particles, followed by a pozzolanic reaction, whereby a cemented product is formed which is the long-term stabilizing agent. The cementitious product is typically identified as either or both calcium-silicate-hydrate (CSH) or calcium-aluminate-hydrate (CAH).

The silica and/or alumina for the cement product are solubilized from the clay binder at the high pH associated with hydrated lime. Thus, as sufficient lime is added to the soil, the pH rises to approximately 12.4, resulting in the silica and alumina going into solution and being made available for development of the cementitious product. With sufficient water, the cementitious process will continue as long as the pH is high enough to solubilize the silicate and/or alumina, and calcium and water are present. Formation of the carbonates CSH and CAH occur with low pressure and the carbonates stop growing when they encounter resistance from a soil particle or other obstruction.

What has been described as lime-induced heave, however, based on discussions by Mitchell (1986), Hunter (1988), and Little (1995) interrupts the formation of the cementitious product or carbonation. In the presence of soluble sulfates, a calcium-sulfate-aluminate-hydrate can develop. Little (1995) reports that two forms of the hydrate can develop; ettringite and monosolfoaluminate, although Hunter (1988) identified ettringite and thaumasite. For the purpose of the following discussions, only ettringite will be named, although realize that other hydrates may also be present.

Relative to ettringite, there appears to be two theories as to the observed expansion. Mitchell (1986) and Hunter (1988) attributed the observed expansion of the soil matrix as a result of growth of the crystal. Puppala (2005) and Little (2010) attribute expansion of the soil matrix to the hydration of the ettringite crystal. In any event, it appears that the presence of ettringite is necessary for the soil matrix to heave in the classical lime-induced heave scenario.

If sufficient water is not available, growth of ettringite and other hydrates will stop, but can resume if water is made available at a later date. Lime-induced heave of pavement subgrade in Las Vegas, Nevada documented by Mitchell (1986) and Hunter (1988) clearly illustrates what can happen if the development or hydration of expansive minerals occur after the subgrade is compacted and pavement constructed.

## Review of Selected Case Histories

The sited case studies by Mitchell (1986) and Hunter (1988) were well documented and clearly proved a case for lime-induced heave through the formation of ettringite and other hydrates after the subgrade was compacted and the pavement structure constructed.

Hunter (1988) reports that the limed layer increased in approximate thickness equivalent to the magnitude of observed heave and had a corresponding reduction in density and strength. It was also reported that observable white or light colored mineral aggregates were present within the expanded portion of the limed layer, with quantities varying from 30 to 60% by volume of the limed layer.

Perrin (1992) identified three cases of subgrade heave attributed to lime-induced heave. Two of the cases sited were in the Dallas area. The cases in the Dallas area were identified as Loyd Park, Joe Pool Lake and Cedar Hill State Park, Joe Pool Lake.

For both cases, Perrin (1992) identified the heave as consisting of transverse and longitudinal ridges attributed to shear failures within the limed layer. At Loyd Park, the ridges were up to 10.2 centimeters (cm) in height. Spacing of ridges was not provided for Loyd Park. At Cedar Hill State Park, ridges up to 0.3 cm in height were measured. Transverse ridges were estimated to be at 3.7 to 4.6 m on-center, in some cases extending completely across the roadway.

Perrin (1992) reports X-ray diffraction (XRD) on samples of lime-treated material from Loyd Park contained "trace" amounts of material intermediate between ettringite and thaumasite. He also states that ettringite and probable thaumasite were present in the limed soils at Cedar Hill State Park, but no quantitative estimate was provided. It was also noted at Cedar Hill, that the limed layer exhibited a slight reduction in Plasticity Index (PI) with a mean PI of 31.

Puppala et al (2012) presented an example of heave of an airport taxiway at Dallas/Fort Worth Airport in Irving, Texas at least partially attributed to lime-induced heave. The pattern of heave was described as irregular, sometime affecting localized areas 0.3 to 0.6 m in diameter, with the magnitude of heave varying from 0.05 m up to 0.3 m. Lateral expansion attributed to the heave resulted in series of longitudinal cracks within an asphalt-surfaced taxiway shoulder. The adjacent rigid pavement was in good condition, with minor shrinkage cracks at few locations. Puppala (2012) pointed out that heavy rainfall in the area may have contributed to the formation of ettringite and resulted in the heaving of the flexible pavement sections.

Puppala et al (2012) also presented X-ray powder diffraction of selected lime-treated soil samples obtained from below the taxiway shoulder showing a strong presence of ettringite. The amount of ettringite encountered reported by Puppala range between 600 to 1080 cps. The heave was attributed to hydration of the ettringite, rather than the actual formation of the mineral.

## Case History

**Project –** The project consisted of construction of four new roads; Miller Road, Challenger Drive, Discovery Street, and Endeavor Lane, totaling approximately 2,220 linear meters, within a new industrial business park in Midlothian, Texas. Design pavement consists of a 18.3 m wide, undivided road with a 20.3 cm thick, 24,131.65 kilopascal (kPa) compressive strength reinforced concrete pavement over a 20.3 cm thick clay subgrade stabilized with a minimum of 9 percent by dry weight (29.295 kilogram per square meter) hydrated lime.

During construction, the pavement subgrade for Challenger Drive experienced heave attributed to lime/sulfate reaction.

**Geologic Setting and Soil Characteristics –** The site is located within a relatively flat alluvial/colluvial filled floodplain over residual soils of the Cretaceous Age Eagle Ford Group. The upper 1.2 m to 4 m consists of highly plastic CH clay with occasional sand and fine gravel partings near its base with the underlying Eagle Ford residual soils.

The alluvial soils are underlain by severely weathered shale, dually classified as a highly plastic, CH clay in accordance with the Unified Soil Classification System (USCS). The severely weathered shale extended to depths of 7 to 9 m where it transitioned into relatively unweathered shale.

A summary of index tests is provided in Table 1.

Table 1. Summary of classification tests. Averages shown in parenthesis.

| Soil Type | Moisture Content, Range | Liquid Limit, Range | Plasticity Index, Range |
|---|---|---|---|
| Alluvial Clay | 26 – 42 (34) | 63 – 81 (67) | 34 – 45 (39) |
| Residual Clay | 29 – 40 (36) | 74 – 99 (94) | 36 – 63 (61) |

The field investigation was conducted in two phases; January 2014 and December 2014. Total soil suction profiles were developed for all borings on undisturbed tube samples. Representative suction profiles are provided in Figure 1 for two borings in the specific area experiencing heave that were sampled in January 2014 and December 2014.

Total suction tests were performed in accordance with ASTM D 5298 using Whatman No. 42 filter paper, using the calibration curve provided in the ASTM. Since the trend in the suction profile is used for analysis, not the specific value, no additional calibration curve is developed.

Based on extensive experience and the suction profiles shown in Figure 1, the upper soils are considered to be seasonally active to depths varying from approximately 2 m to 3 m, dependent upon prevailing weather. Identification of the seasonal activity was used to calculate the potential for movement as discussed later.

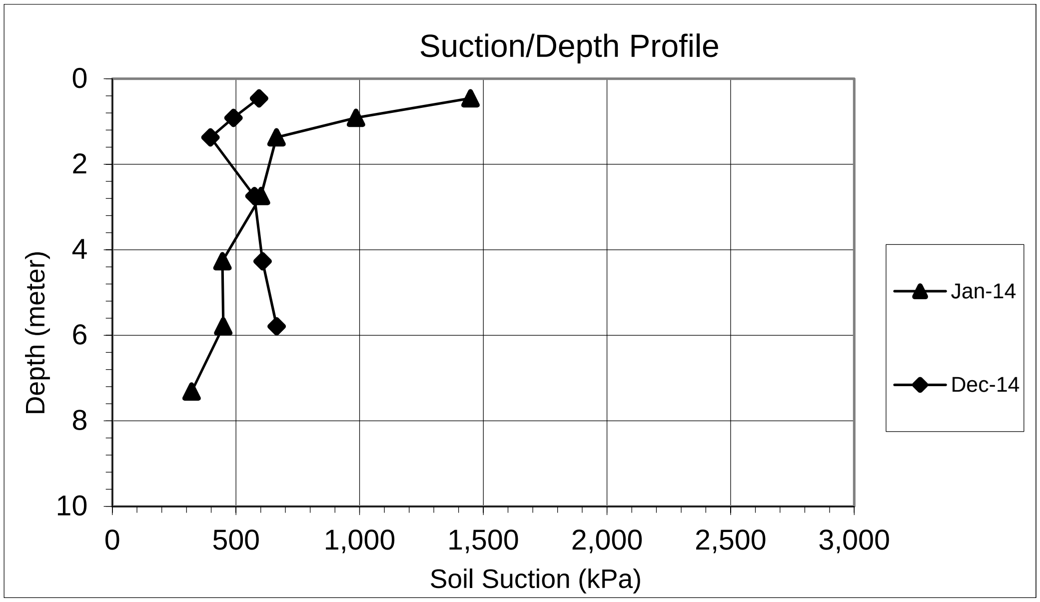

Figure 1. Total Suction Versus Depth. Tests conducted in accordance with ASTM D 5298.

**Soluble sulfates –** Soluble sulfate content was determined during the geotechnical investigation performed in 2014. Tests were performed in accordance with Texas Department of Transportation (TxDOT), Test Method 145E. Table 2 below summarizes the quantity of soluble sulfates. Sample No. 4 is from the vicinity of the experienced heave in Challenger Drive.

Table 2. Pre-construction soluble sulfate test results. Tests performed in accordance with TxDOT Test Method 145E. Sample 4 is from area of observed heave.

| Sample No. | Result (ppm) |
|---|---|
| 1 | 1420 |
| 2 | <100 |
| 3 | 100 |
| 4 | 14,560 |
| 5 | 920 |

At the time of the field investigation in 2014, ground water was present at depths of 2.4 m to 3.7 m below grade. Ground water in the geologic setting fluctuates, but is generally present at depths of less than 4.5 m even after periods of extended drought.

**Construction Sequence –** Installation of site utilities and mass earthwork were performed from June 2015 through late January 2016. Both Miller Road and Discovery Street required all fill to achieve required plan profile. Endeavor Lane required cuts of 0.3 m to 0.6 m over an approximate length of 155 linear meters, with the balance of roadway being either on-grade or fill. Challenger Drive required 0 to 0.3 m of fill except between Sta. 8+00 to Sta. 9+55, where 0.3 m to 0.6 m of cut was required to achieve plan profile. Field density and moisture tests were performed on utility backfill but not on mass fill below the roadway.

Prior to application of lime, samples of the subgrade were obtained on approximate 250-foot centers from all 4 roadways. Samples were tested to determine PI. The samples from each road subgrade exhibiting the highest plasticity were then tested to confirm required lime for stabilization. Both lime series (reduction in PI versus percent lime added) and Eades & Grim series (ASTM D 6276) were performed. Lime series test results for the subgrade conditions in Challenger Drive are provided in Table 3. Results of the Eades & Grim series for the same soil are provided in Table 4.

Lime series and Eades & Grim tests indicated 8 percent hydrated lime would be required for stabilization. City of Midlothian ordinance requires one percent over the tested value; therefore, a minimum of 9 percent hydrated lime was specified. Initial preparation of the subgrade, application of lime, mixing and compaction were performed in accordance with TxDOT Item 260.

Table 3. Lime Series Results for Challenger Drive.

| Sample | Percent Lime | Liquid Limit | Plastic Limit | Plasticity Index |
|---|---|---|---|---|
| 1 | 0 | 77 | 27 | 50 |
| 2 | 4 | 73 | 48 | 25 |
| 3 | 6 | 73 | 53 | 20 |
| 4 | 8 | 74 | 59 | 15 |

Table 4. Eades & Grim (ASTD D6276) test results for Challenger Drive.

| Percent Lime | pH |
|---|---|
| 4 | 12.2 |
| 6 | 12.3 |
| 8 | 12.4 |

Initial application of lime slurry and mixing of lime occurred in early February 2016. Final mixing was performed after a minimum 72-hour mellowing period. Gradation tests to evaluate percent passing the 4.445 cm, 1.905 cm and #4 sieve were performed in accordance with TxDOT Test Method 101E after the final mix to confirm mixing operations. Field density testing was performed during compaction and/or one day after. Table 5 summarizes the dates of testing and placement of concrete for each roadway.

Table 5. Construction sequence, all dates in 2016.

| Roadway | Gradation Testing | Field Density | Concrete Placement |
|---|---|---|---|
| Challenger Drive | February 10 | March 7* | March 23 & 25 |
| Discovery Street | February 9 | March 22 & 23 | March 25 |
| Endeavor Lane | February 8 | March 28 | March 28 &29 |
| Miller Road | February 12 | March 28 | April 4 |

*Initial compaction was performed on March 7 prior to subgrade heave.

Compaction of Challenger Drive subgrade was performed on March 7, 2016. Compaction results for Challenger Drive are shown in Table 6. Percent compaction is relative to ASTM D 698 density.

Table 6. Field density and moisture tests, pre-heave, Challenger Drive. Percent compaction based on ASTM D 698.

| Location | Field Moisture (%) | Field Density (kg/m$^3$) | Compaction Level (%) |
|---|---|---|---|
| STA 2+00 | 38.2 | 1,263.9 | 98.1 |
| STA 5+00 | 37.9 | 1,267.1 | 98.4 |
| STA 8+00 | 36.9 | 1,243.0 | 96.5 |
| STA 11+00 | 37.3 | 1,255.8 | 97.5 |
| STA 14+00 | 38.0 | 1,244.6 | 96.6 |
| STA 17+00 | 38.3 | 1,249.4 | 97.0 |
| STA 20+00 | 37.7 | 1,239.8 | 96.3 |
| STA 23+00 | 39.2 | 1,265.5 | 98.3 |

Pavement reinforcing was placed on Challenger Drive on March 8, 2016. Work was suspended when the site was subject to an estimated 5.1 to 7.6 cm of rainfall over a 4-day period. Upon inspection to continue work, relatively uniformly-spaced ridges developed within the limed layer between Sta. 3+50 to Sta. 11+00. The heave was attributed to sulfate-lime reaction, i.e., lime-induced heave.

As seen in Figure 2, multiple transverse “ridges” and one longitudinal “ridge” were noted in the subgrade. The longitudinal ridge generally followed the approximate center line of the roadway. The transverse ridges were on approximate 4.6 m to 7.6 m centers. Height of the ridges varied generally from 5 to 8 cm up to a maximum of 20 cm.

An elevation survey performed after the ridges developed found that, in the relatively smooth areas, the surface had risen 2.54 to 5.08 cm above original grade. Density tests indicated, in the relatively smooth areas, no loss of density or gain in moisture.

Due to development of heave within the Challenger Drive subgrade, no other limed subgrades were compacted pending further study.

**Forensic Investigation –** Considering observed conditions on March 14, 2016, the initial conclusion was that the subgrade had undergone lime-induced heave. However, elevation surveys indicated the grades where generally 2.5 cm to 5 cm above plan grade, but with the exception of the observed ridges, was relatively uniform. This magnitude of heave was consistent with that calculated for seasonal moisture changes using the empirical procedure developed by McDowell (1959) and modified by the Texas Highway Department, TxDOT Test Method 124E, based on drying to approximately 1 to 2 m below subgrade.

If post-compaction development or hydration of ettringite was responsible for the failed condition, then the ettringite had to be relatively uniform given the observed condition. As noted by the vehicle tire tracks shown in Figure 2, there was also no noticeable loss of subgrade strength outside of the ridges.

Figure 2 illustrates the observed subgrade condition on approximately March 14, 2016.

Figure 2. Photo of general failed condition, Challenger Drive.

Close inspection of the ridges indicated that the limed subgrade appears to have failed in shear, as shown in Figure 3 and did not exhibit a typical pattern of heave, which would be anticipated to be more lens-shaped (high point, tapering towards the edge). In addition, both Mitchell (1986) and Hunter (1988) described heave areas where ettringite formed as moist and soft because of loss of compaction or density.

Figure 3. Close-up of shear failure. Note IPhone below reinforcing at left for relative size.

Nine samples of the subgrade were obtained and tested for plasticity. Five of the samples were obtained from heaved ridges. The balance came from the relatively uniform compacted subgrade.

Test results are summarized in Table 7. The anticipated reduction in plasticity, with the normal variation exhibited in Samples 1 and 8, was obtained.

Table 7. PI Results, Post-Heaved Subgrade, Challenger Drive.

| Sample No. | Station No. | Liquid Limit (%) | Plastic Limit (%) | Plasticity Index (PI) |
|---|---|---|---|---|
| 1 | 3+50 | 75 | 55 | 20 |
| 2(∗) | 3+51 | 71 | 56 | 15 |
| 3 | 5+45 | 74 | 60 | 14 |
| 4(∗) | 5+50 | 73 | 61 | 12 |
| 5 | 6+65 | 70 | 58 | 12 |
| 6(∗) | 6+70 | 69 | 54 | 13 |
| 7 | 8+10 | 68 | 57 | 11 |
| 8(∗) | 8+15 | 71 | 52 | 19 |
| 9(∗) | 9+55 | 60 | 47 | 13 |

∗ Sample obtained from the “heaved” or “ridge” portion of subgrade.

Six of the subgrade samples were also tested for soluble sulfates. Three of the tests were obtained from the ridges, with the balance from the relatively undisturbed areas. Tests were performed in accordance with TxDOT Test Method 145E. Test results are provided in Table 8.

Table 8. Soluble Sulfate Test Results

| Sample No. | Location | Result (ppm) |
|---|---|---|
| 1 | STA 3+50 | 6,880 |
| 2(∗) | STA 3+51 | 7,760 |
| 3 | STA 5+45 | 6,840 |
| 4(∗) | STA 5+50 | 9,120 |
| 5 | STA 6+65 | 8,800 |
| 6(∗) | STA 6+70 | 11,760 |

*Sample obtained from the “heaved” or “ridge” portion of subgrade.

Soluble sulfates were present varying from 6,840 parts per million (ppm) to 11,760 ppm. No discernable difference was noted between the amount of soluble sulfates in samples from the ridges versus samples from undisturbed areas. The range of soluble sulfates was also relatively consistent with that encountered in Sample 4, Table 2 which was obtained and tested during the initial geotechnical investigation.

To limit delay of construction, the contractor was instructed to blade the subgrade to required elevation then compact with a smooth-tired roller. Field density tests were performed on March 23, 2016 to confirm that a minimum of 95% of ASTM D 698 density had been achieved. Test results are provided in Table 9.

Table 9. Post-Heave Compaction Results

| Station No. | Moisture Content (%) | Dry Density (kPa) | Percent Compaction |
|---|---|---|---|
| 5+00 | 43.1 | 3.69 | 98.0 |
| 8+00 | 40.0 | 3.64 | 99.3 |
| 11+00 | 41.3 | 3.53 | 96.3 |
| 17+00 | 40.6 | 3.58 | 97.8 |

Reinforcing steel was placed and concrete poured on March 25, 2016. The subgrade for the balance of the streets was compacted from approximately March 22 through March 29, with the steel and concrete paving completed shortly thereafter. All concrete was in-place by the approximate middle of April 2016. No other subgrade exhibited movements similar to that observed on Challenger Drive.

Four samples of the subgrade from Challenger Drive were subsequently tested for the presence of ettringite. Samples were submitted to Dr. Asish R. Basu at the University of Texas at Arlington and subject to XRD using an X-ray diffractometer.

According to Dr. Basu, XRD is a rapid analytical technique used for the identification of crystalline minerals. An intense X-ray beam generated by the cathode ray tube is directed toward the powder sample. The interaction of the rays with the samples produces the diffracted rays. These diffracted rays are then detected, processed and counted. Scanning the sample through a range of D-Spacing angle allows identification of minerals since each mineral has a set of unique D-Spacing angle with standard reference patterns.

Two samples were submitted from heaved ridges and two from the relatively undisturbed area. Test results are provided in Figure 4. XRD results indicated ettringite was present at less than 200 counts per second (cps). Based on Dr. Basu’s interpretation, quantities of ettringite present were limited.

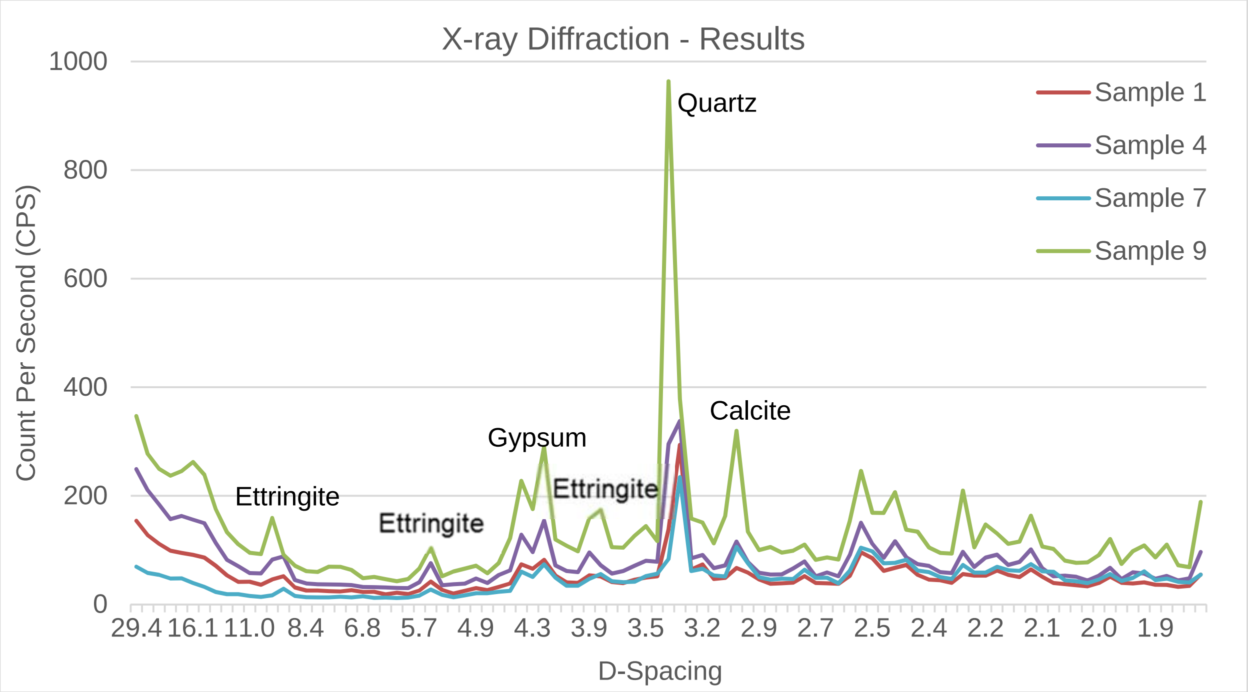

Figure 4. X-Ray Diffraction Results.

It is important to note that Leyland et al. (2015) found that quantification of clay minerals using the XRD technique is "problematic" and highly dependent upon the specific procedural technique. It is therefore possible that ettringite and/or other expansive hydrates were present and missed in either the sampling or XRD process.

However, if lime-induced heave of the subgrade between the ridges was causing the observed shear failure, then the presence of soluble sulfates and development of the expansive hydrate would have to be very uniform. This does not seem plausible given the natural variation in most soils. On the other hand, if the ridges are lime-induced heave, then they would be expected to be lens-shaped and would not exhibit shear.

Alternatively, the behavior can be explained if the natural subgrade heaved after the lime stabilization process was completed, and the observed failures are associated with lateral expansion and closure of shrinkage cracks. Because of the rigidity of the limed layer, the horizontal pressure results in shear, with one portion of the limed layer sliding over the adjacent limed material. This type of failure hypothesis also accounts for the lack of reduction in strength or density in the undisturbed material between the ridges.

This similar appearing phenomena was noted at a golf course in Carrollton, Texas located northwest of Dallas. Relatively dry weather in the Summer and Fall of 2015 resulted in development of shrinkage cracks in an expansive clay. The golf course watered sufficiently to allow the grass to grow across the shrinkage cracks. Following heavy rainfall over an approximate 24-hour period, conditions shown in Figure 5 were noted prior to maintenance crews mowing the fairways. Close inspection of the "wrinkled" Bermuda grass noted partially closed shrinkage cracks under the grass at each of the ridges inspected. It is interesting to note the similarity between conditions shown in Figure 5 versus Figure 2.

Figure 5. “Wrinkles” within fairway grass associated with closure of shrinkage cracks in underlying soils.

## Summary and Conclusions

The lime-stabilized subgrade for a site in Midlothian, Texas experienced what has been characterized as lime-induced heave associated with formation and/or hydration of ettringite or other expansive hydrates. An alternative hypothesis for the observed phenomena is presented which consists of vertical and horizontal expansion of subgrade below the lime layer, with subsequent stress failure of the limed layer in shear.

The failed subgrade exhibited development of ridges spaced in a relatively uniform pattern with virtually undisturbed lime-stabilized “plates” between ridges. The ridges appeared to be associated with shear failure between adjacent “plates” with one plate riding over the adjacent plate.

Post-failure XRD analysis did not detect the presence of significant amounts of ettringite in samples from either the ridges or the undisturbed plates. Because of the limited scope, it is possible that expansive hydrates were present and not detected; however, the physical condition of the post-heave subgrade would not appear to support the classical description of the lime-induced heave.

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