Moisture Migration in Geogrid Reinforced Expansive Subgrades

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ABSTRACT
Highways in Texas, Arkansas, Colorado, Wyoming and other parts of the United States are often constructed atop expansive clay subgrades. Considerable damage to flexible pavements has been observed in these areas in the form of longitudinal cracking. A geogrid placed between the subgrade and base layers has been used successfully in Texas as a stabilization alternative to prevent longitudinal cracking, although the mechanism of geogrid reinforcement is not well understood. This study involves measurement of the time variation in water content of an expansive clay subgrade beneath a flexible pavement to investigate if differential volume changes in the subgrade are a cause of longitudinal cracking. Two years of moisture monitoring and visual observations indicate that significant moisture fluctuations occur in the clay subgrade under the unpaved shoulder of the road, while negligible moisture fluctuations occur in the clay subgrade under the pavement. This contrast in water content changes between the shoulder and pavement indicates that both bending and stretching of the subgrade are probable causes of longitudinal cracks.

1. INTRODUCTION

1.1 Motivation

The Texas Department of Transportation (TxDOT) has observed longitudinal cracking in flexible pavements constructed atop expansive clay subgrades. Clays are considered expansive when they experience volume change upon wetting and drying, and are often characterized by a plasticity index (PI) greater than 20. Longitudinal cracks occur parallel to the roadway and can extend a significant distance, as shown in Figure 1(a). Further, they have often been observed by TxDOT to extend through the base course into the subgrade. These cracks are undesirable, as they provide a pathway for moisture infiltration and increased ease of base course particle migration, both of which accelerate roadway degradation (Sebesta 2004). A mechanism of longitudinal cracking relevant to flexible pavements atop expansive clay subgrades is differential volume change across the width of the roadway. This occurs due to moisture infiltration from rainstorms or moisture removal due to evapotranspiration. Due to the low structural stiffness of flexible pavements compared to concrete pavements, stress redistribution due to differential movement may result in brittle failure of the pavement system. As this mechanism is independent of vehicle loading, it may be used to explain several pavement failures observed by TxDOT before opening to traffic. An improved understanding of the migration of moisture in highway subgrades will enhance implementation of strategies for prevention of longitudinal cracking in pavements.

A strong linkage between moisture migration and longitudinal cracking has not been well established in the literature. Accordingly, the goal of this study is to investigate the migration of moisture under the pavement in order to assess the likelihood of differential shrinkage and swelling between the center and edges of the pavement. Specifically, the horizontal and vertical components of the volumetric strain due to shrinkage and swelling may impose tensile, shear, and bending stresses at the point under the pavement at which moisture does not fluctuate. An exaggerated representation of the vertical component of subgrade movement is shown in Figure 1(b). The first case shows the edges of the pavement bending downwards, as the subgrade soil in the shoulder shrinks during drying. The second case shows the edges of the pavement bending upwards as the subgrade in the shoulder swells during wetting. In both cases, differential movement between the shoulders and the centerline of the road will lead to longitudinal cracks that are closer to the edge of the pavement, similar to those observed in Figure 1(a).

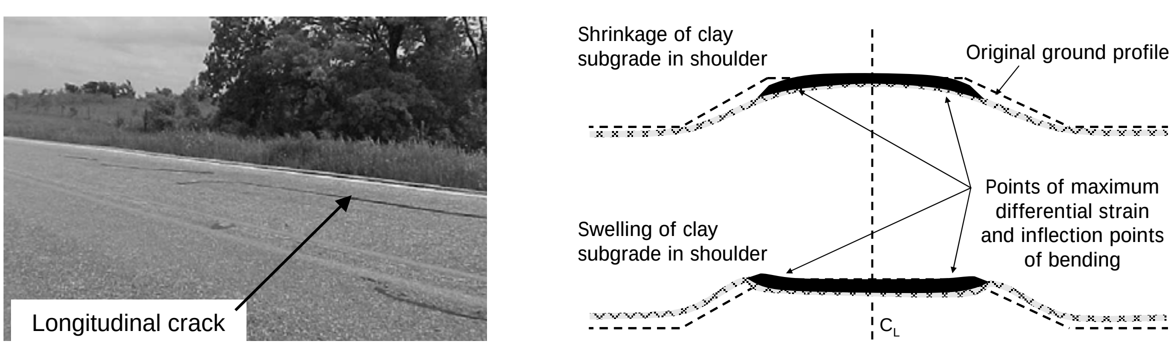


Figure 1. (a) Flexible pavement with longitudinal crack; (b) Schematic of cracking due to subgrade volume change

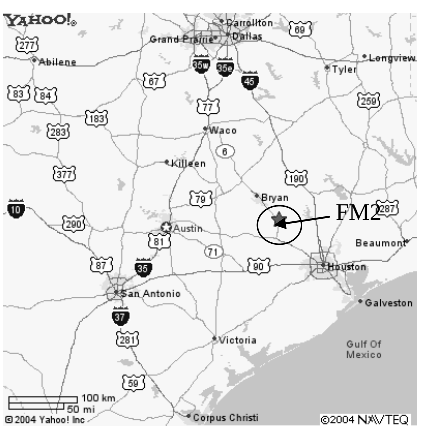
The effects of volume change in expansive clay subgrades on pavement performance have been addressed by removal of the expansive clay, placement of a stiff pavement structure over the expansive material, or by lime treatment of the subgrade. Removal of soil over the length of a roadway is cost-prohibitive, and the swell pressures of expansive soil can be high enough to exceed the tensile strength of concrete. Lime treatment has been found to be inadequate in expansive clays containing sulfates. In these clays, growth of ettringite mineral crystals has been observed upon the addition of lime (Mitchell and Dermatas 1992). Ettringite crystal growth has been observed to lead to significant volume changes in the subgrade. Although this issue has been addressed by allowing time for ettringite crystal formation before compaction of the lime treated soil, problems have still been encountered due to inadequate dosing of lime and spatial variability in the sulfate concentration along the length of a roadway. In response to the difficulties encountered in conventional treatment options, TxDOT has investigated the use of geogrid reinforcement for subgrade reinforcement. Geogrids have been observed to work well on several roads in eastern Texas over the past five years, such as FM1915 in Millam County and SH7 and FM2 in Bryan district (Zornberg *et al.* 2008). Geogrids have been proposed to increase the stiffness of the subgrade, to help bridge cracks, to limit the passage of cracks from the subgrade into the base course, and to increase the tensile resistance of the pavement. The normal stress on the geogrid is negligible compared to that in retaining wall and embankment applications, so conventional geogrid design methodologies are inappropriate. Additional research is needed to define the material properties that lead to an improvement in pavement performance.

An ongoing research project at The University of Texas at Austin has focused on the investigation of geosynthetic reinforcement of subgrades, mechanisms of longitudinal cracking, and moisture migration in clay subgrades. This project includes a full-scale field monitoring component. Specifically, several geosynthetic-reinforced test sections were installed during the rehabilitation of the FM2 road, near Navasota, TX. Horizontal and vertical profiles of moisture sensors were installed in several of the test sections at FM2. This paper describes the details of the moisture sensor installation and calibration, presents results from moisture sensors installed into the subgrade component of several pavement profiles at FM2, and evaluates trends in the moisture data useful for investigation of the mechanism of longitudinal cracking.

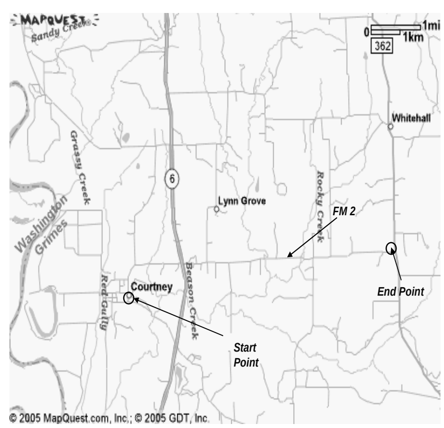
1.2 Pavement Rehabilitation at FM2

1.2.1 FM 2 Description

Texas Farm-to-Market Road No.2 (FM2) is located in the Grimes County, in southeast Texas. Figure 2(a) shows FM 2 relative to major metropolitan areas in Texas. The total length of the road is 6.4 miles of which 2.4 miles lie towards the west of State Highway 6 (SH 6) at Courtney and rest 4 miles continues eastward and ends at FM 362 as shown in Figure 2(b). The average daily traffic (ADT) was 800 in 2002 and is expected to increase to 1300 vehicles in 2022. Trucks account for 6.6 percent of the ADT. The expected total number of equivalent 18-kip single axle loadings (ESAL) is 91,000 in one direction for the 20 year period from 2002 to 2022. The speed limit on FM2 is 55 miles per hour.



(a)



(b)

Figure 2. (a) Location of FM 2 relative to major metropolitan areas in Texas; (b) Layout of FM 2

1.2.2 Pavement Rehabilitation

A typical pavement cross section of the FM2 pavement before rehabilitation is shown in Figure 3. The roadway was severely deteriorated before rehabilitation, with longitudinal cracking and rutting. Degradation was likely due to both water seepage through the cracked asphalt and water infiltration into the subgrade clay. Due to the relatively thick existing base course layer (0.4 m), TxDOT decided to scarify only the top 0.25 m of this material. The proposed scarification plan for the new pavement test sections is shown in Figure 3. The roadway has a slope of 3% from the centerline to the edge of the road, and there is approximately a 0.8 m drop-off from the edge of the pavement to the trough of the drainage ditch.

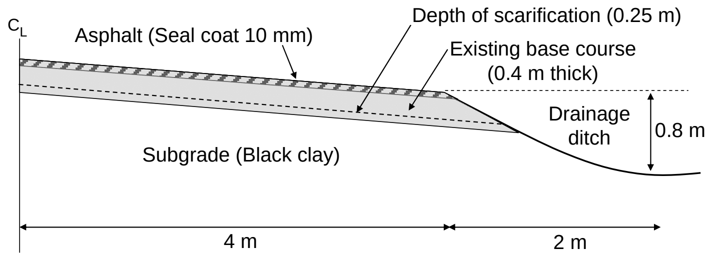


Figure 3. Original pavement cross-section at FM2 with scarification plan (not to scale)

After scarification, TxDOT decided to treat the soil with lime before re-compaction to provide a stiff foundation for the new flexible pavement. After scarification, lime treatment, and compaction of the existing base course, a layer of geogrid reinforcement was placed onto the road. This was followed by an additional 175 mm of compacted base course and a seal coat of asphalt. It should be noted that the existing subgrade was not included in the scarification or lime treatment plans, likely due to workability issues with the clay of high plasticity. Accordingly, the overall goal of the rehabilitation plan at FM 2 was to stiffen the road above the expansive clay subgrade. Of the possible mechanisms of geogrid reinforcement, the intention of using the geogrid in this rehabilitation was to prevent translation of volume changes in the subgrade into the base course. Construction occurred during the summer of 2005, and finished in Fall 2005.

The University of Texas at Austin proposed a modification to this rehabilitation program to by changing the type of geogrid at different sections, and by not using lime treatment in some of the sections. Specifically, eight test sections were proposed to investigate different types of geogrids and the use or not of lime stabilization, as summarized in Table 1. These test sections include an unreinforced section and three geosynthetic-reinforced sections. Geosynthetic types 1 and 2 are geogrids while geosynthetic type 3 is a woven geotextile. The eight pavement cross sections were repeated four times each (for a total of 32 sections) throughout the length of the road in order to account for changes in behavior due to location and environmental conditions (slope, soil conditions, vegetation). The location of the different pavement cross sections along the length of the road are shown in Figure 4. Moisture sensors were installed into the subgrade soil at several locations along FM 2 to monitor typical moisture migration patterns under the pavement and in the shoulders. This study focuses on the results from two vertical profiles of moisture sensors installed at Stations 199 and 184, and one horizontal profile installed at Station 84, as shown in Figure 4.

Table 1. Pavement cross-section descriptions in FM2 project

Pavement test section	Lime treatment*	Geosynthetic
1	Yes	No reinforcement
2	Yes	Geogrid 1
3	Yes	Geogrid 2
4	Yes	Woven geotextile
5	No	No reinforcement
6	No	Geogrid 1
7	No	Geogrid 2
8	No	Woven geotextile

* Lime treatment used for scarified pre-existing base course

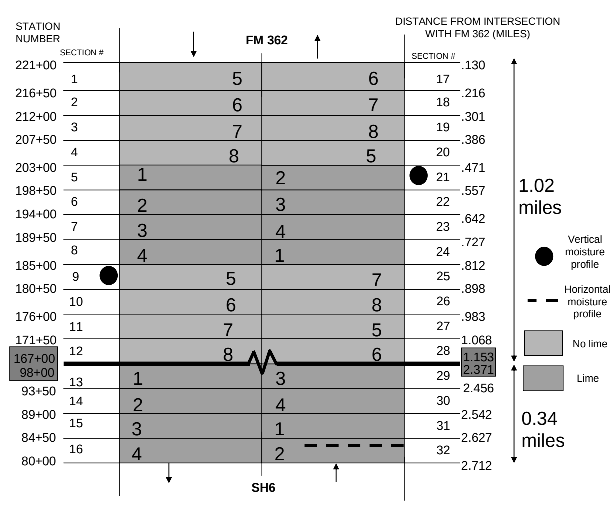


Figure 4. FM 2 layout with moisture sensor profile installation locations

2. MATERIALS

The clay subgrade at FM 2 varies along the four miles of pavement. Cores of the first 3 meters of soil were obtained at three locations. The thicknesses of the soil layers at the moisture sensor installations are shown in Figure 5(a). Two predominant clays were noted: a red clay with medium plasticity index (PI=35) and a black-gray clay with high plasticity index (PI=50). The black-gray clay is common in the Bryan district and is colloquially referred to as "Blacklands". At the end of the borings (around 3 meters) an intact sandy clay layer was collected. A survey was conducted to obtain an elevation profile of the pavement-shoulder surface at Station 199, as shown in Figure 5(b). The soil profile at this location is also included in this figure. The seal coat of asphalt extends to ±4.0 m and partially covers the run-out of the base course. Vertical profiles of the porosity of the black clay at Station 199 for two times during the year are shown in Figure 5(c). The average porosity (*n*) is 0.45 and the dry density (ρ_d) corresponding to this porosity is 1500 kg/m^3 (assuming that the soils are saturated and G_s = 2.7). A shrinkage curve was obtained for an intact core of the black clay, as shown in Figure 5(d). The shrinkage limit (SL) is 13.

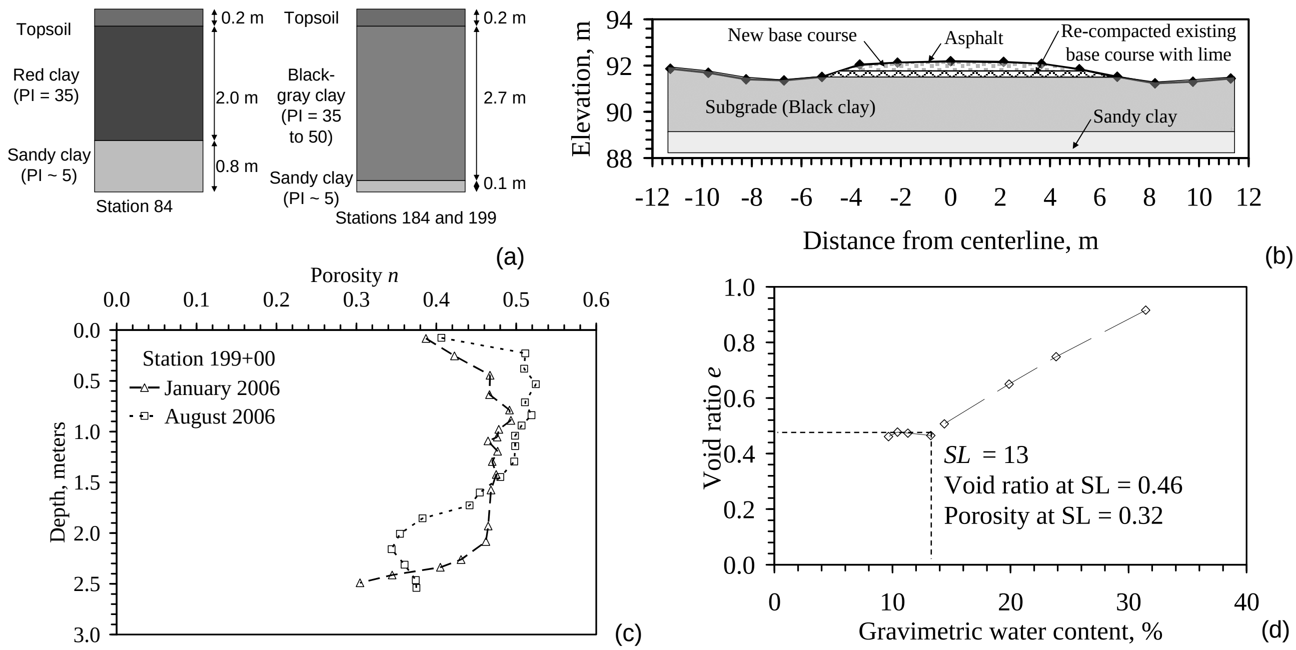


Figure 5. (a) Boring summary; (b) Elevation profile at Station 199; (c) Porosity profile; (d) Shrinkage curve

The travel time for moisture to pass from the shoulder to the center of the pavement can be estimated using the hydraulic conductivity of clay when saturated (K_s). The hydraulic conductivity of a core of the black clay (having a gravimetric water content *w* = 28% or porosity *n* = 0.43) was determined to be 7x10^{-10} m/s using a flexible wall permeameter. The hydraulic conductivity of the red clay remolded at its optimum water content is 5x10^{-9} m/s, about an order of magnitude more permeable than the black clay. The lower PI of the sandy clay indicates that it is more permeable than the overlying clays, indicating it may be a secondary boundary for moisture entry into the subgrade.

3. EQUIPMENT

3.1 Sensor Description and Calibration

ECH$_2$0 sensors, obtained from Decagon, Inc., were used in this study to infer the gravimetric water content at particular locations in the subgrade. These sensors consist of a capacitor circuit embedded within a protective resin. The sensors measure the time required for the capacitor to charge upon application of a potential difference (Decagon 2006). The soil acts as the dielectric material between the capacitor plates, so the time required to charge the capacitor is sensitive to the dielectric permittivity of the soil. Changes in the relative amounts of air and water in the soil during wetting and drying, as well as changes in density during shrinkage/swelling, result in changes in dielectric permittivity. The charge time of the capacitor is correlated in this study with the gravimetric water content of the soil, as this parameter is only sensitive to changes in the mass of water (assuming that the mass of solids is constant). Although the soil may be saturated during swelling, the mass of water will increase as the density increases. For a saturated soil, changes in gravimetric water content are directly proportional to changes in the void ratio. The ECH$_2$0 sensors have low power requirements compared to other moisture sensors (time domain reflectometry, neutron gauge), are relatively small, are inexpensive, and can be used with conventional dataloggers such as the Decagon EM50 or the HOBO dataloggers.

The procedures for installation were different for the horizontal and vertical arrays of sensors. The horizontal array was installed in compacted red clay, while the vertical arrays were installed in quasi-undisturbed conditions. Accordingly, the moisture sensors were calibrated for compacted red clay in the lab, and separately for the black clay in-situ. A barrel of red clay was dried in the lab and several 3 kg samples were conditioned to a range of gravimetric water contents expected in the field (5 to 25%). Specimens of the red clay were compacted to a dry density (ρ_d) of 1600 kg/m^3 in a rectangular mold sized to fit the sensor with 30 mm of clearance on each side. A piston compactor was used to control the energy imparted to the soil during compaction, and the moisture sensor was placed into the middle of three lifts. After compaction, a measurement was made with the moisture sensor. The relationship between the gravimetric water content of the red clay and the sensor reading is shown in Figure 6(a). In a strict sense, this calibration curve is valid for the unsaturated red clay at this particular dry density. Accordingly, it may not provide the exact water content for the clay after swelling or shrinkage occurs. Nonetheless, this calibration equation provides a first estimate of the water content in the subgrade. For the black clay, the sensor output was correlated with the gravimetric water content of a sample of soil obtained from the location at which the moisture sensor was installed, as shown in Figure 6(b). The average porosity and dry density from the borings that were conducted at the time of installation are also shown. A linear calibration equation was obtained for this soil, falling above the 1:1 line. The range in gravimetric water content of 29 to 41 shown in this figure reflects the initial gravimetric water content during installation of the moisture sensors. This calibration curve also includes data from sensors from arrays at other locations in the black clay that are not discussed in this paper.

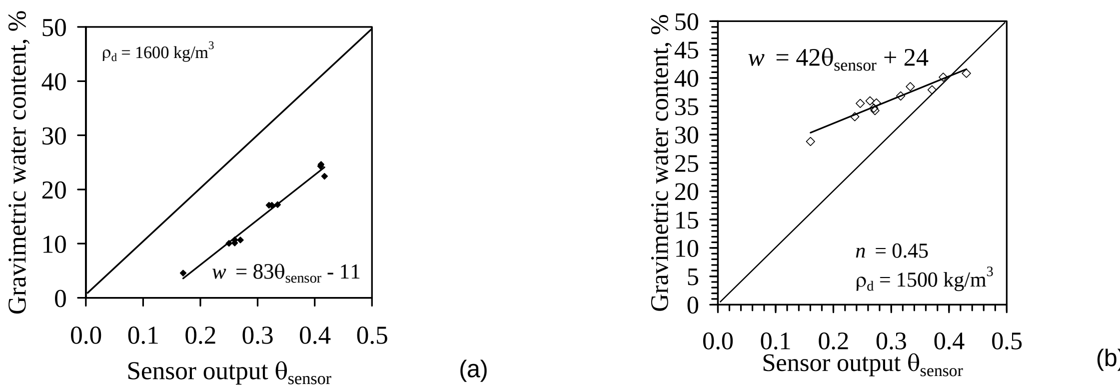


Figure 6. Moisture sensor calibration: (a) Calibration for remolded red clay; (b) Calibration for in-situ black clay

3.2 Moisture Sensor Installation

The pavement profile and horizontal sensor locations at Station 84 are shown in Figure 7(a), while those for the vertical profiles at Stations 184 and 199 are shown in Figures 7(b) and 7(c). The low hydraulic conductivity of the asphalt seal coat (<10^{-9} m/s) and the slope of the roadway indicate that rainfall onto the pavement will runoff into the drainage ditch, so it is considered impermeable. The drainage ditch is assumed to be the primary infiltration pathway into the subgrade. The horizontal array of sensors is useful to assess the movement of water under the road, while the vertical arrays are useful to assess moisture fluctuations in the soil profile without the influence of the pavement boundary.

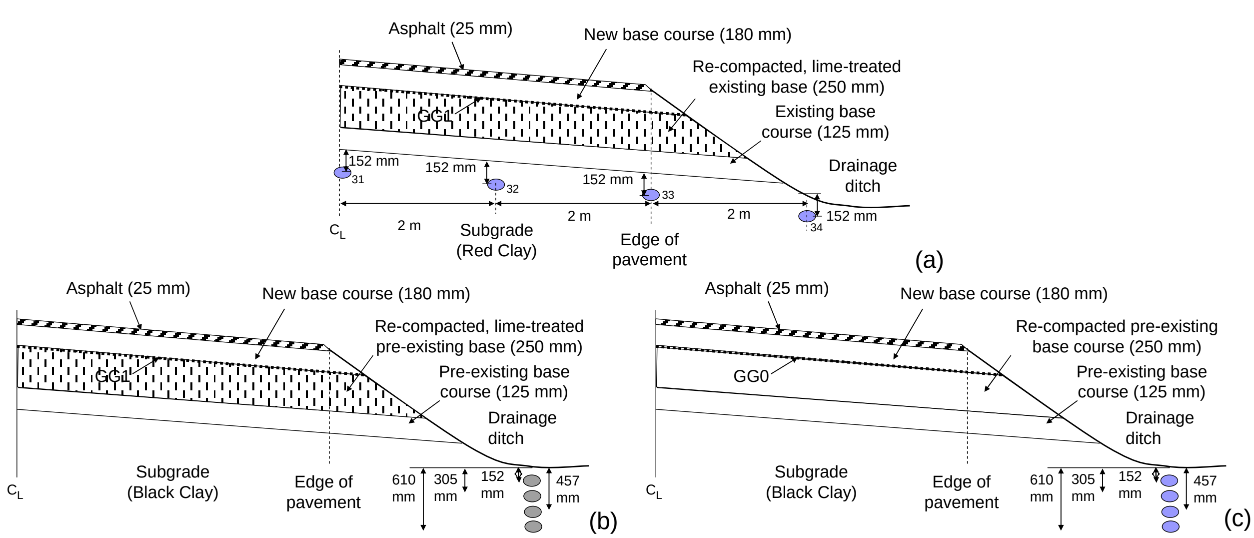


Figure 7. Sensors: (a) Horizontal array at Station 84; (b) Vertical array at Station 184; (c) Vertical array at Station 199

The moisture sensors in the horizontal array at Station 84 were installed in remolded soil (consistent with the calibration). For this location, a trench perpendicular to the direction of the road was excavated through one of the lanes using a backhoe [Figure 8(a)]. Care was taken to separate the base course and the subgrade for later replacement of the road section [Figure 8(b)]. The soil was leveled at the sensor locations [Figure 8(c)], the sensors were placed as indicated in Figure 7(a), and the subgrade was carefully backfilled around the sensors. The sensor cables were passed through a corrugated plastic tube to a mailbox containment system [Figure 8(d)]. The cables were connected to a datalogger inside the mailbox containment system for easy access [Figure 8(e)]. The moisture sensors in the vertical sensor arrays at Stations 184 and 199 were installed into intact soil by creating a pilot holed for the sensor. After digging a 0.75 m deep hole at the monitoring location, a saw blade was used to create a small slit into the soil using several blows from a rubber mallet [Figure 8(d) and 8(e)]. After carefully removing the saw blade, the moisture sensor was inserted into the slit, and soil was backfilled over the sensor end [Figure 8(f) and 8(g)]. The subgrade was then backfilled into the hole and compacted by hand using the hammer.

Figure 8. Moisture sensor installation procedures: (a) Trenching; (b) Separation of base and subgrade; (c) Leveling of installation site; (d) Protective tubing and datalogger containment system; (e) Datalogger; (f) Tools for pre-insertion of sensor; (g) Pre-insertion; (h) Installed sensor; (i) Compaction near sensor head

4. FIELD MONITORING RESULTS

4.1 Weather Data

Although the closest weather station to the site is at Hempstead, approximately 3 miles from the road, this weather station has only been in operation since January 2006. Accordingly, the historic weather patterns were obtained from a weather station located in College Station, which is also in the Bryan district of Texas. The monthly average records of temperature and precipitation for last 30 years in College Station (WSI Corporation 2005) are shown in Figure 9. The average high temperature was around 36 °C in August and average low temperature was 3 °C in January. The average annual precipitation was calculated to be 1013 mm, with high rainfall amounts in May, June, September and October. The site has two dry seasons in a year divided by two rainy seasons.

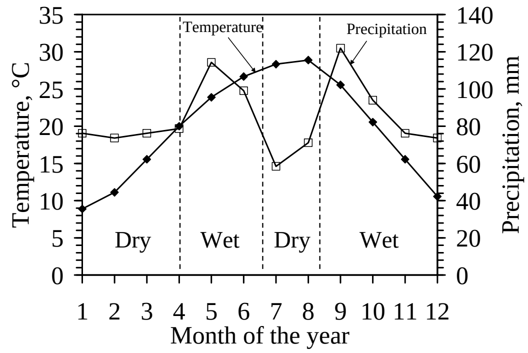


Figure 9. Average monthly climate data based on 30 years of weather records from College Station

Daily weather data from the station in Hempstead, TX was more useful for day-to-day assessment of the environmental conditions at the FM2 site. The precipitation is shown in Figure 10(a). This figure indicates that periods of intense rain occurred between October and February of 2006, while periods of little rainfall were observed in the late spring and late summer. This is consistent with the pattern of two wet and two dry seasons shown in Figure 9. The temperature and relative humidity at Hempstead are shown in Figure 10(b). This figure indicates that the relative humidity fluctuates between 50 and 92%, while the temperature ranges from 0 to 31 °C.

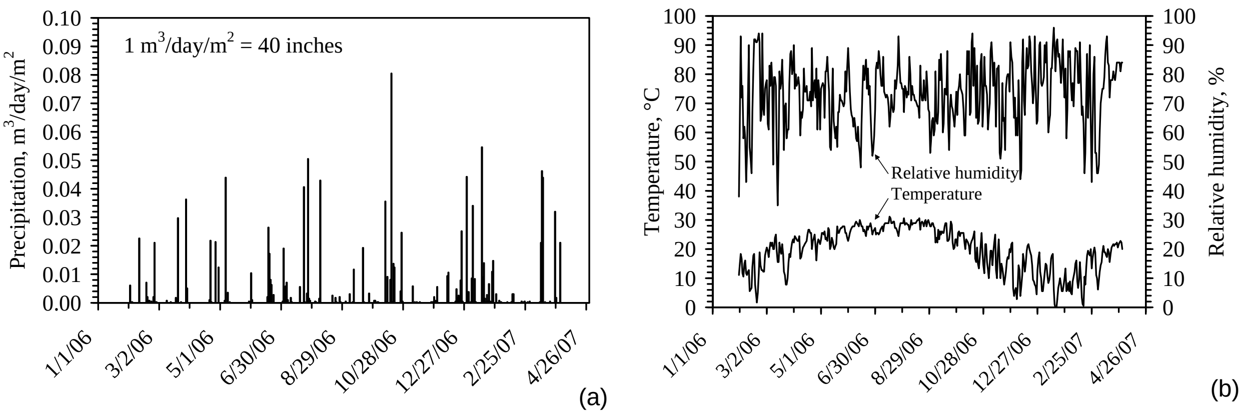


Figure 10. Weather data at Hempstead: (a) Precipitation data; (b) Temperature and relative humidity data

4.2 Gravimetric Moisture Profiles from Borings

The samples obtained from split-tube samples during the borings were used to determine the in-situ water content profiles at different times of the year. The gravimetric water content profiles at the times of two different borings are shown in Figure 11(a) and 11(b) for Stations 184 and 199. The soil has a relatively dry surface layer (with w < SL), likely due to the onset of a dry period. However, the gravimetric water content values deeper in the profiles from January 2006 are representative of relatively dry conditions, while the profiles from August are representative of relatively wet conditions. However, the gravimetric water content difference is not significantly different for the two periods.

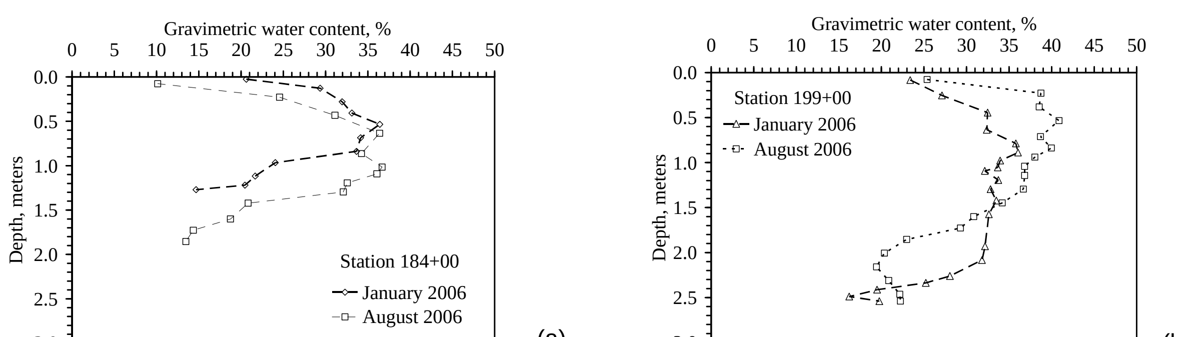


Figure 11. Gravimetric water content profiles from the boreholes: (a) Station 184; (b) Station 199

4.3 Horizontal Moisture Profile Results from Sensors

The monitoring results for the horizontal array at Station 84 are shown in Figure 12(a). The installation time for Station 84 was May 26, 2005, which was before the roadway had been rehabilitated (construction finished in fall 2005). The datalogger did not start working consistently until July 28, 2005 due to an issue with the batteries. Discussion with the site operators indicates that the site was relatively dry during construction in the summer of 2005. This dry period is reflected in the significant drop in gravimetric water content measured by Sensor 34 in the drainage ditch. The shrinkage curve for this soil was not obtained, but a gravimetric water content of 20% during this dry period is likely close to the shrinkage limit. After December of 2005, the moisture sensor 34 in the ditch showed significant fluctuations in water content, ranging from 16% to 46%. However, the water content inferred by the three sensors under the road was about 30% and did not fluctuate. A slight increase in water content was observed by the sensors under the pavement, likely due to spatial equilibration of gravimetric water content after construction. Despite the difference in moisture fluctuations between the subgrade in the drainage ditch and that under the pavement, no longitudinal cracks have been observed to date. This location is geogrid-reinforced, and the base course is lime treated, so the pavement is relatively stiff. As the soil at this location is relatively wet under the pavement, an extended dry period would be required to cause different movement. However, there has not been an extended dry period in the time since construction.

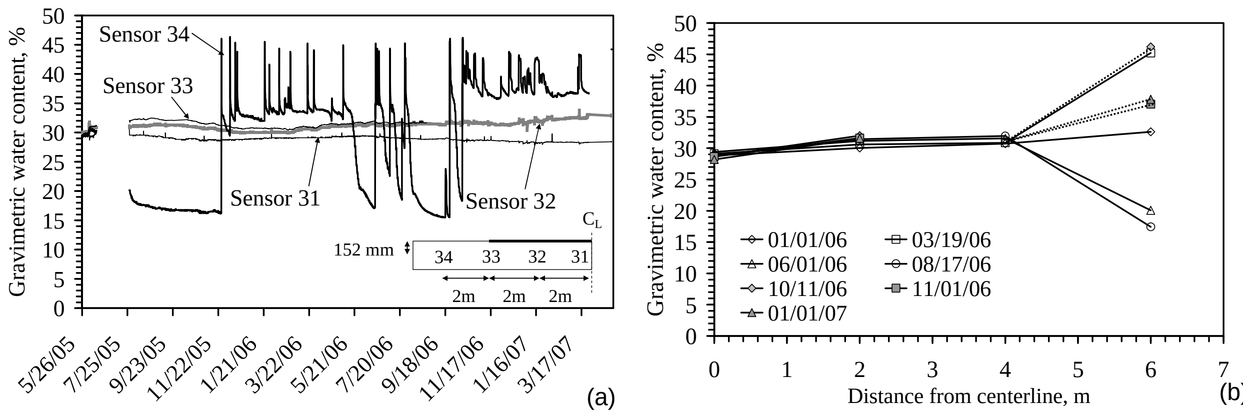


Figure 12. Moisture data for Station 84 (red clay): (a) Time series for each sensor; (b) Horizontal moisture isochrones

A comparison between the precipitation and the gravimetric water content at the shoulder of Station 84 is shown in Figure 13. The spikes in water content in the clay in the drainage ditch are generally consistent with the timing of rainfall events at Hempstead (5 miles from FM2), although there are some obvious inconsistencies (10/20/2006). There was a dry period in the summer of 2006 during which the soil dried, but the rest of 2006 and 2007 were relatively wet.

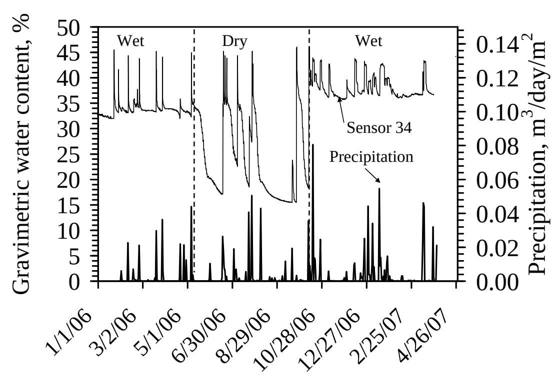


Figure 13. Comparison between gravimetric water content in the drainage ditch with precipitation (Station 84)

4.4 Vertical Moisture Profile Results from Sensors

Horizontal moisture sensor arrays were also installed under the road at several other locations, but the installations were damaged by lawnmowers and rodents. Accordingly vertical arrays of sensors were installed in the drainage ditch at Stations 184 and 199 one year after the installation of the sensors at Station 84. These installations were installed to infer the range of water contents in the field, as well as the rate of movement of wetting or drying fronts in the subgrade under the shoulder. The time series for the sensors at Station 184 are shown in Figure 14(a), and vertical moisture profiles at different times are shown in Figure 14(b). The water content at this location was observed to vary between

26% and 43%, consistently above the shrinkage limit (13). In particular, the sensor at 610 mm routinely showed an increase in water content of 5% in the period of 2-3 days. Using the saturated hydraulic conductivity (k_s) obtained in the laboratory, this travel time is associated with a gradient of 3400 [$i = d/(k_s t)$]. This high gradient is due to wetting of a relatively dry soil. A longer time is required for the soil to dry than to wet, as the hydraulic conductivity of unsaturated soil is less than saturated soil, and as the gradient due to evapotranspiration is lower than that associated with wetting of a dry soil. The surface of the soil shows a wider variation in water content than deeper in the profile. This location has no shade from trees, so dry conditions are expected.

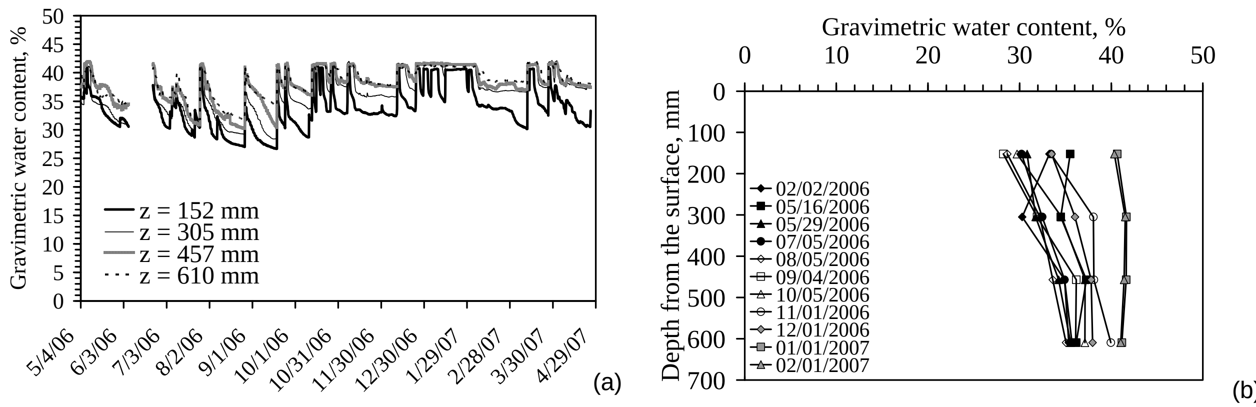


Figure 14. Gravimetric water content data for Station 184: (a) Time series for each sensor; (b) Isochrones

The gravimetric water content time series for the vertical array of sensors at Station 199 is shown in Figure 15(a), and selected moisture profiles are shown in Figure 15(b). All the sensors showed similar trend in gravimetric water content with time. The gravimetric water content was observed to vary between 30% and 43%. This location is shaded by trees, and ponded water was routinely observed during most field trips to the site, which indicates why the subgrade in the drainage ditch did not reach as low of gravimetric content values as that at Station 184.

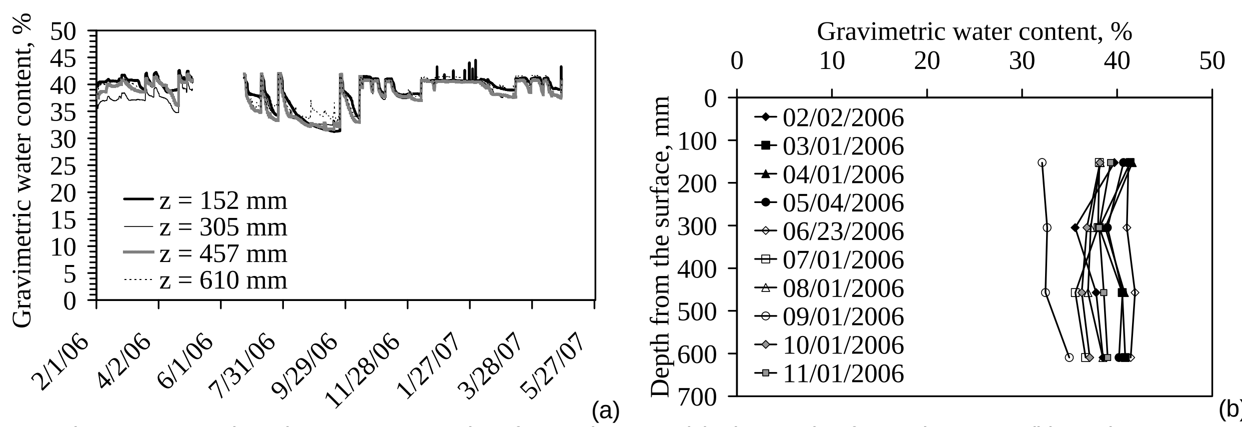


Figure 15. Gravimetric water content data for Station 199: (a) Time series for each sensor; (b) Isochrones

The daily changes in gravimetric water content for Stations 184 and 199 are shown in Figures 16(a) and 16(b). Positive increases in water content of 14% were observed during the course of a day, during heavy rainfall (with ponding) occurring after a dry period. However, significant negative changes in gravimetric water content are less likely (*e.g.*, less than 3% changes in water content were observed in a day) due to the lower hydraulic conductivity of unsaturated soils.

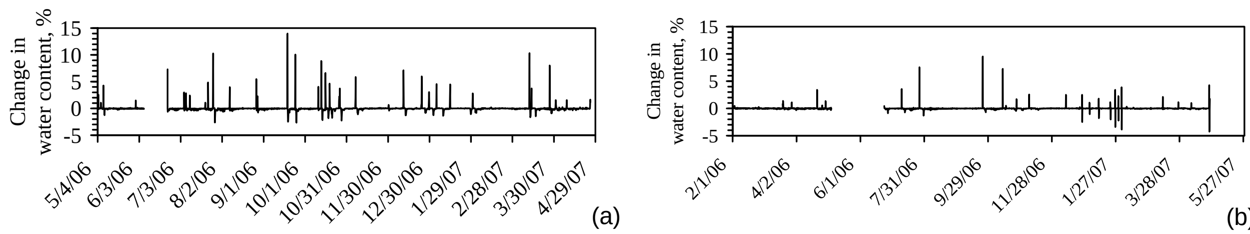


Figure 16. Change in water content of the surface sensor (152 mm): (a) Station 184; (b) Station 199

A comparison between the gravimetric water content measured by the sensors closest to the ground surface in the drainage ditch at Stations 84 and 199 is shown in Figure 17. The timing of the changes in water content is similar for the two sites, despite the different soil types. The magnitude of moisture variation is similar for the two sites, with large changes in gravimetric water content occurring over the period of several days.

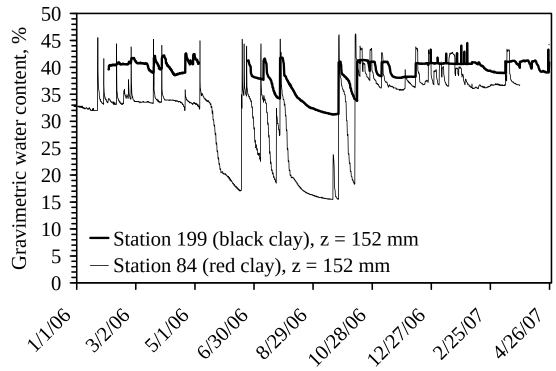


Figure 17. Comparisons between surface gravimetric water content measurements in the drainage ditch

5. IMPLICATIONS OF RESULTS ON GEOGRID REINFORCEMENT OF EXPANSIVE SUBGRADES

The gravimetric water content measurements indicate that moisture fluctuations can occur rapidly during wetting of clays of high plasticity. However, the results indicate that moisture migration is negligible from the drainage ditch to the center of the pavement due to the limited pathways for moisture migration. In fact, the fluctuations in gravimetric water content were not even observed under the edge of seal coat of the pavement. Due to the contrast in water content fluctuations from the shoulder of the road to those made under the road, a differential change in volume can be expected. The location of the changes may have implications on the application of geogrid reinforcement in expansive subgrades. Geogrid reinforcement can be used to increase the stiffness of the soil near the edge of the pavement, with the goal of withstanding volume changes in the subgrade during moisture fluctuations. The geogrid should extend into the shoulder of the pavement to prevent the shoulder from pulling the pavement apart laterally. The geogrid may also provide increased tensile stress to the neutral axis of the pavement upon bending.

6. CONCLUSIONS

This study summarized moisture monitoring results in the subgrade under an instrumented highway in Eastern Texas, with the goal of investigating the mechanisms of longitudinal cracking in expansive clay subgrades. The moisture sensors used in this study were found to work well in the harsh environment of a pavement subgrade (high temperature, high compaction strain, volumetric changes), and were inexpensive enough to permit replacement if damaged by straining or animals. Field measurements of gravimetric water content indicate that moisture fluctuations occur primarily in the drainage ditch adjacent to the pavement. However, little moisture migration was observed from the shoulder to the center of the pavement. Although structural damage has not been observed in the pavement in the year and a half of service, the moisture trends support the phenomena of differential volume change as the cause of longitudinal cracking.

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