Monitoring of Moisture Fluctuations in a Roadway over an Expansive Clay Subgrade

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ABSTRACT

An expansive subgrade beneath a newly constructed roadway in Central Texas was instrumented using volumetric moisture content and matric suction sensors. Sensors were installed during construction, facilitating an evaluation of the hydraulic behavior in the subgrade beneath a temporary flexible base with a prime coat and a final asphalt surface. Monitoring indicated that the two surfaces had differing hydraulic boundary conditions. The asphalt surface acted as an impervious layer that reduced the infiltration of moisture into the subgrade, while the flexible base surface did not appear to provide a hydraulic barrier and allowed for more rapid moisture fluctuations through the entire subgrade. Additionally, monitoring of the pavement surface via total station surveying verified this behavior with the profile of the roadway undergoing differential movement at the edge for the asphalt surface but not for the flexible base surface. Overall, the hydraulic moisture fluctuations of the subgrade were affected by the different pavement surfaces, and total station technology was able to characterize the surficial profile movement.

INTRODUCTION

Expansive subgrades have shown to be particularly problematic for flexible pavements as environmental conditions, such as the heave and settlement of the pavement edges due to seasonal moisture fluctuations, can cause significant longitudinal cracking. This issue is of major concern along the I-35 corridor between Dallas and San Antonio due to the abundance of expansive soil deposits. Pavement design in Texas has conventionally relied on an index, the Potential Vertical Rise (PVR) as outlined in McDowell (1966), which estimates volumetric change based on a soil's Atterberg Limits. More recent guidelines in the mechanistic-empirical pavement design guide (MEPDG) call for the use of water-flow analysis to account for changes in mechanical behavior with changes in volumetric moisture content. However, these analyses require proper understanding of how moisture content and matric suction vary seasonally, and few studies exist that examine these seasonal changes. One field study involved continuous monitoring of gravimetric moisture content fluctuations and periodic monitoring of matric suction fluctuations close to the shoulder of a roadway near Houston, TX (Puppala et al., 2011). Climatic conditions, particularly surface evaporation and average monthly rainfall during the summer months, vary significantly between Houston and Central Texas. Therefore, a field examination of moisture content and suction fluctuations in Central Texas is needed to further understand expansive subgrade behavior in relation to pavement design.

The hydraulic properties of a roadway's upper pavement layer are an important input for modeling moisture flow beneath pavements (Hansson et al. 2005). Asphalt surfaces are assumed to be impermeable and hydraulically passive without cracks, but the properties for the unbound road material and fractures, or cracking, in the roadway are necessary to adequately model moisture fluctuations beneath pavement structures. Both asphalt and flexible base materials are used as surfaces for roadways in Texas, either as a temporary or final finished pavement surface. Consequently, a study to examine how each material affects the seasonal fluctuations in expansive subgrades would be particularly beneficial.

Lastly, examinations of the relationship between moisture fluctuations and roadway performance have been limited in field studies. One method involved the use of a non-prism total station to periodically measure the profile of a roadway (Roodi et al., 2016). With this technology, a visual representation of the heave and settlement of the pavement edges was obtained during regular field visits. However, the study did not examine how moisture fluctuations in the subgrade affected the surface of the roadway, as sensors were not installed at each field site. A study was therefore conducted to correlate the performance and profile of a pavement structure with moisture fluctuations in the subgrade material.

SITE LOCATION AND CHARACTERIZATION

The field site was located on a Farm-to-Market road approximately 25 miles northeast of Austin, Texas. Roadway construction consisted of repaving and expanding the road, as well as the construction of numerous driveways connected to the road. A location beneath one of these driveways was selected for moisture monitoring because it was deemed as the worst-case scenario for pavement performance against environmental conditions, with only a thin asphalt layer and a lack of geo-grid reinforcement in the base. The construction schedule for the driveway consisted of a year in which a temporary flexible base surface was placed and sealed with a prime coat followed by the placement of the final asphaltic surface. This variation in surface material provided a comparison of the hydraulic behavior of the underlying subgrade with differing pavement surfaces. The pavement structure consisted of 2 in. (5.1 cm) of asphalt underlain by 5 in. (12.7 cm) of flexible base material. The subgrade consisted of approximately 5 ft. of an expansive clay, the Branyon clay as identified by USDA soil surveys, underlain by a tan clay. Bulk samples of the soils were taken and characterized for their Atterberg Limits, according to ASTM 4318, and grain-size distributions via wet sieving and hydrometer testing, according to ASTM D422. Results from this characterization are shown in Table 1. According to the USCS classification system from ASTM D2487, the Branyon clay is classified as a fat clay (CH), and the underlying tan clay is classified as a lean clay (CL).

Table 1. Summary of subgrade properties

Soil	Liquid Limit	Plasticity Index	Fines Content (%)	Clay Content (%)
Branyon Clay	65	34	93	55
Tan Clay	36	17	94	52

A centrifuge-based swelling methodology, developed at the University of Texas at Austin and outlined in Zornberg et al. (2017), was used to characterize the subgrade's swelling potential. Tests were performed at a dry condition, three percentage points dry of the optimum gravimetric moisture content and at the maximum dry density estimated using correlations from the U.S. Navy Design Manual (1962). This correlation resulted in an initial volumetric moisture content of 0.310. Strains at the end of primary swelling from testing on both soils and the swell-stress curve for the Branyon clay are shown in Figure 1.

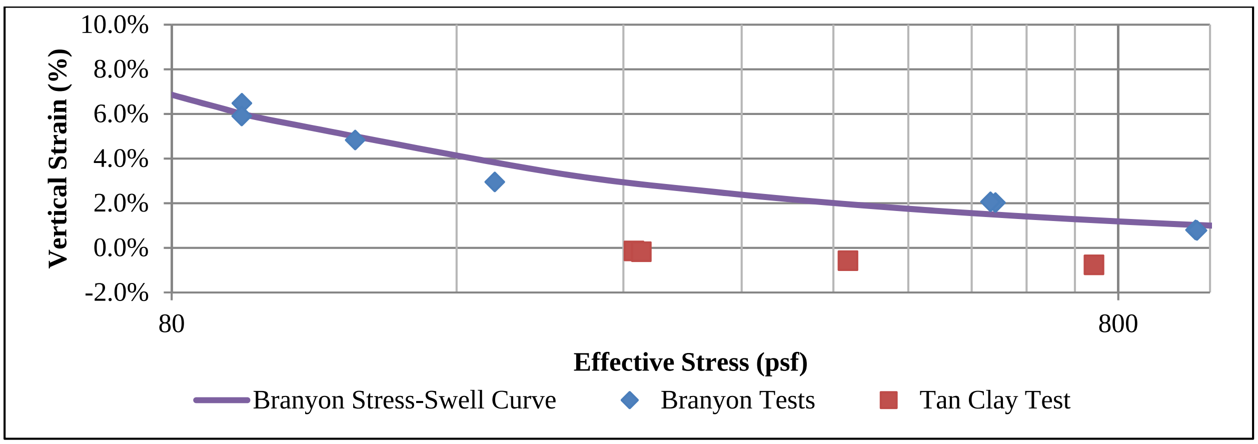

Figure 1. Swelling test results for subgrade soils

Swelling test results indicated that the tan clay experienced negligible strain upon wetting. By integrating the Branyon clay's swell-stress curve across the range of stresses from the top of the subgrade to the tan clay, the potential vertical rise of the deposit was calculated as 1.76 in. (4.47 cm), indicating that the driveway would experience heave during seasonal moisture fluctuations.

HYDRAULIC MONITORING OF THE SITE

Hydraulic monitoring of the subgrade at the site involved the use of Decagon 5TE capacitance moisture sensors and MPS-2 water potential sensors. The moisture content sensors use an oscillator at a fixed frequency to measure the dielectric permittivity of the soil and calculate the corresponding volumetric moisture content using Topp's equation. Because the temperature of the surrounding soil affected the reading, a linear correction was applied to the sensors using the method outlined in Kocarek and Kodesova (2012). The water potential sensors use a ceramic disk that comes into hydraulic equilibrium with the surrounding soil matrix and calculates the matric suction using the calibrated soil-water retention curve of the ceramic disk. The range of the water potential sensors was 25% of the reading, plus 2 kPa for the range of -9 to -100 kPa. Because the suction sensors need to come into hydraulic equilibrium, the sensors were found to operate best upon drying of the soil. Both sensors were connected to data loggers that recorded readings every 30 minutes.

Site monitoring was separated into two time periods: one starting in January 2016, after the flexible base with a prime coat was placed as the temporary surface of the roadway, and the other starting in December 2016, after the asphalt surface was placed. Sensors were placed at depths of 0.5 ft. (0.15 m), 1.5 ft. (0.46 m), and 4 ft. (1.37 m) below the subgrade-base interface in the Branyon clay and at a depth of 5.5 ft. (1.68 m) below the subgrade-base interface in the tan clay. The sensors were placed in a cut used for the installation of a drainage culvert and were located approximately 1 ft. (0.30 m) horizontally away from the subgrade-culvert interface. The sensor locations are shown below in Figure 2 for both the flexible base and final asphalt surfaces. Note that the approximate location of the vertical array of sensors is shown via an orange dot in Figure 2a and 2c.

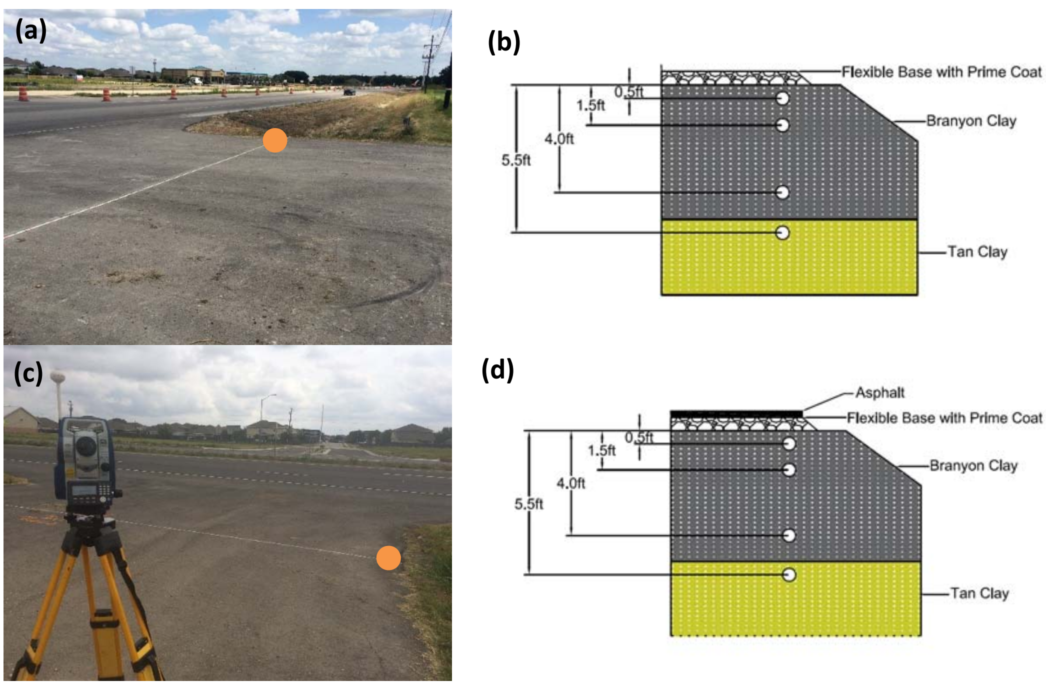

Figure 2. FM 685 site: (a) Pavement with flexible base surface, (b) Site layout for flexible base surface, (c) Pavement after asphalt placement, (d) Site layout for asphalt surface

Volumetric moisture content fluctuations and dates are shown in Figure 3, with a black line delineating the two time periods. Note that z in the following figures indicates the depth below the base-subgrade interface. Additionally, the precipitation data at the site, taken from a nearby weather station, is shown in Figure 4 for the duration of monitoring.

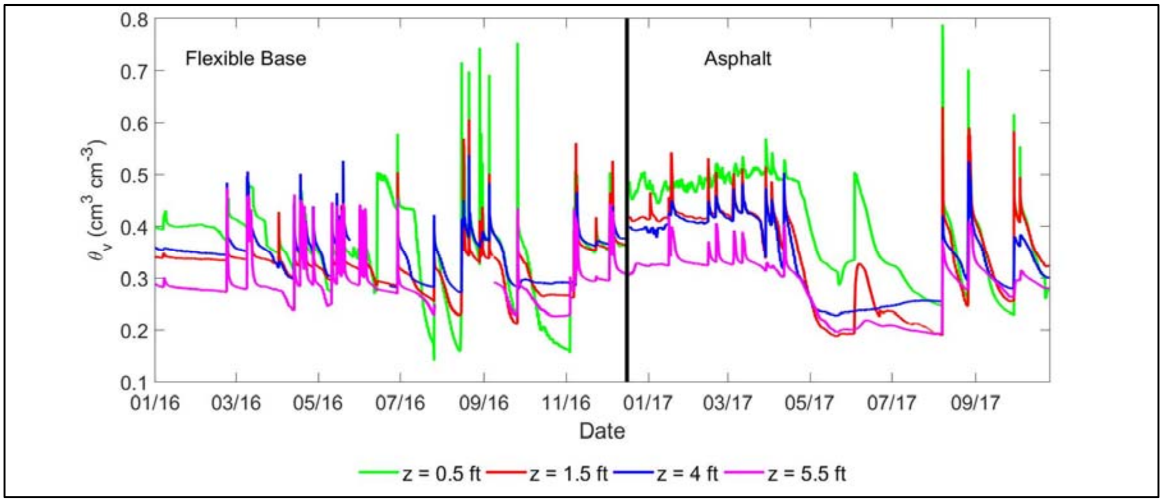

Figure 3. Subgrade volumetric moisture content fluctuations

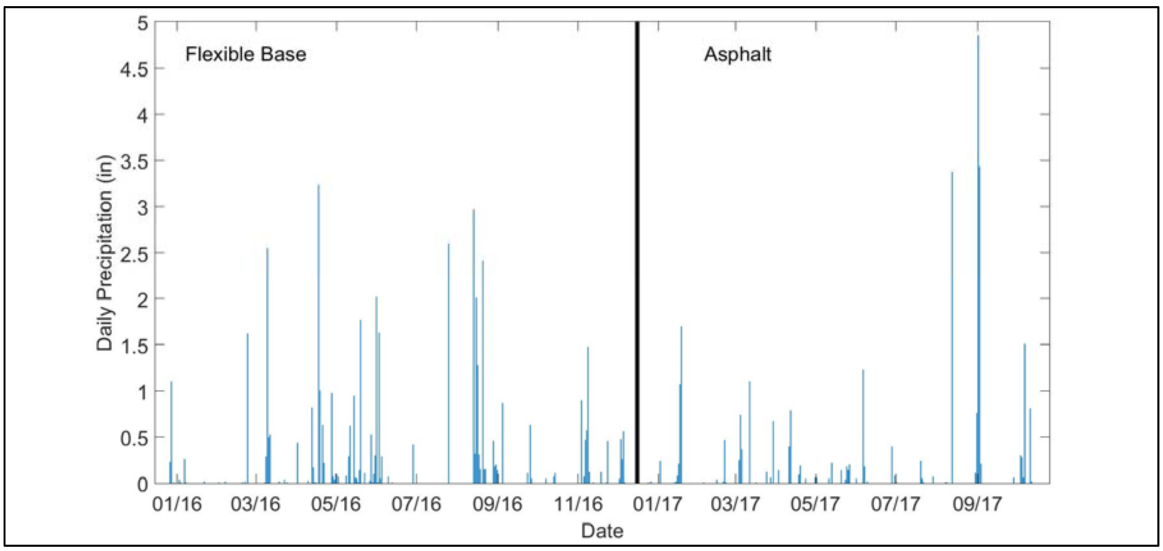

Figure 4. Precipitation data at site

Several important conclusions can be drawn from the monitoring of the volumetric moisture content. Prior to the asphalt placement, the soils wetted and dried rapidly. This rapid fluctuation of moisture is attributed to the prime coat not appearing to provide a hydraulic barrier. Rainfalls of less than 1 in. (2.54 cm) were shown to wet the entire portion of the Branyon clay as seen in June 2016. Following the asphalt placement, drying of the soil occurred over a longer time frame, and the sensors at depth did not show the same moisture fluctuations under lower rainfall events, as seen in May 2017. The upper sensor did show instability in its readings following the placement of the asphalt until April 2017. Additionally, the soil became drier than the condition prescribed for centrifuge testing under both pavement conditions. Based on the results, the change in the upper boundary condition affected moisture fluctuations in the subgrade. Fluctuations in matric suction are shown in Figure 5.

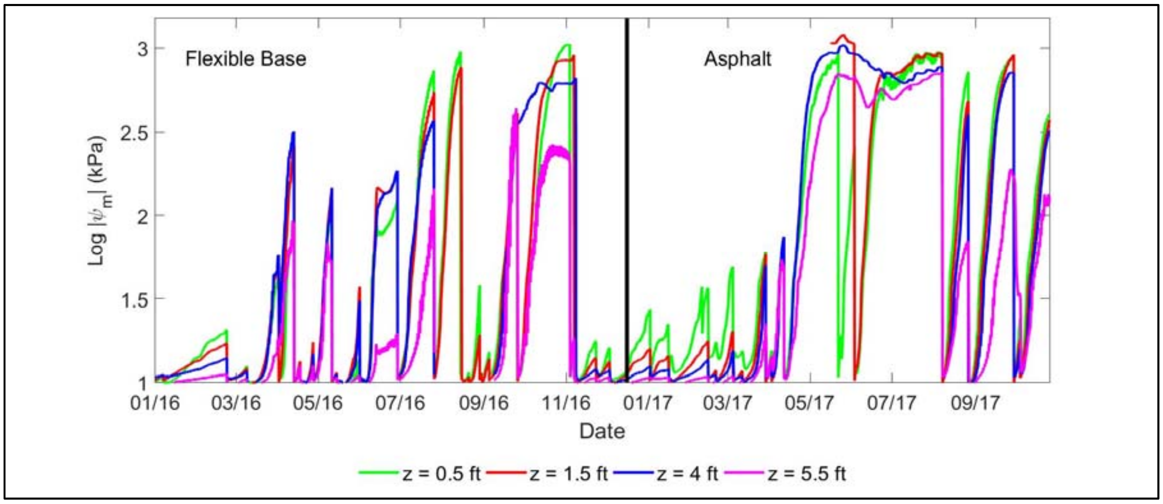

Figure 5. Subgrade matric suction fluctuations

Matric suction fluctuations, however, did not show as significant of a difference between the two time periods. While the sensors experienced problems recording readings near saturation, they performed well during drying periods. During the time flexible base time period, the matric suction sensors tended to increase at a differing rate during the winter months but at a similar rate during the rest of the year for the sensors in the Branyon clay. As with the moisture content fluctuations, the matric suction tended to drop uniformly with the advancing moisture front during the flexible base period, apart from rainfall in September 2016. After the placement of the asphalt, similar trends were seen with the rate of drying differing between the winter and rest of the year and with the maximum matric suction in the deposit. However, there were more rainfall events which didn't saturate the deposit, including a partial saturation event in June 2017. As such, the trends were not as distinct as the moisture content's trends for the matric suction fluctuations between the two time periods.

To further determine the differences in the surficial boundary, individual rainfall events were examined. Rainfall events with similar environmental conditions, i.e. temperature and relative humidity, were selected for each pavement surface during the drying phase. Moisture fluctuations recorded during these events beneath the flexible base surface and asphalt pavement surface are shown in Figure 6. Note that the cumulative and maximum precipitation rates, as taken from a nearby weather station, were 0.83 in. (2.10 cm) and 0.65 in./hr. (1.65 cm/hr.) for the flexible base surface and 1.23 in. (3.12 cm) and 0.71 in./hr. (1.80 cm/hr.) for the asphalt surface. Rainfall lasted approximately an hour for the flexible base case and two hours for the asphalt case.

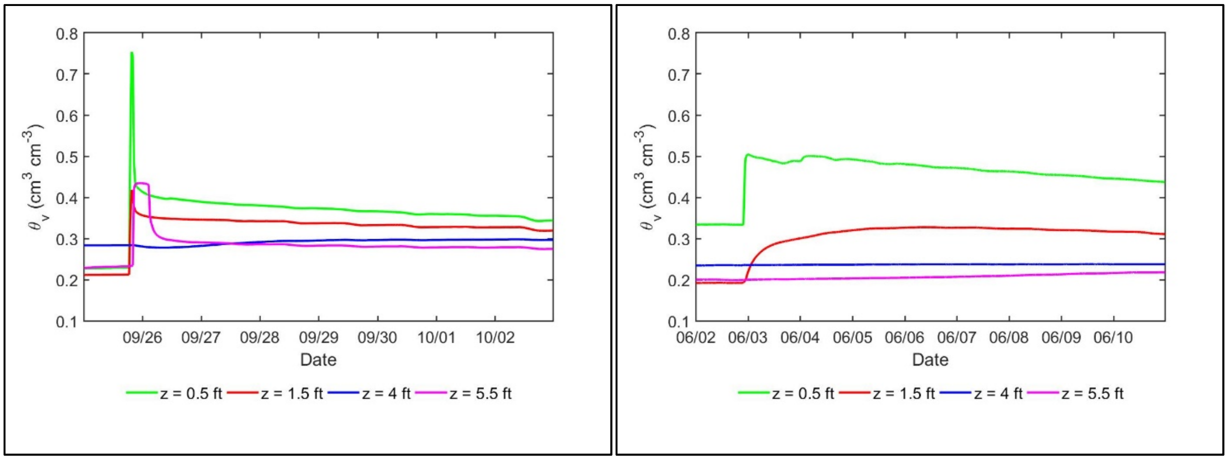

Figure 6. Subgrade moisture fluctuations during a rainfall event for a flexible base surface (left) and asphalt surface (right)

Both rainfall events had the moisture front reach the upper sensor in the deposit soon after the beginning of rainfall. However, the moisture infiltration during the flexible base time period was able to permeate through to a depth of 1.5 ft. rapidly, and the sensor in the tan clay was also wetted. This wetting of the tan clay may be due to the complex geometry of the site next to the culvert structure and the exposure of the tan clay in the drainage ditch. The bottom Branyon clay sensor was only partially wetted during this time, but the response was seen within a day of the rainfall event. For the rainfall over the asphalt surface, the moisture front took a longer time to permeate through the subgrade with the sensor at a depth of 1.5 ft. showing only a partial wetting and the bottom Branyon clay sensor not showing a response. This difference is attributed to the asphalt surface acting as an impervious barrier with more runoff occurring at the surface. While the upper sensor was initially wetter for the asphalt case, these trends were additionally seen in other rainfall events in which the upper sensor was in a drier condition.

Trends in both the overall and rainfall events hydraulic monitoring indicated that the asphalt surface is an impervious cover for the subgrade. Conversely, the flexible base surface with a prime coat does not appear to provide a hydraulic barrier to the underlying subgrade.

MONITORING OF PAVEMENT DEFORMATION

The roadway surface was monitored via total station survey and a technique outlined in Roodi et al. (2016). A line was painted as a target above the approximate locations of the sensors in the deposit, at a horizontal spacing of 1 ft. (0.30 m) at the edges and 2 ft. (0.61 m) in the middle of the roadway. A non-prism total station was used to measure deflections at each target in the roadway during regular site visits, which in turn were turned into profiles normalized by the centerline’s elevation. Three site visits occurred while the flexible base was the temporary roadway surface, and four additional visits occurred after the asphalt surface was paved.

The volumetric moisture content at depth for each visit with the flexible base surface is shown in Table 2. Roadway profiles taken while the flexible base was the surface are shown in Figure 7. Note that the instrumented portion of the roadway lies on the right side of the figure.

Table 2. Volumetric moisture content at depth for surveying over flexible base surface

Date	0.5 ft	1.5 ft	4.5 ft	5.5 ft
6/9/2016	0.316	0.315	-	0.288
11/15/2016	0.367	0.358	0.369	0.299
12/8/2016	0.368	0.370	0.385	0.318

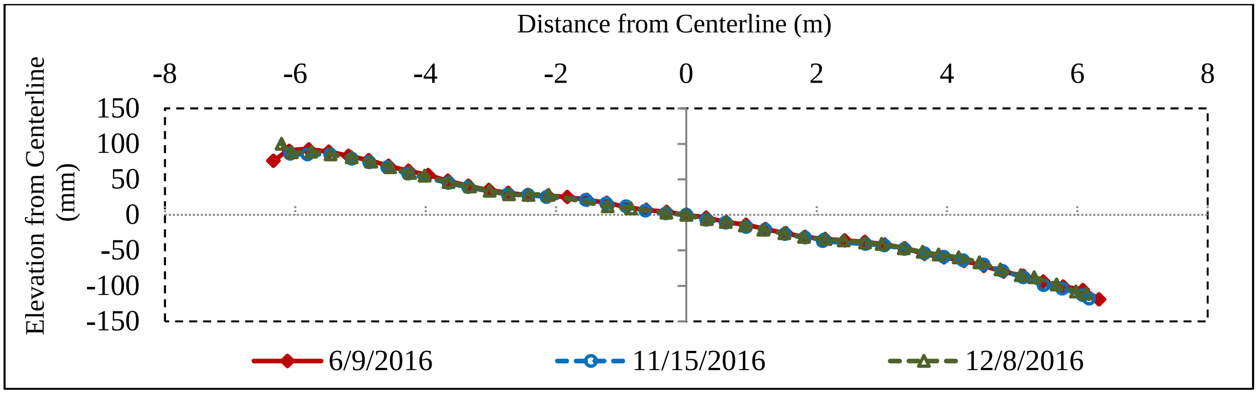

Figure 7. Flexible base pavement profile over time

During both the summer and winter monitoring, the profile of the roadway is consistent. There does appear to be a heave of approximately 25 mm (1 in.) during the December reading, but this may be a misreading as a heave was not observed under the instrumented section. These results indicated that the profile of the roadway did not change upon different moisture conditions in the subgrade beneath the flexible base surface. A potential explanation for this behavior stems from flexible base not appearing to perform as a hydraulic barrier, allowing for moisture to infiltrate throughout the entire deposit. If the entire deposit was undergoing similar moisture fluctuations, differential movement between the centerline and edges would not have been evident.

Monitoring of the roadway profile after the asphalt pavement differed from the flexible base performance. The first visit occurred at the end of spring in May 2017 during which the soil was drying out. The second visit took place approximately two weeks after the rainfall event from Figure 6. The third visit took place in July 2017 during the drying of deposit. The final visit took place at the end of August 2017 following a period of five days with a cumulative precipitation of 9.38 in. (23.83 cm). Table 3 has the moisture content data at depth for each of the site visits, and Figure 8 shows the profile of the instrumented edge of the profile. Note that the profile of the roadway did not show significant fluctuation in its profile away from the edges of the pavement.

Table 3. Volumetric moisture content at depth for surveying over asphalt surface

Date	0.5 ft	1.5 ft	4.5 ft	5.5 ft
5/17/2017	0.316	0.191	0.230	0.203
6/15/2017	0.388	0.271	0.239	0.217
7/13/2017	0.285	0.213	0.254	0.201
8/29/2017	0.428	0.434	0.408	0.385

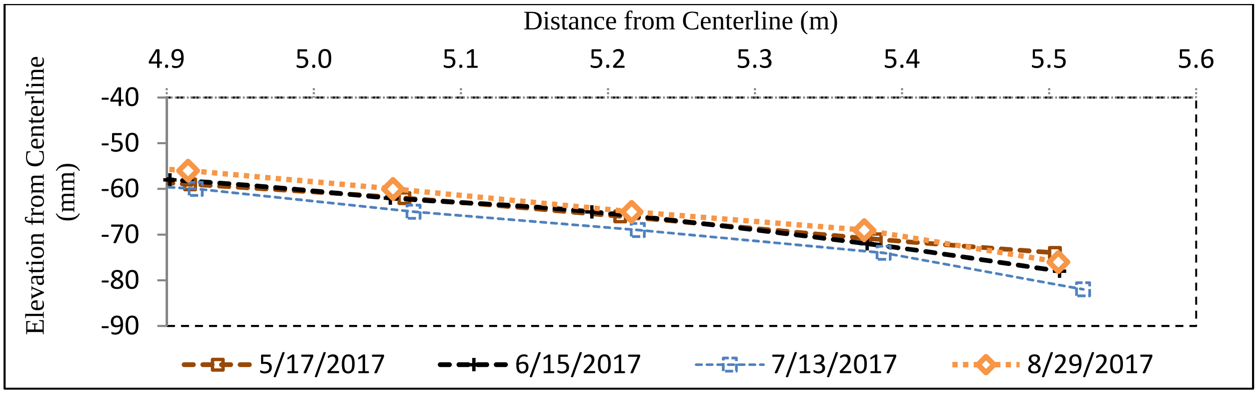

Figure 8. Profile of south edge of roadway after asphalt placement

Unlike the flexible base surface, the profile of the asphalt surface shows significantly more fluctuation during both drying and wetting. A settlement of approximately 10 mm (0.4 in.) was measured between the relatively wetter profile of May 2017 and the dry month of July 2017, corresponding with a drier upper portion of the deposit from Table 3. This upper region sees a higher amount of fluctuation due to the lower overburden stress. Between the July and August readings, the heavy rainfall translated into a significant amount of heave at the edge of the roadway. These height fluctuations are typical of roadways on an expansive deposit, leading to longitudinal cracking near the edges. Note that the profile of the roadway differed between the wetting and drying periods with a steeper slope found on the outer 0.1 m of the roadway during the drying period. While cracking did not occur over the observed timeframe, this location is within the typical location in which environmental cracks would be expected.

CONCLUSIONS

To understand moisture fluctuations in expansive subgrades beneath pavement structures in Central Texas, a field site was instrumented with moisture content and matric suction sensors beneath a temporary flexible base and final asphalt pavement and monitored continuously to evaluate its hydraulic behavior. Examining different surface materials at this field site revealed changes in the hydraulic behavior of the underlying subgrade material under different pavement surfaces and how this behavior affects the roadway profile.

For the hydraulic behavior, the two surfaces influenced the wetting and drying of the subgrade. The flexible base surface exhibited behavior that allowed for moisture to quickly permeate through the entire deposit. The asphalt surface did see moisture infiltrate to the upper portion of the deposit, but the moisture front did not always permeate through the entire deposit. These results indicate that the asphalt cover acted as an impervious barrier that had more runoff whereas the flexible base surface did not appear to form a hydraulic barrier. Results from the matric suction sensors were not as distinct between the two time periods, however.

The roadway profile was tracked during regular field visits via non-prism total station surveying equipment. The flexible base surficial profile showed that it remained relatively similar during wetting and drying months. The asphalt surficial profile indicated that there was differential settlement and heave that matched the hydraulic history of the site. Overall, the results of this study demonstrated the subgrade's hydraulic fluctuations varied between the two differing pavement surfaces which was seen in the surficial pavement performance.

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