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EVALUATION OF VERTICAL DEFLECTIONS IN GEOSYNTHETIC REINFORCED PAVEMENTS CONSTRUCTED ON EXPANSIVE SUBGRADES

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ABSTRACT

Longitudinal cracks are characteristic and problematic distresses that develop in roadways founded on expansive clay subgrades. Precipitation patterns in arid or semi-arid climates often lead to significant changes in the moisture content of the subgrade soils. In the active zone of moisture fluctuations, the moisture content may vary over time from nearly saturated to very dry conditions. This may cause considerable deformations (swelling or shrinkage) when the subgrade involves expansive clays. The volume changes are expected to result in differential deformations in roads, which ultimately lead to the development of longitudinal cracks. Over the past decade, basal geosynthetic reinforcement has been used by the Texas Department of Transportation (TxDOT) to mitigate the environmentally-induced longitudinal cracks. However, to date, little field data has been collected to understand this process. This paper uses field performance data to evaluate the fundamental mechanisms involved in the development of longitudinal cracks in roads constructed on expansive clay subgrades. In addition, the effectiveness of geosynthetic basal reinforcement is evaluated as a mitigation approach. Four sets of test sections were identified on three farm-to-market roads founded on expansive clay soils in Williamson, Travis, and Atascosa counties, Texas. Vertical deflections of the surface of the test sections have been studied over time by the use of total station instrument. Twenty eight transverse sections were identified and their elevations have been monitored using total station. The changes in elevation within the identified transverse sections are evaluated. These changes are correlated against the environmental changes in the area as well as the expansive properties of the subgrade soil and presence of longitudinal cracks on the roads. The results of this study provide valuable insights into the mechanisms involved in the development of longitudinal cracks and the use of geosynthetic reinforcements to mitigate the environmentally-induced longitudinal cracks and associated pavement distresses.

1. INTRODUCTION

The detrimental impact from expansive subgrade soils on pavement structures has been a major challenge faced by departments of transportation such as the Texas Department of Transportation (TxDOT). The main type of distress that has been reported in roads founded on expansive subgrades is the development of environmentally-induced longitudinal cracks. The longitudinal cracks have been found to be as wide as a few centimeters and as deep as a few meters. The longitudinal cracks have often been associated with other types of distresses, such as excessive vertical deflections, infiltration of water into the pavement layers, and slope stability issues, which all lead to poor quality of riding. A key technique that has been implemented by TxDOT to mitigate detrimental impact from expansive subgrades is the use of geosynthetics to reinforce the base layer (Zornberg et al., 2012; Roodi and Zornberg, 2012). Geosynthetic reinforcements are installed within base course layer or at the interface between subbase and base layer. However, the actual mechanisms that govern contribution of geosynthetic reinforcement into the road performance have remained unclear. The purpose of this paper is to study the conceptual model that has been introduced for performance of pavements constructed on expansive subgrades and to evaluate the impact of using geosynthetic reinforcement on the performance. This study involved monitoring of vertical deflections in reinforced and unreinforced test sections founded on expansive subgrades, and evaluation of the consistency of measured deflections with the conceptual model. The field study program, the monitoring technique, and the collected data are presented in this paper.

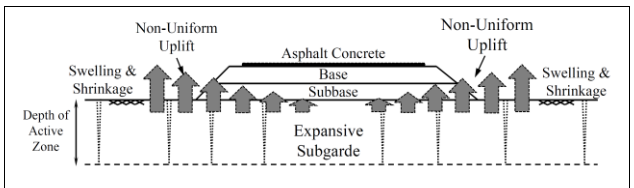

Fig. 1. Non-uniform environmental loading imposed to road structures by expansive subgrades (Roodi and Zornberg; 2012)

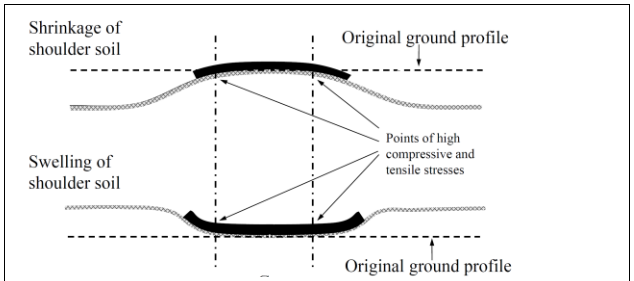

Fig. 2. Conceptual model for generating environmentally induced longitudinal cracks in pavements (Gupta et al. 2008)

2. CONCEPTUAL MODEL

As shown in Figure 1, construction of a relatively impervious pavement structure over expansive soil restrains water access to areas located beneath the center of the road. However, the shoulder areas have unrestricted access to water. Consequently, while the shoulder areas will often swell and shrink due to changes in the soil moisture content, the center area experiences little changes. Therefore, the edges of the pavement structure tend to bend downward during dry seasons and upward during wet seasons (Figure 2). Cyclic wet and dry seasons result in a non-uniform uplift loading applied to the pavement structure, and, consequently, in differential movements between the center and the edges. This leads to points of high compressive stress during wet seasons and high tensile stress during dry seasons. Accordingly, longitudinal cracks typically develop in the pavement during dry seasons.

Consistent with this mechanism, longitudinal cracks have been reported to occur or widen towards the end of dry seasons. The cracks have also been reported to often partly close during the wet season.

The use of geosynthetic reinforcements has been shown to redistribute the non-uniform uplift load such that the points of high stress transfer from the paved area to the shoulder areas. With the presence of geosynthetic reinforcements, the bending deflection in the reinforced layer mobilizes the interface shear between the reinforcement and the surrounding unbound aggregate layer. The interface shear induces tensile force within the geosynthetic, which its reaction will be applied to the unbound aggregate as additional confinement. The additional confinement helps preventing initiation or propagation of the environmental longitudinal cracks. Significant benefits have been reported from the use of geosynthetics in reinforcement of pavements on expansive subgrades in mitigating the extent and severity of longitudinal cracking on the road surface (Zornberg et al. 2012, Zornberg et al. 2013).

3. FIELD STUDY

A field program was designed to monitor vertical deflection of roads constructed on expansive subgrades and to correlate the deflection with the road performance.

4. TEST SECTIONS

Three locations were identified where the roads have been constructed on expansive subgrades. Significant distresses have been reported on the roads in form of severe longitudinal cracks. Figure 3 illustrates the location of the identified roads including Farm to Market Road 972 (FM972), Turnersville Road, and Farm to Market Road 2924 (FM2924).

The FM972 section is located in Georgetown, Texas, 55 km (34 miles) northeast from central Austin, TX. The road extends for almost 23 km (14 miles) from Interstate Highway 35 (IH35) on the west to State Highway 95 (SH95) on the east. For the purpose of this study, two sections of the road, which are located 11 km (7 miles) away from each other, were identified. They are referred to as FM972-Segment I and FM972-Segment II. Each identified section extends for almost 1.5 km (0.9 mile). The sections were selected from among the worst performing areas in terms of distresses associated with expansive subgrades.

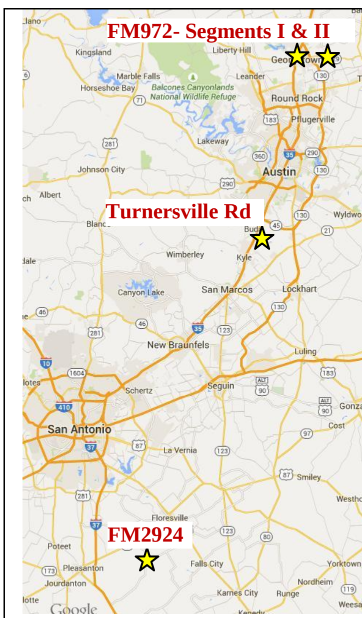

Fig. 3. Location of the identified test sections

Turnersville Road is located 27 km (17 miles) south of Austin in Buda, TX. This road extends from IH35 on the west side to Williamson Road on the east. The identified section for this study starts from 4 km (2.5 miles) east of IH35 and extends for 1.8 km (1.1 miles) from Turnersville Road South to Crane Road. Historical data indicates poor performance of the road. Numerous maintenance operations have been performed to improve the quality of the road, but with limited success. The main reported distresses include severe longitudinal cracking, edge cracking, and excessive vertical deflections, which has led to very poor quality of riding.

FM2924 is located southeast of San Antonio in Atascosa County, TX, and extends for 6.5 km (4 miles) from FM99 to FM791. The old unreinforced section of the road was reconstructed in late spring 2014 and replaced by a geogrid-reinforced flexible base constructed on top of the stabilized subbase. Five months after reopening, the road exhibited four major distresses including edge failure, structural failure at intersections, wheel path rutting, and seal coat bonding issues (Scullion and Sebesta, 2014).

5. MARKING OF TRANSVERSE SECTIONS

To monitor vertical deflections of the roads, a total of seven transverse sections were identified in each test section. The transverse sections were selected from areas that were found to perform well as well as from areas with poor performance in terms of environmental longitudinal cracks. This helped assess the difference in vertical deformation behavior in well-performed as compared to poorly-performed areas and correlate this difference with the development of longitudinal cracks.

Identified transverse sections were marked on pavement surface. First, a two to three inches wide transverse stripe was marked perpendicular to the central line of the road with the use of duck tapes. The stripe was then painted with permanent white spray paint. Then, starting from the center line, circular orange marks were painted on top of the white stripe with 30-cm (1-ft) spacing toward the edges of the pavement. The displacements of orange marks were eventually monitored to evaluate vertical deformation of the road surface over time.

Monitoring of deflections using Total Station

Total station instrument was used to obtain information on the vertical deflection of the marked transverse sections. The instrument model and the distance of shooting were selected to provide minimum accuracy of 2 mm in reading elevations. As illustrated in Figure 4, the operation was first carried out with regular total stations in which a prism should be held at target point. Then the regular total station was replaced by a prism-less total station that allows shooting at target points without holding a prism. The replacement provided faster and safer operation in the field as well as same level of accuracy.

Fig. 4. Using total station and prism to monitor vertical deflection of the marked transverse sections

In order to read elevation of the marked transverse sections, the total station was installed on the side of the roads not more than 60 m (200 ft) from each section. Then the instrument was pointed at each orange mark along the transverse sections, and the coordinates of the point were recorded. Transverse profile of the road could be obtained by analyzing the recorded coordinates and connecting them accordingly. Transverse profiles have been obtained over time for all marked sections on a regular.

6. RESULTS AND DISCUSSION

FM972-Segment I

Transverse Sections Characteristics: As summarized in Table 1, transverse test sections in FM972-Segment I extend over more than 335 m (1100 ft) of the road. Four of the transverse sections were found to be in good condition namely with no/minor cracks on the road. The other three sections exhibited minor cracks.

Soil Characterization: Soil samples were collected from the subgrade soil at several locations in the test sections area. Atterberg limit tests were conducted on the collected samples and the Liquid Limit (LL) of subgrade soil was reported to range from 71 to 79. The Plastic Limit (PL) was found to be 28. Thus, the Plasticity Index (PI) of the soil was found to vary from 43 to 51, which is categorized as high to very high expansive soil according to classifications by U.S. Army Corp of Engineers (USACE) (1983), the U.S. Bureau of Reclamation (2004), and the correlation recommended by Chen (1988). In addition, in-situ moisture content of collected soil samples was found to vary from 36 to 40 %, which indicates that the soil has been in relatively wet condition.

Weather Conditions: Environmental condition of the road has been evaluated by studying the precipitation data collected from two nearby weather stations. Figure 5 summarizes precipitation history in FM972 in terms of weekly rain from January 2014 to June 2015. The time period of the surveys conducted in this study is also marked on the graph. Evaluation of the data presented in this figure indicates that the road has been in a relatively wet period during the surveys.

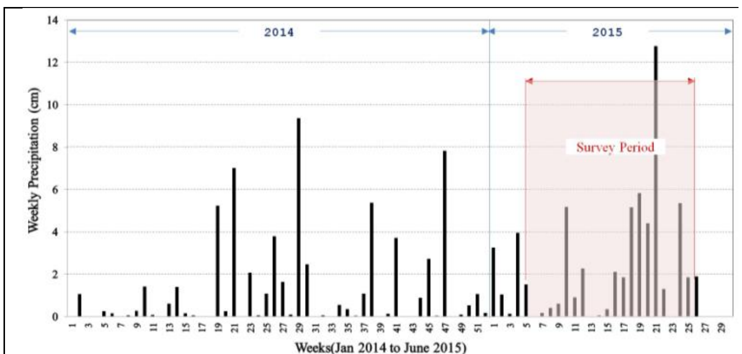

Fig. 5. Precipitation data in FM 972

Total Station Readings: A total of three total station surveys have been conducted on this part of FM972 between March 13rd and June 24th 2015. In each survey, the elevation of the painted points of the seven transverse sections was recorded and the transverse profile of the road was generated. The transverse profiles are illustrated in Figure 6. The zero point on the horizontal axis represents the centerline of the road. Elevations of the painted points on the road relative to the elevation of the centerline are plotted on the left and the right of the centerline. FM972 is a two-way, two-lane, east-west road in which yellow stripe separates between traffics moving in opposite directions. The profile illustrated on the right of the centerline, represents the eastbound of the road and the profile on the left represents the westbound.

Table 1. Summary of monitoring program and results for transverse test sections in FM972-Segment I

Transverse Section No.	Distance to Next Section, m (ft)	Observed Performance*	Total Station Surveys		Transverse Profile Characteristics			
					Left Lane** (West Bound)		Right Lane** (East Bound)	
			No. Surveys	Surveys Period	Initial Slope	Change in Slope	Initial Slope	Change in Slope
Section 1	30 (100)	Good	3	3/13 to 6/24/2015	0%	~ 0%	1%	~ 0%
Section 2	75 (250)	Good	3	3/13 to 6/24/2015	0.4%	~ 0%	0.1%	~ 0%
Section 3	75 (250)	Good	3	3/13 to 6/24/2015	1.5%	~ 0%	-1.5%	~ 0%
Section 4	15 (50)	Fair	3	3/13 to 6/24/2015	0.75%	~ 0%	2.5%	~ 0%
Section 5	135 (440)	Fair	3	3/13 to 6/24/2015	0.25%	~ 0%	5%	~ 0%
Section 6	15 (50)	Good	3	3/13 to 6/24/2015	1.5%	~ 0%	1.85%	~ 0%
Section 7	--	Fair	3	3/13 to 6/24/2015	1.4%	~ 0%	1.7%	~ 0%

* Observed Performance: Good = zero or very minor cracks; Fair = slightly cracked; Poor = severely cracked.

** Left and Right lanes are referred to sides as depicted in the transverse profile sketches.

Transverse profiles resulted from different surveys are illustrated with different colors in Figure 6. Evaluation of the curves presented in this figure reveals that the transverse profiles of the east and west bounds have remained essentially unchanged in all sections. This indicates that in this section of the road the subgrade soil has not imposed significant differential vertical deflection to the road structure, which is consistent with the observed good/fair conditions of the road.

The differential vertical deflection of the road surface has been quantified with the initial slope and change in the slope over time in each transverse section. As summarized in Table 1, although the initial transverse slopes were very different among the marked sections, all east bound and west bound sections exhibited negligible change in slope.

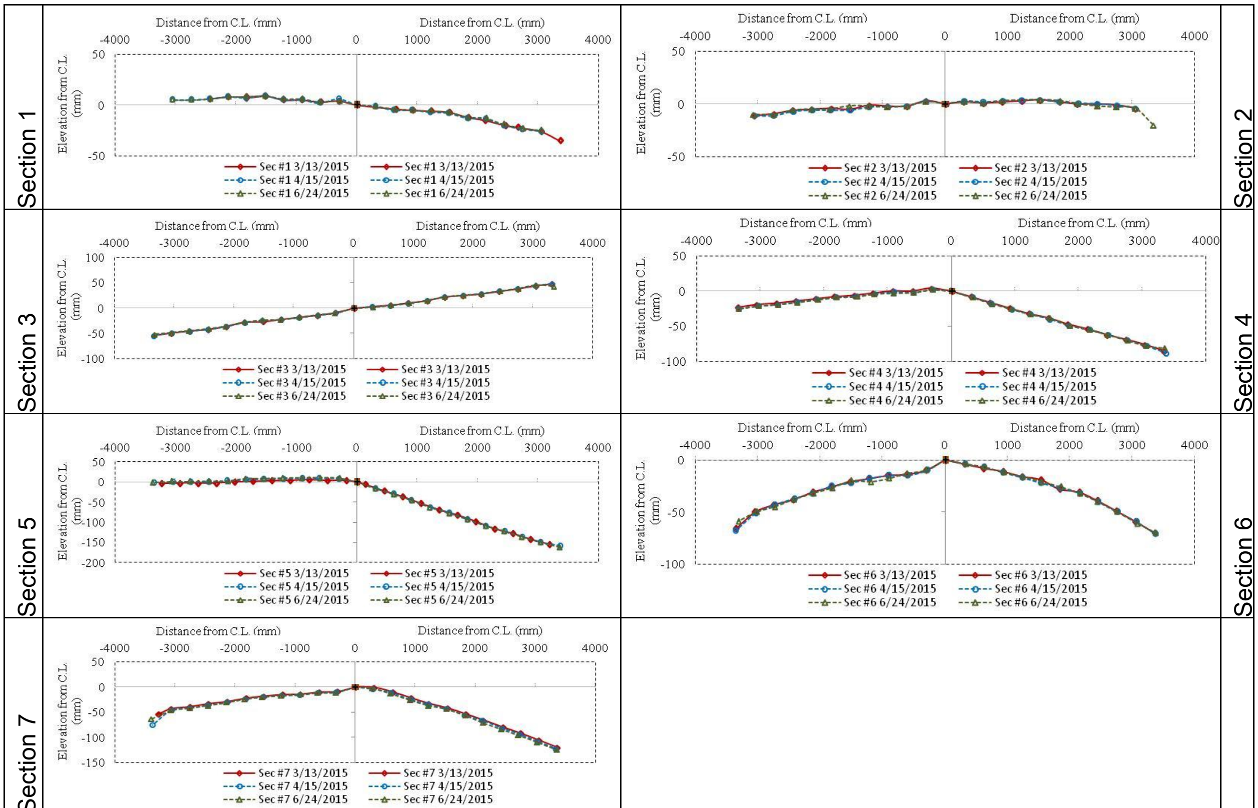

Fig.6. Results of total station surveys of test sections in FM972-Segment I

FM 972 – Segment II

Transverse Sections Characteristics: As summarized in Table 2, transverse test sections in FM972-Segment II extend over more than 365 m (1200 ft) of the road. Four of the transverse sections, including Sections #2, #3, #5, and #6, were found to be in poor condition with severe longitudinal cracking or faults. The other three sections were found to be in good condition.

Soil Characterization: Soil samples were collected from subgrade soil in FM972-Segment II and their plasticity properties were characterized. The Liquid Limit (LL) of the samples was found to be between 70 and 77, the Plastic Limit (PL) was found to vary from 24 to 27, and, thus, the Plasticity Index (PI) was found to vary from 43 to 53. Therefore, similar to FM972-Segment I, the subgrade soil in FM972-Segment II is categorized as high to very high expansive soil. In-situ moisture content of collected soil samples was also found to vary from 36 to 39 %, which is the same range as that in FM972-Segment I. This further indicates that the subgrade soil has been in relatively wet condition.

Weather Conditions: Weather condition of FM972 was discussed in previous section. It was found that significant rains have been reported during the time period that the surveys have been conducted. Consequently, the subgrade soil is expected to be in relatively wet condition for the duration of this study.

Total Station Readings: A total of four total station surveys were conducted on this part of FM972 between February 10th and June 24th 2015. The transverse profiles of the test sections are shown using different colors in Figure A.1 with the similar procedure described for FM972-Segment I. The profiles illustrated on the right of the centerline represent the eastbound of the road and the profiles on the left represent the westbound.

Evaluation of the curves presented in Figure A.1 indicates different vertical deflection behavior in sections with observed good condition as compared to sections with poor condition. Similar to the sections in FM972- Segment I, in FM972- Segment II the transverse profiles of the east and west bounds were found to be essentially unchanged in sections with observed good conditions (Sections #1, #4, and #7). However, in all sections with observed poor performance (i.e. Sections #2, #3, #5, and #6) significant vertical deflections have been recorded. The vertical deflections were found to be positive, i.e. in upward direction, and to be more significant in the edges the pavement. This is consistent with the described conceptual mechanism for pavements constructed on expansive subgrades. According to this mechanism, edges of pavements founded on expansive subgrades tend to heave during wet season, when the subgrade soil expands in the shoulder area, and to settle during dry season, when the subgrade soil tend to shrink. This cycle of upward and downward vertical deflections in the edges leads to the development of longitudinal cracks in pavements, particularly close to the edges. As illustrated in Figure A.1, poor condition of Sections #2, #3, #5, and #6 are attributed to the cracks observed on the edges of the eastbound of the road (i.e. the right lane on the profiles), whereas the westbound lanes are found to be in good condition. Vertical deflections were also found to be significant only in the edge of the eastbound lanes. It can be envisioned that cycles of heave and settlement that have been repeated over time have been the main reason for development of the observed cracks. Maximum positive deflection between first survey on February 10th and last survey on June 24th was found to be 18, 16, 9, and 20 mm, respectively for Sections #2, #3, #5, and #6.

The differential vertical deflections of the test sections were evaluated with the initial slopes and changes in the slopes summarized in Table 2. Although the initial transverse slopes were different among the marked sections, all westbound sections exhibited almost zero change in the slope. This is consistent with the good conditions have been observed in the westbound sections. The slope of the eastbound sections, however, has changed in the sections with the observed poor condition. The changes were found to be negative indicating reduction in the slope magnitude.

Table 2. Summary of monitoring program and results for transverse test sections in FM972- Segment II

Transverse Section No.	Distance to Next Section, m (ft)	Observed Performance *	Total Station Surveys		Transverse Profile Characteristics			
					Left Lane** (West Bound)		Right Lane** (East Bound)	
			No. Surveys	Surveys Period	Initial Slope	Change in Slope	Initial Slope	Change in Slope
Section 1	60 (200)	Well	4	2/10 to 6/24/2015	2%	~ 0%	1.6%	~ 0%
Section 2	135 (440)	Poor	4	2/10 to 6/24/2015	0.3%	~ 0%	1.5%	-0.5%
Section 3	21 (70)	Poor	4	2/10 to 6/24/2015	1.5%	~ 0%	1.4%	-0.3%
Section 4	75 (250)	Well	4	2/10 to 6/24/2015	1.7%	~ 0%	0.6%	~ 0%
Section 5	52 (170)	Poor	4	2/10 to 6/24/2015	1.1%	~ 0%	1.3% un-cracked portion	~ 0% un-cracked portion
Section 6	27 (90)	Poor	4	2/10 to 6/24/2015	1.2%	~ 0%	2.1% un-cracked portion	-0.3% un-cracked portion
Section 7	--	Well	4	2/10 to 6/24/2015	0.1%	~ 0%	1.1%	~ 0%

* Observed Performance: Good = zero or very minor cracks; Fair = slightly cracked; Poor = severely cracked.

** Left and Right lanes are referred to sides as depicted in the transverse profile sketches.

7. TURNERSVILLE ROAD

Transverse Sections Characteristics: As summarized in Table 3, transverse test sections in Turnersville road extend over more than 490 m (1600 ft) of the road. The transverse sections were selected from areas with observed good, fair, or poor performance. Sections #3, #5, and #6 have exhibited severe cracks and faulting, whereas Sections #2, #4, and #7 were found to be slightly cracked. Section #1 has been observed to be in good condition.

Soil Characterization: Atterberg limit tests conducted on soil samples collected from Turnersville road subgrade resulted in the Liquid Limit (LL), the Plastic Limit (PL), and the Plasticity Index (PI) of 57, 20, and 37, respectively. Therefore, similar to FM972 subgrade soil, the subgrade soil in Turnersville road is categorized as high to very high expansive soil according to classifications by U.S. Army Corp of Engineers (USACE) (1983) and the U.S. Bureau of Reclamation (2004), and the correlation recommended by Chen (1988).

Weather Conditions: Precipitation data in Turnersville Road was collected from two nearby weather stations. Both stations have reported a relatively dry year for 2014. However, they have recorded different data in 2015. While the data collected from one of the stations shows relatively wet months from January to April, the other station has reported a dry season for the same period of time. This indicates the variability of the weather condition in this region that should be taken into account in the analysis.

Total Station Readings: From February 19th to July 2nd, five total station surveys were conducted on Sections #1 to #5, whereas four surveys were conducted on Sections #6 and #7. The transverse profiles of the test sections in the surveys are shown using different colors in Figure A.2 with the similar procedure described for FM972- Segment I. The profiles illustrated on the right of the centerline represent the eastbound of the road and the profiles on the left represent the westbound.

Vertical deflections of the road surface were found to be different among the seven transverse sections. Similar to the sections in good condition in FM972, it was found that Section #1 in Turnersville Road has exhibited very limited vertical deflection. As illustrated in Figure A.2 very minor change was measured in the elevation of the painted points in Section #1. The slope of both right and left lanes did not change significantly in this section (Table 3). Transverse slopes in Section #2 were also found to remain essentially unchanged.

Sections #3, #4, and #5 exhibited significant drops in the elevation of their right lanes. This settlement can be attributed to the shrinkage of the expansive subgrade during the period of this study. The maximum settlement was found to be at the edges of the pavement, which is consistent with the described conceptual mechanism for pavements constructed on expansive subgrades. The maximum settlements were measured as 55, 49, and 28 mm in Sections #3, #4, and #5, respectively. As presented in Table 3, as a result of the settlements, significant increase was measured in the right lane transverse slopes. The increase was found to be as large as +2 and +1.7 % for Sections #3 and #4, respectively. It should be noted that the wide crack on the right lane of Section #3 could potentially provide a faster and easier access to water for pavement base and subbase layers as well as for the expansive subgrade. This could impose slope stability issues as well as exacerbating impact from the expansive subgrade.

In contrast with the settlements observed in other sections, left lanes in Sections #6 and #7 exhibited positive vertical deflections, which indicate swelling of the expansive subgrade in this area (Figure A.2). Maximum vertical deflection was recorded as +18 and +30 mm in Sections #6 and #7, respectively, which has led to reduction of -0.5 and -1 % in the slope of the left lanes. However, the right lanes of Sections #6 and #7 exhibited zero or negative change in the elevation, which is consistent with the shrinkage observed in other sections. The expansion of the subgrade soil observed in the left lanes can be attributed to the geographical features in this area. As shown in Figure A.2, left side of the road in Sections #6 and #7 is bound by residential areas that created a natural pond for accumulation of rain water or other runoffs. The impact of this natural pond can clearly be seen in the difference in the vegetation of the right side of the road as compared to the left side. Accumulation of water in the pond could potentially provide additional access to water for the subgrade soil, which has led to the observed expansion.

Table 3. Summary of monitoring program and results for transverse test sections in Turnersville road

Transverse Section No.	Distance to Next Section, m (ft)	Observed Performance *	Total Station Surveys		Transverse Profile Characteristics			
					Left Lane** (West Bound)		Right Lane** (East Bound)	
			No. Surveys	Surveys Period	Initial Slope	Change in Slope	Initial Slope	Change in Slope
Section 1	21 (70)	Good	5	2/19 to 7/2/2015	2.4%	~ 0%	1.2%	+0.2%
Section 2	58 (190)	Fair	5	2/19 to 7/2/2015	5.6%	-0.4%	1.7%	-0.2%
Section 3	200 (650)	Poor	5	2/19 to 7/2/2015	3.6%	-0.1%	0.2%	+2% un-cracked portion
Section 4	52 (170)	Fair	5	2/19 to 7/2/2015	3.2%	+0.3%	1.2%	+1.7%
Section 5	130 (430)	Poor	5	2/19 to 7/2/2015	2.9%	+0.2%	3.8%	+0.7%
Section 6	30 (100)	Poor	4	3/12 to 7/2/2015	-1.6%	-0.5%	1.2%	+0.2%
Section 7	--	Fair	4	3/12 to 7/2/2015	-0.9%	-1%	1.2%	~ 0%

* Observed Performance: Good = zero or very minor cracks; Fair = slightly cracked; Poor = severely cracked.

** Left and Right lanes are referred to sides as depicted in the transverse profile sketches.

8. FM2924 (GEOSYNTHETIC REINFORCED SECTION)

Transverse Sections Characteristics: Characteristics of the transverse test sections in FM2924 are summarized in Table 4. A total of seven transverse sections were marked on this road in June 2015 from which five sections were found to be in good or fair conditions with zero or very minor crack or deflection. Even in Sections #2 and #3, which are categorized in poor condition, the cracks were found to be insignificant. These sections are categorized in poor conditions because of the large vertical deflection that was observed at the time of marking, which can be attributed to significant traffic loads. The comparatively better performance that has been observed in FM2924 test sections can be attributed to the use of geosynthetic to reinforce the base layer.

Soil Characterization: Characterization of soil samples collected from FM2924 indicated that the subgrade soil in this area is potentially more expansive than the subgrade soil in other test sections. The Liquid Limit (LL) and the Plastic Limit (PL) were found to be 80 and 24, which resulted in the Plasticity Index (PI) of 56. This result classifies the subgrade soil as very high expansive clay. The in-situ moisture content of soil was found to be 37 %.

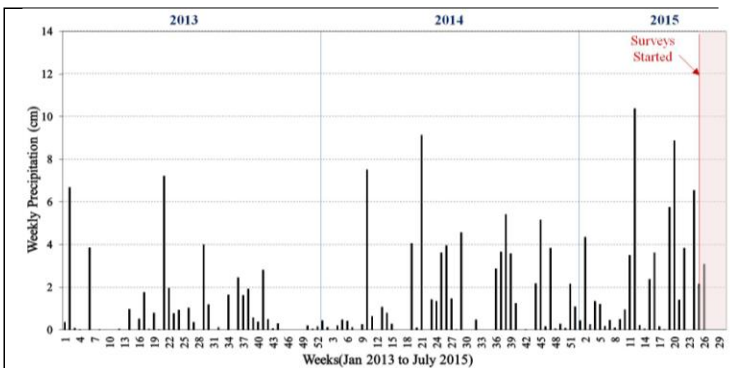

Fig. 7. Precipitation data in FM2924

Weather Conditions: Figure 7 presents precipitation data collected from a nearby weather station in FM2924. The horizontal axis of this graph corresponds to week numbers from the beginning of the year 2013 until July 2015. The vertical axis corresponds to weekly precipitation in terms of centimeter. Evaluation of the data presented in this figure indicates that the road experienced a relatively dry year in 2013. Starting from May 2014, the weather condition in this area has been comparatively wet with a few dry periods in between the rainy months. At the time the total station surveys started, the road has experienced cycles of wet and dry periods.

Total Station Readings: As listed in Table 4, since the transverse test sections in FM2924 were marked recently, only a single or two total station surveys have been conducted at the time of writing this paper. Therefore, the findings of this section should be treated with caution, but the significance of using geosynthetic reinforcement, which is a major focus in this study, is further underlined by these data.

Comparative evaluation of the test sections conditions in FM2924, FM972, and Turnersville Road, highlights the significance of geosynthetic reinforcement layer in the performance of the pavements constructed on expansive clays. While the test sections in all three locations have been founded on similar subgrade soil and have been exposed to similar environmental conditions and traffic loads, the test sections in FM2924 were found to be in significantly better condition. As demonstrated in Figure A.3, in contrast to the wide and deep cracks have been observed in the test sections in FM972 and Turnersville road, zero or very minor environmental longitudinal cracks were found in the test sections in FM2924. This indicates that the geosynthetic reinforcement was effective in mitigating the main distress associated with the expansive subgrade. The geosynthetic reinforcement was able to reduce the severity or delay opening of environmental longitudinal cracks in FM2924 test sections.

Comparison between the measured transverse slopes in the three locations also reinforces the significance of the application of geosynthetic reinforcements. While the three locations were reconstructed at relatively close period of time and have experienced comparatively similar cycles of wet and dry seasons, it can be envisioned that the differential vertical deflections have been realized in FM972 and Turnersville Road have been significantly larger than those in FM2924. This can be understood by comparison of the current transverse slopes to the initial design slope. Since all test sections were selected from straight areas of the roads, it can be assumed that they were designed and constructed with the standard transverse slope of 1.5 % to 2.5 %. However, the presented data indicates significant difference between the current transverse slopes in the geosynthetic reinforced road and the unreinforced roads. As presented in Tables 1 to 3, the current transverse slope of the left lanes were found to vary from 0 to 1.5 %, from 0.1 to 2 %, and from -1.6 to 5.6 %, respectively for FM972-Segment I, FM972-Segment II, and Turnersville road. In the right lanes, the slopes were found to vary from -1.5 to 5 %, from 0.6 to 2.1 %, and from 0.2 to 3.8 % in FM972-Segment I, FM972-Segment II, and Turnersville road, respectively. These large deviations from the original design slopes indicate significant vertical deflections in form of settlement or expansion, which have been imposed over time to the pavement structures. It can be envisioned that, consistent with the described conceptual mechanism for pavements constructed on expansive subgrades, the imposed vertical deflections have been more severe in the edges; hence the road surfaces have remained flat and only the slopes have changed. In cases that the differential vertical deflections between center and edges have been too large, such as Section #3 of Turnersville road and Section #5 in FM972-Segment II, severe longitudinal cracks have been developed.

Application of geosynthetic reinforcements in FM2924 could minimize change in the design transverse slopes. As presented in Table 4, slopes measured for marked transverse sections in FM2924 were found to range from 1.4 to 2.6 %. This indicates very minor change as compared to the design slopes, which highlights significance of geosynthetic reinforcement in mitigation of the differential vertical deflections and accompanied longitudinal cracks.

Table 4. Characteristics of test sections in FM 2924

Transverse Section No.	Distance to Next Section, m (ft)	Observed Performance*	Total Station Surveys		Transverse Profile slopes	
			No. Surveys	Surveys Period	Left Lane Slope	Right Lane Slope
Section 1	30 (100)	Good	2	06/30 ~ 08/01	2.3%	1.8%
Section 2	70 (225)	Poor	2	06/30 ~ 08/01	2.4%	1.9%
Section 3	55 (185)	Poor	2	06/30 ~ 08/01	2.2%	1.6%
Section 4	43 (140)	Good	2	06/30 ~ 08/01	2.5%	1.7%
Section 5	85 (275)	Good	1	07/02 ~ 08/01	2.6%	1.4%
Section 6	28 (90)	Good	1	07/02 ~ 08/01	2.3%	1.4%
Section 7	--	Fair	1	07/02 ~ 0/8/01	2.1%	1.9%

* Observed Performance: Good = zero or minor cracks; Fair = slightly cracked;

Poor = severely cracked or large deflections.

** Left and Right lanes are referred to sides as depicted in the transverse profile sketches.

9. SUMMARY AND CONCLUSIONS

Four sets of transverse test sections were marked on three roads founded on expansive subgrades in Texas. Turnersville road and FM972 were constructed as unreinforced roads, whereas FM2924 was reinforced with geosynthetic reinforcement. Vertical deflections of the marked sections were monitored over time by the use of total station instrument. Transverse profile of the test sections were then generated and change in the profiles was compared with the conceptual mechanism for pavements constructed on expansive subgrades. The main findings that result from evaluation of the measured data are summarized below:

Consistent with the conceptual mechanism, it was found that the pavements edges did exhibit larger vertical deflections than the centers.

Consistent with the conceptual mechanism, it was found that wet condition of subgrades induces positive vertical deflections in pavement surface (i.e. heave) while dry condition result in negative deflection (i.e. settlement).

It was found that the sections with observed good performance showed limited vertical deflections and minor change in their slope. The sections with poor or fair performance were found to have experienced comparatively larger vertical deflections particularly in the edges of the road, which led to significant change in their transverse slopes.

In cases where the differential vertical deflection between center and edges was found to be too large, severe longitudinal cracks have been developed.

Geosynthetic reinforcements were found to be successful in mitigating distresses associated with expansive subgrades. The test sections in the geosynthetic reinforced road were found to perform significantly better than the test sections in unreinforced roads.

Comparison of the current transverse slopes with the initial design slopes further underlined the significance of using geosynthetic reinforcements as a technique to improve road conditions on expansive subgrades. While the current transverse slopes of unreinforced sections were found to significantly deviate from the original design slope, the geosynthetic reinforced sections have exhibited minor change from the original design slope.

ACKNOWLEDGEMENTS

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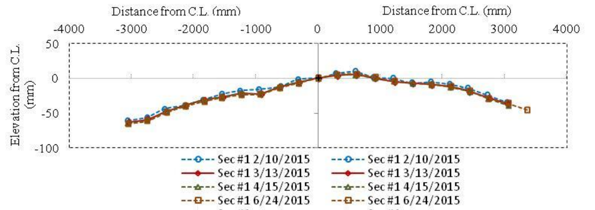
APPENDIX

Section 1



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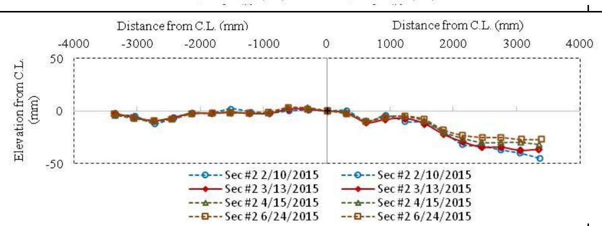

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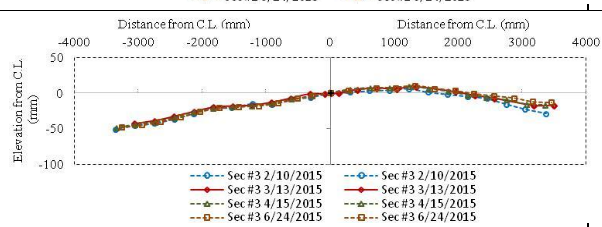

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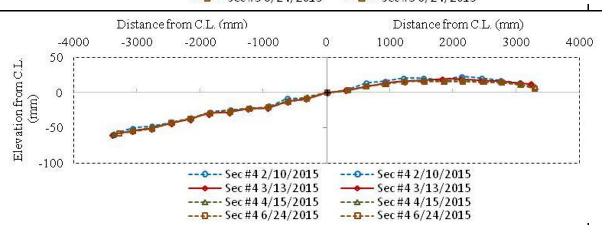

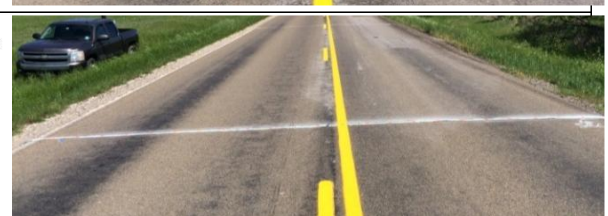

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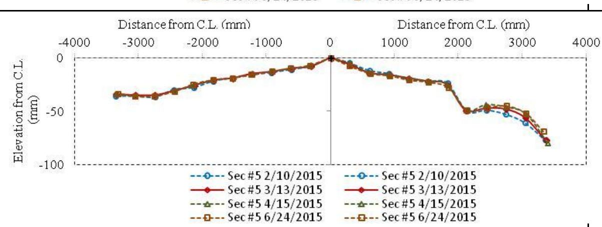

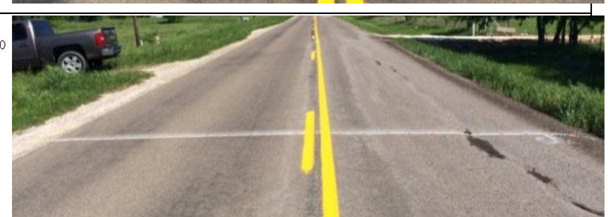

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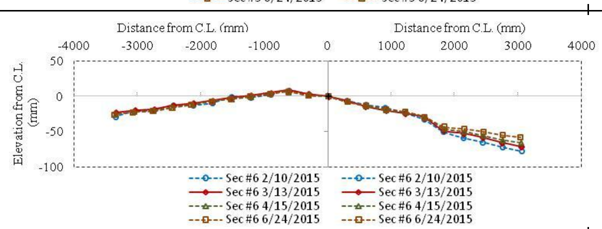

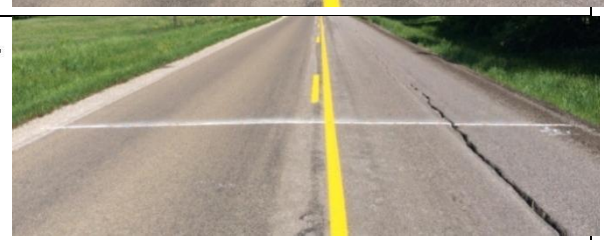

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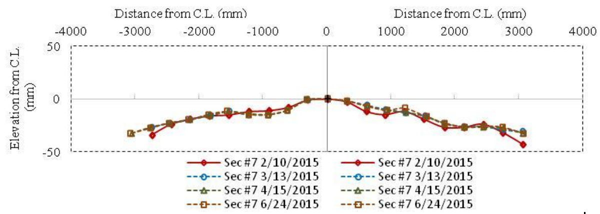
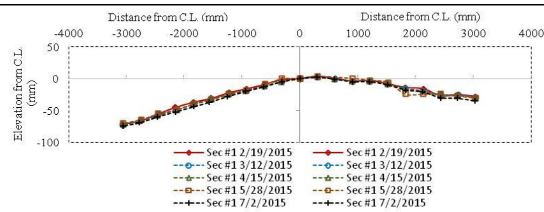


Fig.A.1. Results of total station surveys and road conditions in FM972- Segment II

Section 1



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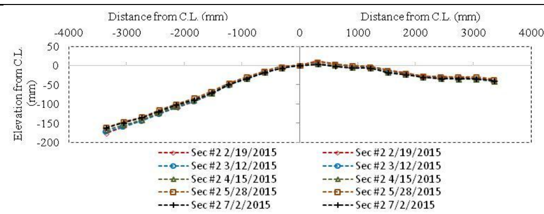

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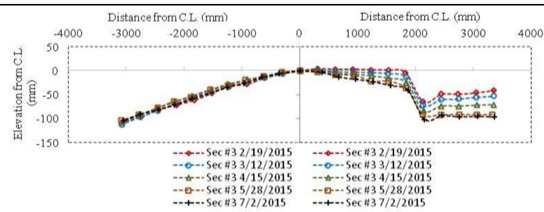

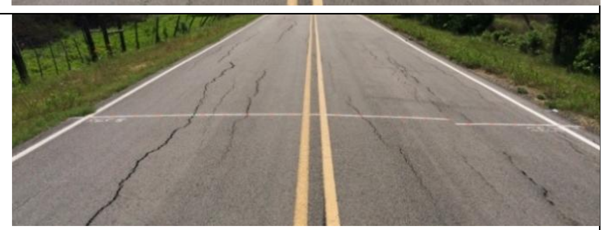

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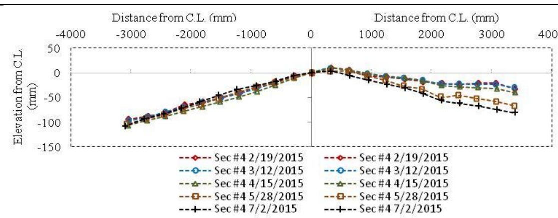

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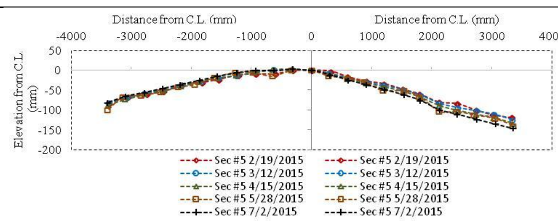


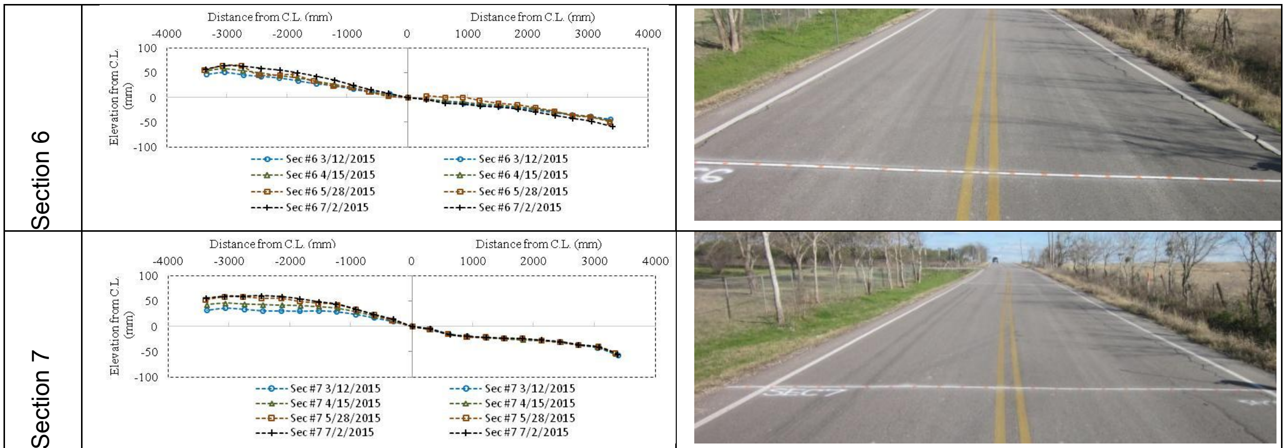
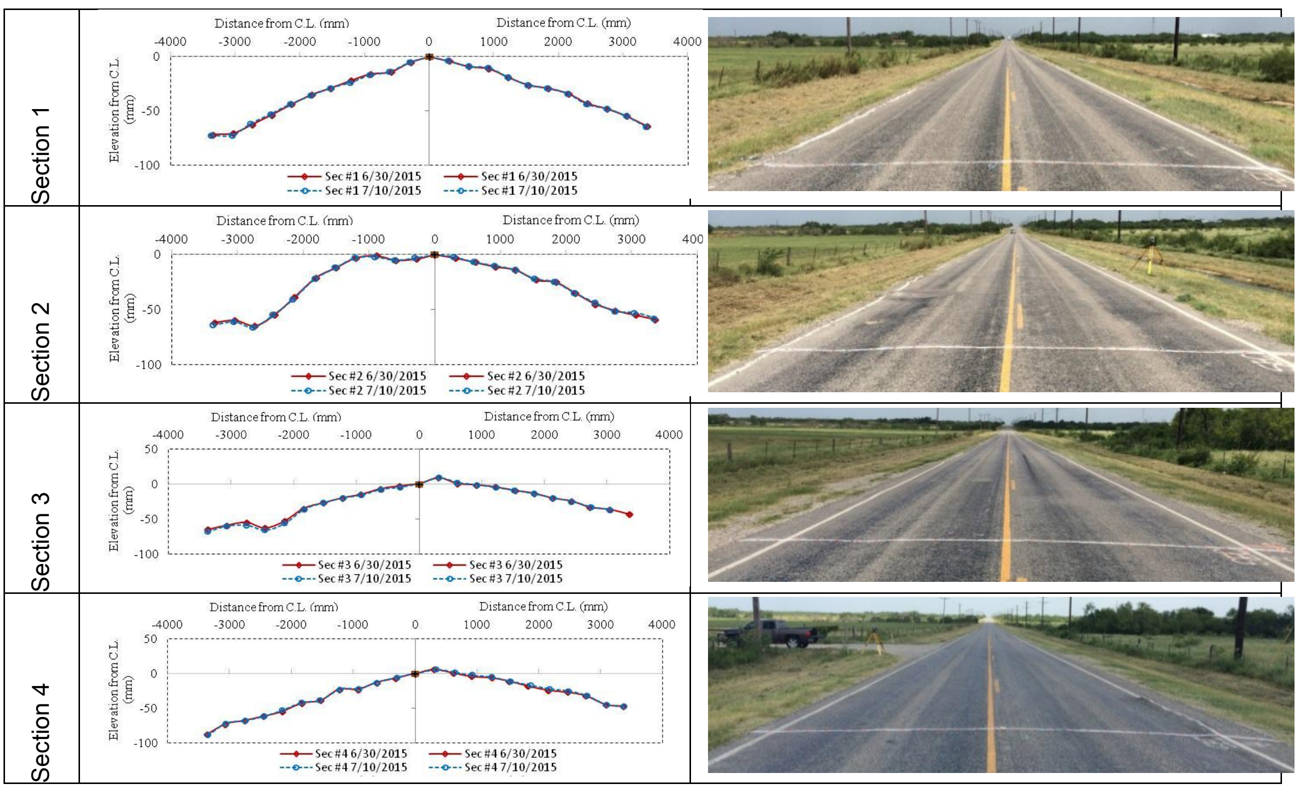


Fig.A.2. Results of total station surveys and road conditions in Turnersville road



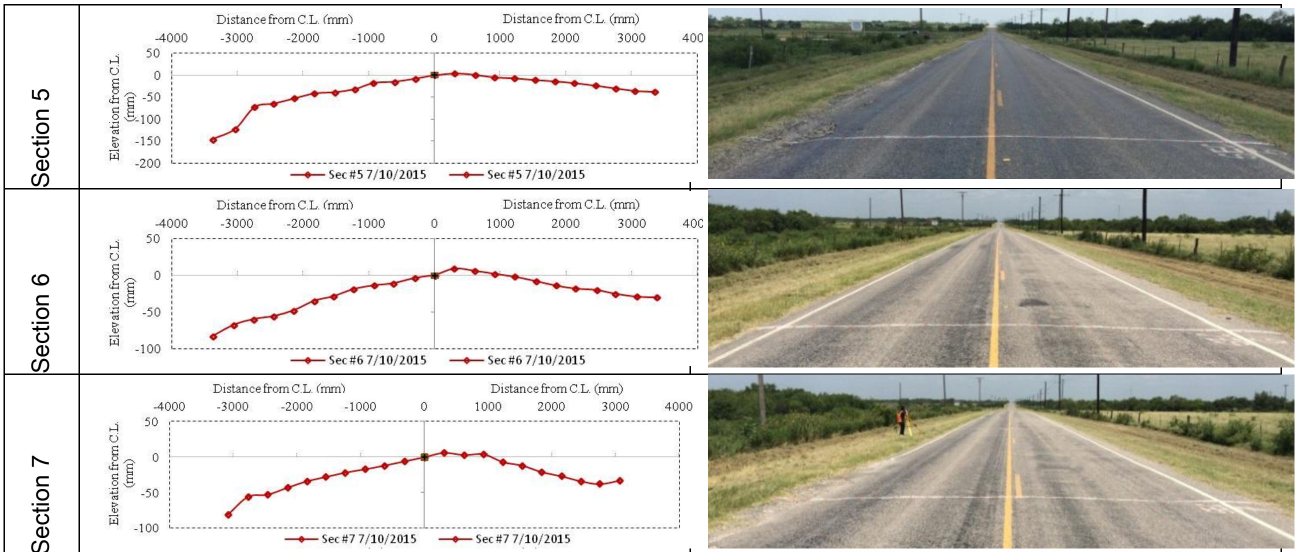


Fig. A.3. Results of total station surveys and road conditions in FM2924