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# Measuring Thermal Effect in the Structural Response of Flexible Pavement Based on Field Instrumentation

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**Abstract:** Temperature affects the structural response of flexible pavement in two ways. Firstly, the pavement material expands and contracts for temperature variations and produces thermal strain. Secondly, when pavement temperature changes, the modulus of the asphalt concrete (AC) changes and consequently, the stress-strain responses for a particular vehicle also change. This study describes both of these phenomenon based on field instrumentation on an interstate pavement, Interstate 40 (I-40), in the state of New Mexico, United States of America. Continuous horizontal strains at the bottom of the AC and vertical stresses at different depths of the pavement are measured for an eighteen-wheel vehicle from June 8 to November 3, 2012. The horizontal strains are measured with installed Horizontal Asphalt Strain Gauges (HASGs) and the vertical stresses with Earth Pressure Cells (EPCs). Results show that the vertical stresses and the horizontal strains at the bottom of AC layer increase up to 1.88 and 1.41 times, respectively, in the afternoon than those in the morning for the climate condition in New Mexico for the above mentioned period.

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***Key words**: Diurnal effects; Flexible pavement; Horizontal strain; Temperature variations; Thermal effect, Vertical stress.*

## Background

Hot Mix Asphalt (HMA) is composed of crushed stones and asphalt binder. The crushed stone provides internal friction to the mixture and the binder generates bonding among the aggregate. Rheological properties of asphalt binder are largely dependent of temperature. The Dynamic Modulus (|E*|) of HMA is thus dependent of temperature. Therefore, HMA exhibits higher modulus in lower temperature and lower modulus in higher temperatures. This is why, the modulus of HMA is evaluated at different temperatures and the corresponding structural responses are predicted using numerical analysis or different design guides such as AASHTO, MEPDG etc. [1, 2]. Thus, temperature is considered the leading factor for characterizing a particular asphalt concrete (AC) mixture.

Schwartz and Carvalho [3] determined seasonal variations of the modulus of AC using a parametric study in MEPDG and observed that HMA modulus increased to more than 3.5 times for a 37.5 mm thick asphalt layer in the winter compared to the summer. The diurnal variations of the modulus and the structural response were not studied in this literature.

Orr [4] conducted a Falling Weight Deflectometer (FWD) test to measure *in situ* modulus of the pavement material at various temperatures. The researcher discovered that the modulus of the HMA in the winter increased to more than 4 times than that in the summer. However, there is a serious weakness in Orr’s test method. An impulse load of different magnitude, normally 40 kN (9.0 kip), is applied in the pavement surface and deflections at seven different radial points are measured. While backcalculating using computer based software such as ELMOD, this load is assumed static in backcalculating the modulus. Therefore, the results may not be close to the accurate ones.

Figueroa [5] analyzed the diurnal and the seasonal modulus variations of AC. The researcher reported that the HMA modulus increased in winter (15512 MPa) dramatically from that in the summer (1724 MPa). Some diurnal effects were also considered in his study. It was reported that the modulus was the maximum at 8:00 am and the minimum at 6:00 pm. The above studies did not focus on the structural response of the pavement due to traffic and thermal loads.

Swett [6] attempted to characterize the seasonal variations of pavement layers’ modulus using the *in situ* measurement of pavement stress and strain. The researcher measured a noticeable larger asphalt strain than the predicted strain for increasing time of loading. The ratios of measured stresses and predicted stresses were between 2 and 2.5 for subbase and subgrade. Therefore, no tangible conclusion was drawn in the study.

Al-Qadi et al. [7] analyzed the vertical stress and horizontal for different vehicle speeds, tire inflation pressures and temperatures using full scale field test and numerical analysis. The researchers successfully correlated the relationship of vertical stress with temperature and observed that the vertical varied exponentially with temperature. However, the variations of horizontal strain with temperature, thermal strain, the combined thermal and vehicle strain are still not discussed. All of these parameters vary with HMA mixtures, construction method and equipment used, and the local climate.

The authors of the present study are thus motivated to study the structural response of the flexible pavement diurnally for New Mexico’s typical HMA and local conditions. Seasonal effect is not studied as the data collection started in from October, 2012. The horizontal strain at the bottom of the AC (300 mm depth) and vertical stress at four different depths were measured for 0.83 MPa (120 psi) tire pressure vehicle loading. The responses were measured continuously from June 8 to November 3, 2012 for the

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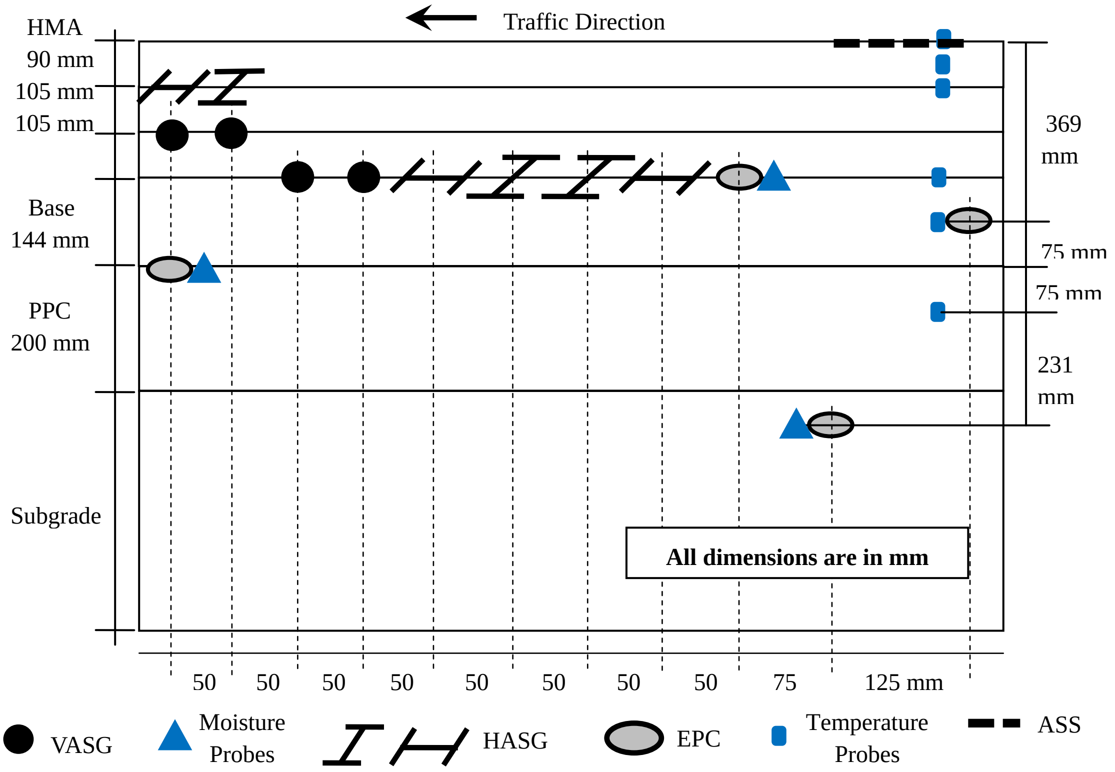

**Fig. 1.** Longitudinal Profile of the Instrumented Section.

newly constructed pavement. The temperature variations were also recorded continuously through installed temperature probes.

## Objectives

The main objective of this study is to evaluate the diurnal variations of stress and strain in flexible pavement for an eighteen-wheel vehicle (tire inflation pressure 0.83 MPa [120 psi]). The thermal strain, the tensile strain at the bottom of the AC and the vertical stresses at different depths of the pavement based on the instrumentation section are discussed here.

## Field Installation and Data Collection

### Instrumented Section

The instrumented section is located on Interstate-40 (I-40) east bound lane at mile post 141 in the state of New Mexico, USA. This section has four different layers. The top 300 mm (12 in) layer is HMA followed by a 144 mm (5.75 in) crushed stone base course. There is a subbase layer, called Process Place and Compact (PPC) of 200 mm (8 in) thickness and finally, underlain by the natural silty soil. The instrumentation profile view along with the installed sensors is shown Fig. 1.

A total of 40 sensors are installed in the instrumented section to measure the vertical stress, horizontal strain, temperature variations, moisture variations, wheel wander and weight of the vehicle. The sensors are located at different elevations and positions of the section.

(a) (b)

**Fig. 2.** Installation of the HASGs and the EPCs.

### Horizontal Asphalt Strain Gauges (HASGs)

The horizontal strain at the bottom of the asphalt layer is a vital parameter in fatigue performance characterization. A total of 12 HASGs, six oriented in longitudinal direction and six oriented transversely were installed at the bottom of the asphalt layer to measure the asphalt strain. The array of gauges was centered in the outside wheel path with 600 mm (2 ft) offset from center to capture the wheel wander of traffic. Prior to paving, the HASGs have been held in position with some sand binder mix as shown in Fig. 2(a).

### Earth Pressure Cells (EPCs)

Four EPCs were installed at the top of the granular base layer, at the middle of the base, on the top of the PPC layer and on the top of the subgrade. A 300 mm (12 in) square hole was prepared to accommodate the 225 mm (9 in) diameter EPC as shown in Fig. 2(b). The depth of the hole was approximately 63 mm (2.5 in). A 75 mm (3 in) wide by 75 mm (3 in) deep trench was made with pick axes to accommodate the sensor's cable. The cable was inserted into 25 mm (1 in) diameter corrugated aluminum pipe. This could protect the cable from the larger crushed stone. The EPCs were then placed such that they each had the exact elevation in the section. All the positions and elevations of the sensors were surveyed carefully and recorded for analysis.

### Other Sensors and Equipment

Six temperature probes were inserted at different depths of the pavement to measure the average, the maximum, and the minimum temperatures every half an hour. Three Axle Sensing Strips (ASSs) measured the wheel wander of vehicle and weigh-in-motion measured the weight of vehicle. The section also has two Vertical Asphalt Strain Gauges (VASGs) at the top of first lift of HMA layer and six VASGs at the bottom of HMA layer. Three moisture probes were installed at the layer interfaces. A roadside weather station was erected for the accurate measurement and modeling of the climate. Data from the sensors were recorded through a high-speed data acquisition system and processed by data analysis software called DaDisp.

## HMA Mix

Dense graded SuperPave (SP) mix, type SP-III was used in this section, which is widely used in New Mexico. This mix contains around 35% plant screened Recycled Asphalt Pavement (RAP) materials. Performance Grade (PG) binder PG 70-22 was 4% (by weight of mixture). The gradation of the SP mix aggregate is shown in Table 1. The maximum aggregate size was 25 mm (1in). About 5% of the materials pass through a No. 200 sieve (0.075 mm).

## Results and Discussion

### Temperature Analysis

The pavement surface absorbs the heat from sunlight and transfers it to the underneath colder material. At night, this process is opposite. The surface material draws up the heat from underneath the materials and transmits it to the air. Therefore, temperatures of the pavement materials are not the same all day long. This temperature variation makes changes in the mechanical properties of the pavement materials. The horizontal strains are measured at two different depths (90 mm and 300 mm) and the vertical stresses are measured at four different depths, i.e., 300, 369, 444 and 750 mm. Therefore, temperature variations at these depths are critical in this study.

Air and the surface temperatures are the minimum around 9:00 am and the maximum around 3:00 pm as shown in Fig. 1. However, the minimum and the maximum temperatures at the bottom of the AC are observed around 11:00 am and 9:00 pm respectively. These values are measured at 8:30 am and 4:30 pm, respectively, at 90 mm depth. The peak strains were also observed at these times as shown in Figs. 4 and 5.

**Table 1.** Gradation of the Aggregates.

| Sieve Size | % Passing |
|---|---|
| 25 mm (1 in) | 100 |
| 19 mm (0.75 in) | 99 |
| 12.5 mm (0.5 in) | 87 |
| 9.5 mm (0.375 in) | 72 |
| 4.75 mm (No. 4) | 42 |
| 2.375 mm (No. 8) | 26 |
| 1.185 mm (No. 16) | 20 |
| 0.67 mm (No. 30) | 16 |
| 300 µm (No. 50) | 11 |
| 150 µm (No. 100) | 7.9 |
| 75 µm (No. 200) | 5 |

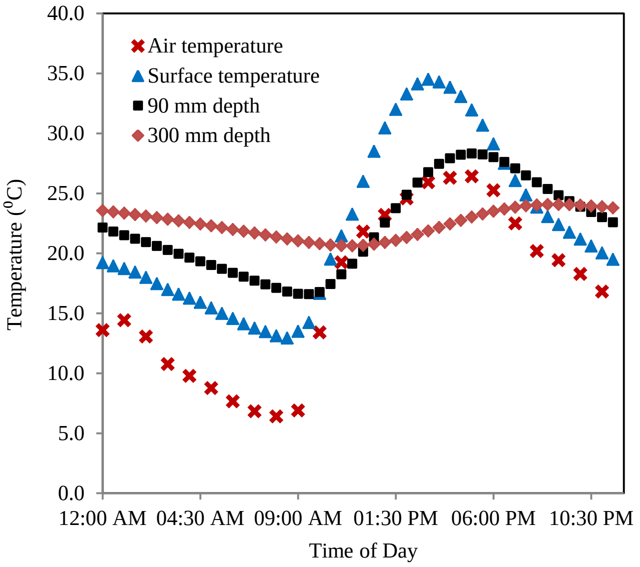

**Fig. 3.** Temperature Variation over the Day on October 24, 2012.

The temperature variation is reasonable as some time is required to penetrate the heat from the surface to the underneath material. When the air temperature decreases, the pavement temperatures also decrease. It takes some time for the pavement material to release the heat. Therefore, the surface temperature is higher than the air temperature. When the air temperature increases, the surface material absorbs the heat from solar light. Thus, the temperature remains higher than the air temperature. The same trend is observed for 90 mm depth. For the other depths, the temperatures are above the air temperature at night and lower in the afternoon and evening.

### Horizontal Strain

Fig. 4 shows the variations of thermal strain and the envelope of the thermal and vehicle induced horizontal strain at the bottom of the HMA layer on October 24, 2012. The thermal strains at 12:00 am (mid-night) are considered the reference to plot the variations. The peak-to-peak thermal strain at the bottom of AC is 342 microstrains (µε or µm/m) on that day. Thermal strain means the strain which develops for thermal expansion and contraction of HMA for day-night temperature variations. The horizontal strain for 0.83 MPa (120 psi) vehicle load is 71 µε in the morning and 86 µε in the afternoon, 1.21 times higher than the strain in the morning. This

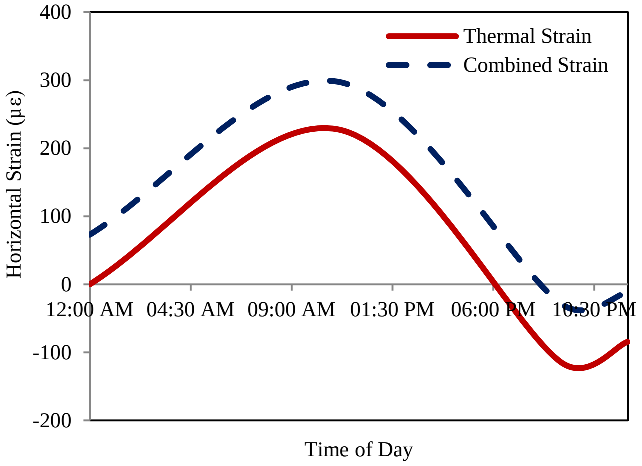

**Fig. 4.** Horizontal Strain at 300 mm Depth on October 24, 2012.

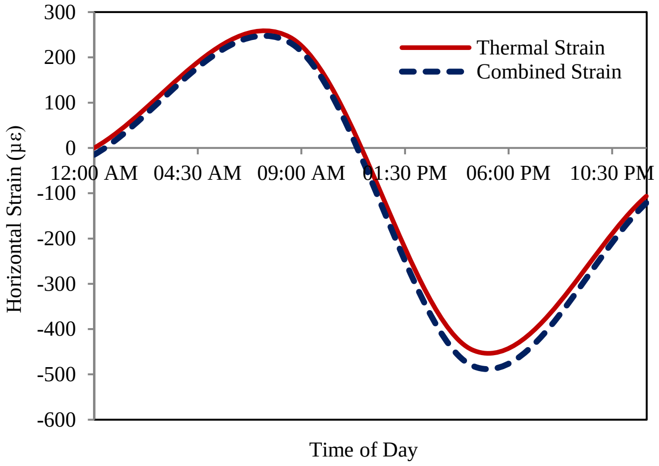

**Fig. 5.** Horizontal Strain Variations at 90 mm Depths on October 24, 2012.

structural response has also been analyzed for some other days. These factors are 1.41, 1.34, 1.16 and 1.15 for July 08, July 17, September 15 and November 4, 2012 respectively. It can be observed that this factor is higher in the summer than that of in the fall.

Regarding sign convention, vehicle induced tensile strain is tensile at the bottom of asphalt concrete. Thermal strain increases (towards tensile) with decrease in pavement temperature and vice versa. If the mid-night (12:00 am) is considered the datum, thermal strain is positive in early morning and negative (or sometimes close to zero) in the afternoon.

The horizontal strain variations for thermal loading and for the combined thermal and vehicle loading are shown in Fig. 5 for the depth of 90 mm. The peak-to-peak thermal strain at the bottom of AC is 690 με on October 24, 2012. The horizontal strain for 825 kPa (120 psi) vehicle load is -12 με in the morning and -35 με in the afternoon, 2.92 times higher than the strain in the morning. The negative sign of the strain means the horizontal plane is located at the upper zone (compressive zone) of the neutral axis.

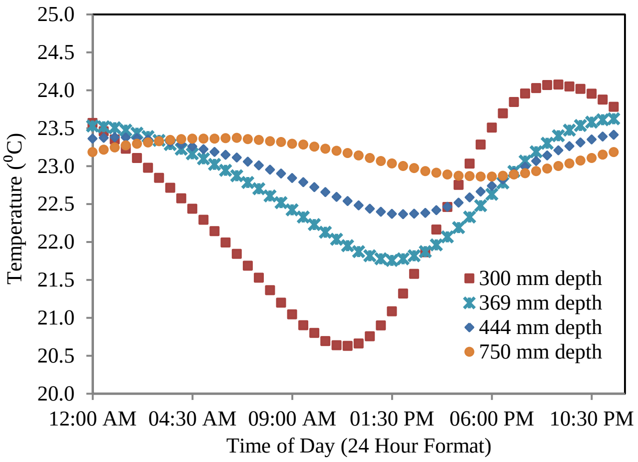

**Fig. 6.** Temperature Variations at Different Depths on October 24, 2012.

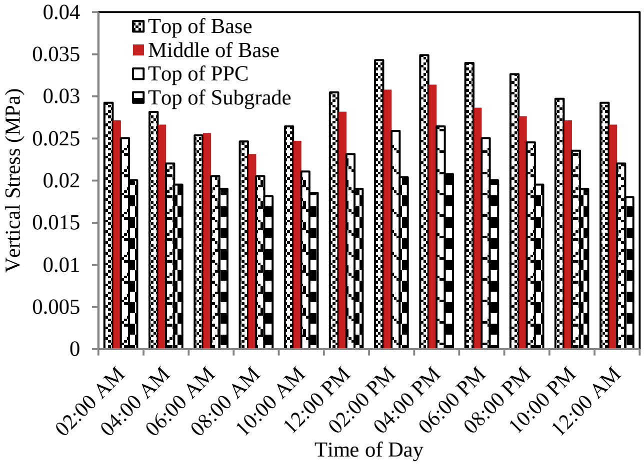

**Fig. 7.** Vertical Stress at Different Depths on October 24, 2012.

## Vertical Stress

The vertical stresses are measured at four different depths of the pavement (i.e., on the top of the base, at mid-base, on the top of the PPC and the Subgrade); the corresponding depths are 300 mm, 369 mm, 444 mm and 750 mm respectively. The temperature variations at these four depths are plotted in Fig. 6. The temperature differentials decrease with increase in depth. The peak-to-peak temperature difference at 300, 369, 444 and 750 mm depths are 3.4, 1.9, 1 and 0.5℃, respectively, on the October 24, 2012.

The vertical stress decreases with increase in depth at any time of a day. These stress distributions over the day for a 0.083 MPa (120 psi) vehicle at the four different depths are plotted in Fig. 7. The stress magnitude decreases after midnight and reaches the minimum around 8:00 am in the morning. Then, it increases with daylight and reaches the summit around 4:00 pm. The minimum temperatures at different depths were measured between 12:00 pm and 6:00 pm as shown in Fig. 6. Therefore, the temperature variations of the above materials have the direct impact on the stress value at different layers of pavement.

The minimum stress on the top of the base, at the middle of the base, on the top of the PPC and the Subgrade are 0.025 MPa (3.58 psi), 0.023 MPa (3.36 psi), 0.021 MPa (2.98 psi) and 0.018 MPa (2.63 psi) respectively. The maximum values at these depths are 0.035 MPa (5.06 psi), 0.031 MPa (4.55 psi), 0.026 MPa (3.83 psi) and 0.02 MPa (3.01 psi) respectively. Therefore, the stresses in the afternoon are 1.42, 1.36, 1.29 and 1.15 times higher than the stresses in the morning. These increases in stress values at different depths of the pavement for a couple of days during June–November 2012 are listed in Table 2. The increase in modulus decreases with the depth of the pavement. For instance, the moduli increase to 1.43 and 1.23 times at the bottom of asphalt layer and the subgrade, respectively, on June 08, 2012. Another observation is that the degree of increase is greater in summer (June–September) when the temperature differential is normally greater.

Fig. 7 shows that the minimum and the maximum vertical stress are obtained at 8:00 am and 4:00 pm respectively. The stress variations at the bottom of the asphalt and the surface temperatures are correlated in Fig. 8. The vertical stress increases with surface temperature. The best fitted trend lines are drawn in linear and exponential assumptions. Both of these assumptions produce the coefficient of determination ($R^2$) value close to unity. Therefore, conclusion can be drawn that linear assumption is sufficient enough to correlate the vertical stresss at the bottom of the AC with surface temperature. However, the exponential relationship is more accurate than the linear assumption which agrees with the available research.

The increase in vertical stresses at other depths (middle of base, top of PPC and top of subgrade) with surface temperature are plotted in Fig. 9. It is observed that the trends of vertical stress at the other depths are similar to stress at the top of base. The effect of surface temperature decreases with increase in depth. The variations are linear at the beginning. However, the last data shows that these are exponential at higher temperatures.

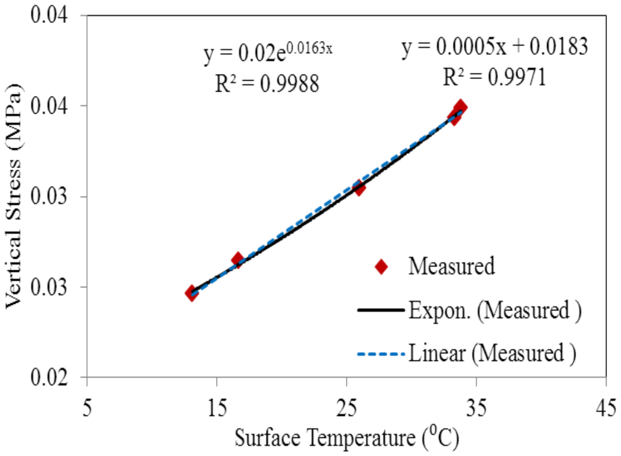

**Fig. 8.** The Variations of Vertical Stress at the Bottom of HMA with Surface Temperature.

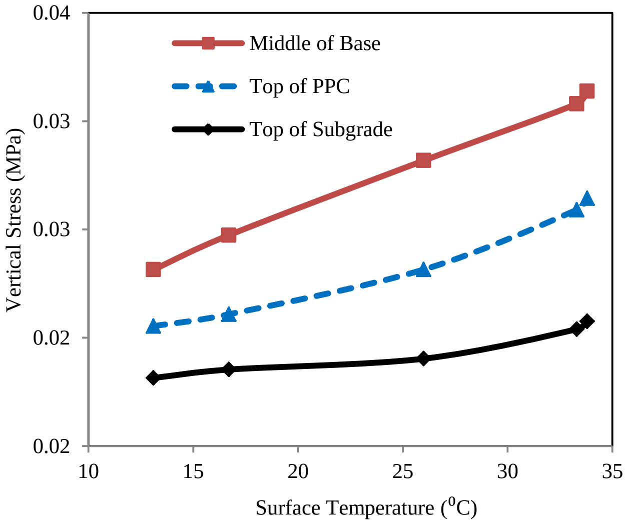

**Fig. 9.** Variations of Vertical Stresses with Surface Temperature at other Depths.

## Application Notes

This study discusses the diurnal variation of stress and strain in flexible pavement. It dictates that the horizontal strain is critical only in the morning. The strain is in compressive zone in the afternoon. Therefore, the morning time vehicle should have higher impact on pavement design and much more precaution is to be adopted in characterizing traffic in the morning, especially for fatigue life analysis. In addition, the slow moving heavy vehicle, which generally produces greater strain than that of fast moving vehicle, may be debarred to the pavements which are susceptible to be failed in fatigue. In addition, the thermal strain at any depth of the pavement is much greater than the vehicle produced strain. This should be considered for reducing the probability of low temperature cracks, longitudinal surface down crack and fatigue crack.

On the other hand, the vertical stress is higher in the afternoon for decrease in modulus value for greater temperature, up to 1.88 times, as measured in this study. Therefore, the potentiality of rutting is higher in the afternoon. For reducing rut depth, heavy and slow moving traffic may be discouraged in the afternoon for the pavement which has greater possibility of rutting. It can also be concluded that the diurnal vertical stress and horizontal strain variations are higher in the summer than those in the fall, considering this small span of data. A complete seasonal effect is not included for lack of whole year data.

**Table 2.** Increase in Vertical Stress in the Afternoon.

| | Top of Base | Middle of Base | Top of PPC | Top of Subgrade |
|---|---|---|---|---|
| June 08, 2012 | 1.88 | 1.69 | 1.41 | 1.32 |
| June 09, 2012 | 1.75 | 1.53 | 1.34 | 1.23 |
| July 08, 2012 | 1.63 | 1.57 | 1.40 | 1.24 |
| September 15, 2012 | 1.48 | 1.42 | 1.31 | 1.21 |
| October 24, 2012 | 1.42 | 1.36 | 1.29 | 1.15 |
| November 3, 2012 | 1.41 | 1.40 | 1.32 | 1.18 |

## Conclusions

The present study describes the thermal stress without vehicle load and thermal effect on stress and strain response of pavement material for moving vehicle load. The study also presents the diurnal vertical stress and horizontal strain variations in flexible pavement. Note that this study did not consider the thermal effect on the installed sensors. The material property of the sensors may change with temperature which may cause little change in results. Based on the field measured stress and strain the following conclusions can be drawn:

- The structural responses at the different layers of pavement are largely dependent of the temperature variations of the day.
- The vertical stress and the horizontal strain at any depth of the pavement are smaller in the morning when the temperature is lower and larger in the afternoon when the temperature is higher.
- The vertical stress at any depth of the pavement varies linearly in small surface temperature range and exponentially with larger surface temperature range.
- Horizontal thermal strain at any depth of the pavement is normally tensile in the morning and compressive in the afternoon. This effect must be considered in design and analysis of pavement.

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## References

1. Ovik, J.M., Birgisson, B., and Newcomb, D.E. (2000). Characterizing seasonal variations in pavement material properties for use in a mechanistic-empirical design procedure, *Report No. MN/RC-2000-35*, Submitted to Minnesota Department of Transportation, St. Paul, Minnesota, USA.
2. Drumm, E.C. and Meier, R. (2003). LTPP data analysis: Daily and seasonal variations in in-situ material properties, NCHRP Wed Document 60 (Project 20-50 [7/12]): Contractor's Final Report, National Cooperative Highway Research Program, Transportation Research Board, Washington DC, USA..
3. Schwartz, C. and Carvalho, R. (2007). Evaluation of Mechanistic-Empirical Design Procedure, Final Report, MDSHA Project No. SP0077B41, UMD FRS No. 430572, Office of Material Technology, Maryland State Highway Administration, Lutherville, MD, USA.
4. Orr, D.P. (2005). Seasonal variations of in situ materials properties in New York State: FWD testing and data analysis to define seasonal variability, *CLRP Report No. 05-01*, New York State Department of Transportation, New York, USA.
5. Figueroa, J.L. (2001). Monitoring and analysis of data obtained from moisture temperature recording stations, Final Report, Job No. 14589(0), Report No. FHWA/OH-2001/09, Ohio Department of Transportation, Columbus, OH, USA.
6. Swett, L.J. (2007). Seasonal variations of pavement layer moduli determined using in situ measurement of pavement stress and strain, M.S. Thesis, Department of Civil and Environmental Engineering, University of Maine-Main, USA.
7. Al-Qadi, I. (2004). The Virginia smart road: The impact of pavement instrumentation on understanding pavement performance, *Journal of Association of Asphalt Paving Technologists*, 73, pp. 427-466.