Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 5(2):121-127

Assessment of Stress and Strain Instrumentation in Accelerated-Pavement Testing

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Abstract: Pavement sensors are widely used in accelerated pavement facilities and in full-scale instrumented test sections to allow for validation of analytical models and to assess the effects of different control variables such as temperature and tire configurations. In spite of their essential role in instrumented facilities, only a limited number of studies have been conducted to assess the accuracy, repeatability, and survivability of pavement sensors. The primary objective of this study was to determine the survivability and repeatability of stress and strain measurements. In addition, seasonal variation and the use of sensor technology to monitor the evolution of pavement damage at the Louisiana Accelerated Load Facility (ALF) were investigated. Pavement performance and responses were analyzed over a 40-month period in which 625,000 cycles were applied on the test section. Results of this analysis indicated that repeatability and survivability of strain and stress sensors were acceptable. In addition, pavement responses were strongly influenced by the temperature during testing.

***Key words**: Pavement damage; Pavement instrumentation; Seasonal variation.*

Introduction

Accelerated-pavement testing (APT) provides an economical and beneficial solution to assess the validity of mechanistic-empirical pavement design methods in an environment that closely resembles actual in-service field conditions. Such facilities provide an accurate measure of pavement performance under controlled loading conditions at a relatively moderate cost. Construction practices are the same as in real field conditions, and the level of confinement is similar to pavement operating conditions. In addition, incorporation of pavement instrumentation with APT allows the validation of analytical models as well as the calibration of model response variables based on actual field data [1]. Pavement instrumentation also helps researchers develop a better understanding of pavement responses, which is essential if accurate design routines are to be developed. It also contributes to the understanding of the effects of different control variables, such as temperature, moisture, and tire configurations, which are often approximated in current pavement design methods.

Since their introduction in the early 1900s, pavement sensors have considerably evolved and are now capable of providing stable and durable measurements of pavement responses if properly installed and calibrated [2]. Different types of sensors are now available to measure strain, stress, deflection, temperature, frost depth, and moisture. Despite their wide use in APT facilities and in full-scale instrumented test sections, only a limited number of studies have been conducted to assess the accuracy, repeatability, and survivability of pavement sensors. This is an important issue in order to quantify pavement performance, given that the evolution of damage is the primary indicator of failure progresses in pavement systems. To date, only a few attempts were made to tackle these problems, as the scarcity of experimental measurements did not allow for setting a valid ground for assessment.

To this end, the primary objective of this study was to determine the survivability of sensors once in service and repeatability of stress and strain measurements. In addition, seasonal variation and the use of sensor technology to assess the evolution of pavement damage were investigated at the Louisiana Accelerated Load Facility (ALF). Pavement performance and responses were analyzed over a 40-month period to assess the repeatability and survivability of stress and strain measurements, seasonal and thermal variations, and the feasibility of using instrumentation to monitor evolution of pavement damage.

Background

Sensor Technology

When instrumenting a pavement structure, response parameters such as vertical stress, horizontal and vertical strains, and deflections are of primary interest. However, environmental parameters such as temperature, frost depth, and moisture content are also needed if pavement response data are to be thoroughly interpreted. For a successful instrumentation strategy, at least two types of response (stress, strain, or deflection) should be compared simultaneously [2]. However, earlier research has emphasized the importance of stress and strain measurements to predict pavement performance, given that a direct correlation does not exist between these responses and pavement surface deflection [2]. Unfortunately, accurate measurement of these quantities is a difficult task and requires adequate selection, calibration, and installation of pavement instrumentation. The following sections provide an overview of pavement strain and stress sensors technology.

Strain Gauges

Strain responses in bituminous layers are usually measured using

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Note: Submitted September 15, 2011; Revised September 30, 2011; Accepted October 5, 2011

electrical resistance strain gauges. When a strain occurs in the pavement, a thin wire inside the gauge is stretched, which causes a change in its electrical resistance. The major problem with this type of gauge is its durability. If the high strain that the gauge is subjected to during construction exceeds its range of operation, it may be damaged or destroyed. Therefore, major improvements have been introduced to increase the fatigue and moisture resistance of these gauges. The most common types of electrical resistance strain gauge used in bituminous materials are the Kyowa strain gauge, the Dynatest® H-type strain gauge, and foil-type strain gauge.

Stress Sensors

Earth pressure cells (also called soil stress gauges) consist of a pressure sensor with a transducer to convert the pressure into a measurable signal [3]. The most common type of pressure cells is the diaphragm cell. The principle of these transducers is that a pressure acting on the diaphragm of the cell will cause a deflection that can be transformed into an electrical signal by strain gauges attached to the inside of the diaphragm [4]. This type of pressure cell has been shown to provide a linear response to the applied stress, regardless of the surrounding stiffness. Two factors affect pressure cell performance: the ratio of the gauge thickness to its diameter (aspect ratio) and the ratio of the gauge stiffness to that of the surrounding material. Ullidtz found that the recorded and correct stresses would be close if the aspect ratio is very small and the ratio of stiffness very high, which means that the cell should be very stiff compared to the surrounding material [4].

Evolution of Pavement Damage

Pavement distresses may be related to a number of factors including traffic, environment, and construction and material deficiencies. Three main Hot-Mix Asphalt (HMA) distresses are directly related to traffic loading (other factors such as construction deficiencies may contribute to the acceleration of the deterioration): fatigue, rutting, and top-down surface-initiated cracking. While the progression of rutting and top-down cracking damage may be evaluated directly by the increase in damage at the pavement surface, fatigue cracking can only be assessed after failure has occurred and propagated to the surface. Therefore, the use of instrumentation would be beneficial to monitor the progress of fatigue damage prior to its propagation to the surface.

Fatigue cracking is due to the cyclic application of traffic loading. This failure mechanism is usually related to the tensile strain at the bottom of the HMA layers, which can be measured using strain sensors. The evolution of fatigue damage consists of three main stages [5]: (1) initial reorientation of the material; (2) steady state fatigue crack growth in which the evolution of fatigue damage is fairly constant; and (3) unstable crack growth in which the rate of damage increases rapidly as failure is imminent. Under constant stress amplitude such as in APT, tensile strain in the material is expected to increase gradually while stiffness would gradually decrease as cyclic softening of HMA is observed. The extent of pavement damage may be affected by the rate of loading, the use of traffic wander, and possible delays in the experiment. It is also noted that fatigue damage may result without any visible sign of crack as the result of the growth of micro-cracks and the gradual loss of cohesion of the mix under repeated loads [6].

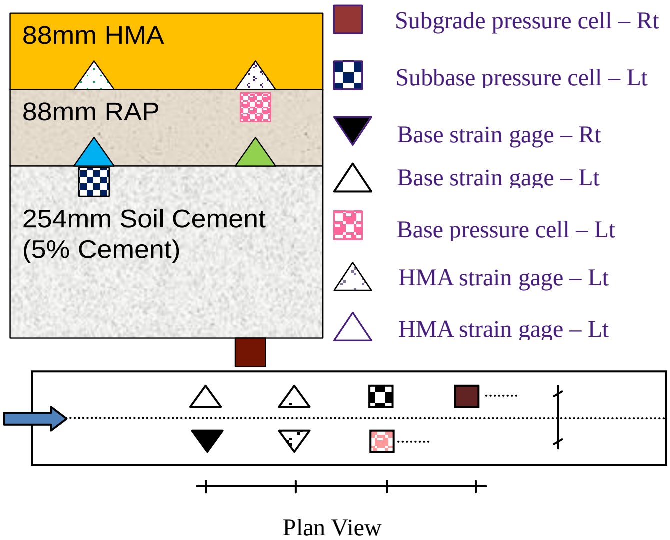


Fig. 1. Pavement Design and Instrumentation Plan in Test Lane 3-1.

Experimental Setup

The Louisiana Accelerated Loading Facility

The Louisiana Accelerated Loading Facility (ALF) is a full-scale transportable pavement test device that simulates the effect of traffic loading on full-scale pavement by applying controlled wheel loading in a repetitive manner [7]. This setup has the same design as the ones located at the Turner-Fairbanks Highway Research Center; however, temperature at ALF is not controlled during testing. This loading system applies a constant truck wheel load at a speed ranging from 13 to 19 km/h. The loading length of the ALF is 26 m with approximately 10 m of constant velocity loading of the wheel. The load applied on the pavement can be varied from a wheel weight of 43.4 kN to 111.25 kN by adding static load plates.

This study deals with the results of Lane 1 in Experiment III, which was designed and constructed to evaluate the feasibility of using Reclaimed Asphalt Pavement (RAP) materials as an aggregate interlayer. Although this study focuses on the results of the first lane, two additional lanes were constructed and tested to compare the performance of the RAP interlayer to a regular granular base layer. The results of the evaluation of the effectiveness of the RAP interlayer as a stress-relieving layer between a cement-treated subbase and HMA, in lieu of crushed stone, have been presented elsewhere [8]. Fig. 1 illustrates the pavement design in this test section (Lane 1). A 38-mm layer of surface mixture was placed on top of a 50-mm binder course. The binder course was placed on top of an 88-mm RAP interlayer and a 254-mm cement-stabilized subbase layer.

Normal construction practices were followed according the Louisiana Standard Specifications for Roads and Bridges. Construction of the test lanes consisted of first removing three existing test lanes down to the top of the existing embankment. A perforated drainpipe system was then installed along the test section on both sides. The stabilized subbase layer was subsequently constructed with 5% cement content. Compaction of the stabilized subbase was monitored using nuclear density gauge and revealed an average percentage of compaction of 99.4%. Compaction of the RAP interlayer was achieved using a steel roller with no vibration. This interlayer was placed similar to a granular base layer by mixing it with water (7.1% moisture content) to aid in the compaction process. The HMA mixture was placed according to the Louisiana Department of Transportation and Development (LADOTD) specifications; volumetric and density properties were acceptable. More details about the construction process have been presented elsewhere [7].

Instrument Description and Installation

All instruments were embedded in the pavement sections during construction. Load-associated instruments included pressure cells and strain gauges, which were installed at the bottom of the different pavement layers (Fig. 1). Instruments were placed 381 mm apart in the longitudinal direction and 190mm from the centerline of the lane in the transverse direction. Three pressure cells, manufactured by Geokon, were used to measure vertical stress in the pavement system. This sensor consists of two circular steel plates welded together around their rims to create a cell approximately 225 mm in diameter and 6.35 mm thick. External pressure acting on the cell is balanced by an equal pressure induced in an internal fluid placed inside the gauge. This sensor has a pressure range of up to 690 kPa.

The responses of TML model KM-100-HAS strain gauges were used in this study to measure the longitudinal strain in the pavement structure. This model is a full bridge, with a 350-Ω resistance and a strain capacity of ±5,000 μstrain. These gauges were reported to provide excellent durability and robustness with a survivability rate of 96% during the paving process [9]. In the described experiment, none of the four strain gauges failed during construction. However, since the focus in this study is given to measurements made in the bonded layers, only the results of the two gauges in the HMA are presented.

Pressure cells were installed in this section so that the bottom side was leveled with the top of the RAP interlayer and the cement-stabilized subbase. A hole was dug to accommodate the fluid-housing unit of the pressure cell, and the gauge was then leveled in its position. Any angular aggregates were manually removed to protect the sensitive side of the gauge. A thin layer of sand was then placed beneath the sensitive side to avoid tilting of the gauge during construction. Installation of the H-type strain gauges was a delicate operation. When gauges are installed in a HMA layer, as in this project, they can be subjected to very large strains during compaction of the pavement layer. After installation, the major problem involves damage caused by moisture. The gauges may also suffer from fatigue before the HMA does. In this segment of the project, correct alignment and leveling of the gauge was first checked. A small quantity of binder was then poured around the gauge to ensure correct alignment and that the gauge would not move during construction. Loose mixture was then placed on top of the gauge and manually compacted to provide a protective layer against direct contact with the paver and excessive compaction effort. Vibration was not allowed within approximately 1.5 m from the gauge location.

The data acquisition system used in the experiment was a Megadac 3415A and was programmed to collect data at a frequency of one measurement every 0.005sec to ensure continuous measurements as the wheel travels on top of the pavement. It had up to 512 channels and 64 megabytes of internal non-volatile onboard memory. The software used to control the data acquisition system was Optim’s TCS95. This software was used like a workbook, where all information about the test definition was stored in a unique TCS test file. Sensors’ data were extracted from the TCS software to Microsoft Excel, where analysis of the data was conducted. No filtering or smoothing was applied to the data in this study.

Testing Process

In the presented experiment (Experiment III), a dual 11R22.5 radial ply truck tire maintained at a constant speed of 17km/h was used. In average, 35,000 repetitions per week were applied. Three load levels were applied with a wander distribution of ±381mm around the lane centerline. In the first stage, a load of 43.4kN was applied for 200,000 cycles. In the second stage, a load of 53.6kN was applied for an additional 325,000 cycles. In the third and final stage, a load of 63.8kN was applied for an additional 150,000 cycles. It was estimated that approximately 2.3×10^6 Equivalent Single Axle Loads (ESALs) were applied over the course of this experiment. It took approximately three years and four months to apply these loading cycles on the three lanes. The loading was applied alternatively between the test lanes in 25,000 pass increments in an attempt to minimize environmental effects and seasonal variations between the three test lanes.

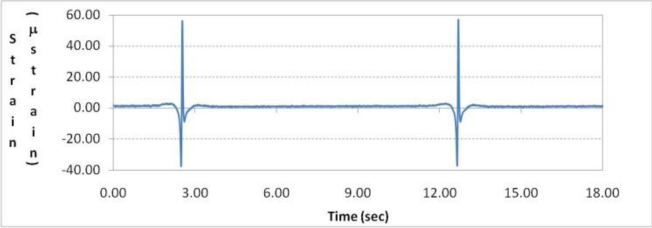
Rutting measurements were conducted after each increment of 25,000 load applications using the ALF profilograph. Rutting ranging between 10 mm and 19 mm was defined as the failure condition for the pavement. Field measurements also included Falling Weight Deflectometer (FWD) deflection testing, crack survey, and assessment of mix densification using a Pavement Quality Indicator (PQI). Rutting measurements and a pavement crack survey showed that Lane 1, which is evaluated in this study, exhibited superior performance when compared to the other two test lanes with only 5 mm rutting after 525,000 cycles and 10mm surface rutting at the end of the experiment. No major surface cracks have been observed in this test lane throughout the experiment. More details about the performance of the test lanes have been presented elsewhere [8].

Results and Data Analysis

Field measurements were used to assess repeatability of stress and strain measurements, seasonal variations, and the use of sensor technology to monitor the evolution of pavement damage.

Instrument Responses to Vehicular Loading

Fig. 2(a) presents a typical strain signal measured at a depth of 88mm after 50,921 cycles, as multiple passes are applied directly on top of the sensors. These signals agree with the characteristics of



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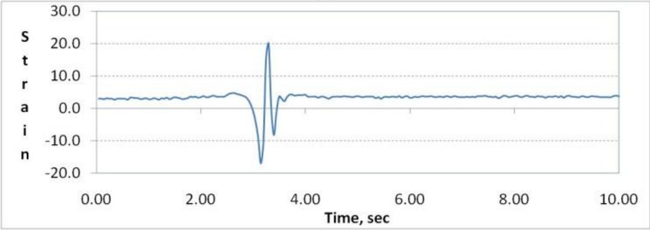
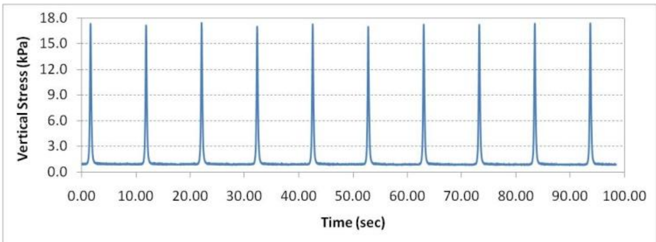


(b)

Fig. 2. Typical measured longitudinal Strain at the Bottom of the HMA Layers (88.1 mm) after (a) 50,921 and (b) 365,000 Passes.



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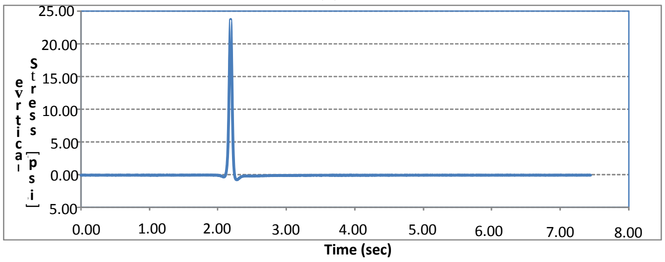


(b)

Fig. 3. Measured Vertical Stress (a) on Top of the Subgrade Layer (225,000 Passes); (b) at the Bottom of the Surface Layers (225,000 Passes).

these measurements as reported by past investigators [10, 11]. The longitudinal strain response first shows compression, then tension, and finally compression again. The second compression peak is always lower than that of the first, and it was sometimes non-existent in the measurements. The longitudinal strain measurements were consistent until approximately 350,000 passes; after that, the signals appeared noisier but the peak response could still easily be extracted, see Fig. 2(b).

Fig. 3(a) presents a typical stress signal measured at a depth of 430 mm as multiple passes are applied directly on top of the sensors. Due to the dynamic nature of the load, pressure cell response coincided with the vertical principal stress only when the wheel was exactly on top of the instrument. The width of the response depends mainly upon the speed of the vehicle and the depth of the measurement. As expected, mostly compressive stress was

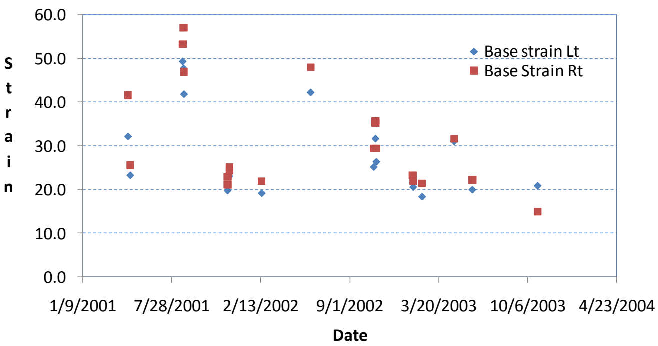


Fig. 4. Longitudinal Strain Measurements at the Bottom of the HMA Layers (88.1 mm).

measured in the vertical direction. However, a small tension at the beginning and the end of the vertical stress pulse was observed in the pressure cell located at the bottom of the HMA layers after 225,000 passes, Fig. 3(b). This may be due to slight tilting or failure of the cell as the number of passes increased or as the load level was raised. Pressure cell data after 225,000 passes were not used in the presented analysis, as they appeared inaccurate.

Strain Measurements Repeatability

Fig. 4 presents the measured longitudinal strain throughout the experiment; numerical values are given in Table 1. The two strain gauges presented in this figure are at the same depth of 88 mm (at the bottom of the HMA layers). However, one of the strain gauges (Base Strain Lt) was installed underneath the left wheel of the dual tire while the second strain gauge (Base Strain Rt) was installed underneath the right wheel. The data presented in Fig. 4 represent the maximum response for ten subsequent passes at a given time and date. The variability (coefficient of variation) between subsequent passes on the same date and time is presented in Table 1.

As shown in Fig. 4, the two sensors provided the same trend of measurements in which considerable variation is noticed due to seasonal variations (i.e., increase in strain during the summer seasons) and increase in number of passes (i.e., overall decrease in the strain measurements). The average coefficient of variation between the two sets of measurements was 7.5%. A statistical analysis of variance was conducted between the two sets of measurements presented in Table 1 and revealed that the two data groups are not statistically different (Number of observations = 20; $F = 0.61$; $F_{critical} = 4.1$; and $P = 0.44$).

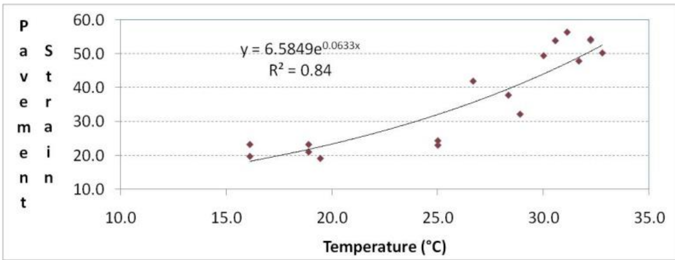
Thermal Variation

Due to the viscoelastic nature of HMA, significant variation in the measured response is expected with the change in temperature. Fig. 5(a) illustrates the change in the measured strain at the bottom of the HMA with the change in ambient temperature for the first load level (i.e., up to 200,000 passes). As shown in this figure, pavement strain was found to vary exponentially with temperature, which is in agreement with the findings of previous research studies [11, 12]. While the measured strain was influenced by the change in temperature, it is expected that other factors such as change in

Table 1. Longitudinal Strain Measurements at the Bottom of the HMA Layers.

Measurement ID (1)	1 (2)	2 (3)	3 (4)	4 (5)	5 (6)	6 (7)	7 (8)	8 (9)	9 (10)	10 (11)
Passes	25,060	47,505	75,030	93,079	99,635	160,175	160,361	160,547	160,733	175,000
Temperature (^oC)	28.9	18.9	30.0	31.7	26.7	16.1	16.1	25.0	25.0	19.4
Base Strain Gage (Lt)	32.2	23.3	49.4	47.8	41.9	23.3	19.8	23.1	24.4	19.2
COV (%)	0.8	0.7	0.7	1.7	0.7	4.6	1.7	0.6	0.9	1.0
Base Strain Gage (Rt)	41.6	25.6	53.3	57.0	46.9	23.0	21.2	24.4	25.2	21.9
COV (%)	1.2	1.5	1.1	1.7	0.6	0.7	1.1	0.9	1.2	0.8

Measurement ID (1)	11 (2)	12 (3)	13 (4)	14 (5)	15 (6)	16 (7)	17 (8)	18 (9)	19 (10)	20 (11)
Passes	200,360	225,000	237,031	237,356	248,143	250,000	275,365	349,000	365,000	487,000
Temperature (^oC)	30.6	21.7	20.6	21.1	16.7	21.7	13.3	23.3	28.9	25.0
Base Strain Gage (Lt)	42.3	25.2	35.8	31.7	26.4	21.5	18.4	31.1	20.0	20.9
COV (%)	1.9	1.1	0.5	2.0	0.6	0.8	0.9	1.2	0.7	1.5
Base Strain Gage (Rt)	48.0	29.5	35.8	35.2	29.4	23.3	21.4	31.7	22.2	15.0
COV (%)	2.0	0.7	0.6	0.6	0.6	0.8	1.1	0.9	1.8	1.1



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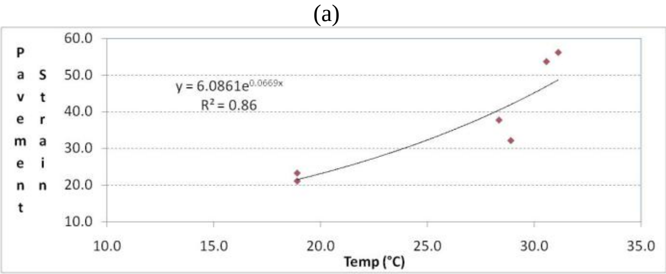

(b)

Fig. 5. Variation of Longitudinal Strain with Ambient Temperature (a) Throughout the Experiment and (b) in the Early Loading Stage.

measurement conditions and materials' damage need to be considered to explain change in strain throughout the experiment. These factors are discussed further in the subsequent sections of this paper.

Fig. 5(b) illustrates the variation of the measured strain in the early stage of the experiment (up to 50,000 passes). In this stage, minimum change is expected in the pavement and measurement conditions. As shown in this figure, a similar exponential regression line may be used to fit the data in this case. To level the effect of temperature from the measurements, this regression equation was used to determine the response at a reference temperature of 25℃ using correction factor determined from the following model:

$$CF = e^{0.0669(T-25)} \qquad R^2 = 0.86 \tag{1}$$

where CF = correction factor to shift measured strain from a temperature T to a reference temperature of 25℃. Fig. 6 presents

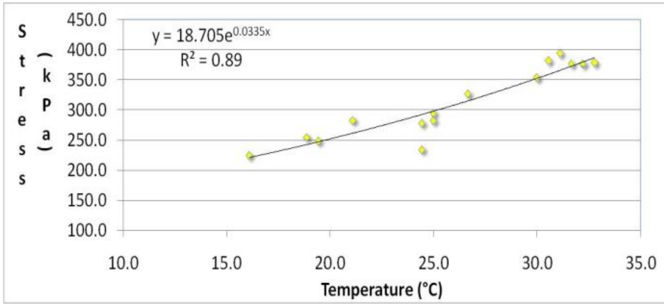

Fig. 6. Variation of Vertical Stress with Ambient Temperature.

the change in the measured vertical stress at the bottom of the HMA layer as a function of temperature. As shown in this figure, measured stress was also found to vary exponentially with the change in temperature. Similarly, a regression model was developed to shift the measured stress to a reference temperature of 25℃:

$$CF = e^{0.0344(T-25)} \qquad R^2 = 0.99 \tag{2}$$

Evolution of Pavement Damage

Based on Eqs. (1) and (2), measured responses were shifted to a reference temperature of 25℃. Shifting of the measurements allowed characterizing the effect of pavement damage without confounding it with the effect of temperature. Fig. 7 illustrates the variation of the temperature-corrected strain at the bottom of the HMA layers with the number of passes. As shown in this figure, the measured strain increased slightly at the beginning of the experiment but then decreased progressively with the increase in number of passes. After the second load level was applied, an increase in strain was noted followed by a gradual decrease in the response. Although it is expected that with the increase in pavement damage, the measured strain would gradually increase, indication of material weakening, a reversed trend was observed. Similar trends were observed in a past experiment at the Louisiana Accelerated Loading Facility [13].

A number of hypotheses may explain this phenomenon; however,

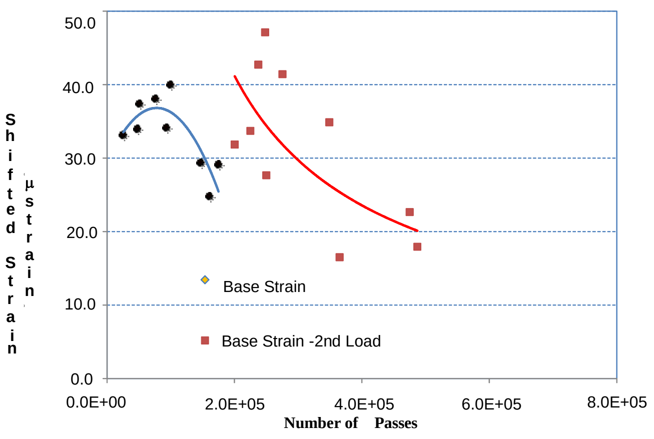

Fig. 7. Variation of Longitudinal Strain with Number of Passes.

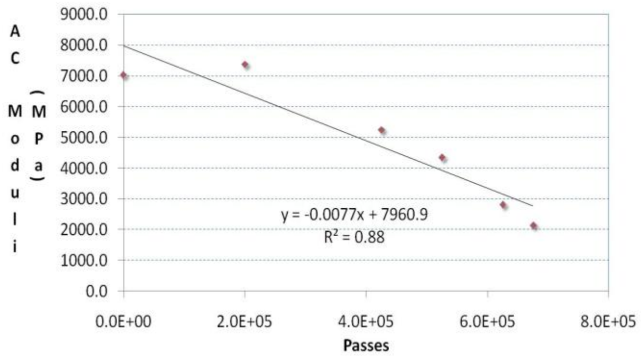

Fig. 8. Variation of Backcalculated HMA Moduli with the Increase in Number of Passes.

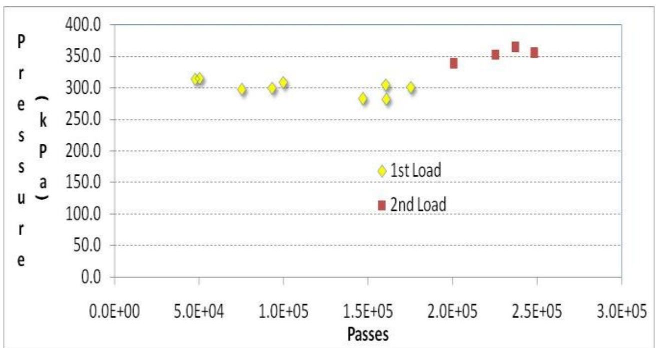

Fig. 9. Variation of the Vertical Stress at the Bottom of the HMA Layers with the Number of Passes.

validation is needed in future studies. One possible explanation is that with the increase in number of passes, the strain gauges dispersed the material around them, resulting in less contact with the surrounding medium and, therefore, a smaller strain was measured. This hypothesis is supported by the results presented in Fig. 8, which shows that the backcalculated HMA moduli from FWD testing decreased continuously throughout the experiment indicating progressive damage of the material. These FWD tests were conducted at a relatively uniform temperature ranging from 38°C to 45°C. Other factors may also contribute to this trend such as stiffening or fatigue of the gauge, crack initiation near the gauges, and debonding with the surrounding medium.

Fig. 9 presents the variation of the temperature-shifted vertical stress with the number of passes. As shown in this figure, measured vertical stress remained constant with the increase in number of passes during the first load level. After the second load level was applied, an increase in vertical stress occurred, followed by a constant response. As it was previously noted, responses of the gauge after 225,000 passes were not used in the analysis. This behavior was expected since the stress applied on the material mainly depends on the magnitude of the external load and not on the level of damage in the material.

Conclusions and Recommendations

The primary objective of this study was to determine the survivability and repeatability of stress and strain measurements. In addition, seasonal variations and the use of sensor technology to monitor the evolution of pavement damage in APT facility were investigated. Based on the results of this analysis, the following conclusions may be drawn:

- Repeatability of strain measurements is acceptable and is supported statistically by comparing the responses of the gauges located at the bottom of the HMA layers. The average coefficient of variation between the two gauges was 7.5%. Throughout the experiment, variability between successive passes was less than 5%.
- Survivability of the gauges was acceptable as none of the gauges failed during installation. After construction, longitudinal strain measurements were consistent until approximately 350,000 passes; after that, the signals appeared noisier but the peak response could still easily be extracted. The pressure cell provided accurate measurements until 225,000 passes. After that, the gauge appeared to be failing.
- Pavement responses are strongly influenced by the temperature during testing. An exponential model provided acceptable description of this variation.

Further research is recommended to confirm findings and validate hypotheses laid down in this study. While current sensor technology provides repeatable and reliable measurements of pavement responses in the initial stages of loading, new technology is needed to obtain accurate characterization of damage evolution in pavement. While this research investigated repeatability and survivability of pavement sensors, it is recommended that future research evaluate the accuracy of the stress and strain measurements as well as the influence of installation methods on sensors' readings.

Acknowledgements

The financial support provided by the Louisiana Transportation Research Center (LTRC) is greatly appreciated. The authors would like to acknowledge the assistance of K. Gillespie, G. Crosby at the Pavement Research Facility of LTRC, and M. Davis, and J. Chatagnier of Louisiana State University.

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