Characterization of Seasonal Variations on Airport Pavement Layer Responses using In-Situ Measurements

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ABSTRACT

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In order to investigate seasonal effects on airport asphalt pavement, the FAA Airport Technology R&D Branch performed full-scale loading tests on the instrumented Falling/Heavy Weight Deflectometer (F/HWD) round up asphalt pavement test section. The pavement responses under the Heavy Weight Deflectometer (HWD) and the moving traffic loading were collected in April and August 2018, respectively. Two computer programs were utilized in the analysis of the field tests: LEAF, a computer program for the static analysis of asphalt concrete pavements; and SAPSI, a computer program for the dynamic analysis of asphalt concrete pavements based on the linear viscoelastic layer theory. This paper performed a case study on the responses of embedded gauges under the HWD loading during two seasons. It was found that: 1) Temperature significantly affected the Hot Mix Asphalt (HMA) modulus and the stress of the subgrade; 2) Static backcalculation generated values that were three times higher than the modulus used in pavement design; and 3) Compared to the dynamic model, the static model overestimated the pavement responses (stresses).

BACKGROUND

Asphalt concrete (AC) layers exhibit strong temperature-dependent behavior resulting in seasonal variation in their modulus throughout the life of a pavement, the surface deflection data can identify the structural capacity changes from its corresponding backcalculated moduli (Irwin, 1989), which is strongly related to pavement performance. It is the premise of pavement mechanistic-empirical design methods and is used to control stresses and strains as a response to traffic loads.

The FAA operates a state-of-the-art, full-scale pavement test facility dedicated solely to airport pavement research. Located at the William J. Hughes Technical Center near Atlantic City, New Jersey, the National Airport Pavement Test Facility (NAPTF) provides high quality, accelerated test data from pavements subjected to simulated aircraft traffic. In October of 2010, the FAA constructed a Falling/Heavy Weight Deflectometer (F/HWD) Round-Up in the NAPTF, with the following primary objectives:

- Recognize the value of deflectometer equipment in pavement structural evaluation.
- Demonstrate the proficiency of the equipment.
- Compare collected F/HWD data to a static and rolling dynamic load using the NAPTF test vehicle.
- Compare collected F/HWD data amongst different manufacturers.
- Compare backcalculated pavement material properties using the different manufacturer's F/HWD data.
- Evaluate specifications and methodologies for existing F/HWD equipment for use in pavement design and construction.

In the routine testing of NAPTF, nondestructive deflection testing has become one of the primary means of characterizing the in-situ structural capacity of flexible pavements. Realizing the impact of the asphalt temperature at the time of testing is significant. This is primarily due to the fact that HMA is a viscoelastic material for which the properties depend on the rate of loading and temperature. In addition, there are several environmental variables which affect pavement material behavior and performance in highway design (AASHTO, 2008). These variables include: (i) subgrade moisture content, (ii) temperature, (iii) solar radiation and atmospheric conditions, and (iv) site geological conditions. The first two variables have received primary consideration in many mechanistic pavement design procedures. However, the Enhanced Integrated Climate Model (EICM) considered more parameters such as climatic conditions, characteristics of pavement structure (AC and unbound layers), drainage, and surface properties.

To further quantify the effect of temperature cycles on resilient modulus, the dynamic software SAPSI (Chen, 1987) was revised to accommodate the viscoelasticity characteristics of asphalt concrete for each frequency up till approximately 250 Hz as well as soil modulus. The HMA dynamic modulus data from the laboratory testing, and non-destructive Falling Weight Deflectometer (FWD) test results have been used to develop relationships between seasonal changes and stiffness.

OBIECTIVES

The objective of this paper was:

- Develop a dynamic analysis approach that can incorporate dynamic modulus of asphalt concrete and to investigate the seasonal temperature effect on pavement dynamic responses;
- Obtain the viscoelasticity character of HMA and verify it through full-scale test results.

LITERATURE REVIEW

Seasonal Variations on Layer Modulus

The aggregate in the HMA mixture contributes internal friction to the matrix, while the asphalt cement provides cohesion. Since the stiffness of asphalt cement is dependent upon temperature, the change of modulus is significant and depends on temperature fluctuations in a given climate and therefore it should be included in the pavement design. This causes lower modulus when temperatures are high in the summer and a higher modulus when temperatures are low in the winter. In addition, seasons have a significant effect on the pavement soil resilient modulus. Resilient modulus changes with variation of the soil moisture content. In April and May, due to the melting of ice, the moisture content of the subgrade increases and saturates the soil. This leads to a lower resilient modules value. As the moisture begins to drain out during the warmer months ahead, the subgrade moduli increases again and reaches its peak in the months of December and January. Varying precipitation can also affect the subgrade moisture content, thus affecting the resilient moduli, the effect of precipitation on moisture content of subgrade is substantial (Hossain et al., 2000).

Moreover, the Long-Term Pavement Performance (LTPP) program was initiated to establish the FWD deflection database. The Federal Highway Administration (FHWA) sponsored earlier studies (Khazanovich, 2001 and Von Quintus, 2002) to backcalculate the elastic layer modulus' values from deflection basins measured on all LTPP test sections and included those computed values in the LTPP database. The latest report (Von Quintus, 2015) summarizes backcalculated elastic layered modulus from deflection basins measured on all test sections included in the LTPP program. The report documents the backcalculation program packages and procedures used to calculate the layer modulus. Effects of temperature, moisture and existing structure of pavement on measurement were also investigated.

HMA Viscoelasticity and unbound material Damping

Viscoelastic material response is comprised of elastic and viscous responses corresponding to the behavior of a solid and a liquid, respectively. There are two general methods to characterize viscoelastic materials (Huang, 1993): (i) by mechanical models, and (ii) by a creep compliance curve.

The behavior of an asphalt concrete material can be modeled using a combination of springs and dashpots (Huang, 1993). The most basic models include the Maxwell and Kelvin models. The Maxwell model consists of a linear spring and a viscous damper in series. The Kelvin model consists of a linear spring and a viscous damper in parallel. More complex viscoelastic models include the standard solid model and the Burger's model. The standard solid model combines Kelvin and spring models in series, while Burger's model consists of Kelvin and Maxwell models in series. For hysteretic damping, the complex modulus is constant with frequency, and can (for small damping) be written as (Hajj, et al 2012, Chatti et al 2006).:

$$E^* = E\left(1 - 2\beta^2 + 2\mathrm{i}\beta\sqrt{1-\beta^2}\right) = E_1 + iE_2 = \left|E^*\right|\cos\varphi + \left|E^*\right|\sin\varphi \qquad (1)$$

where $i = \sqrt{-1}$, E is Young's modulus of elasticity, and β is the damping ratio. E_1 is the elastic modulus component, E_2 is the viscous modulus $|E^*|$ is the absolute value of the complex modulus (E^*), the angle φ is the phase angle, which can be determined from lag between the peak strain and the peak stress.

The best model (among the four models described above) for describing the response of asphalt concrete is the Burger's model. While not perfectly suited for real material behavior, its strain response under constant stress shows many of the characteristics observed under creep testing in the laboratory. It is important to note, however, that both the real and imaginary parts of the complex modulus are zero at zero frequency and vary non-linearly with increasing frequency. The unbound material can be considered as hysteretic damping (Chatti, 2006).

HWD Dynamic Stationary Loading and Moving Speed Loading

The FWD pulse durations ranged from 0.030 to 0.050 seconds and can simulate trucks moving at 45 mph. It is believed that the measured deflection can reflect the responses of moving traffic. On the other hand, it was found that the pavement responses decrease as the speed increased (Sebaaly, 1993). As the speed increases from 5 mph to 50 mph (8 km/h to 80 km/h), the magnitudes of three pavement responses (longitudinal tensile strain, compressive strain at the top of subgrade, and vertical shear strain) decreased by 30-70%, depending on the pavement thickness (Wang, 2011).

COMPUTER PROGRAM FOR CALCULATING FREQUENCY-DOMAIN

In the frequency-domain solution, the dynamic response of the pavement subjected to a harmonic load can be modeled as a layered system subjected to uniform surface area (Kausel et al, 1981). Considering steady state harmonic forces, the displacements at a given frequency can be obtained in equations that are complex-valued and correspond to the steady-state solution in the SAPSI program (Chen,1987).

COMPUTER PROGRAM FOR CALCULATING PAVEMENT RESPONSES

Modeling the dynamic response of the pavement subjected to an FWD pulse requires the full-time histories of the load and deflection. First, the load time history is transformed to the frequency-domain using the Fast Fourier Transform (FFT). Second, unit response functions are computed at several particular frequencies. Third, unit response functions at other frequencies are estimated using an interpolation scheme. Fourth, the load and unit response functions are multiplied in the frequency domain to obtain the response of the pavement in the frequency domain. Last, the inverse FFT is applied to yield the pavement response in the time domain. The theoretical accuracy of the solution in SAPSI has been developed by Chen (1987) for steady-state problems. Chatti et al. (1995) verified its accuracy using the PACCAR Test Track in Mount Vernon, Washington.

NAPTF F/HWD ROUND-UP TESTING SITE

The F/HWD Round-Up pavement section was constructed at the Federal Aviation Administration (FAA) National Airport Pavement Test Facility (NAPTF), which is located at William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. Flexible test pavement and subgrade were constructed on medium strength subgrade with a CBR value of approximately 5 which, when plugged into the empirical equation, gives an estimated value of approximately 7,500 psi. The subgrade was constructed in control lifts of approximately 8 inches to the depth shown in Figure 1.

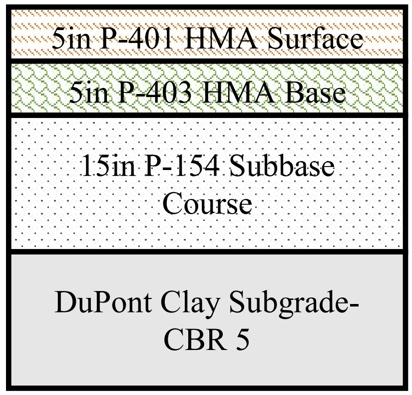


Figure 1. F/HWD Round-Up testing structure layout

RESULTS AND DISCUSSION

Comparison of SAPSI Results with Static Layer Elastic Theory

The HWD load-deflection data was processed using the FAA BAKFAA backcalculation program to obtain the layer moduli for the pavement layers. The deflection basins at 35,000 lbs. load are shown in Figure 2. The average backcalculated moduli and material properties are summarized in Table 1.

Table 1. Layer Properties for HWD Round-Up Pavements Section

Layer Name	Thickness (in)	Unit Weight (pcf)	Poisson Ratio	Backcalculated Modulus (psi)
AC	10	140	0.35	1,249,973 (54 ºF) 372,520 (100 ºF)
Base	15	135	0.40	102,847
Subgrade	∞	125	0.45	25,679

It was found that the backcalculated soil modulus （25,679 psi） was approximately three times higher compared to the designed soil modulus 7,500 psi(CBR=5). It is because of this that inputting a divisor of 3 was recommended when designing the pavement using an in-situ backcalculated unbound materials modulus in the 1993 American Association of State Highway and Transportation Officials (1993 AASHTO) highway design manual . It was also found that the HMA layer modulus changed greatly at temperatures of 54 ºF and 100 ºF. With the restriction of static backcalculation, the computer program provided only a single value for the HMA surface layer. On the other hand, choosing a correct frequency input in MEPDG is also important. The loading frequency of the falling weight deflectometer (FWD) (Katicha et al, 2008) is similar to that of a vehicle loading at a high speed (loading pulse from FWD is estimated to be between 0.025 to 0.035 seconds). In order to convert the dynamic modulus as a function of frequency to the dynamic modulus as a function of loading time for input in MEPDG, Witczak et al (2002) suggested that a frequency of 10 Hz be used to represent highway speeds and, therefore, that the dynamic modulus that result at 10 Hz be used. Others, however, suggested frequencies of 18 Hz (Oh and Fernando, 2011) and 33 Hz (Leiva-Villacorta, 2012). Hence, significant error could result between calculated and measured strain responses under different frequencies when using backcalculated moduli in a mechanistic model.

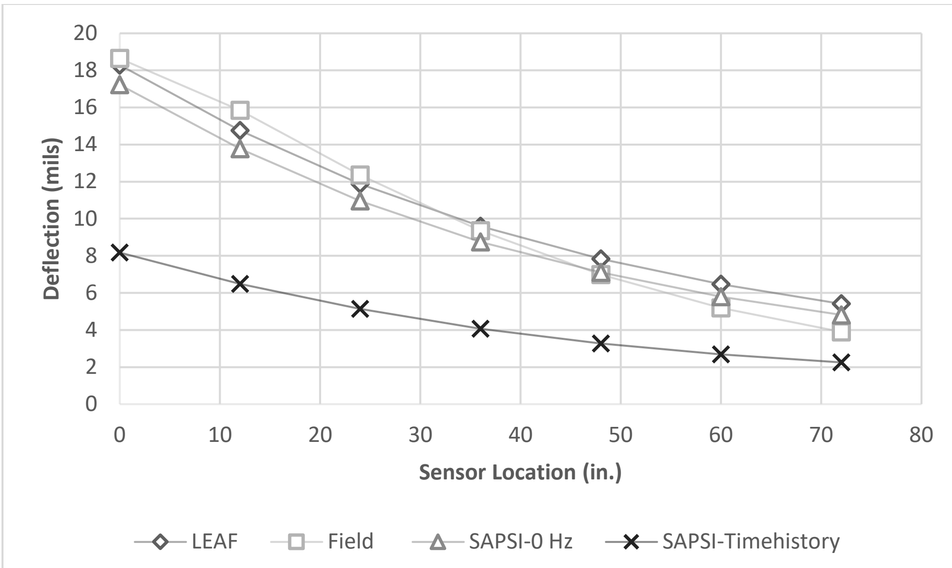
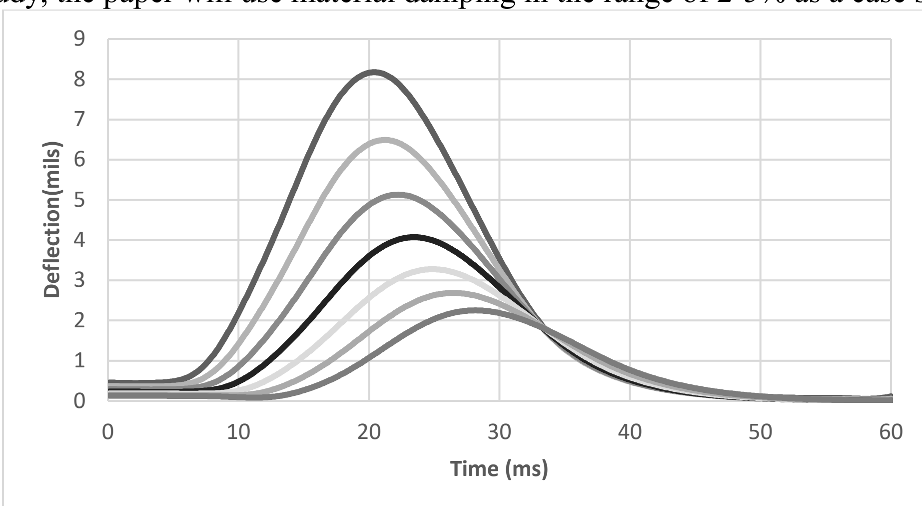


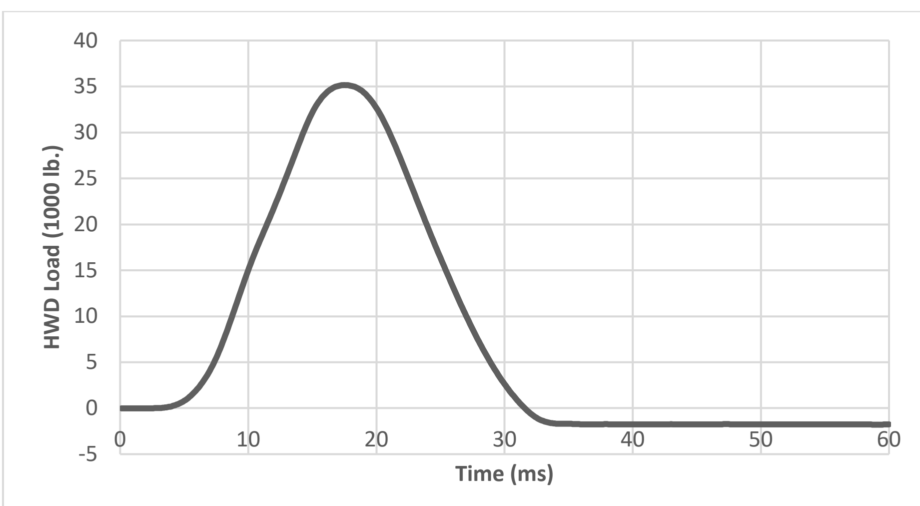
Figure 2. Comparison of Measured and Calculated Deflection Basin (54 ºF)

The static backcalculation BAKFAA program was performed in order to obtain the layer modulus and the result was summarized in table 1. Figure 2 plots the following results: (1) the HWD deflection basin measurement; (2) the LEAF calculations; (3) the calculated deflection at 0 Hz under the maximum load of time history; and (4) the peak deflection under HWD load history calculated using SAPSI. It is found that the deflection from BAKFAA can match well with HWD measurement; deflection at 0 Hz can also be accurate compared to the LEAF program. However, the dynamic analysis using backcalculated modulus from BAKFAA can lead to measurements that are approximately 50% lower than the real measurement. This indicates that the dynamic responses are much lower than the results using static analysis. It may raise concerns on the compatibility of HWD equipment dynamic characteristics and the layer elastic theory assumption. Obviously, the dynamic analysis provides more realistic simulations compared to the static analysis for HWD equipment. The trafficking on the FWD round up testing site shows that the traffic load speed has a great effect on the pavement responses in the pavement surface deflection, subgrade strain, and stress. With the increase of the wheel speed, the strain and stress on the pavement decreases steadily. On the other hand, the FWD loading is trying to simulate the load under with a traffic speed of 40-50 mile/hour; therefore, static backcalculation will overestimate the layer modulus if the HWD has an impulse dynamic loading. It is one of the reasons that the deduction factor is used to lower the backcalculation value when it is considered as one of the inputs of pavement design.

Figure 3 shows the calculated dynamic responses using SAPSI, both the HWD load time history and laboratory dynamic HMA modulus plotted in figure 4 were used as the inputs of SAPSI. The asphalt dynamic modulus could be assumed as a constant value with a frequency; or frequency dependent in which the modulus increased as the frequency increased; or temperature dependent in which the modulus increased as the temperature decreased. In the following dynamic pavement analysis, the HMA modulus in the figure 4 will be used as inputs to calculate pavement responses. To simulate a heavy aircraft, a 35,000 lb weight was loaded onto the pavement during airport pavement analysis. Reference (Bazi, 2019) illustrated that the damping ratio of unbound materials and asphalt materials are 2% and 5%, respectively. Since the damping properties of these materials are not well established and it is out of scope in this study, the paper will use material damping in the range of 2-5% as a case study.



(a) HWD deflection time history



(b) HWD load time history

Figure 3. Predicted deflection time history from SAPSI

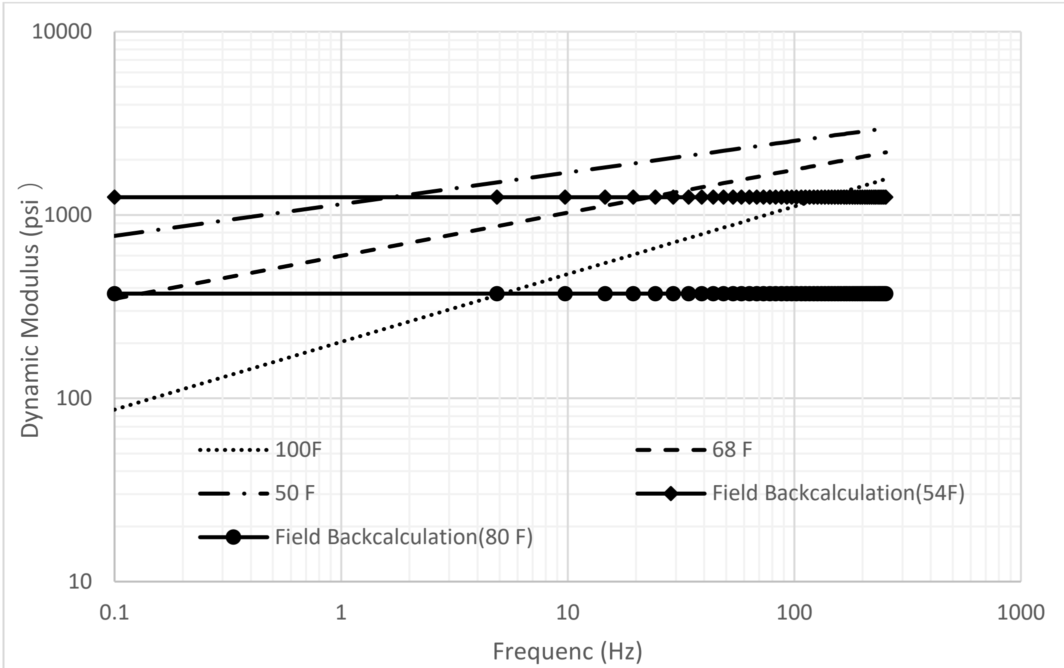


Figure 4. Dynamic modulus with the temperature and frequency

Stress at Pressure Cell of Field Measurement

During testing most strain gauges are broken due to the high pressure imposed from the pavement rolling equipment, but the pressure cell at the subgrade is believed to be in good condition. Therefore, stress responses were recorded for the HWD's controlled loading. Using layer backcalculated moduli, stress and strain responses in the asphalt, base, and subgrade were predicted for four specific HWD loading levels, which are approximately 50000 lb., 24000 lb., 36000 lb., and 50,000 lb. The corresponding responses were collected to be compared to the predicted responses. This case study focused on the pressure cell embedded in the subgrade. A typical plot of the resulting data is shown in Figure 5 and 6. Compared to the dynamic model, the layer elastic theory overestimated the pavement responses by 20-30% in these two figures. They also show the stresses of the pavement due to seasonal effects. For these analyses, an examination for different seasons indicated that the comparisons of pavement responses between the HWD dynamic load and its stress measurement at 24000, 36000, and 50,000 lbs. had a great change. It was found that the SAPSI prediction is about two times higher than the measurement, considering static backcalculation typically overestimates the layer moduli, it is believed that the dynamic analysis in the backcalculation will produce the most appropriate analysis. However, due to the difficulty of dynamic backcalculation, the deduction factor may be a reasonable solution to bridge the gap between static and dynamic backcalculation.

Compared to the static analysis, the dynamic analyses simulate a more accurate HWD loading condition.

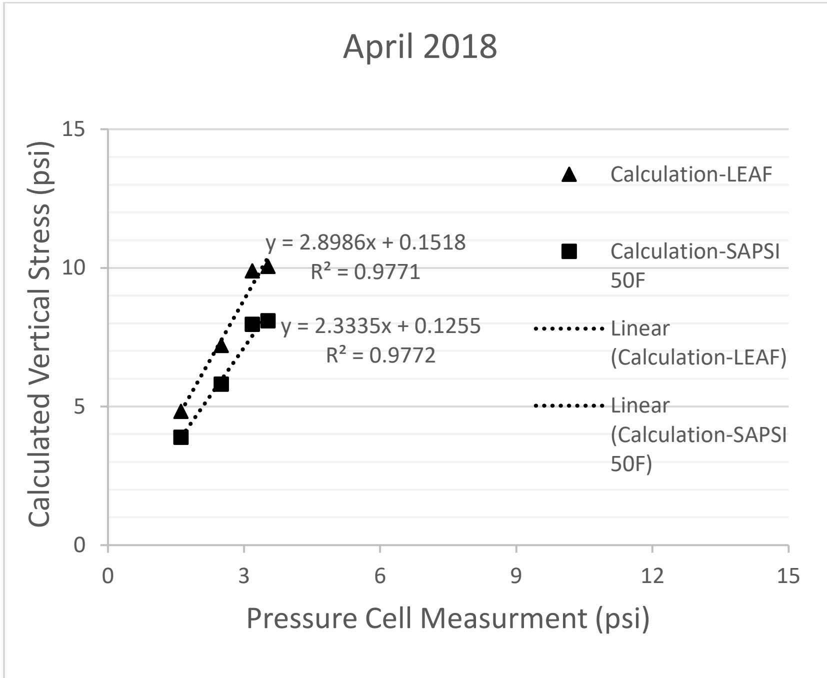


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Figure 5. Soil pressure under HWD loading in April testing (pressure cell depth =25.5 in. from the pavement surface)

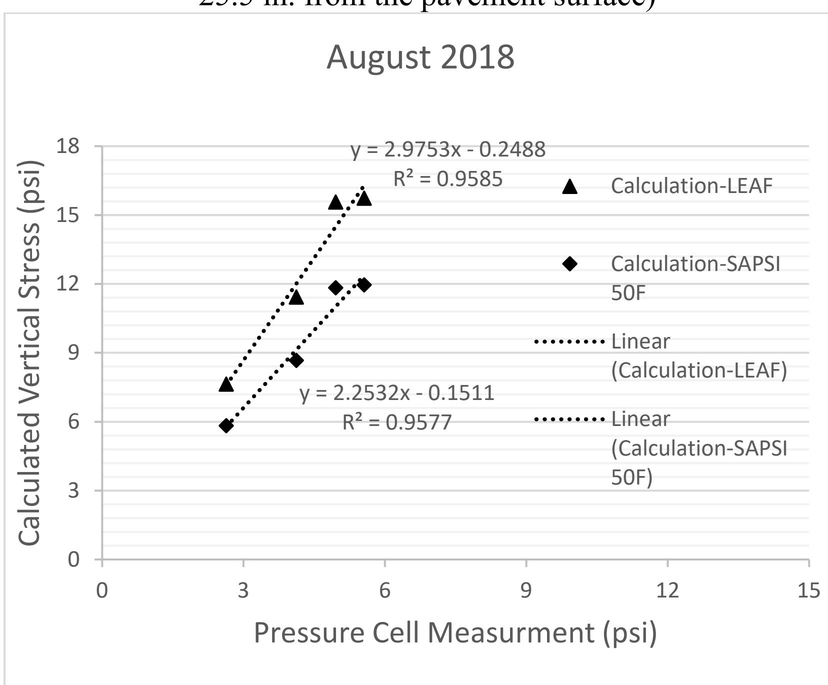

Figure 6. Soil pressure under HWD loading in August testing (pressure cell depth=25.5 in. from the pavement surface)

SUMMARY AND CONCLUSIONS

This paper presented the effect of seasonal changes on pavement responses. Appropriate viscosity–temperature relationships obtained by asphalt material laboratory testing and in-situ layer modulus backcalculated from HWD testing data were used to predict the stresses in the pavement and subgrade and which were related to seasonal change. Predicted and measured values of stress in the soil were compared. Based on the findings of this study, the following conclusions can be made:

1. Dynamic analysis is an effective tool in predicting HMA pavement responses. The approach can be treated as an alternative method to static analysis. However, in order to verify this finding, more pavement sections should be employed in the backcalculation procedure.
2. Asphalt dynamic modulus at different temperatures can be measured in the lab and can be one of the most important factors impacting the design and performance of flexible pavement. Temperature significantly affect the HMA modulus, the stress of subgrade.
3. The static backcalculation of the computer software, BAKFAA, led to an overestimated modulus considering the characteristics of HWD impulse loading. The backcalculated soil modulus was approximately three times higher than the soil modulus typically used as pavement design inputs.
4. In-situ subgrade stresses due to the HWD loading are comparable with stresses predicted using the dynamic model if considering an overestimated in-situ modulus, however further studies are needed to determine the correct use of layer modulus.
5. The dynamic analysis will provide an alternative insight in the current pavement design concept using the layer elastic theory. Compared to the dynamic analysis, it appeared that the layer elastic theory overestimated the pavement responses by 20-30%.

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