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Seasonal and Diurnal Variations of Backcalculated Layers Moduli in Flexible Pavements and FWD Testing Guidelines

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ABSTRACT

Seasonal and diurnal variations can significantly impact FWD measurements and, thus, deflection-based parameters such as backcalculated layer moduli. There is a need to evaluate and quantify these effects. The backcalculated layer moduli data from the LTPP SMP study were analyzed within each climatic region. The effects of seasonal and diurnal changes were quantified, and related with the ambient temperatures were related to develop general measurement guidelines. The HMA layer moduli showed minimal variation during the spring and fall seasons in every climatic region while consistently higher based on the deflections measured before noon. However, temperature correction, generally applied to HMA layer moduli, can eliminate the FWD measurements' temperature impacts. Since the unbound layers moduli are backcalculated from the single measured deflection basins on the surface, temperature and moisture conditions at the time of measurements can affect those material properties. The base and subgrade moduli showed minimal variation within the spring and fall seasons' temperature ranges. Therefore, such temperature within each climatic region may result in these layer moduli values closest to their representative in-field conditions. Also, the unbound layer showed no effect of time within a day, suggesting FWD testing can be conducted at any time during the day. Based on the results, the preferred temperature ranges for FWD measurements are 55 to 70°F and 65 to 75°F in freeze and non-freeze regions, respectively. FWD measurements can be conducted at any time of the day. The preferable seasons for testing are spring and fall in all climatic regions.

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Keywords: Falling Weight Deflectometer, FWD Testing guidelines, Flexible pavements, Climatic zones, Flexible pavement's layer moduli, Long-Term Pavement Performance, Seasonal Monitoring Program.

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INTRODUCTION

Evaluating a pavement's structural capacity involves Falling Weight Deflectometer (FWD) measurements and deflection analysis. These measurements are of vital importance in assessing the structural performance of pavements both at the network and project level. However, temporal variations (i.e., seasonal temperature and moisture and diurnal temperature changes) influence these measurements. Consideration of this influence on the FWD measurements is necessary for accurate assessment of the pavement conditions and reducing the potential for under- or over-estimating pavement structural performance. Besides, the evaluation of these temporal variations and quantifying their effects on the measurements will assist in a better understanding of the derived pavement back-calculated layer moduli based on the measured FWD deflections.

The Long-Term Pavement Performance (LTPP) initiated the Seasonal Monitoring Program (SMP) study to enhance understanding of the environmental factors and their effects on pavement structural and functional performance. The two major environmental factors are temperature and moisture. The design of the SMP study aimed to evaluate the influence of temporal changes in the pavement structural characteristics due to the diurnal and seasonal variations of these factors. The primary measure of a change in the pavement structural characteristics is the FWD deflection data. The LTPP SMP sites were instrumented to measure the local weather, subsurface moisture, and temperature to explain the observed temporal changes on the FWD measurements. Therefore, the data can be analyzed to seek the full potential of the FWD deflection data for investigating the corresponding pavement conditions for both flexible and rigid pavements.

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While the LTPP SMP study was initiated to obtain data on the influence of temporal changes on pavement surface deflections, seasonal and diurnal data have not been analyzed to improve the deflection measurement practices. Besides, there is a need to evaluate the availability of the data along with its extent to quantify the effect of temporal FWD measurements on derived pavement parameters. Therefore, the main objectives of this paper are to (a) evaluate the availability and extent of current data in the LTPP SMP study for flexible pavement sections (b) assess the effects of temporal (seasonal and diurnal) FWD measurements on the derived pavement parameters, and (c) propose general recommendations for the improved use of FWD measurements.

BACKGROUND

The temperature and moisture variations in bound and unbound pavement layers affect the material properties of materials, and as a result, the pavement responses under load can vary. These pavement response variations will impact the pavement damage accumulations and, subsequently, the performance of a pavement system.

Effect of Temperature on Asphalt Materials

The seasonal and diurnal variation of asphalt pavement temperature is related to environmental factors such as air and surface temperatures. The stiffness of the asphalt concrete (AC) layer is directly related to its temperature. Therefore, the temperature-dependency of AC materials results in diurnal and seasonal variations in their structural performance. Internal temperature changes within the AC layers caused by fluctuations in air temperature and solar radiation are the primary cause of their moduli changes and, thus, the structural performance of AC materials. A part of the changes in stiffness can also be related

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to binder properties that change over time because of age hardening and micro-cracking (Lukanen et al. 2000). Therefore, pavement surface temperature is a critical factor that requires due consideration as part of any pavement deflection testing program.

A significant amount of work is available on the temperature correction of the FWD data. Temperature corrections are applied to the measured FWD data on raw deflections (Chen et al. 2000, Kim et al. 1995, Mun Park et al. 2002, Schmalzer 2018), deflection basin parameters (Lukanen et al. 2000, Mun Park et al. 2002, Zheng et al. 2019), or on the backcalculated modulus (Fernando et al. 2001). These corrections make use of non-linear correction functions of temperature empirically. However, Fernando et al. pointed out that temperature correction of the FWD deflections may not be suitable for project-level analysis because such methods alter the deflection basin's actual shape. Instead, it recommends temperature correction of the backcalculated modulus(8). The literature also showed that correcting the raw FWD deflections or deflection basin parameters could be problematic because of the highly empirical, non-linear functions used for temperature correction (Schmalzer 2018).

Effect of Environment on Unbound Materials

Resilient modulus (MR) characterizes unbound materials used as a base, subbase, and subgrade layers in pavement structures. MR of the material is a function of its density, the applied stress, and moisture content and is generally assumed to be temperature independent property. While the density of the unbound material may vary with time (related to permanent deformations), it is considered constant in pavement design usually. Therefore, stress level and moisture variations are of primary interest regarding changes in unbound material resilient moduli values.

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A Kansas study investigated the seasonal variations of pavement material properties and behavior due to temperature and moisture changes. Temperature, moisture content, and FWD data were collected every month on four asphalt pavement sections for a year. The subgrade moduli were backcalculated using elastic layer theory using; MODULUS and AASHTO equation. Back-calculation of the subgrade moduli involved dividing the subgrade layer into two sub-layers; a compacted subgrade layer and a natural soil subgrade layer. The compacted subgrade layer resulted in being more sensitive to seasonal variations at all the sites. Although the seasonal temperature variations are not expected to affect the subgrade moduli values; however, the study observed that increasing temperature significantly affected the subgrade moduli values. The subgrade moduli value decreased with increasing temperature. The observed behavior was due to the temperature effects on the stiffness of the AC layer in a pavement structure, which in turn influences the deviatoric or bulk stresses in the subgrade layer. The increasing temperature softens the AC layer, thus increase the bulk stress. The increase in bulk stress resulted in a decrease of subgrade moduli values, as the subgrade soils were cohesive (silty clay soils)—resilient modulus decreases with increasing temperature. The study also concluded that the subgrade moduli calculated from FWD measurements taken at unusually higher pavement surface temperatures resulted in lower back-calculated subgrade moduli irrespective of the backcalculation approach. A possible reason is a violation of the linearity assumption resulting from variable deviatoric stresses on the subgrade (Long et al. 1997).

The behavior of the unbound aggregate base (UAB) and subgrade layers are significantly affected by seasonal moisture and temperature fluctuations. These fluctuations eventually influence the overall performance of the pavements by changing the load-bearing

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capacity of these layers. High moisture content tends to decrease the stiffness of granular and subgrade layers, increase deflections, and, ultimately, reduce the life of the pavement systems (Monismith 1992). Therefore, all pavement design procedures, including AASHTO and the MEPDG, rely on the use of M_R to characterize unbound granular and subgrade layers. A study carried out on five pavement sections in Minnesota observed the effects of seasonal moisture and temperature variations on UAB and subgrade layer. The study involved four different base/subbase aggregate material types commonly used in Minnesota. The study concluded that overall, subsurface material exhibited similar monthly moisture and temperature trends throughout the year. The moisture content increased as the temperature increased from spring to summer months; low moisture content was observed in the fall and winter months. The study also observed seasonal variations in moisture content and temperature in different classes of base and subgrade material, with the highest and lowest moisture readings occurred in summer and winter, respectively (Zegeye Teshale et al. 2019).

As mentioned before, pavement deflections under the application of load by an FWD device vary with the seasonal and diurnal variations of pavement temperature and moisture. The variability in the measured deflections influences the material properties obtained from these deflections using back-calculation analyses. The existing literature has some guidelines on how to conduct FWD measurements in the field that can help minimize the effects of temporal changes of temperature and moisture on the backcalculated parameters. The current recommended FWD deflection measurement guidelines for flexible pavements include (Pierce et al. 2017):

- a. Temperature data should be collected during FWD testing on flexible pavements. Since hot-mix asphalt (HMA) is a temperature-dependent material, the equivalent modulus

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obtained during backcalculation represents the material's temperature at the time of testing. Having accurate temperature data helps determine the correction factor to apply to the backcalculated HMA modulus to obtain a value at a standard temperature [typically 21°C (70°F)] for use in design.

- b. Air and surface temperature should be recorded at each test location, and most FWD equipment has temperature sensors for obtaining such data. The daily average temperatures for five days preceding testing should also be obtained, mainly if the air and surface temperatures will be used to predict the mean pavement temperature.

The above recommended FWD measurement guidelines mostly cover the seasonal or diurnal variations of pavement temperature and moisture so that the influence of these variations on material properties may be quantified by using backcalculation analyses.

DATA ASSESSMENT

Temperature, moisture, and freeze/thaw related changes in pavement layers within a day and over a year can significantly impact the structural characteristics of pavement layers. Such variations in temperature and moisture can influence the material properties of pavement layers and, therefore, affect the pavement structure's response under traffic loads, and ultimately the life of the pavement. However, these effects' magnitude and relationship are not fully understood, making them difficult to address with any degree of confidence in pavement design and evaluation. The LTPP SMP study can overcome this limitation. The SMP study's primary objective is to provide data needed to attain a fundamental understanding of the magnitude and impact of temporal variations in pavement response and material properties due to the separate and combined effects of temperature, moisture, and

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frost/thaw variations. The SMP experiment data and subsequent analysis can provide (Rada et al. 1994):

- a. "The means to link pavement response data obtained at random points in time to critical design conditions;
- b. The means to validate models for relationships between environmental conditions (e.g., temperature and precipitation) and in situ structural properties of pavement materials; and
- c. Expanded knowledge of the magnitude and impact of the changes involved."

Parallel to the above goals, the SMP data may also help develop guidelines for FWD measurements to account for seasonal and diurnal temperature and moisture variations.

Identification of Data Elements

For evaluating the temporal (i.e., diurnal temperature and seasonal temperature/ moisture) effects of FWD measurements on derived pavement parameters, e.g., pavement layer moduli, the first step is to identify the required data elements. Several data elements needed to accomplish the objective of this paper were identified in the LTPP SMP study database. Of particular interest were the pavement structure data, pavement site-specific data, over time monitored performance data, and pavement deflection data along with derived parameters. The LTPP Standard Data Release (SDR) 33 (the currently available data) was examined and used in this study. The identified data elements were extracted from the LTPP InfoPave, imported into a Microsoft Access® database, and stored in different data tables. These tables were set up as a relational database so that these can be manipulated and linked together for various analysis purposes. These data elements are briefly listed below:

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- a. Pavement structure details: cross-sections, age, and material types for all pavement layers
- b. Pavement site-specific data: ambient temperatures, sub-surface temperatures, sub-surface moisture, and precipitation data, and the climatic regions
- c. Monitored FWD deflection data, with air and surface temperatures, temperature gradients, testing dates, and timings
- d. FWD testing based back-calculated layer moduli with testing dates and timings

Data Availability and Extents

The original SMP design included 64 LTPP test sections arranged in a factorial design that covered different pavement types, subgrade types, and climatic regions. Table 1 shows the original experimental design for the SMP study. Planning included 48 flexible sections to be part of this study. The flexible pavements were divided into two categories based on AC thickness—thick > 5 inches and thin < 5 inches AC thickness. Three replicate pavement test sections each were planned for every combination of the pavement and subgrade soil type (i.e., fine and coarse) in each of the four climatic regions (i.e., dry, freeze (DF), dry, no-freeze (DNF), wet, freeze (WF) and wet, no-freeze (WNF) (Rada et al. 1994).

As per SDR 33, the SMP study data in the LTPP database has 67 flexible pavement sections. Table 1 also presents the number and distribution of the currently available flexible pavement sections by HMA thickness, subgrade type, and climatic zone. A significantly fewer number of sections are available in the dry climatic regions as opposed to wet climates.

The primary objective of the data mining was to obtain the seasonal and diurnal availability of FWD deflection-based parameters, i.e., back-calculated HMA, base, and subgrade layer moduli for all the SMP pavement sections. The BAKCAL tables of the LTPP

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database were used to summarize the available number of back-calculated moduli values for each pavement layer within the pavement structure. EVERCALC was the primary software used by LTPP for the backcalculation of the layer moduli. The software is capable of conducting non-linear backcalculation analysis for unbound layers. Table 2 shows the available FWD backcalculated moduli values by the number of passes on the same day for flexible pavement sections. The data includes FWD tests performed between the years 1989 to 2012. An FWD pass serves to distinguish multiple runs of the same lane on the same day (Elkins et al. 2018). The results show that several flexible pavement sections contain multiple FWD passes on the same day. Most pavement sections have at least three passes per day. A few test sections have more than five FWD passes on the same day.

For example, the DF climatic zone has a total of 340 FWD measurement days involving all the nine pavement sections (number in parentheses), i.e., there are 340 FWD test days with one pass per day. Out of those 340 test days, 267 days involved a second FWD pass to measure deflections on these nine sections on the same day. Similarly, 230 days were such where a third FWD pass measured deflections on the same day while 104 days involved a fourth FWD pass. Only 14 days, which included only four of the nine sections, involved a fifth FWD pass for deflection measurements on the same day.

Pavement age and maintenance history of the pavement structure are critical factors that could affect pavement deflection response. The construction number assigned to a pavement section in the LTPP database reflects the later one. The construction number identifies changes in the pavement structure caused by the application of maintenance or rehabilitation treatments. When a test section first enters the LTPP program, it is assigned a construction number of 1. The construction number is then incremented for each subsequent

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maintenance or rehabilitation event regardless of its impact on the pavement structure. For example, crack sealing causes the generation of a new construction event, even though it does not create a significant change in the experiment assignment or pavement structure (Elkins et al. 2018). Therefore, it is essential to consider the construction number of the pavement section at the time of the FWD test and the corresponding measured deflections used for back-calculating pavement structural parameters. Based on the above discussion, the maintenance and rehabilitation activities that cause a change in the construction number assigned to the pavement sections were divided into four categories as following:

- a. Category 0: No maintenance at all.
- b. Category 1: Maintenance work with no significant effect on FWD deflections.
- c. Category 2: Localized patchwork.
- d. Category 3: Maintenance works with a potential effect on pavement structure

Table 3 shows the distribution of the available backcalculated structural parameters of the SMP flexible pavements, shown in Table 2, by the maintenance category based on the assigned construction number for the different climatic regions. For example, referring to Table 3, there are 340 backcalculated pavement structural parameters in the DF region for a single FWD pass. Among these 340 measurements, 233 took place while the pavement sections had a construction number of 1 (newly constructed or maintenance category 0). 81 FWD measurements were undertaken after some minor maintenance works. (category 1; i.e., crack seal, fog seal). Eighteen measurements took place after localized maintenance/rehabilitation works (category 2; i.e., patchworks), while the last eight happened after a significant maintenance or rehabilitation work (category 3; i.e., overlays or full-depth patchworks).

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The sub-surface temperature data from the SMP module were obtained for the flexible pavement sections. This information helped in determining the HMA layer mid-depth temperature used to correct the moduli values. Table 4 shows the available temperature data measured within 30 minutes of the FWD test. Again, more data in the wet regions are due to many sections in these regions.

DATA ANALYSIS AND RESULTS

The back-calculated moduli for each pavement layer obtained from the LTPP SMP database were analyzed separately within each climatic region. Dividing the data and analysis by climatic regions helped better understand the effects of seasonal and diurnal measurements on these parameters. The main factors to investigate the impact of seasonal and diurnal FWD measurements on the back-calculated layer moduli include (a) month and (b) time of FWD measurement. HMA layer thickness is also used as a factor since it is a part of the SMP original design. The maintenance category of the pavement sections is used as a blocking factor. Blocking is a technique that increases the precision in an experiment by reducing the experimental error variance. It is achieved by considering factors believed to affect the response; however, not considered to be of primary importance in the analysis. The data analysis involved the following steps:

1. Identify the flexible pavements sections in the SMP LTPP database in each of the four climatic regions. Note that climatic regions are defined in terms of temperature (i.e., freeze/no freeze) and moisture conditions (i.e., wet/dry).
2. Obtain the structural details, including layer types thicknesses of all available pavement sections. Also, the maintenance history details for all the sections were

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- obtained from the database (i.e., construction no. and type of treatment) and categorized.
3. Extract the backcalculated layer moduli, along with the date and time of FWD measurements, the air and pavement surface temperatures measured at the time of FWD testing, and the temperatures measured at different depths of the structure.
 4. Arrange the obtained data in a relational database.
 5. Evaluate data by using a histogram and boxplot to identify outliers.
 6. The factors used in the analysis included; (a) measurement month discretized into four seasons (i.e., levels) to look at the seasonal effects, (b) measurement time with two levels (before noon and afternoon) for the diurnal effects, (c) maintenance category, (d) HMA layer thickness with two levels; thick (>5 inches) and thin (<5 inches) based on the original SMP experiment (Rada et al. 1994).
 7. Conduct Analysis of Variance (ANOVA) for flexible pavement sections within each climatic region to investigate the significance of temporal effects on each of the layer moduli values. A level of significance of 5% ($\alpha = 0.05$) is used in the analysis.

Figure 1 displays the general diurnal and seasonal HMA layer moduli trends by FWD pass and months, respectively. Figure 1(a) indicates that the HMA layer moduli decrease with FWD pass (i.e., from morning to afternoon) for both thin and thick HMA layers. However, the data show somewhat mixed trends between different climatic regions, which could be because of varying HMA mixtures and field aging on the pavement sections [see **Error! Reference source not found.**(b) and (c)]. As expected, the HMA layer moduli display significant variations with higher values in the winter months and lower values in the summer months [Figure 1(c)]. Also, there is less overall variation in the backcalculated

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moduli values within the summer season (i.e., May, June, and July) than winters (December, January, and February).

Table 5 shows the descriptive statistics of the available HMA layer moduli values with the number (N) of measurements within each climatic region. The HMA moduli value considerably varies within each climatic region, especially in the DF, WF, and WNF regions. The variation can be explained by looking at the histogram and boxplots of the available data in Figure 2. HMA moduli values over 3000 ksi exist in the database for the three climatic regions mentioned earlier, which is potentially a reason for higher standard deviations in these climatic regions.

Figure 3 demonstrates the normality of the data for the DF climatic region after a suitable transformation (e.g., natural log or the square root of the response variable) used in the analysis. This study excludes HMA modulus values higher than 2000 ksi, as these can potentially mask the findings. The satisfaction of the normality assumptions is essential to draw meaningful conclusions from the ANOVA analysis. Similarly, the data were transformed adequately for the rest of the climatic regions to ensure the normality assumptions' satisfaction.

Table 6 summarises the ANOVA results for each layer moduli within every climatic region. Considering the HMA moduli results in the DF climatic region, FWD measurement season, time, AC thickness, and the maintenance category are significant factors affecting the HMA layer modulus values based on a Type I error rate of 5% ($\alpha = 0.05$). However, the interaction (highlighted in bold font) between the FWD measurement season, time, and AC thickness also has a significant influence on the HMA layer moduli values. Thus, one should

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look at the interaction means plot rather than the main effects plot for interpreting the analysis results.

Diurnally, within the DF climatic region, the HMA moduli backcalculated using FWD measurements conducted before noon are higher than the afternoon measurements (see Figure 4). Such a difference can be explained due to the absorption of heat throughout the day by the pavement. There is a significant mean difference (around 200 ksi) between backcalculated HMA moduli obtained from measurements taken before-noon and in the afternoon between the spring and summer seasons. The time has a pronounced effect on backcalculated HMA moduli from FWD measurements obtained over pavements with thick and thin HMA layers. Generally, thin HMA layers tend to display higher moduli values as compared to thick HMA layers. Such a trend can be due to the backcalculation process that estimates higher stiffness values for thin HMA layers than thicker ones. Results show that the mean moduli difference is higher (260 ksi) for thick HMA layers than pavements with a thin HMA layer (170 ksi). Seasonally, HMA moduli values are generally highest for winters, as expected, followed by spring and fall seasons, while the summer season has the lowest moduli values (see Figure 4). A noticeable mean difference (around 400 ksi) exists between moduli values obtained in winter and summer seasons over pavements with different HMA layers. In winters, thicker HMA layers are stiffer than thin layers due to low temperatures, while in summers, the opposite is true. However, higher moduli values for thin HMA layers can also be due to the backcalculation process. Similar analyses were performed for DNF, WF, and WNF climates; however, details of those are not presented in the paper due to space limitation and can be found elsewhere (Hamad 2020); however, a summary is provided in Table 6.

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Different techniques are used in practice to correct the HMA layer moduli values to a standard temperature of 77°F. The LTPP SMP database contains the uncorrected backcalculated HMA moduli. These moduli can be corrected to a standard temperature by using the Asphalt Institute (AI) model shown in Equation (1), as an example:

$$\log E_0 = \log E + 1.47362 \times 10^{(-4)} (t^2 - t_0^2) \quad (2)$$

where;

E_0 = corrected HMA layer modulus in psi;

E = backcalculated uncorrected HMA layer modulus in psi;

t = mid-depth test temperature in °F; and

t_0 = reference temperature = 77 °F

The mid-depth HMA layer temperatures are calculated for each pavement section based on data from the MON_DEFL_TEMP_DEPTH table of the LTPP monitoring module. Figure 5 shows the corrected HMA moduli values for pavement sections in different climatic regions using Equation (1). The figure shows that the AI model performs well in correcting the available HMA moduli within each climate. The data shows the highest variation in HMA layer moduli in the WNF climatic region; hence, more variation in the corrected values. Thus, considering HMA layer moduli, the FWD measurement temperature or weather condition is not critical for flexible pavements. However, a single FWD measurement gives the moduli for all the layers (i.e., surface, base, and subgrade); the underlying unbound layers become critical. Therefore, the general guidelines should consider the variation of moduli values for all layers together.

Figure 6 presents the temperature ranges during FWD measurements in the DF climatic region. ANOVA results showed that the interaction of season and time and season

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and HMA thickness were significant factors for HMA and base layer moduli in the DF climatic region, respectively. Subgrade moduli analysis showed that the season's main effects are essential in defining change in the moduli. The ambient temperature ranges occurring in the spring and fall seasons appear to have the least variation of the moduli values in the HMA layer. Thus, the subgrade and the base moduli backcalculated from using FWD deflection in these temperature ranges would result in values close to the actual. Consequently, the suggested ambient temperature range for conducting FWD in the DF climatic region is between 55 to 70°F.

Similar analyses were conducted for all layer moduli in each climatic region; however, the details are skipped due to limited space, and only brief results are documented for completeness. For pavement sections located in the DNF climate, the unbound layer moduli did not show considerable difference in the spring and fall seasons. Therefore, the ambient temperatures between 65 to 80°F appear to result in the unbound layer moduli values that may be closest to the actual. Based on the observed effects, the spring season's ambient temperatures can help determine the actual unbound layer moduli in the WF climatic region. Thus, the ambient temperature range suggested for FWD deflection measurements for WF climatic region is between 55 to 65°F. For pavements in the WNF climate, the recommended ambient temperature deemed appropriate to result in the unbound layer moduli, representing their actual condition, is between 55 to 75°F. Also, since the time of the day did not appear to affect the unbound layers, as expected, FWD deflections can be measured at any time of the day with the ambient temperature in the suggested ranges within every climate.

Figure 7 shows the monthly variation in layer moduli values for a section in the WF climatic region as an example. The plots show that the HMA layer moduli decrease in the

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summer months while these increase as the temperatures get colder (i.e., winter and fall months). The corresponding base and subgrade moduli values also show monthly (i.e., seasonal variation), which aligns with the ANOVA results for this climatic region.

DISCUSSION AND CONCLUSION

ANOVA analysis was conducted for moduli of each pavement layer within every climatic region individually. The two main factors used in the analysis were FWD measurement season and time of the day and HMA layer thickness and the maintenance category as a blocking factor. Analyses of the backcalculated layer moduli for flexible pavements revealed an essential effect of seasonal and diurnal changes. The HMA layer moduli showed minimal variation in the spring and fall seasons in every climate. Also, the HMA layer moduli were consistently higher, based on the deflections measured before noon. However, temperature correction, generally applied to HMA layer moduli, can eliminate the season, time, and temperature impacts of the FWD measurements. Since the base and subgrade layer moduli are backcalculated from the same deflection basins measured at the surface, temperatures, and moisture conditions at the time of measurements can affect those material properties. Any guidelines concerning FWD testing should, therefore, consider this fact.

The ANOVA results showed the FWD measurement season's impact to be significant on the unbound layer moduli (see Table 6). The base and subgrade moduli showed minimal variation within the spring and fall seasons' temperature ranges. Therefore, such temperature within each climate may result in unbound layer moduli values close to their representative in-field conditions. Also, the unbound layer showed no effect of time within a day, suggesting no limits for FWD measurements regarding a better time for conducting deflection measurements.

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RECOMMENDED GUIDELINES FOR FWD MEASUREMENTS

The recommended general guidelines for FWD deflection testing on flexible pavements based on the SMP data analysis are described below. While such temperature ranges may not be practical for all conditions, testing with the recommended ranges will ensure minimum effects on the derived parameters.

- The recommended temperature range for flexible pavement FWD testing in DF and WF climatic regions is 55 to 70°F.
- The recommended temperature range for flexible pavement FWD testing in DNF and WNF climatic regions is 65 to 75°F.
- FWD testing can be performed at any time of the day.
- Preferable seasons are spring and fall for FWD testing.

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Figure 5 Temperature corrected vs. observed HMA layer moduli

Figure 6 Pavement surface and ambient temperatures during FWD tests - DF climate

Figure 7 Example for monthly variation in layer moduli values — Section 23-1026 (WF)

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Table 1 Original experiment design (Rada et al. 1994) and presently available flexible pavement sections in the LTPP SMP database

Pavement type	Subgrade soil	DF	DNF	WF	WNF	Total
<i>Original experiment design</i>						
Flexible – Thick AC (> 5 inch surface)	Fine	3	3	3	3	12
	Coarse	3	3	3	3	12
	<i>Subtotal</i>	6	6	6	6	24
Flexible – Thin AC (< 5 inch surface)	Fine	3	3	3	3	12
	Coarse	3	3	3	3	12
	<i>Subtotal</i>	6	6	6	6	24
Total flexible pavement sections in design		12	12	12	12	48
<i>Available pavement sections</i>						
Flexible – Thick AC (> 5 inch surface)	Fine	4	-	3	4	11
	Coarse	4	6	26	6	42
	<i>Subtotal</i>	8	6	29	10	53
Flexible – Thin AC (< 5 inch surface)	Fine	-	-	2	3	5
	Coarse	1	1	2	5	9
	<i>Subtotal</i>	1	1	4	8	14
Total flexible pavement sections available		9	7	33	18	67

Note: Number in a cell indicates the desired number of pavement sections.

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Table 2 Available backcalculated parameters by FWD pass—SMP flexible sections

FWD Passes	DF	DNF	WF	WNF
1	340 (9)	207 (7)	779 (33)	599 (18)
2	267 (9)	160 (5)	445 (23)	458 (17)
3	230 (9)	139 (5)	349 (14)	318 (17)
4	104 (9)	59 (5)	150 (13)	114 (17)
5	14 (4)	17 (5)	4 (3)	23 (8)

Note: Values in parenthesis are the number of sections.

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Table 3 Available backcalculated structural parameters by FWD pass and maintenance category in different climatic regions—SMP flexible pavements

Maintenance category	FWD Pass	DF	DNF	WF	WNF
0	1	233 (8)*	117 (4)	382 (28)	381 (17)
	2	192 (7)	98 (4)	284 (11)	284 (14)
	3	167 (7)	80 (4)	228 (11)	208 (13)
	4	77 (7)	36 (4)	97 (11)	77 (13)
	5	8 (3)	15 (4)	3 (2)	12 (5)
1	1	81 (5)*	53 (4)	54 (5)	130 (6)
	2	61 (4)	48 (4)	42 (3)	119 (6)
	3	54 (4)	47 (4)	36 (3)	82 (6)
	4	25 (4)	15 (3)	17 (3)	31 (5)
	5	6 (1)	-	1 (1)	10 (2)
2	1	18 (3)*	17 (1)	92 (6)	21 (4)
	2	14 (3)	14 (1)	53 (3)	13 (3)
	3	9 (2)	12 (1)	44 (3)	1 (1)
	4	2 (1)	8 (1)	18 (3)	
	5	-	2 (1)	-	-
3	1	8 (4)*	20 (3)	251 (29)	67 (8)
	2	-	-	66 (14)	42 (3)
	3	-	-	41 (5)	27 (3)
	4	-	-	18 (4)	6 (1)
	5	-	-	-	1 (1)

Note: Values in parenthesis are the number of sections. *233 + 81 + 18 + 8 = 340

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Table 4 Available HMA layer mid-depth temperatures on FWD measurement days—SMP sections

FWD Passes	DF	DNF	WF	WNF
1	539 (9)	301 (7)	1303 (30)	1149 (17)
2	389 (9)	229 (5)	557 (19)	819 (17)
3	323 (9)	200 (5)	445 (13)	566 (17)
4	132 (9)	98 (5)	193 (13)	211 (17)
5	15 (4)	28 (5)	7 (3)	48 (8)

Note: Values in parenthesis are the number of sections.

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Table 5 Descriptive statistics HMA layer moduli—SMP flexible pavements

Climatic region	N	Mean	Std	Minimum	Q1 ^a	Median	Q3 ^a	Maximum
DF	957	1219.8	1009.9	113.1	613.9	940.9	1581.0	7817.9
DNF	582	1085.6	577.8	102.3	639.2	1015.2	1474.9	2805.2
WF	1739	1113.2	809.1	105.2	606.2	959.5	1387.6	7880.9
WNF	1533	1268.5	1259.5	109.9	438.6	789.8	1605.0	7634.9

Note: HMA moduli values shown are in ksi units. ^a 1st and 3rd quartiles.

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Table 6 Summary of ANOVA results

Source	DF		DNF		WF		WNF	
	DoF ^a	p-value	DoF	p-value	DoF	p-value	DoF	p-value
HMA moduli								
Season	3	0.000	3	0.000	3	0.000	3	0.000
Time	1	0.000	1	0.000	1	0.000	1	0.000
AC th	1	0.005	1	0.588	1	0.445	1	0.077
Maint. Cat.	3	0.000	3	0.000	3	0.000	3	0.000
Season*Time	3	0.003	3	0.022	3	0.177	3	0.018
Season*AC th ^b	3	0.000	3	0.142	3	0.000	3	0.005
Time*AC th	1	0.034	1	0.575	1	0.408	1	0.073
Error	824		514		1570		1236	
Total	839		529		1585		1251	
Base moduli								
Season	3	0.000	3	0.000	3	0.002	3	0.000
Time	1	0.211	1	0.169	1	0.925	1	0.130
AC th	1	0.000	1	0.002	1	0.000	1	0.000
Maint. Cat.	3	0.000	3	0.000	3	0.154	3	0.468
Season*Time	3	0.266	3	0.040	3	0.199	3	0.513
Season*AC th	3	0.000	3	0.055	-	-	3	0.079
Time*AC th	1	0.474	1	0.922	1	0.986	1	0.883
Error	743		433		1227	-	723	
Total	758		448		1239	-	738	
Subgrade moduli								
Season	3	0.000	3	0.000	3	0.000	3	0.000
Time	1	0.073	1	0.517	1	0.294	1	0.450
AC th	1	0.000	1	0.831	1	0.000	1	0.393
Maint. Cat.	3	0.000	3	0.000	3	0.000	3	0.000
Season*Time	3	0.259	3	0.496	3	0.810	3	0.478
Season*AC th	3	0.978	3	0.020	3	0.000	3	0.309
Time*AC th	1	0.083	1	0.080	1	0.392	1	0.950
Error	625		356		1135		1193	
Total	640		371		1150		1208	

^a Degrees of freedom. ^b AC thickness.

Figure 1 Seasonal and diurnal variations in HMA layer moduli

(a) Histogram - HMA moduli

(b) Box-plot - HMA moduli

Figure 2 Visualising available HMA layer moduli data—SMP flexible pavements

Figure 3 Evaluating normality of the HMA moduli data - DF climatic region

Figure 4 Interaction means plot - DF climatic region

Figure 5 Temperature corrected vs. observed HMA layer moduli

(a) Temperature ranges — season and time

(b) Seasonal temperature ranges

Figure 6 Pavement surface and ambient temperatures during FWD tests - DF climate

(a) HMA moduli

(b) Base moduli

(c) Subgrade moduli

Figure 7 Example for monthly variation in layer moduli values — Section 23-1026 (WF)