TECHBRIEF

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Effects of Seasonal and Diurnal FWD Measurements on LTE of JPCP—LTPP SMP Data

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This report won the graduate category of the 2019–2020 Data Analysis Student Contest sponsored by the Federal Highway Administration's Long-Term Pavement Performance (LTPP) program and American Society of Civil Engineers. This report, entitled *Effects of Seasonal and Diurnal FWD Measurements on LTE of JPCP—LTPP SMP Data*, analyzes the effects of seasonal and diurnal falling weight deflectometer (FWD) measurements on the load transfer efficiency (LTE) of jointed plain concrete pavements and develops general guidelines for conducting FWD deflection measurements.

INTRODUCTION

The structural capacity of pavements is typically evaluated by conducting a nondestructive test such as a falling weight deflectometer (FWD). The deflections that are measured with an FWD device are then analyzed to obtain the layer moduli values, such as the elastic modulus of a portland cement concrete (PCC) slab and the modulus of subgrade reaction (*k*-value) in case of rigid pavements. Based on the different deflection-based parameter values, the current pavement condition is then characterized. However, seasonal and diurnal temperature variations affect the measured deflections on rigid pavements. Curling, which is caused by the temperature differential between a slab's surface and bottom side, can occur and subsequently influence the FWD deflection measurements. Thus, if a midslab deflection basin is obtained when the slab is curled down (i.e., the slab's surface is warmer than its bottom side) or corner deflections are obtained when the slab is curled up (i.e., the slab's surface is cooler than its bottom side), the slab may be unsupported. Such conditions will result in more considerable deflections.

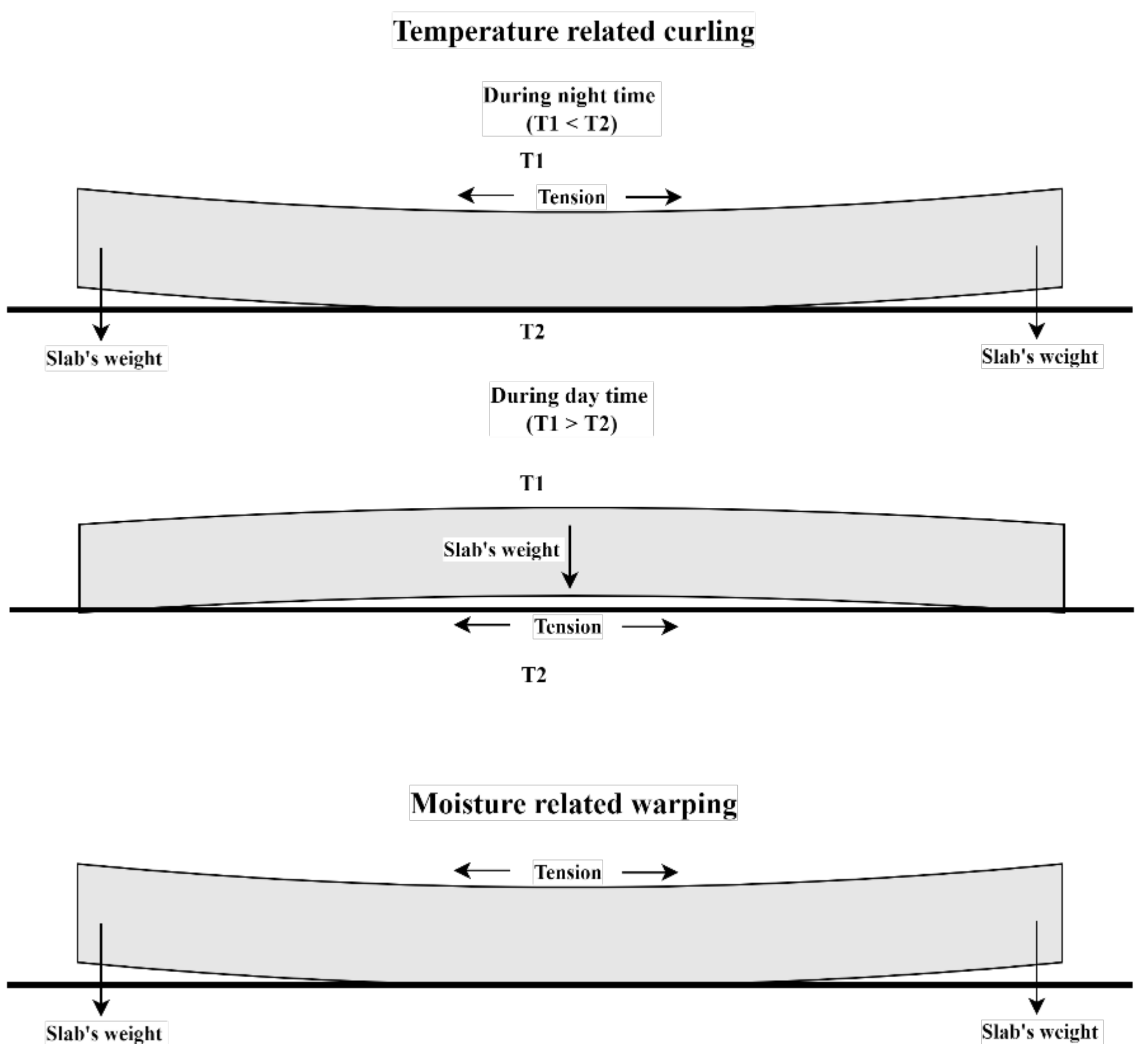
Load transfer efficiency (LTE) is one of the critical elements that can be estimated across joints and cracks by using FWD deflection measurements while evaluating the condition of rigid pavements. Seasonal and diurnal temperature variations also affect the joint and crack behavior in rigid pavements. Elevated temperatures cause the concrete slabs to expand, and this PCC slab expansion, coupled with slab curling, results in locked-up joints. Deflection testing that is conducted on locked-up joints will result in lower and equal joint deflections and higher LTEs, which is misleading regarding a joint's overall load transfer capabilities.

The primary objectives of this TechBrief are to evaluate the effects of seasonal and diurnal FWD measurements on the LTE of jointed plain concrete pavement (JPCP) sections and to develop general guidelines for conducting FWD deflection measurements. The data from the JPCP sections of the Long-Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) study were synthesized and analyzed to accomplish these objectives.

Environmental Effects on a PCC Slab

The environmental effects on a PCC slab can unfold in two ways: deterioration of the concrete itself, which is related to concrete mixture design and construction and is not the focus of this TechBrief; and, volumetric changes that cause the concrete slab to change size either horizontally or vertically. The latter is called curling, which develops because of differential volume changes across the slab thickness. Temperature gradients (i.e., the temperature difference between the surface and the bottom side of a PCC slab at a particular time of the day) cause the slab to curl up or down during the nighttime (negative gradient) and daytime (positive gradient), respectively (see figure 1). Both upward and downward curling increases as the temperature gradients increase (Siddique et al. 2005). This curling results in loss of support at the slab's corners or its center coupled with the self-weight of the slab, and vehicle loads contribute to early-age slab cracking or even slab failure (Choubane and Tia 1995; Jeong and Zollinger 2005; Siddique et al. 2005). Historically, the thermal stress distribution had been considered linear across the slab thickness (Westergaard 1927). However, current research

Figure 1. Diagram. Location of tensile stress under temperature- and moisture-related curvatures.



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T = temperature.

shows that the gradient can be nonlinear (Choubane and Tia 1992; Jeong and Zollinger 2005; Siddique et al. 2005). A drawback of considering a nonlinear thermal gradient is that it results in under- and overestimating the stresses during daytime and nighttime, respectively (Choubane and Tia 1995). The tensile stresses can be as high as 5.5 times larger on the edge and as high as 8.8 times larger at the corner of the slab than stresses induced by a standard axle, once negative gradients occur (Trujillo and Guettero 2019).

Load Transfer at Joints

The doweled transverse joint of a JPCP pavement undergoes deflection when wheel loads are applied. Both sides of the joint deflect because of the transfer of the applied load from the loaded to the unloaded slab. This load transfer occurs due to the load transfer devices (i.e., the dowel bars) in a JPCP. The presence of load transfer devices ensures lesser deflection and stresses in the loaded slabs as compared to undoweled slabs or slabs with free edges (McCracken 2008). The term LTE is used to express a joint's ability to transmit part of the applied load from the loaded slab to the adjacent unloaded one in a JPCP (Ioannides and Korovesis 1992). Several formulations are used to calculate the LTE for a joint. However, the deflection-based index is widely used and is accepted by the American Association of State Highway and Transportation Officials (AASHTO) pavement design guide (AASHTO 1993). The standard way to calculate LTE, which is also used by the LTPP program (Elkins et al. 2018), is the ratio of the unloaded to the loaded vertical displacements measured at a joint on the slab's surface.

As discussed in the Introduction, slab curling is also known to affect the joint and crack behavior of PCC slabs. Expansion of a slab in elevated temperatures coupled with slab curling may cause a joint to lock. Such joint locking results in reduced or equal joint deflections and higher LTE values, whereas the opposite is true in low winter temperatures, during which the joints open as a result of the slab's contraction. A study that evaluated LTE measurements made the following conclusions (Shoukry et al. 2005):

- LTE measurements depend on many factors, including load position, testing time, slab temperature, and load transfer device.
- LTE measurements are significantly affected by testing time and season. For the same joint, LTE measured in winter was less than that measured in summer.
- LTE measurements are affected by joint opening changes, daily and seasonally, as the ambient temperature changes. As the amount of joint opening increases due to slab contraction during the winter, the measured LTE generally decreases.
- LTE measurements increase as a slab's temperature rises.

LTPP SMP Study

To evaluate the effects of seasonal and diurnal FWD-based measured deflections on the computed load transfer capacity of joints, identification of an adequate dataset that contained multiple seasonal and diurnal FWD measurements was crucial. Such extensive FWD data were identified in the SMP study of the LTPP program (FHWA 2019), which was designed to evaluate the influence of temporal changes in pavement structural characteristics attributable to diurnal and seasonal variations in temperature and moisture (Elkins et al. 2018). As the primary measure of a pavement's structural characteristics, multiple seasonal and diurnal FWD deflection measurements are peculiar to the data contained in the LTPP SMP study. Based on the unique nature of the contained data, the SMP study was used to evaluate the effects of seasonal and diurnal FWD measurements on the JPCP sections included in the study.

DATA SYNTHESIS

This section describes the identified data elements, their availability, and the extent to which these data were used to accomplish the study's objectives.

Data Elements

Table 1 presents a summary of the data elements identified for the analysis:

- Pavement cross sections, age, and material types for all layers of JPCP sections.
- Temperature and precipitation data from the climatic module and information on the climatic regions.
- Monitored FWD deflection data with air and surface temperatures, temperature gradients, testing dates, and timings.
- Monitored performance data (LTE values) over time.

Data Elements	LTPP Table	Description
Layer number Layer type Representative thickness Material types	SECTION_LAYER_STRUCTURE	This table contains a consolidated set of pavement layer structure information for all LTPP test sections.
State code SHRP ID Experiment name and number Assign date Construction number Construction number change reason De-assign date	EXPERIMENT_SECTION	This table is the master control table for all test sections and project sites included in the LTPP database.
Precipitation and climatic regions	TRF_ESAL_INPUTS_SUMMARY	The table includes average annual precipitation and freeze index, LTPP experimental climate region, and the source for this classification.
Test date Test time Deflection unit identifier Point location Drop height and load Peak deflection sensor Layer temperature data with depths Lane number Air and pavement surface temperatures measured by instruments on the FWD	MON_DEFL_DROP_DATA	The table contains peak deflection, peak load, and other drop-specific FWD measurements.
	MON_DEFL_TEMP_DEPTHS	This table contains the depth at which temperature gradient data are collected during FWD testing.
	MON_DEFL_TEMP_VALUES	This table includes in-pavement temperature gradient data obtained during FWD testing.
	MON_DEFL_LOC_INFO	This table contains information specific to each point at which testing was conducted.
LTE	MON_DEFL_LTE	This table contains the LTE computed parameter. LTE is computed from FWD measurements at transverse joints and cracks on PCC pavements.

Table 1. LTPP program database tables used to extract data elements (Elkins et al. 2018).

ID = identification; SHRP = Strategic Highway Research Program.

Database Development

The required data were obtained from the LTPP database standard release 33.0 and represented the most recent and up-to-date available data (FHWA 2019). The JPCP sections included in the SMP study were assigned a unique identification (ID) by combining the State code with its Strategic Highway Research Program (SHRP) ID. Multiple data buckets containing the desired data variables were downloaded by using the online InfoPave® features (Elkins et al. 2018). Microsoft® Access® was used to organize the downloaded data elements into various data tables to create a relational database.

Temperature Gradients

The table MON_DEFL_TEMP_DEPTHS of the LTPP program contains the depths at which temperatures are measured during FWD testing (Elkins and Ostrom 2019). These temperatures are different than the surface temperatures measured by sensors attached to the FWD. Generally, a minimum of three temperature measurements that correspond to the top, middle, and bottom of the PCC layer are taken. However, in some instances, the holes for taking temperature measurements were found to be drilled entirely through the bound surface layer into the base material (Elkins et al. 2018). Therefore, the data found in the MON_DEFL_TEMP_DEPTHS table were matched with the representative thickness of the slab. Only the temperature measurements that were obtained within ±1.25 inches of the top surface or bottom side of the PCC layer were used to calculate the temperature gradients (i.e., top minus bottom) for analysis.

Maintenance Categories

The maintenance history data of the available JPCP sections were categorized based on the anticipated effect of these maintenance events on FWD deflections. Four categories were used, as follows:

- Category 0: No maintenance at all.
- Category 1: Maintenance works with no significant effects on FWD measurements.
- Category 2: Localized patchwork.
- Category 3: Maintenance works with significant effects on pavement structure and response.

Available Data and Extents

FWD pass data were obtained for 16 JPCP sections identified in the LTPP SMP study (FHWA 2019). An FWD pass serves to distinguish multiple runs of the same lane number on the same day (Elkins et al. 2018). Table 2 shows the available LTE values for multiple FWD passes on the same day for the available JPCP sections within each climatic region (i.e., dry, freeze (DF); dry, no freeze (DNF); wet, freeze (WF); and wet, no freeze (WNF)) of the SMP study. More data on the wet regions were available because there were more JPCP sections on wet climates. Table 2 includes the data for both locations (i.e., before and after the joint), where deflections were measured to calculate the LTE. The lower of the two LTE values was used in the analysis.

Data Assessment

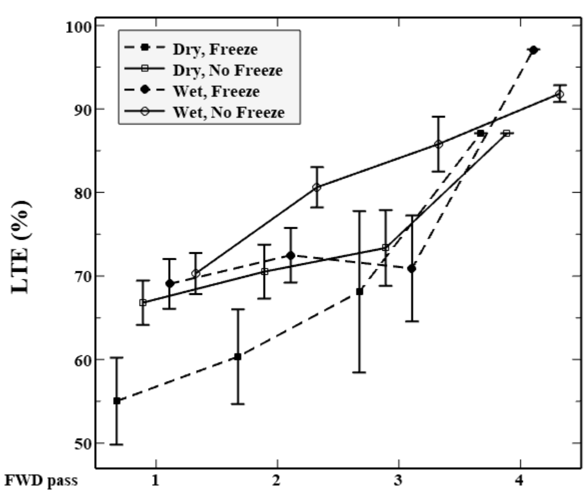
Figure 2 illustrates the effects of diurnal (i.e., by FWD pass) and seasonal FWD deflection measurements on the obtained LTE values in different climatic zones for all JPCP pavement sections in the SMP study. Figure 2 also presents the distribution of the available data within each climatic region, and it shows that LTE values are affected by diurnal and seasonal measurements. Higher LTE values are expected at higher temperatures due to slab expansion and joint locking, whereas lower LTE values correspond to slab contraction occurring during lower temperatures. Table 3 shows the descriptive statistics for LTE values for the available JPCP sections and the available number (*N*) of the LTE measurements within each climatic zone. A higher variation evident from the larger standard deviation (Std. Dev.) was seen in the freeze regions. Therefore, it is essential to consider the diurnal and seasonal temperatures for such measurements for rigid pavements.

Table 2. Available number of LTE (before and after joint) values by climatic regions.tables used to extract data elements (Elkins et al. 2018).

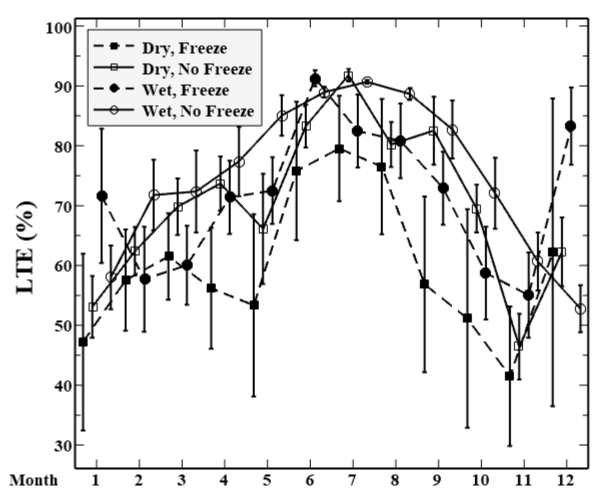
FWD PASSES	DF	DNF	WF	WNF
1	114 (2)	158 (2)	316 (6)	270 (6)
2	88 (2)	120 (2)	228 (5)	168 (3)
3	30 (2)	46 (2)	64 (5)	36 (3)
4	2 (1)	2 (1)	2 (1)	4 (2)

Note: Values in parentheses are the number of sections.

Figure 2. Graphs. Assessments of available LTE data.

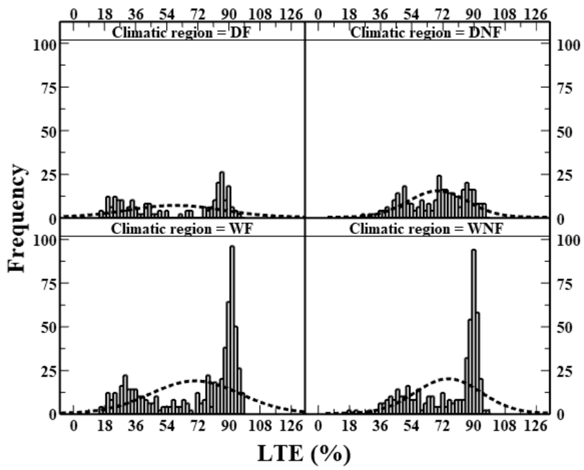


A. LTE by FWD pass.

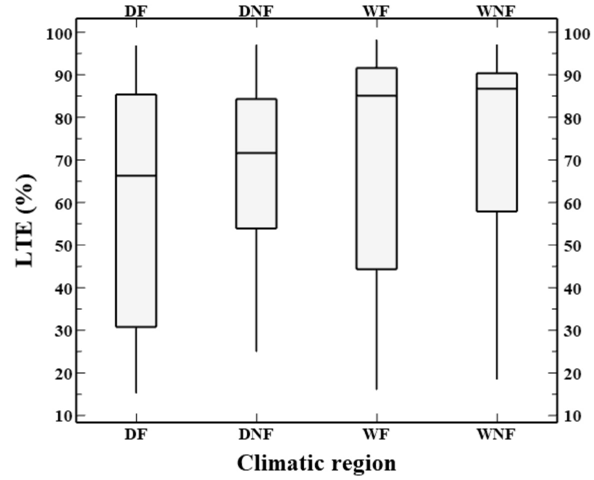


B. LTE by FWD measurement month.

Figure 2. (Continued) Graphs. Assessments of available LTE data.



C. Histogram—available LTE values.



D. Box plot—available LTE values.

Table 3. Descriptive statistics of LTE values.

Climatic Region	*N*	Mean	Std. Dev.	Minimum	Q1*	Median	Q3*	Maximum
DF	234	58.9	27.5	15.2	30.7	66.2	85.3	96.8
DNF	326	69.2	17.0	25.0	53.8	71.6	84.2	96.9
WF	610	70.6	26.0	16.0	44.3	85.0	91.5	98.2
WNF	478	75.2	19.0	18.4	57.8	86.7	90.3	97.0

Q1 = first quartile; Q3 = third quartile.
Note: Values in parentheses are the number of sections.

DATA ANALYSIS AND RESULTS

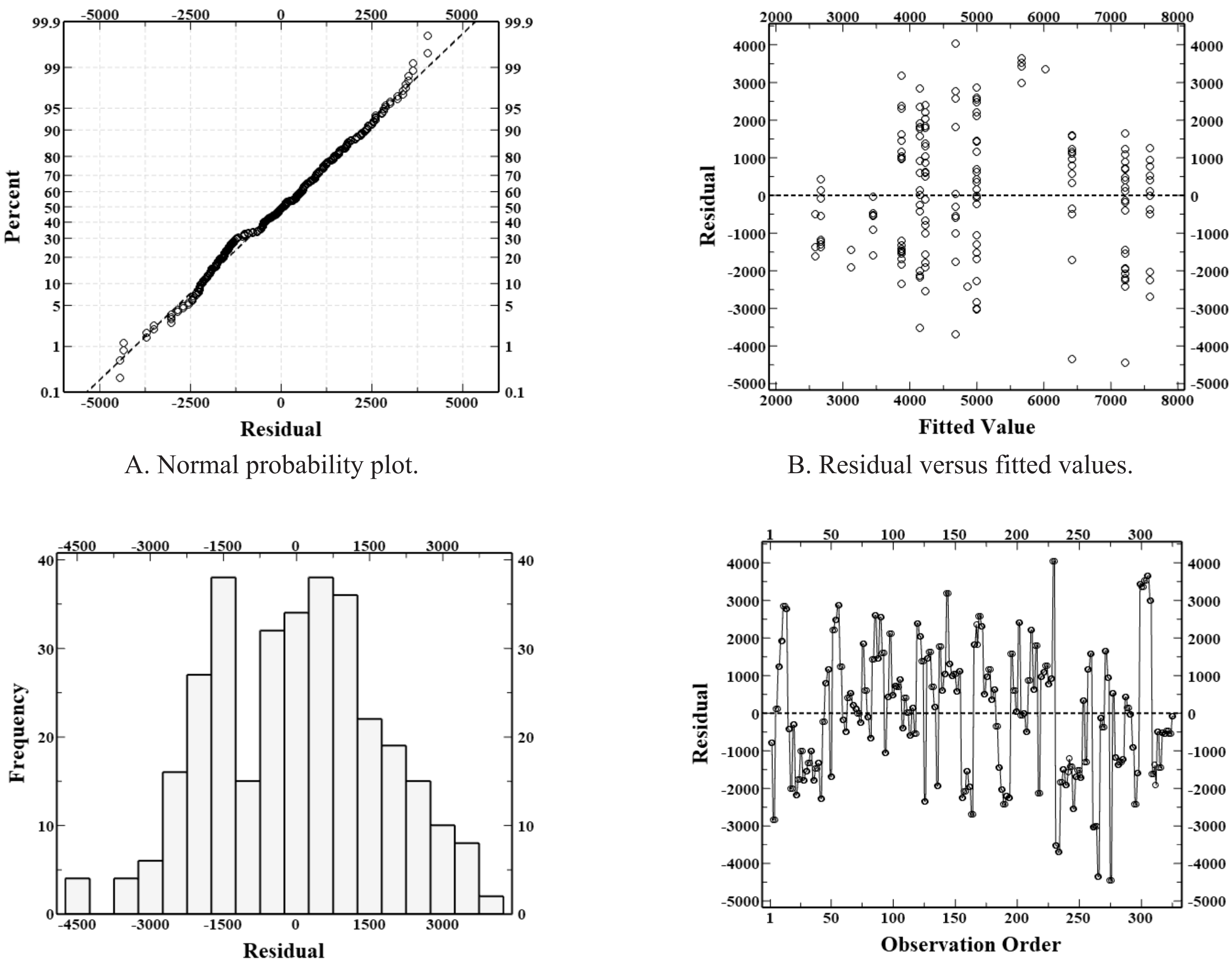
As noted in the Introduction, temperature variations can affect the joint and crack behavior in rigid pavements. Warmer temperatures cause the slabs to expand, and when the expansion is coupled with slab curling, the joints might lock. Therefore, if deflection testing is conducted at the joints when they are locked, the joint deflections will be lower. Resultantly, the determined LTEs will be higher, which is misleading regarding the joint's overall load transfer capabilities. The effects of temporal (seasonal and diurnal) variations on LTE were investigated using data extracted from the LTPP SMP study for the JPCP sections.

Steps for Data Analysis

The analysis involved conducting the following steps:

1. Identifying the variables needed to perform the analysis, including the pavement structure details, LTE values, FWD measurement dates and timings, maintenance history, pavement surface temperature, air temperature, and temperature gradient measurements.
2. Identifying the JPCP pavements sections in the LTPP SMP study within each of the four climatic regions (FHWA 2019). Note that the climatic regions are defined in terms of temperature (i.e., freeze/no freeze) and moisture (i.e., wet/dry).
3. Obtaining the LTE values, 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 for temperature gradient measurements.
4. Extracting and then categorizing the maintenance history details (i.e., construction numbers and types of treatment) for all the sections in the database.
5. Arranging the data in a relational database.
6. Inspecting the data by using a histogram and boxplot to identify outliers.
7. Using two quantifying factors: measurement month discretized into four seasons (i.e., levels) to study the seasonal effects, and measurement time with two levels (before noon and afternoon) to investigate the diurnal effects.

Figure 3. Graphs. Evaluating normality of the LTE data—DNF climatic region.



A. Normal probability plot.

B. Residual versus fitted values.

C. Histogram of residuals.

D. Residual versus observation order.

8. Conducting an analysis of variance (ANOVA) of the JPCP sections within each climatic region to investigate the temporal effects on the joint LTE values.

Figure 3 demonstrates the normality of the data for the DNF climatic region that was used in the analysis. 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.

Discussion on Results

Table 4 presents the ANOVA analysis results for the DF climatic region. The results show that the FWD measurement season significantly affected the LTE values based on a type I error rate of 5 percent ($\alpha = 0.05$). In contrast, the FWD measurement time had no significant effect on the LTE values at the same error rate. The results also show that the interaction between the two factors (i.e., season and time) contributed significantly to the LTE values' variations. Thus, looking at the interaction effects rather than the main effects is essential. Figure 4-A shows that the mean LTE values in the summer varied from 68 percent for the before-noon measurement to 85 percent for the afternoon measurement. In addition, the LTE values differed in the spring and fall within the before-noon and afternoon measurements; however, the difference was not as significant as the summer variations. Figure 4-B shows that the difference of mean LTE values between any pair of seasons and time interactions involving the summer is substantial. Thus, the results suggest that summer LTE values are significantly higher than the values obtained in the other seasons, irrespective of the time of the day, with a more significant difference in the afternoon measurements.

Table 4. ANOVA results for LTE values—DF climatic region.

Source	DoF	Seq SS	Contribution (percent)	Adj SS	Adj MS	*F* Value	*p* Value
Season	3	20,540	12.94	20,158	6,719.5	25.52	**0.000***
Time	1	1,010	0.64	1,031	1,031.3	3.92	0.049
Maintenance category	2	77,063	48.56	73,316	36,658.2	139.22	0.000
Season × time	3	3,743	2.36	3,743	1,247.5	4.74	**0.003***
Error	214	56,350	35.51	56,350	263.3	—	—
Lack of fit	14	16,188	10.20	16188	1156.3	5.76	0.000
Pure error	200	40,163	25.31	40163	200.8	—	—
Total	223	158,707	100.00	—	—	—	—

—No data.
*Significant factor or interaction.
Adj = adjusted; DoF = degrees of freedom; Seq = sequential; SS = sum of squares; MS = mean squares.

To further explain the higher LTE values during the summer, figure 4-C shows the 95 percent confidence interval of the pavement surface and air temperatures at the time of FWD measurements. There was a clear difference between the temperatures recorded while conducting FWD measurements before noon and during the afternoon. This difference suggests that temperatures higher than 80 °F should be avoided while conducting FWD testing on joints because such elevated temperatures significantly increase the observed LTE.

Although the maintenance category can significantly influence the LTE values, it was used as a blocking factor. Blocking is a technique that can increase the precision in an analysis or an experiment by reducing the experimental error variance. It is achieved by considering factors believed to affect the response but not considered to be of primary importance in the analysis. Therefore, no further discussion related to the maintenance category will be presented beyond this point.

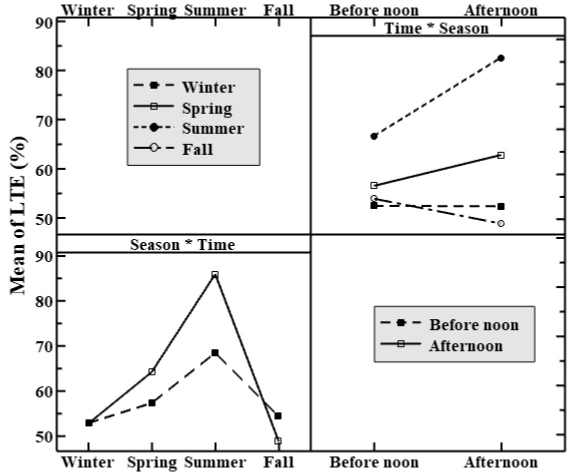
The results of a similar ANOVA analysis for the DNF climatic region show that the interaction of the two factors—the FWD measurement season and time—have more influence on the LTE values than the individual factors (see table 5). The interaction means plot did not show that there was a significant difference between LTE values determined from deflections measured before noon and during the afternoon (see figure 5-A). The overall mean LTE values for the DNF climatic region were higher than for the DF climatic region. A possible explanation for higher LTE values, with no significant difference between the two times of the day, can be the higher range of measurement temperatures. The temperature ranges within the DNF region are higher than 75 °F (figure 5-B). Therefore, temperatures higher than 75 °F should be avoided while measuring LTE at joints to eliminate the effect of locked joints on the observed joint deflections and prevent overestimation of LTE.

Table 5. ANOVA results for LTE values—DNF climatic region.

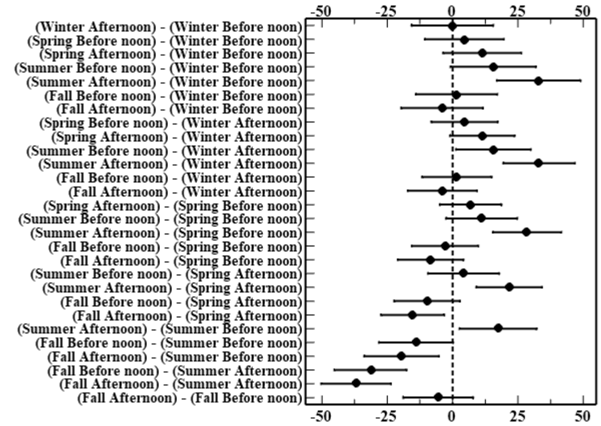
Source	DoF	Seq SS	Contribution (percent)	Adj SS	Adj MS	*F* Value	*p* Value
Season	3	547,985,885	32.70	520,306,982	173,435,661	56.42	0.000
Time	1	33,623,209	2.01	17,249,536	17,249,536	5.61	0.018
Maintenance category	1	87,039,916	5.19	94,121,166	94,121,166	30.62	0.000
Season × time	3	32,552,731	1.94	32,552,731	10,850,910	3.53	**0.015***
Error	317	974,519,223	58.16	974,519,223	3,074,193	—	—
Lack of fit	6	179,477,449	10.71	179,477,449	29,912,908	11.70	0.000
Pure error	311	795,041,774	47.44	795,041,774	2,556,404	—	—
Total	325	1,675,720,963	100.00	—	—	—	—

—No data.
*Significant factor or interaction.

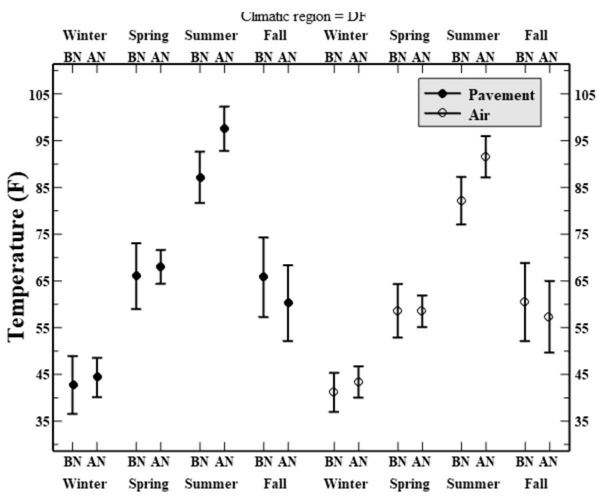
Figure 4. Graphs. ANOVA results—DF climatic region.



A. Interaction means plot.



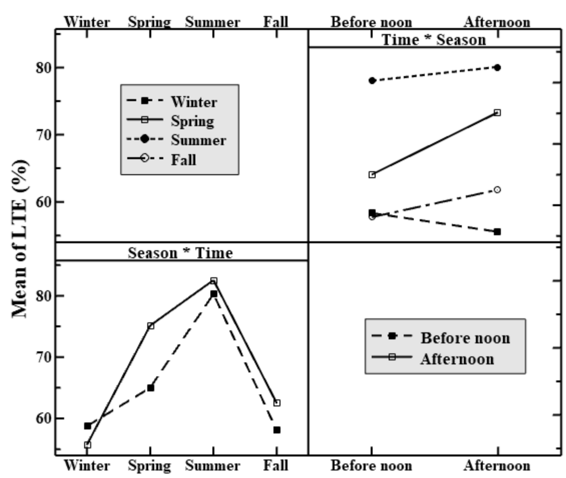
B. Mean difference of LTE values with 95 percent confidence interval for season and time interaction.



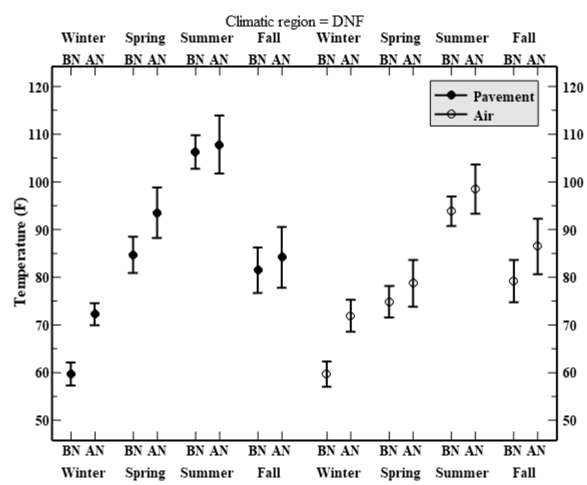
AN = afternoon;
BN = before noon.

C. Pavement surface and air temperatures during FWD measurements.

Figure 5. Graphs. ANOVA results—DNF climatic region.



A. Interaction means plot.



B. Pavement surface and air temperatures during FWD measurements.

The results of the ANOVA analysis for wet regions show that the main effects of the two factors, namely season and time, are significant contributors to the variations in LTE, whereas their interaction is not (see table 6 and table 7). The main effects plot in figure 6-A shows that the mean LTE value during the summer is significantly higher than during other seasons. Figure 6-C shows that any difference involving LTE obtained from FWD conducted during the summer season is significant. For the WNF climatic region, the LTE values were statistically different between all the seasons (figure 6-B and figure 6-D). However, the difference between the winter and spring LTE values (>15 percent) and the summer and spring LTE values (>20 percent) can only be termed as practically different.

The elevated summer season LTE values in the WF climatic region can be attributed to the recorded high-temperature range, that is, higher than 75 °F (80–84 °F) during the FWD measurements (figure 7-A). Similarly, the difference between the seasonal LTE values in the WNF climate is also evident from the temperature ranges during FWD testing (figure 7-B). Again, the higher summer LTE values are attributable to the elevated temperatures recorded during FWD measurements. In addition, an increase in the winter mean LTE values observed in the WF climatic region can be explained by the joints' resistance to movement due to extremely low temperatures, that is, below 35 °F (figure 7-B). Such low temperatures should be avoided while conducting FWD tests.

The diurnal trends in both the WF and WNF climates (figure 6-A and figure 6-B, respectively) indicated that the before-noon measurements result in a lower LTE value than the afternoon measurements. Figure 7-C and figure 7-D show the diurnal temperature ranges at the time of FWD measurements in the wet climatic regions.

Table 6. ANOVA results for LTE values—WF climatic region.

Source	*DoF*	Seq SS	Contribution (percent)	Adj SS	Adj MS	*F* Value	*p* Value
Season	3	756,157,660	13.11	680,113,939	226,704,646	34.88	**0.000***
Time	1	154,530,676	2.68	43,189,635	43,189,635	6.65	**0.010***
Maintenance category	2	1,058,360,121	18.35	1,062,049,115	531,024,558	81.71	0.000
Season × time	3	4,293,469	0.07	4,293,469	1,431,156	0.22	0.882
Error	584	3,795,286,065	65.79	3,795,286,065	6,498,778	—	—
Lack of fit	14	414,978,033	7.19	414,978,033	29,641,288	5.00	0.000
Pure error	570	3,380,308,032	58.60	3,380,308,032	5,930,365	—	—
Total	593	5,768,627,991	100.00	—	—	—	—

—No data.
*Significant factor or interaction.

Table 7. ANOVA results for LTE values—WNF climatic region.

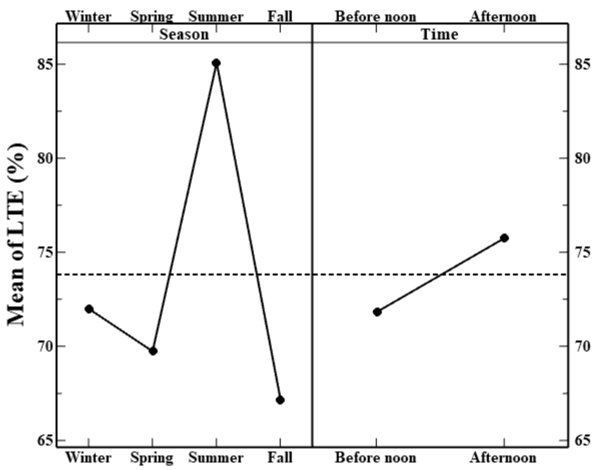
Source	*DoF*	Seq SS	Contribution (percent)	Adj SS	Adj MS	*F* Value	*p* Value
Season	3	47,986	33.88	49,449.3	16,483.1	86.60	**0.000***
Time	1	3,256	2.30	3,217.5	3,217.5	16.91	**0.000***
Maintenance category	1	352	0.25	342.5	342.5	1.80	0.180
Season × time	3	1,161	0.82	1,160.7	386.9	2.03	0.108
Error	467	88,882	62.75	88,882.4	190.3	—	—
Total	475	141,637	100.00	—	—	—	—
Pure error	570	3,380,308,032	58.60	3,380,308,032	5,930,365	—	—
Total	593	5,768,627,991	100.00	—	—	—	—

—No data.
*Significant factor or interaction.

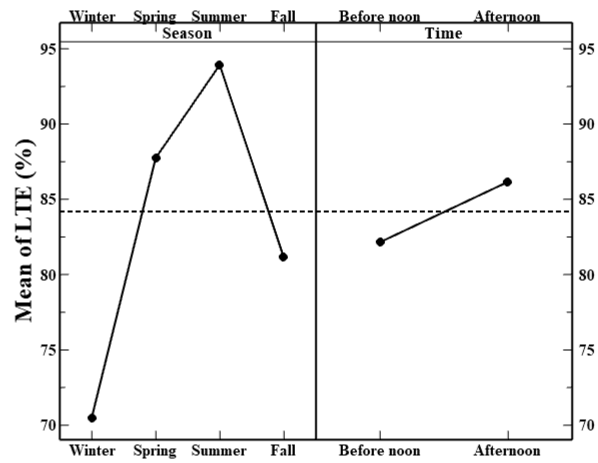
In the WF region, the before-noon air temperatures are not very different from the afternoon temperatures; however, there is a significant difference between the corresponding pavement surface temperature ranges. Such a difference in the pavement surface temperature causes the LTE values that are measured before noon to be lower than the afternoon LTE values. The difference in the diurnal temperature ranges in the WNF climatic region explains the lower before-noon LTE values as opposed to afternoon LTE values.

In general, FWD measurements conducted before noon result in lower LTE values than those measured in the afternoon, irrespective of the climatic region. Therefore, it is beneficial to perform deflection measurements on joints for LTE determination before noon when slabs are flatter. Figure 8 shows the histogram of the temperature gradients data available in the LTPP SMP study for the JPCP sections (FHWA 2019). A zero or near-zero temperature gradient would be ideal for measuring deflections at joints for LTE determination, because such LTE values will depict a joint's actual load transfer capacity. For approximately 60 measurements in the data, the temperature difference was between -1 and 1 °F. The time of these measurements ranged from 8 a.m. to around 1 p.m. Hence, the available data also suggest that diurnally before-noon measurements are ideal for finding a zero gradient temperature condition, which can help identify the condition of the joints accurately.

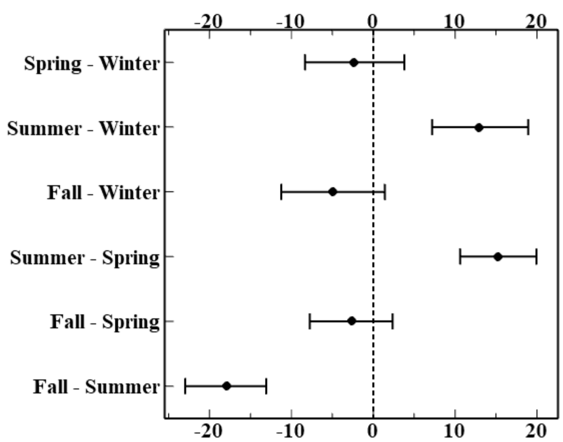
Figure 6. Graphs. ANOVA results—WF and WNF climatic regions.



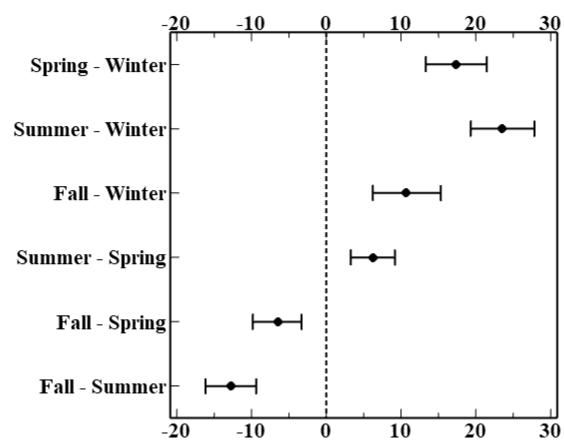
A. Main effects plot for LTE—WF climatic region.



B. Main effects plot for LTE—WNF climatic region.

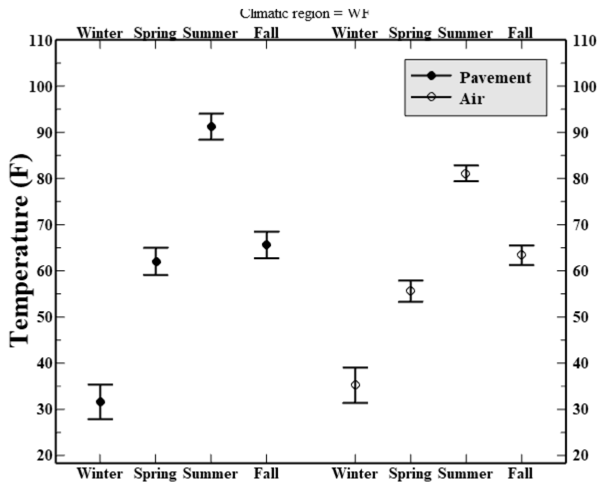


C. Seasonal mean difference of LTE values with 95 percent confidence interval—WF climatic region.

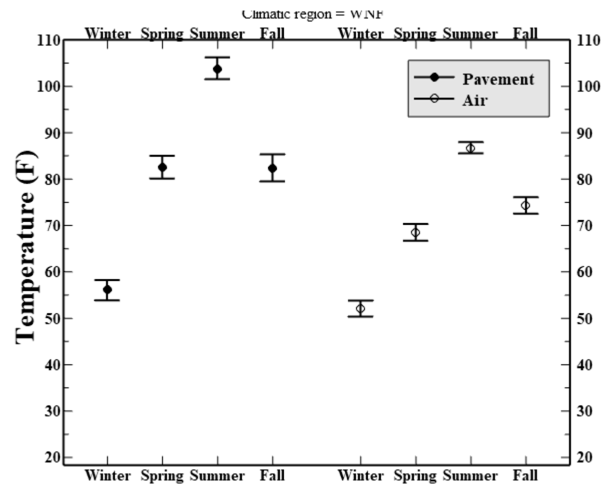


D. Seasonal mean difference of LTE values with 95 percent confidence interval—WNF climatic region.

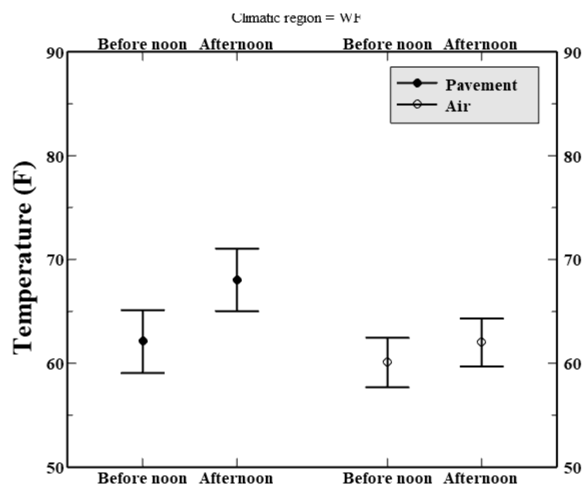
Figure 7. Graphs. Seasonal and diurnal pavement surface and air temperatures.



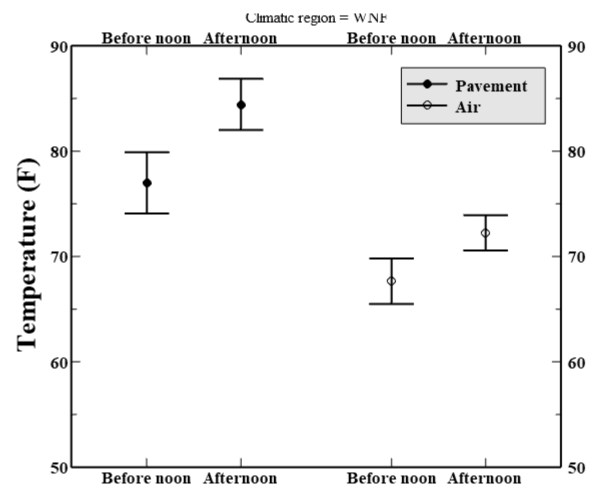
A. WF climatic region.



B. WNF climatic region.

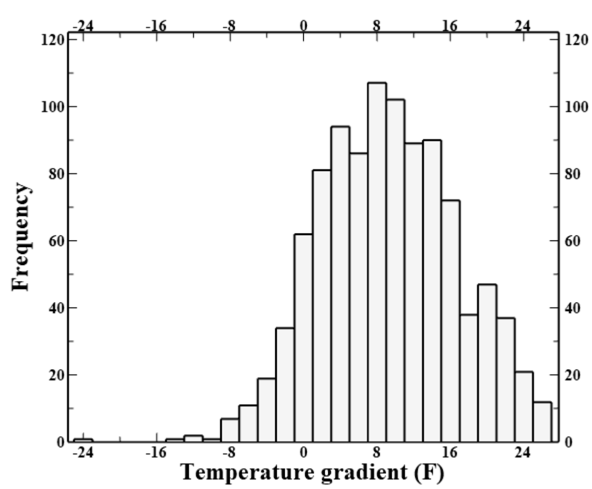


C. WF climatic region.



D. WNF climatic region.

Figure 8. Graph. Histogram of the available temperature gradients data—SMP JPCP sections.



The information presented in the Discussion on Results section could be used to suggest guidelines for FWD deflection measurements based on ambient temperature ranges. Although pavement temperature is known to have more effect on LTE than the ambient temperature, the same ambient temperature may also have a different impact on a concrete slab based on its thickness. However, surface temperature measurements cannot be determined directly in the field for an entire pavement section. Therefore, ambient temperatures are suggested as a guideline for FWD testing. In addition, the concrete slab thicknesses of the 16 JPCP pavements in this study ranged from 8 to 11 inches. The suggested guidelines can be valid for such slab thicknesses.

CONCLUSIONS AND RECOMMENDED GENERAL FWD MEASUREMENT GUIDELINES

The LTPP SMP study is a valuable data resource that can help identify, model, and characterize the effects of temporal (i.e., diurnal temperature and seasonal temperature/moisture) variations on different pavement performance-related parameters (FHWA 2019). Multiple measurements related to various aspects of the pavement performance and environmental factors available in the database made this analysis possible. The study presented in this TechBrief used the multiple FWD deflection measurements and temperature data to formulate general guidelines for FWD measurements on rigid pavements.

FWD measurements are conducted on both rigid and flexible pavements. The backcalculated hot-mix asphalt layer moduli that are obtained by using deflections measured by FWD are typically corrected for temperature. However, there is no comparable correction process for rigid pavements. Therefore, it is vital to have general guidelines for conducting FWD tests on rigid pavements to accurately characterize their condition. Based on the analysis and the discussion of the results, some general guidelines can be formulated and should be adhered to, when possible, to conduct FWD testing on concrete pavements. The following guidelines can help ascertain actual pavement joint conditions and load transferability:

- Avoid conducting FWD deflection measurements to calculate a joint's condition and estimate its load transfer capability when temperatures are above 75 °F because elevated temperatures tend to lock up the joints, due to slab expansion, and result in higher LTE values.
- Avoid performing FWD deflection measurements when temperatures are below 35 °F because lower temperatures will also result in LTE values that will not truly represent a joint's conditions owing to its resistance to movement.
- Perform FWD measurements before noon, if possible, to decrease the chances for the PCC slabs to curl down, which can result in locked joints. Thus, the determined LTE values will depict the actual load transfer capability of the joint.

FUTURE WORK

The TechBrief is based on an analysis of one of the FWD deflection-based parameters, LTE, of the rigid pavements. A similar study can be conducted for other FWD deflection-related parameters, such as PCC layer moduli, modulus of subgrade reaction (*k*-value), and void potential under the concrete slab for rigid pavements. The results from such future studies can be used to determine comprehensive FWD measurement guidelines to help engineers better characterize the performance of, and measure the actual condition of, rigid pavements

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