SUMMARY**REPORT**

Long-Term Pavement Performance International Data Analysis Contest

2017–2018 Graduate Category

Use of LTPP SMP Data to Quantify Moisture Impacts on Fatigue Cracking in Flexible Pavements

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This report won the graduate category of the 2017–2018 International Data Analysis Contest sponsored by the Federal Highway Administration's Long-Term Pavement Performance (LTPP) program and American Society of Civil Engineers. This report, entitled *Use of LTPP SMP Data to Quantify Moisture Impacts on Fatigue Cracking in Flexible Pavements*, analyzes the impact of moisture infiltration through surface cracking on the longevity or performance of a pavement.

INTRODUCTION

Moisture increase in pavement subsurface layers has an essential influence on granular material properties and affects expected pavement performance. Over time, moisture variations in the base layer of a flexible pavement depend on water infiltration after rain and pavement surface conditions. Consequently, the base layer resilient modulus (MR) is decreased considerably, which leads to premature failure and reduced service life of the pavement. This report presents LTPP data analyses for quantifying the effect of moisture infiltration through surface cracking on flexible pavement performance. Subsurface moisture data obtained through the Seasonal Monitoring Program (SMP) time-domain reflectometers (TDRs) are an excellent source to quantify the moisture related damage in different climatic regions. The MR of the base decreases with an increase in moisture. However, the reduction in base MR is about 2 to 13 percent and 93 to 175 percent for the pavement sections located in dry freeze (DF) and wet freeze (WF) climates, respectively. The primary reason for higher moisture variations in WF climates is more surface cracking coupled with higher precipitation levels. The results show that the base moisture values do not vary significantly in dryer climates because of low precipitation and cracking levels. Due to increased moisture and corresponding base MR values, the performance of pavement sections located in WF climates is adversely affected. The findings imply that adequate and timely preservation techniques, such as a surface seal, can enhance a pavement's service life significantly, especially in WF climates. Therefore, cracks should be sealed when the extent of wheelpath (WP) fatigue cracking is below 6 to 7 percent.

Currently, pavement preservation is an increasingly widespread practice among agencies interested in cost-effectively extending the lives of their pavements. Highway agencies have learned that, if preservation treatments are applied at an appropriate time, this can help in improving and slowing the deterioration rates for existing pavements (Haider and Masud 2018). While pavement preservation isnot expected to increase the structural capacity of an existing pavement substantially, it generally leads to improved pavement performance and longer service life. However, there are challenges in the adoption of such practices. Selection of preservation treatments depends on the preexisting conditions and other factors contributing to the deterioration of existing roadways. One of the most influential factors affecting flexible pavement performance is moisture variations within a pavement system, which is mainly caused by infiltration of rainfall water through surface cracking. The SMP study in the LTPP was designed to investigate and quantify moisture variations related to damage in flexible pavements.

The primary objectives of the report are as follows:

- Evaluate the effect of surface cracking on moisture in the base layer.
- Quantify the impact of water infiltration and moisture change on the strength properties of base layers.
- Evaluate the effect of base layer strength properties on predicted long-term pavement performance.
- Develop guidance for optimum timings of surface seals for different climates.

These objectives were accomplished by synthesizing and analyzing the SMP pavement sections' moisture and pavement performance data.

BACKGROUND

This section describes potential sources of water causing moisture variations in pavement systems. Also, the impact of moisture on pavement performance is documented.

Sources of Water Infiltration into Pavement Layers

Water can enter pavement unbound layers through many sources and subsequently affects the in situ moisture in these materials. The primary sources of moisture variation within a pavement system include external elements, such as precipitation and the groundwater table. Also, pavement surface conditions (cracking/discontinuities), drainage, shoulders, edges, and pavement cross-sections can also facilitate moisture infiltration (Masud 2018; Petry et al. 2006).

Moisture-Related Damage in Flexible Pavements

One of the most influential factors affecting pavement performance is the moisture content within the pavement system. As early as 1820, John MacAdam noted that, regardless of the strength (thickness) of the pavement structure, many roads in Great Britain prematurely deteriorated due to saturation of pavement subgrade (Cedergren 1994). Moisture damage in pavements manifests in the form of moisture-caused and moisture-accelerated distresses. Moisture-caused distresses include asphalt stripping in flexible pavements and durability cracking in rigid pavements. Moisture-accelerated distresses are those caused by other factors (e.g., traffic loading) but accelerate with an increase in moisture (National Cooperative Highway Research Program (NCHRP) 2004). Many properties of unsaturated soils, such as shear strength, permeability, and volume, vary significantly with a change in moisture content. The increase in moisture affects the durability and strength characteristics of soils, and consequently, the ability of unbound layers to support the heavy loads and their repetitions (Rao 1997).

While investigating pavement response to a varying level of moisture, Salour and Erlingsson (2013) concluded that an increase in moisture of unbound granular materials considerably reduces the back-calculated modulus of base layers. Various field monitoring studies suggest that a change in moisture can occur after rainfall, and it can increase up to 50 percent in addition to the natural seasonal variations (Hedayati et al. 2014). Variation in moisture levels in the field depends on the climate of a location and can be difficult to interpret. This potential increase in moisture is often neglected while estimating moisture variation in pavement unbound layers. However, such changes of moisture, along with axle loads, can accelerate pavement deterioration. Therefore, it is essential to develop a moisture prediction model that can accurately capture both seasonal and temporal moisture changes and later incorporate results in the lifecycle assessment of infrastructures (Hedayati and Hossain 2015). The infiltration of water from the road surface followed by a rainfall event can be a significant cause of premature pavement deterioration (Dan et al. 2017). While moisture conditions are relatively stable at the bottom of the pavement system, the moisture condition in the upper pavement structure can vary between very dry and fully saturated conditions depending on the rainfall duration and intensity. Moisture content of materials near pavement edges and in proximity of surface cracks usually shows higher variations due to rainfall events (Salour 2015). Considering water infiltration through cracks and joints is particularly important in the estimation of sublayer moisture and its effect on the MR (Witczak et al. 2000).

Despite considerable research in recent years on moisture-related damage in pavements, there are still several gaps in knowledge and practice. One of the primary concerns at the pavement design stage is protecting the base, subbase, and subgrade layers from becoming saturated or even being exposed to prolonged high moisture conditions over time. Many pavement engineers would also add hot mixed asphalt (HMA) and portland cement concrete to this list because excessive moisture coupled with freezing has badly impacted the properties of these materials (NCHRP 2004). This report evaluates the effect of water infiltration due to cracks and associated moisture variations in base materials and subsequent impacts on base MR values.

SMP LTPP

Previous research highlighted that moisture variation within unbound layers is one of the leading factors for premature pavement deterioration (Haider et al. 2018; Haider et al. 2019). Therefore, this report hypothesizes that moisture variation in unbound layers (i.e., base layer) can be related to the amount of fatigue cracking in different climatic zones. To validate this hypothesis, an important challenge was to identify a dataset documenting the subsurface moisture levels in the base layer. Only the SMP study has TDRs installed at different depths in many pavement sections. The performance monitoring data were also recorded for those pavement sections. The SMP study was designed to characterize the magnitude and impact of temporal variations in pavement response and the material properties due to the separate and combined effect of moisture, temperature, and frost/thaw variations. It also includes a higher monitoring frequency of deflections, longitudinal profile, and distress surveys on 64 SMP LTPP test sites. In addition to performance data, other measurements—including subsurface moisture, temperature, rainfall, and surface elevations—were also recorded at these sites (Elkins et al. 2003). The SMP study has a comprehensive database for subsurface moisture and temperature records. Because of the uniqueness of the SMP study, SMP data were identified as the best available source to quantify moisture damage in flexible pavements. The research team primarily focused on surface cracking (particularly fatigue cracking), precipitation, and subsurface moisture data.

DATA SYNTHESIS

This section describes the data elements and data selection process to accomplish the objectives of the study.

Data Selection Criteria

Various data elements from the SMP LTPP sections were reviewed and collected for further analyses to meet the objectives of this study. Of particular interest was the data assessment of SMP sites with an unbound base material having sufficient subsurface in situ moisture, precipitation, and performance time-series data. The SMP sections with 3 yr or more of subsurface moisture data were identified and used in the subsequent analyses. The timing of pavement maintenance actions for each section to obtain the amount of unsealed fatigue cracking in a month was also considered. While analyzing the data, the research team tracked the time series of all the desired variables (i.e., subsurface moisture, precipitation, and fatigue cracking). As mentioned above, the SMP flexible sections with only unbound base layers were analyzed. To test the hypothesis of this report, four SMP flexible pavement sections with appropriate data were identified (two pavement sections each in WF and DF climates). It should be noted that a limited number of sites also facilitated indepth analyses for more precise quantification of the relationship between moisture variation and associated change in base material properties. Therefore, in this report, the data from only four SMP pavement sections were analyzed in detail. However, as work is ongoing, the extents of all available SMP sections with the appropriate data are also briefly discussed.

Database Development

The required data were obtained from the LTPP database standard release 30.0 (Elkins et al. 2003). All SMP test sections were assigned a unique ID by combining State code and Strategic Highway Research Program (SHRP) ID. Multiple data buckets for desired variables were downloaded using online Infopave™ features. The downloaded data elements were organized in various tables to create a relational database.

Data Elements

The following data elements were identified for the analysis:

- Section inventory (State code, SHRP ID, site location, climatic region, assign date, construction number, and survey date).

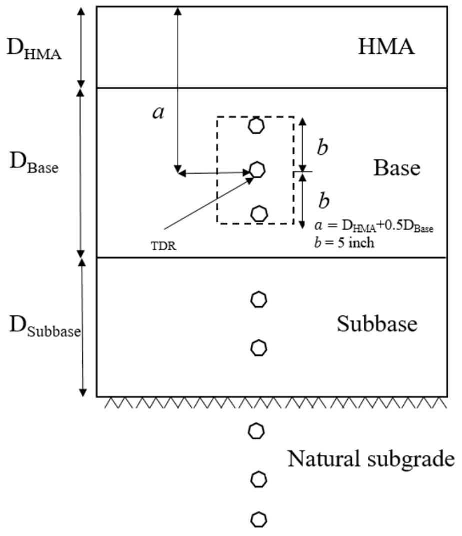
- Pavement structure (layer type, representative layer thicknesses, survey width, and survey length).
- Performance data (percent fatigue cracking for all severity levels).
- Climatic data (subsurface moisture obtained from TDRs and precipitation (rainfall and snow combined)).
- Materials (sieve size analysis, Atterberg limits, and specific gravity).

Subsurface Moisture and Precipitation Data

TDRs are installed in all the SMP pavement sections to measure the in situ subsurface moisture at different depths. Also, the SMP database has volumetric and gravimetric moisture data at different depths (dry densities were used to convert volumetric moisture to gravimetric moisture content) (Elkins et al. 2003). Gravimetric moisture data were used for further analysis.

Moisture data at the middle of the base layer were obtained from TDRs for each site. Unique section IDs were matched with TDR numbers to estimate the exact depth of subsurface moisture measurements within the base layer. For example, if the middle depth of the base layer is 15 inches from the surface (a = 15 inches), then the average of the moisture measured using TDRs located within ±5 inches (b = 5 inches) of a reference point (i.e., moisture was calculated by averaging moisture measured by TDRs between the depths of 10 to 20 inches) was calculated. However, the base layer was often shallow and only one TDR was encountered for obtaining subsurface moisture data. The schematic of these calculations representing the moisture variations within the base layer is shown in figure 1.

Figure 1. Illustration. Subsurface moisture measurements.



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Where:

a = depth from the pavement surface to the middle of the base layer.

b = distance equals to 5 inches on both sides of the middle point of the base layer.

D = thickness of a pavement layer.

Pavement performance temporal data were matched to obtain the total monthly precipitation amount (i.e., rainfall and snow). Table 1 provides a summary of the data types and the corresponding LTPP data tables used for analysis in this report.

Table 2 presents the summary of selected SMP sites' inventory, layer structure and properties, subsurface moisture depth, and available number of years for the data elements used in the data analysis.

Materials Data

Materials data elements were extracted by following the guidelines from the LTPP information management system materials module. Site-specific materials data were available for most of the SMP sites. Materials data needed to calculate base layer MR were obtained by combining unique ID and layer numbers. Linked SHRP IDs were used to obtain data for those SMP sections with missing site-specific materials data. Sieve size distributions, Atterberg limits, and specific gravity data elements were extracted by combining various data tables in the database. Sieve size analysis data were used to obtain D_{60} (grain diameter at 60 percent passing) as shown in table 2.

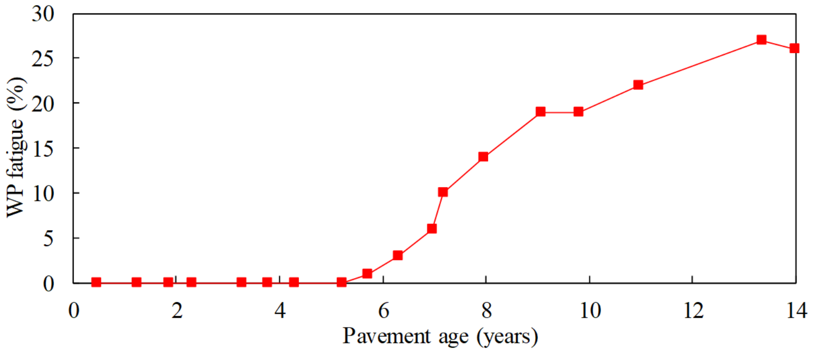
DATA ANALYSIS AND RESULTS

This section presents the subsurface moisture variations with surface cracking and potential impacts of subsurface moisture variations on base MR. Subsequently, the influence of base MR on long-term pavement performance in terms of predicted fatigue cracking are discussed. Based on the results, appropriate crack sealing application timings are recommended to extend the service life of flexible pavements in different climates.

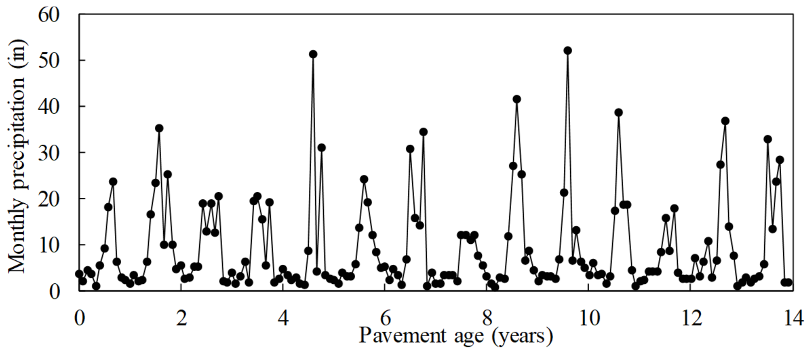
Methodology

As mentioned in the Background section, many external and internal sources can cause subsurface moisture variations in pavement unbound layers. Surface discontinuities, such as cracks, allow water to infiltrate the sublayers. Bottom–up fatigue is a classic example of through cracking that would allow the surface water to

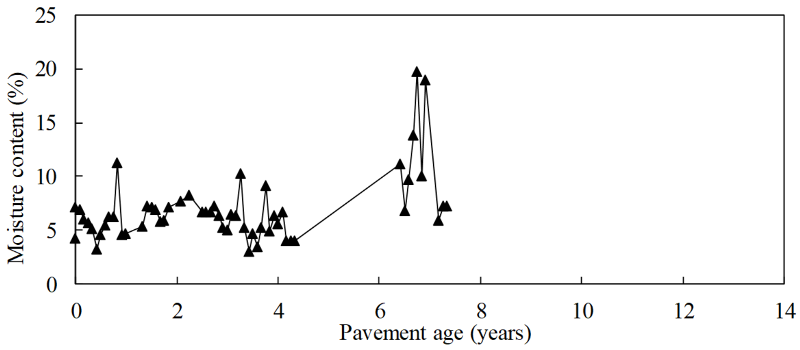
Figure 2. Graphs. Temporal cracking, precipitation, and subsurface moisture: section 36-0801.



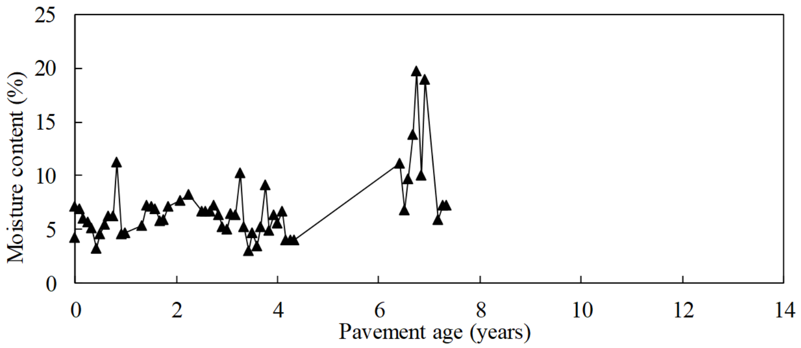
A. Fatigue cracking.



B. Total monthly precipitation.



C. Subsurface moisture variations.



D. Fatigue cracking and subsurface moisture relationship.

Table 1. LTPP database tables used to extract data elements.

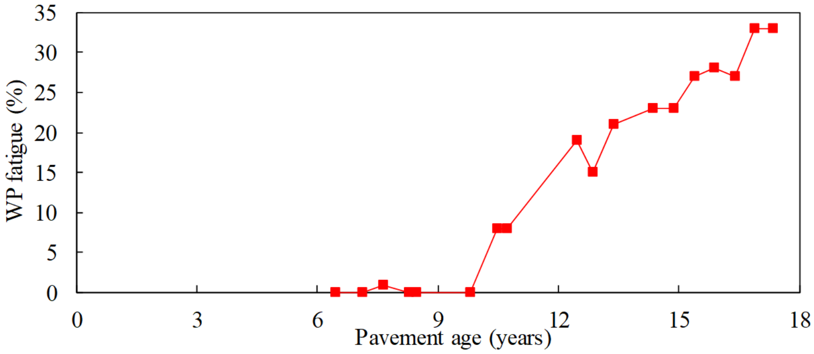
Type of Data	Data Element Chosen	Relevant LTPP Tables	Table Description
General information	LTPP section inventory	EXPERIMENT_SECTION	The three key fields that define a unique record in this table are STATE_CODE, SHRP_ID, and CONSTRUCTION_NO, which form the primary backbone of relational links within the LTPP database.
General information	LTPP section inventory	SECTION_LAYOUT	This table contains section layout and location information. This table contains combined data from INV_ID, INV_GENERAL, SPS_ID, SPS_GENERAL, and SPS_PROJECT_STATIONS.
Structure	Layer thickness and material type	SECTION_LAYER_STRUCTURE	This table contains a consolidated set of pavement layer structure information for all LTPP test sections.
Material	Sieve size analysis	TST_SS01_UG01_UG02	This table contains the gradation of unbound coarse grained granular base, subbase, and subgrade materials.
Material	Atterberg limits	TST_UG04_SS03	This table contains the Atterberg limit test results for unbound granular base, subbase, and subgrade materials.
Material	Specific gravity	TST_UNBOUND_SPEC_GRAV	This table contains the specific gravity of unbound base and subgrade materials.
Climate	Subsurface moisture	SMP_TDR_AUTO_moisture	This table contains the volumetric and gravimetric moistures calculated using TDRs.
Climate	Subsurface moisture	SMP_TDR_DEPTHS_LENGTHS	This table contains information on the physical characteristics of the TDR probes, including the depth at which the probe is installed, the length of the probe, and its installation date.
Climate	Precipitation	CLM_VWS_PRECIP_MONTH	Virtual weather station monthly precipitation statistics and calculated parameters. The fields in this table are populated only when data for 24 d or more are available for a month.
Climate	Water table depth	SMP_WATERTAB_DEPTH_MAN	This table contains manual observations of the distance from the pavement surface to the water table. A null in the WATERTAB_DEPTH indicates that no water was found in the observation piezometer well.
Performance	WP fatigue	MON_DIS_flexible_CRflexibleK_INDEX	This table contains cracking indices for flexible pavements using HPMS, MEDPG, and NPRM definitions.

Table 2. Section summary and layer structure for flexible pavement with granular base.

Unique ID	State	Experiment Type	Climatic Regions	HMA Thickness (Inches)	Base Thickness (Inches)	Percent Passing 200 (Base)	D_{60} (Inch) (Base)	PI (Base)	Specific Gravity (Base)	Data Availability (Yr)	Moisture (TDR) Depth (Inches)
16-1010	Idaho	GPS-1	DF	10.9	5.4[a]	7.8	0.32	NP	2.65	5	14.02
30-0114	Montana	SPS-1	DF	7.7	12.4[b]	8.2	0.33	NP	2.65	7	13.19
36-0801	New York	SPS-8	WF	5	8.4[b]	8.1	0.68	NP	2.83	7	9.45
83-1801	Manitoba	GPS-1	WF	4.4	5.6[c]	9.6	0.19	3	2.71	7	7.87

[a] Soil-aggregate mixture (308).
[b] Crushed gravel (304).
[c] Gravel (302).
NP = nonplastic; PI = plasticity index; D_{60} = grain diameter at 60 percent passing.

Figure 3. Graphs. Temporal cracking, precipitation, and subsurface moisture: section 83-1801.



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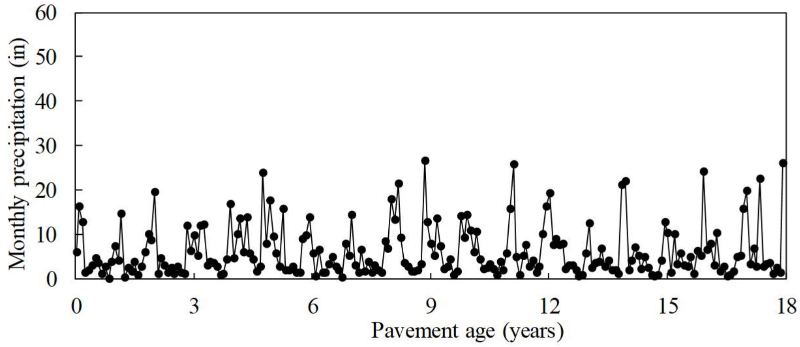
A. Fatigue cracking.



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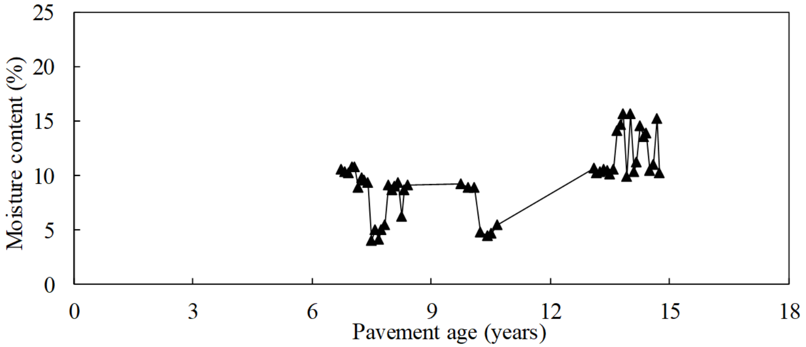
B. Total monthly precipitation.



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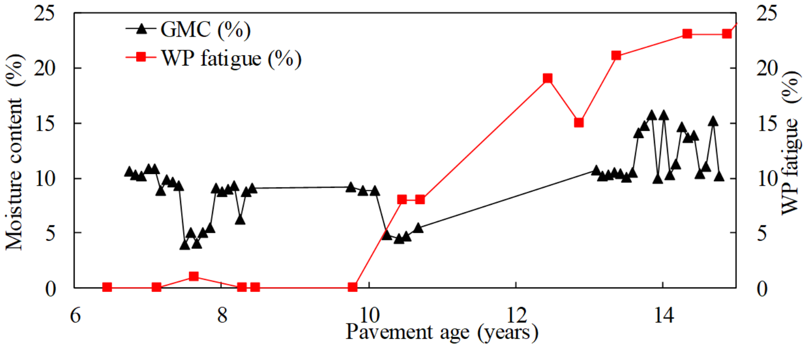
C. Subsurface moisture variations.



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D. Fatigue cracking and subsurface moisture relationship.

Table 3. Summary of regional climatic and performance data.

Unique ID	Climatic Regions	Fatigue Cracking Maximum (Percent)	Fatigue Cracking Minimum (Percent)	Monthly Precipitation Maximum (Inches)	Monthly Precipitation Minimum (Inches)	Maximum Gravimetric Moisture (Percent)	Minimum Gravimetric Moisture (Percent)
16-1010	DF	7	0	24	0	6.9	1.5
30-0114	DF	25	0	25	0	4.6	1.8
36-0801	WF	27	0	52	1	19.7	3
83-1801	WF	33	0	27	0	15.7	4

infiltrate the base layer. However, the amount of water infiltration is expected to be more in locations with higher precipitation levels.

The amount of fatigue cracking over time was related to seasonal moisture levels at different depths in the pavement structure. The primary objective is to identify the additional amount of moisture in the sublayers due to a change in surface cracking extent and severity over time in different climates. Subsequently, material properties (i.e., MR) can be related to different moisture levels. The guidelines developed in this report can assist highway agencies in proactive maintenance practices to mitigate moisture-related damage due to surface cracking. Agencies can estimate the maximum cracking extent at which cracks should be sealed to reduce water infiltration rate into sublayers.

Table 3 shows the descriptive statistics of observed cracking, precipitation levels, and subsurface moisture content for the SMP pavement sections. Higher levels of cracking, precipitation, and moisture can be observed in wet climates.

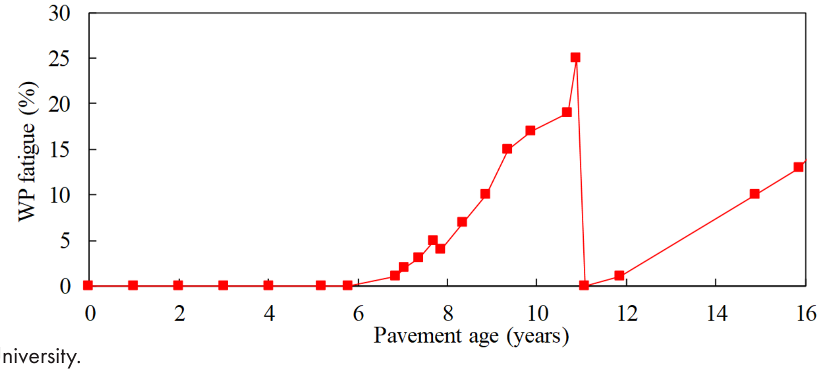
Effect of Cracking and Precipitation on Base Layer Moisture

Figure 2 and figure 3 show the impact of cracking and precipitation on base layer moisture for SMP sections 36-0801 and 83-1801 located in a WF climate, respectively. Figure 2-A and figure 3-A show the observed cracking progression for sections in a WF climate. The observed performance shows that cracking accelerated approximately at the 6th and 10th yr of pavement service life for sections 36-0801 and 82-1801, respectively. Figure 2-B and figure 3-B present the precipitation profiles for these two sections. Higher precipitation levels over the years were observed for section 36-0801. Figure 2-C and figure 3-C show aggregate base moisture variation over time. Finally, figure 2-D and figure 3-D illustrate the combined progression of base moisture and cracking levels for the SMP study period. It is evident from figure 2 and figure 3 that, when the pavements are new with minimal cracking, base moisture only showed cyclic variations. However, when the cracking progressed nearly from 5 to 7 percent (average 6 percent), the base moisture variations became very high at both sites.

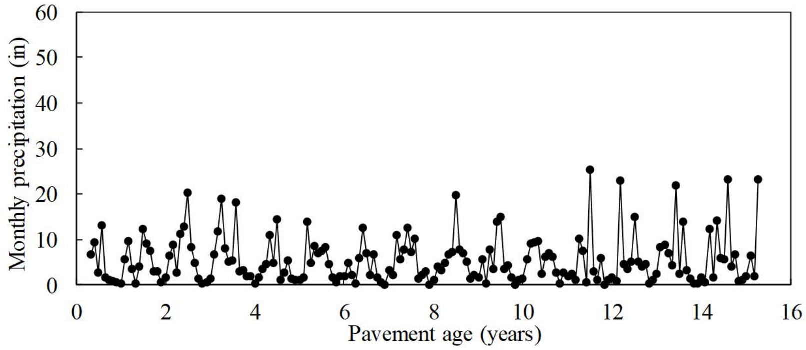
The data for SMP sections 30-0114 and 16-1010 located in a DF climate are shown in figure 4 and figure 5, respectively. Compared to WF climates, low precipitation levels and less variation in base moisture were observed in DF climates (table 3). The small changes in base layer moisture can be explained by a low precipitation level and also slightly thicker HMA layer in these two sections. Moreover, due to the dry climate, most of the water may evaporate, and less water is available to infiltrate unbound layers. Figure 4-C shows that, in 8 yr of observed moisture data, the variations in subsurface moisture are very low. Even with 3 to 4 percent cracking, the subsurface moisture did not show much variation (figure 4-D). Figure 5-D also shows that, for section 16-1010 when the pavement was new, the subsurface moisture did not vary significantly. Also, even when cracking levels were between 5 to 6 percent, subsurface moisture showed insignificant variations. Likely reasons for these limited changes in subsurface moisture are low precipitation levels in DF climates, a thick HMA layer, or low levels of cracking.

Figure 6 shows moisture profiles with depth for the selected SMP sections before and after a considerable amount of cracking. These profiles help visualize the overall moisture variation in the pavement system for the sites located in wet and dry climactic regions. It is evident from the moisture profile that a change in moisture is more pronounced at the top few inches of the pavement section (i.e., up to base/subbase layers). The relative change in moisture is negligible below subbase levels. Figure 6-A and figure 6-B show variation in the base layer moisture in pavement sections located in a WF climate. More substantial variations in moisture in WF climates are mainly because of higher rainfall and greater extent of cracking for the selected pavement sections. In contrast, the overall change in the base layer moisture for the selected sites located in DF climates is minimal, which is mainly because of low precipitation in these particular locations (figure 6-C and figure 6-D).

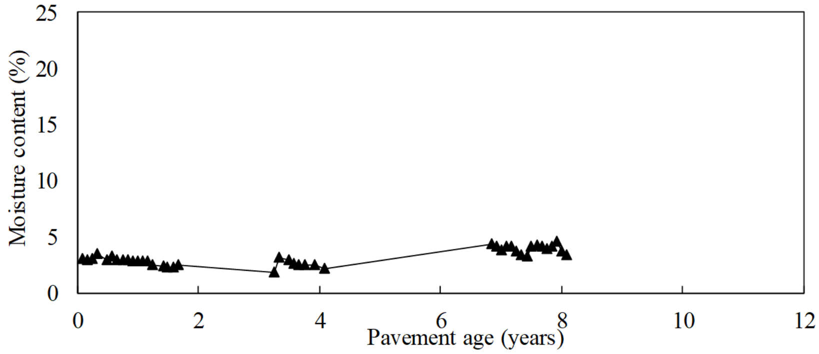
Figure 4. Graphs. Temporal cracking, precipitation, and subsurface moisture: section 30-0114.



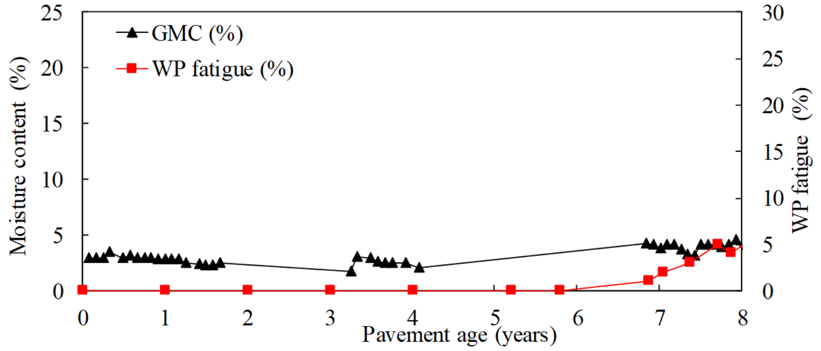
A. Fatigue cracking.



B. Total monthly precipitation.

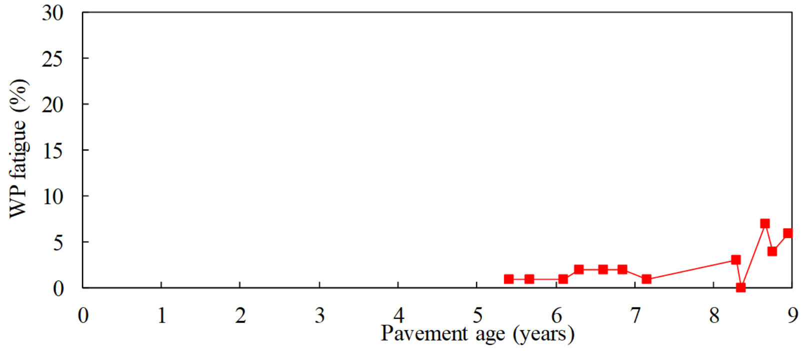


C. Subsurface moisture variations.

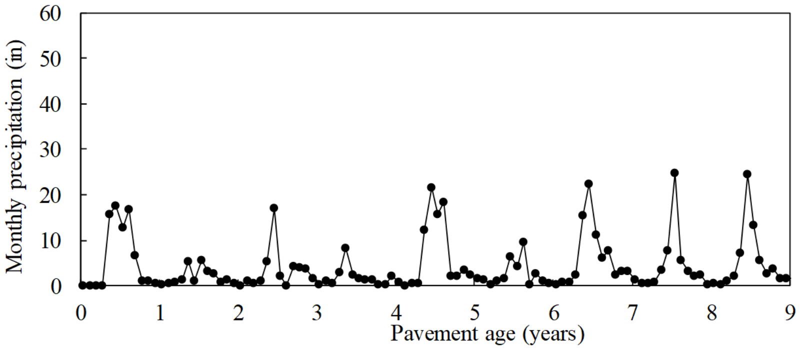


D. Fatigue cracking and subsurface moisture relationship.

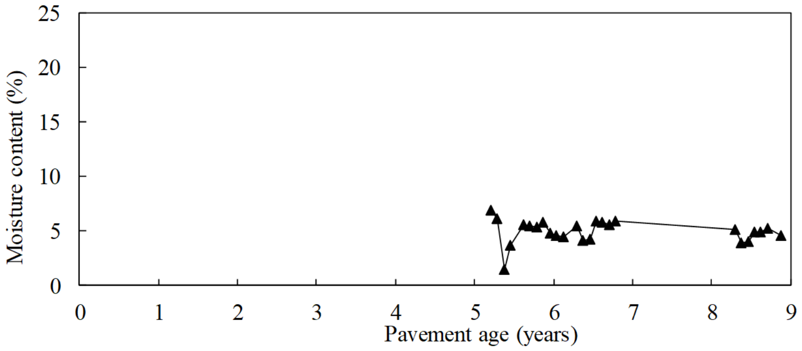
Figure 5. Graphs. Temporal cracking, precipitation, and subsurface moisture: section 16-1010.



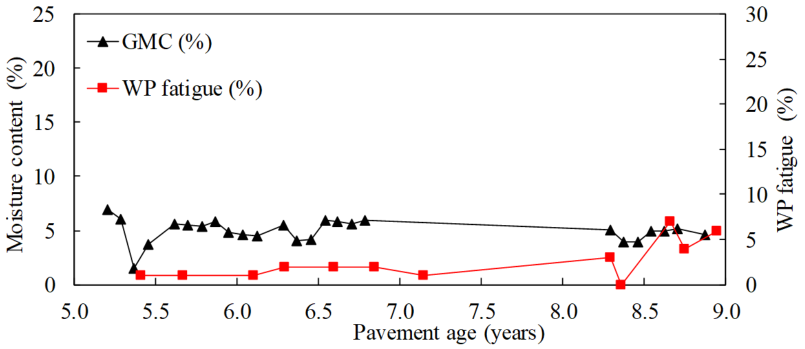
A. Fatigue cracking.



B. Total monthly precipitation.

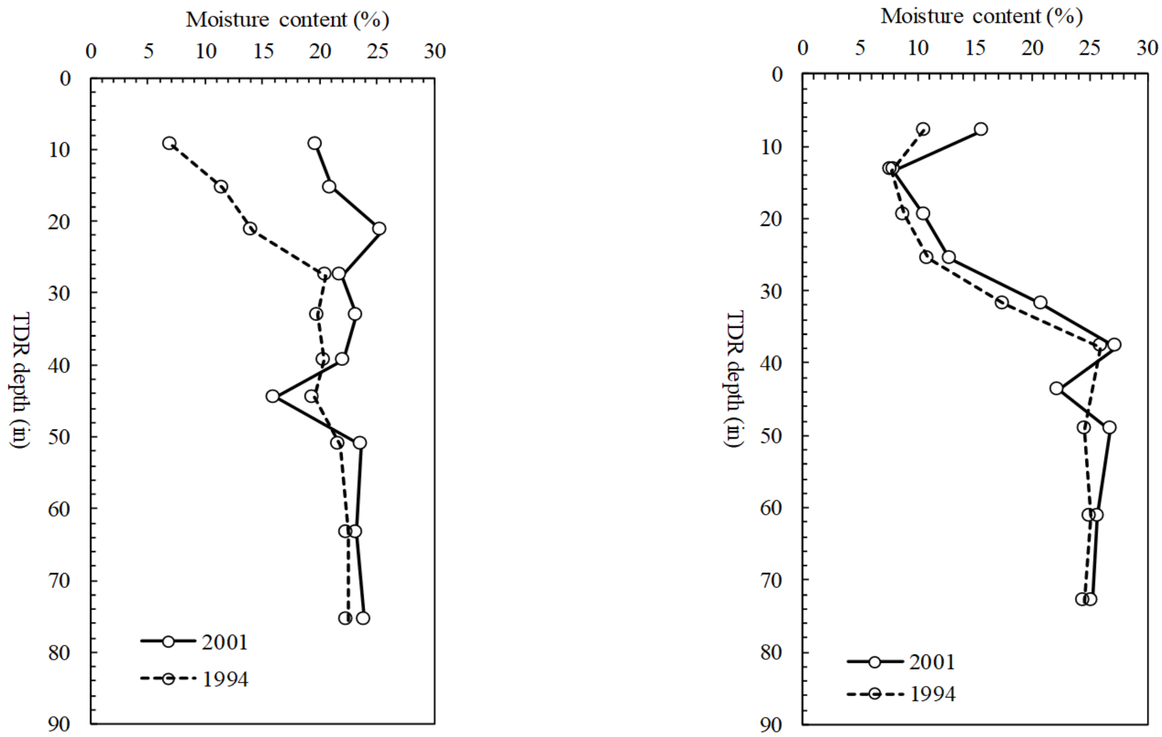


C. Subsurface moisture variations.



D. Fatigue cracking and subsurface moisture relationship.

Figure 6. Graphs. Moisture variation with depth before and after cracking.



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A. Section 36-0801 (WF).

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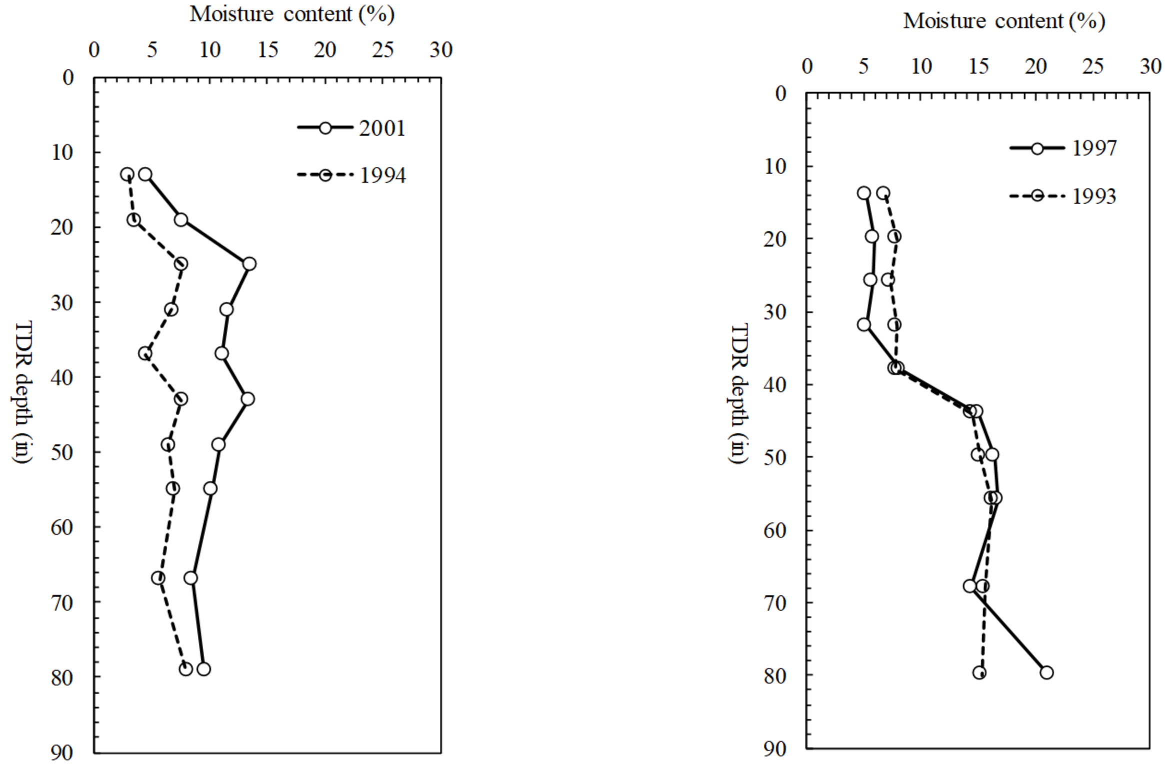
B. Section 83-1801 (WF).



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C. Section 30-0014 (DF).

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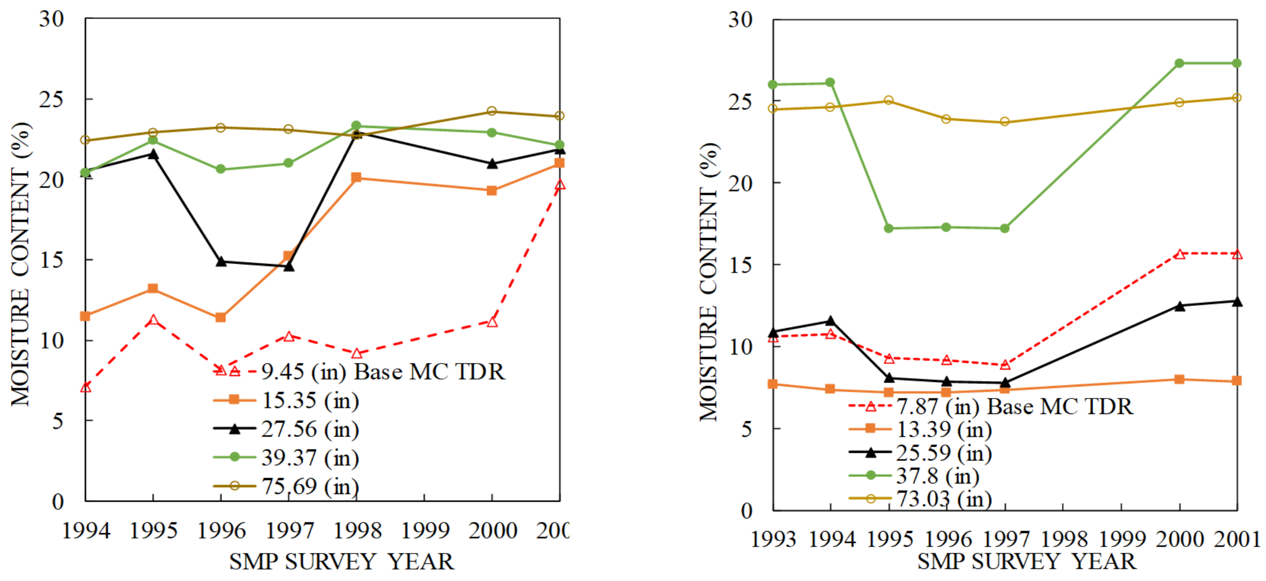
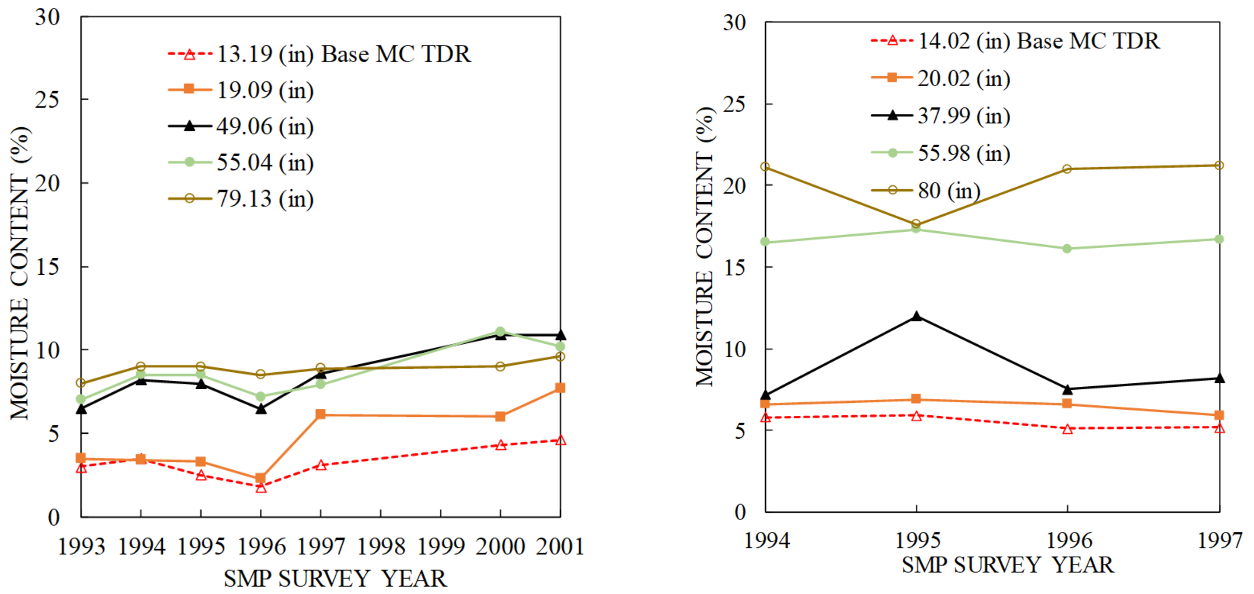
D. Section 16-1010 (DF).

Figure 7. Graphs. Moisture variation with depth and age.



A. Section 36-0801 (WF).

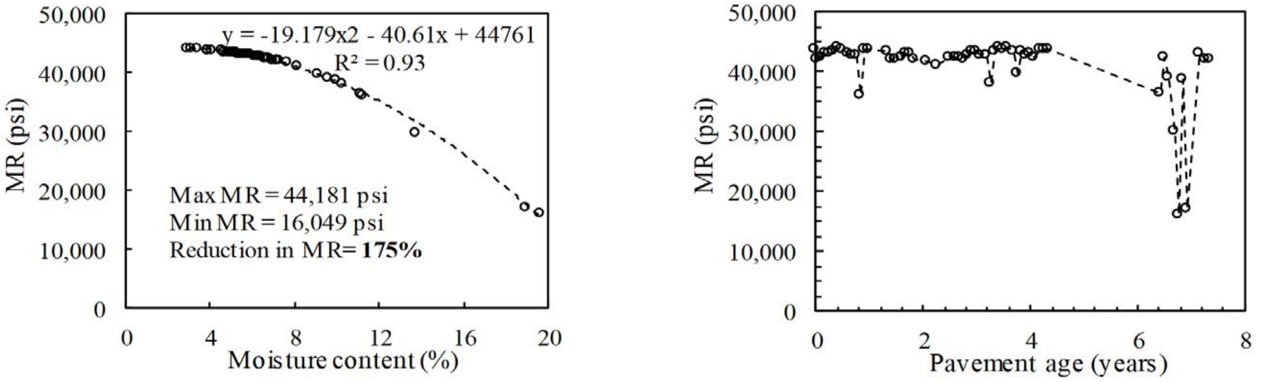
B. Section 83-1801 (WF).



C. Section 30-0014 (DF).

D. Section 16-1010 (DF).

Figure 8. Graphs. Effect of base moisture on MR over time.



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A. Section 36-0801 (WF) moisture versus MR.

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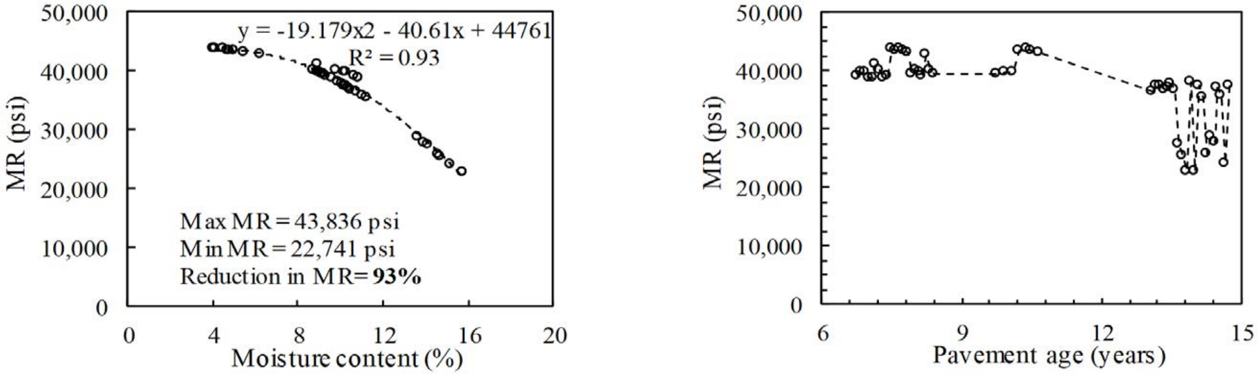
B. Section 36-0801 (WF) pavement age versus MR.



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C. Section 83-1801 (WF) moisture versus MR.

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D. Section 83-1801 (WF) pavement age versus MR.

Finally, to verify the observations from figure 6, moisture data were also plotted with age and depth, as shown in figure 7. Higher base moisture variations can be seen in WF climates. The moisture content increased with time since more cracking was observed as the pavements aged (figure 7-A and figure 7-B). On the other hand, relatively lower base moisture variations and increases in age were observed for the pavement sections located in DF climates (figure 7-C and figure 7-D).

Base Moisture and MR Relationship

The unbound base and subbase layers are an integral part of a pavement structure. Moisture variations within subsurface layers can have an impact on the material properties (i.e., MR). Consequently, the difference in material properties will affect the structural capacity of the whole pavement structure. The *AASHTOWare® Pavement ME Design* guide uses the following moisture-modulus or Witzack model to determine the variation in MR of the unbound layers with moisture change (NCHRP 2000):

$$\log \frac{M_R}{M_{R(opt)}} = a + \frac{b-a}{1+\exp\left(\ln \frac{-b}{a} + k_m.(S-S_{opt})\right)} \qquad (1)$$

Where:

M_R = resilient modulus at the degree of saturation (S) expressed in decimal.

$M_{R(opt)}$ = resilient modulus at the maximum dry density and optimum moisture.

a = minimum of log (M_R/$M_{R(opt)}$).

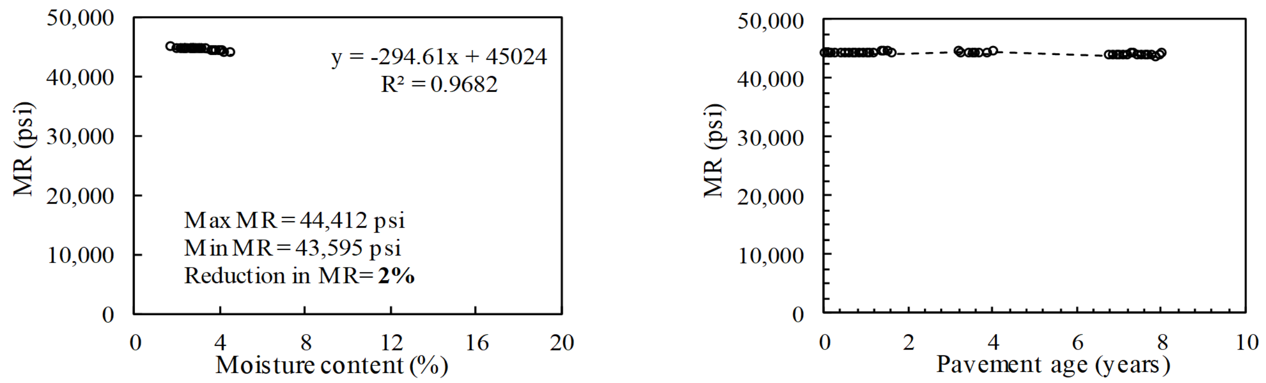
b = maximum of log (M_R/$M_{R(opt)}$).

a, b, and k_m = -0.5934, 0.4, and 6.1324 for fine-grained materials.

a, b, and k_m = 0.3123, 0.3, and 6.8157 for coarse-grained materials.

$S - S_{opt}$ = variation in the degree of saturation expressed in decimal.

Figure 8. Graphs. Effect of base moisture on MR over time (Continued).



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E. Section 30-0114 (DF) moisture versus MR.

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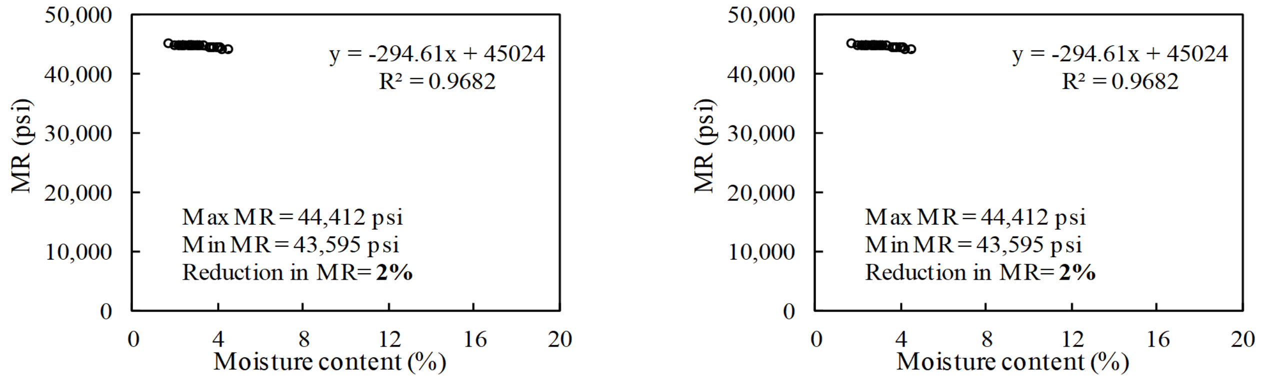
F. Section 30-0114 (DF) pavement age versus MR.



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G. Section 16-1010 (DF) moisture versus MR.

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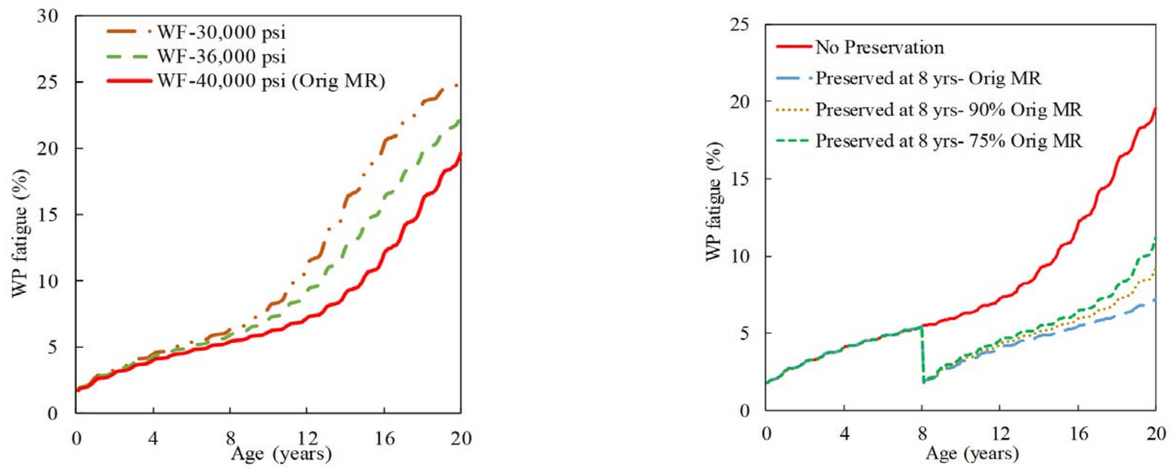
H. Section 16-1010 (DF) moisture versus MR.

Equation 1 is used to calculate base MR due to variation in in situ moisture. This model needs several inputs, including percent passing 200, liquid limit, plastic limit, D_{60}, and specific gravity. All the required inputs were obtained from the LTPP database for all the sections. The estimated MR for base materials with a change in moisture levels based on equation 1 is shown in figure 8. The results show that, as the moisture increases, the base MR decreases. For the sites in WF climates, the maximum change in the base layer MR was between 93 to 175 percent (figure 8-A and figure 8-C). However, change in MR is very small (i.e., 2 to 13 percent) for the pavement sections located in DF climates, as shown in figure 8-E and figure 8-G). Finally, figure 8-B, figure 8-D, figure 8-F, and figure 8-H show the base MR decrease due to moisture with age. As mentioned before, since higher moisture increase was observed in pavement sections located in WF climates, mainly when the pavement sections were older (i.e., a higher amount of cracking), more MR reduction was observed.

Impact of Base MR on LTPP and Surface Sealing Application Timings

The moisture variation and its adverse impact on base MR were quantified for the pavement sections in WF climates. Since the reduction in base MR values is only critical in WF climates, this section only considers the impact of those changes on pavement performance. A flexible pavement section was considered with 8-inch HMA, 8-inch granular base, and 6-inch granular subbase layers to evaluate the impact of base MR on long-term performance. Long-term performance was predicted for approximately 14 million equivalent single axle loads by using *AASHTOWare® Pavement ME Design* (NCHRP 2004). A weather station located in the State of New York was used to simulate WF climates. A base MR value of 40,000 psi, as observed in the field, was assumed as the original material property. Subsequently, to simulate the effect of moisture increase based on the field observations, reduced MR values of 90 and 75 percent of the original MR value were assumed.

Figure 9. Graphs. Preservation treatment plan WF–thick section.



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A. Effect of MR on WP fatigue.

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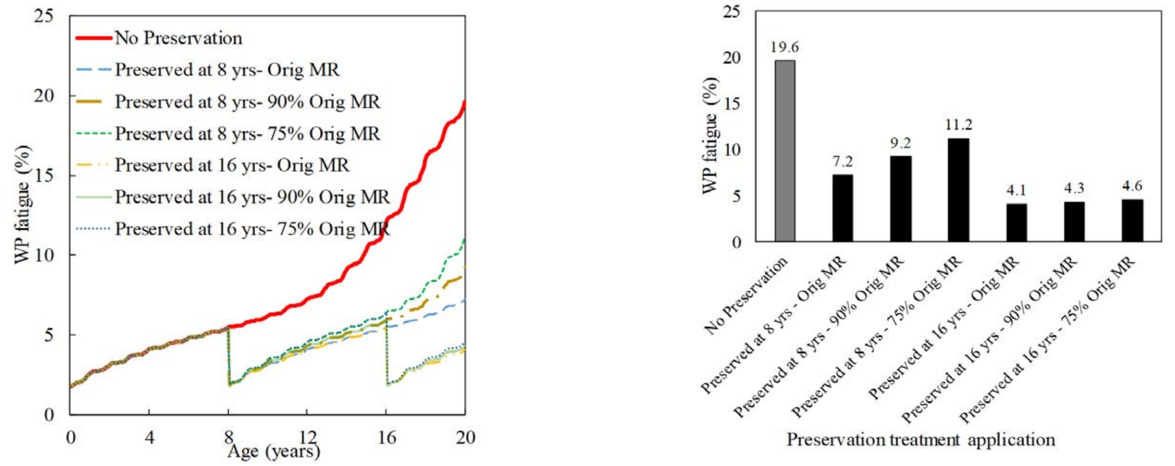
B. Preservation at 8 yr.



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C. Preservation at 8 and 16 yr.

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D. Effect of preservation after 20 yr.

The reduced MR values of 90 and 75 percent of the original were assumed to characterize the stiffness of the base layer after the application of a particular preservation treatment (e.g., crack sealing). It is known that preservation treatments cannot restore materials to their original strength. However, this can extend the service life of the pavements by retarding the deterioration rate.

Comparisons of predicted performances by *AASHTOWare® Pavement ME Design* were made by considering the base MR original strength (40,000 psi), 90 percent of original MR (36,000 psi), and 75 percent of the original MR (30,000 psi). These variations in MR values should be based on the moisture increase observed in the actual materials.

Treating cracks in asphalt pavements is a major part of road maintenance. The objective of any crack treatment is to minimize the intrusion of water into underlying layers of the pavement structure. Water infiltration into the base layers of a pavement may lead to pavement structural failures. Crack treatments fall into three broad categories—crack sealing, crack filling, and surface sealing. Crack sealing can be performed on "working" cracks (e.g., cracks that are more than 0.125 inches wide in the summer and significantly larger in the winter). It is commonly used as a transverse crack treatment; however, crack sealing can be used for any crack treatment operation. Crack filling is generally used on cracks that do not open and close due to environmental conditions. It is commonly used as a longitudinal crack treatment (Decker 2014). Last, surface seals (i.e., slurry seals, microsurfacing, and chip seals) can be used to seal larger crack areas with low to medium severity (Seitllari and Kutay 2018). These types of treatments can be used to seal block and fatigue cracking.

Figure 9 shows an example of a preservation plan (surface seal application timing) by using *AASHTOWare® Pavement ME Design* for a pavement section located in a WF climate. The first crack sealing application was planned as the cracking reached a threshold of 6 percent (as identified for the sites located in WF climates) in about 8 yr of service life (figure 9-B). The application cycle will repeat once the pavement reaches the same cracking limit at about 16 yr, as shown in figure 9-C. The overall effect of crack sealing on cracking progression is shown in figure 9-D. The results show that the pavement service life can be significantly extended at a lower level of cracking when crack sealing is applied at the appropriate times (i.e., 6 percent cracking).

Preservation plans presented in this report by using crack sealing treatments can be used as a guideline when moisture variations are only limited to aggregate base material MR. However, to accurately estimate the preservation treatment application timing, strength properties of the entire pavement structure must be given due importance while predicting long-term performance.

CONCLUSIONS

The report presents LTPP data analyses for quantifying the effect of moisture infiltration through surface cracking on flexible pavement performance. Based on the results, following can be concluded:

- The SMP data can be used to investigate the moisture variations in pavement layers, and the impact of different climates on moisture variations can be quantified.
- Moisture-related damage is very high in WF climates (93 to 175 percent reduction in MR). It is critical to prevent the unbound layers from moisture-related damage due to infiltration, especially before the MR reduction becomes significantly high. It is essential to apply preservation treatments when the fatigue cracking extent is below 6 to 7 percent.
- Subsurface moisture variations did not show much impact on the sites located in DF climates (2 to 13 percent reduction in MR). For the pavement sites in DF climates, damage associated with other factors like high temperature is more critical.
- Timely selection and application of preservation treatments could substantially enhance the pavement's life.
- The preservation treatments can be incorporated during the design stage by using *AASHTOWare® Pavement ME Design*.

FUTURE WORK

A limited number of pavement sections were used in this report to demonstrate the process of quantifying the impact of infiltration on expected pavement performance by using *AASHTOWare® Pavement ME Design*. More pavement sections should be included in the analysis for more precise quantification of moisture-related damage. Ongoing work will include all the SMP pavement sections that satisfied the data selection criteria (32 flexible and 11 rigid SMP pavement sections) to develop a subsurface moisture prediction model for the aggregate base located in different climates.

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