TECHBRIEF

Impact of Environmental Factors on Pavement Performance in the Absence of Heavy Loads

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This document is a technical summary of the Federal Highway Administration Long-Term Pavement Performance Program report, *Analysis of the Study of Environmental Effects in the Absence of Heavy Loads* (FHWA-HRT-16-084).

The Long-Term Pavement Performance (LTPP) Program monitors the performance of pavements constructed using different materials that are subject to varied traffic loads across many climates. One experiment category developed by the program for study is the effect the environment has on pavement deterioration. The data analysis results summarized in this TechBrief use test sections from an LTPP Specific Pavement Studies (SPS) experiment, Study of Environmental Effects in the Absence of Heavy Loads (SPS-8), matched with test sections from other LTPP experiments that have normal truck traffic to compare and show the proportion of total damage caused by environmental effects. This analysis, which looked at data collected over a 15-year period, also identified many practical design and materials effects, including some very informative results.

Introduction

Initiated as part of the Strategic Highway Research Program, the primary purpose of the SPS-8 experiment was to characterize the impact of environmental factors

The Long-Term Pavement Performance (LTPP) Program is a large research project for the study of in-service pavements across North America. Its goal is to extend the life of highway pavements through various designs of new and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices. LTPP was established under the Strategic Highway Research Program and is now managed by the Federal Highway Administration.

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on pavement performance. The primary objectives of this experiment were the following:

- Identify and quantify the effect of environmental factors and design on asphalt concrete (AC) pavement and jointed plain concrete pavement (JPCP) performance in the absence of heavy loads.
- Establish environmental effects and develop recommendations for mitigating these effects through effective designs and materials selection.
- Estimate the proportion of total pavement damage caused by environmental factors.

The data collected from the LTPP test locations, including the SPS-8 test sections, are contained in the LTPP database and can be accessed from LTPP InfoPave™.[1] The database was established to provide permanent storage for different pavement design features, materials properties, and performance information for use in future analysis and evaluation by State transportation departments.

"Environment," in the context of this study, includes climatic factors (e.g., moisture, rainfall, temperature, and freeze/thaw) and foundation/subgrade type (e.g., frost-susceptible, expansive, fine-grained, coarse-grained, and soil properties such as percent clay and silt). The absence of heavy loads in the context of this study is defined as traffic applied to the SPS-8 test section that is typically less than 10,000 equivalent single axle loads a year. By contrast, companion LTPP test sections, such as the Strategic Study of Structural Factors for Flexible Pavements (SPS-1), Strategic Study of Structural Factors for Rigid Pavements (SPS-2), and General Pavement Study (GPS) sections with similar design features, have 10 to 100 times as much or more traffic as the SPS-8 sections.

Assembly of Database and Analysis

Information assembled for this study included detailed design, materials, construction, and performance data for each SPS-8 test section. All performance data were compared at 15 years because most of the sections had exceeded that time period. In addition, a site-by-site analysis of the SPS-8 projects was conducted.

To perform the analysis for this study, companion test sections were identified from among the SPS-1, SPS-2, and GPS experiments that matched the design and materials characteristics of the SPS-8 sections. In terms of traffic, table 1 shows a dramatic difference in the annual truck levels (Federal Highway Administration Class 4 to 13) between the SPS-8, Asphalt Concrete Pavements on Granular Base (GPS-1), Jointed Plain Concrete Pavements (GPS-3), SPS-1, and SPS-2 sections.

These large differences in annual truck traffic levels between the experiment groups made it possible to make meaningful direct performance comparisons of the effect of traffic and environmental factors on pavement damage and performance.

Results From SPS-8 and Companion Test Sections

One outcome of the comprehensive analyses performed using data from the low-trafficked SPS-8 and companion high-trafficked

Table 1. Mean annual truck traffic for SPS-1/GPS-1, SPS-2/GPS-3, and SPS-8 sections.

LTPP Experiment	Mean Annual Number of Trucks in LTPP Lane
SPS-1 and GPS-1	280,124
SPS-2 and GPS-3	693,123
SPS-8	7,586

SPS-1, SPS-2, GPS-1, and GPS-3 projects was the compilation of the impact of various environmental and design factors on pavement performance. Use of these factors demonstrates an innovative approach for examining individual pavement performance measures (e.g., key distresses and pavement roughness) to gain a better understanding of how pavement damage is initiated and exacerbated. By understanding the possible initiators and aggravators of individual pavement distresses, engineers can better select the appropriate design features and materials properties to mitigate the impact of environmental factors.

AC Pavement Results

The impacts of truck traffic, pavement thickness, and the environment on key distress types and smoothness, as well as recommendations to address these impacts, are summarized as follows:

- **AC fatigue cracking:** This distress includes all alligator and linear cracks that occur in the wheelpaths expressed as a percentage of total lane area. Traffic loadings characterized as average annual daily truck traffic (AADTT) were shown to be very significant in initiating fatigue cracking. The low-traffic SPS-8 sections had very little fatigue cracking, but the higher-traffic SPS-1 and GPS-1 sections had much greater AC fatigue cracking. AC thickness was a significant factor in mitigating fatigue cracking. Fatigue cracking was aggravated in warmer climates (higher in situ AC temperatures), by higher base/subgrade moisture content, and by lower subgrade fine sand content.

  Recommendations to minimize fatigue cracking include using appropriate AC layer design thickness, particularly in warmer and wetter climates and with subgrades with low sand content (e.g., fine-grained soils). Field results show that these environmental conditions are much more conducive to fatigue cracking. However, in colder climates, field results show that AC thickness does not have such a significant effect on fatigue cracking.

  Because traffic loadings (AADTT) were shown to be very significant in initiating fatigue cracking, improving future AADTT and axle load spectra estimates for individual project designs would result in pavement designs that would have lower fatigue cracking.

- **Rutting (permanent deformation):** Similar to fatigue cracking, AADTT loadings were shown to be very significant in initiating total rutting in all pavement layers. The low-traffic SPS-8 sections had very little rutting. Increased AC thickness was a significant factor in mitigating total rutting. Rutting was aggravated in wet climates as the number of wet days increased. The moisture content in the base/subgrade was higher in these areas.

  Some recommendations to decrease or minimize total rutting include improved consideration of AC thickness, binder, and mixture selection, especially in warmer and wetter climates. Field results show that these environmental conditions are more conducive to total rutting.

- **Transverse cracking:** Lower AC in situ temperature (as found in colder climates), higher numbers of air freeze/thaw cycles, and subgrade type (e.g., active and fine-grained soil types and reduced fine sand content) were shown to have initiated and also aggravated transverse cracking. Higher plasticity index of the soil also aggravated or increased transverse cracking. One surprising finding was that there was substantial transverse cracking in no-freeze climates. This finding has been observed by different agencies in trying to calibrate the AASHTOWare™ Pavement ME Design transfer functions.[2] Both Arizona and Georgia have significant levels of transverse cracks that cannot be explained by cold temperature events. Another surprising finding was that the amount of transverse cracking was far greater when the level of truck traffic was higher (e.g., SPS/GPS compared with SPS-8).

  Some recommendations to reduce the amount of transverse cracking include performing additional research to explain the occurrence of transverse cracks in warm areas (e.g., potential permanent shrinkage mechanism) and analysis showing the unexpected relationship between truck traffic and the occurrence of more transverse cracking in higher-traffic AC pavements.

- **Materials durability distress:** Higher AC temperature (i.e., warmer climates) was identified as the common initiator of the various mechanisms related to AC materials durability distress (i.e., bleeding, block cracking, potholes, and raveling). Aggravation variables identified include lower freeze/thaw cycles (as found in warmer climates) and a larger number of wet days.

  One recommendation to minimize durability distress includes greater consideration of the individual distress types that make up the materials durability distress in AC materials selection, specifically for warm and wet climates. Mixture durability distress is most prominent in warm and wet climates.

- **Smoothness (International Roughness Index (IRI)):** Higher subgrade clay content and higher traffic applications both appear to be initiators of loss of smoothness over time. The main aggravator was a larger number of annual freeze/thaw cycles.

Recommendations to improve smoothness include addressing the subgrade component through improved treatments to stabilize clay-type subgrades. Also, the impact of traffic on smoothness loss can be addressed using techniques that reduce fatigue cracking, rutting, transverse cracking, and materials durability distress.

Thickness is a critical design feature that affects AC distress and IRI. AC thickness was found to be significant for fatigue cracking, rutting, and smoothness loss. For these distresses and IRI, increasing AC thickness leads to lower levels of the distress and improved smoothness. Table 2 summarizes the findings of environmental and design variables included in this study that initiate

Table 2. Environmental and design factors that initiate and aggravate AC pavement distress.

Distress Type	Initiators (Mechanistic Basis)	Aggravators (Increasing Distress)	Impact of AC Thickness in Mitigating Distress
Fatigue cracking.	Higher AADTT.	• Warmer climates (which lead to higher AC temperatures). • Higher base/ subgrade moisture content. • Lower subgrade fine sand content (e.g., fine-grained soils).	Thinner AC layers experienced increased fatigue cracking.
Rutting (permanent deformation).	Higher AADTT.	High number of wet days (which affects base/subgrade moisture content).	Thinner AC layers exhibited increased rutting.
Transverse cracking.	• Lower AC in situ temperature. • More air freeze/ thaw cycles. • Subgrade type (fine-grained soil types and reduced fine sand content).	• Higher AADTT far higher transverse cracking. • Higher Plasticity Index (PI). • Large amount of transverse cracking in no-freeze climates.	Not significant.
Materials durability distress.	Higher AC temperature.	• Fewer freeze/thaw cycles. • Higher number of wet days.	Not significant.
Smoothness (IRI).	• Higher subgrade clay content. • Higher AADTT.	More freeze/thaw cycles.	Reduced AC thickness led to greater smoothness loss.

and aggravate AC pavement distress and loss of smoothness.

JPCP Results

The suggested improvements to JPCP design and materials selection are presented as follows for the key distresses and smoothness:

- **JPCP transverse fatigue cracking:** Traffic loadings were shown to be very significant in initiating transverse fatigue cracking in JPCP. The low-traffic SPS-8 sections had very little fatigue cracking, but the higher-traffic SPS-2 and GPS-3 sections had much higher amounts at 15 years. Portland cement concrete (PCC) thickness was also a very significant factor in mitigating fatigue cracking. Fatigue cracking was aggravated in warmer climates with higher in situ PCC temperatures (and gradients), increased in drier climates with lower precipitation, and increased on coarse-grained subgrades.

  Recommendations to reduce fatigue cracking include using appropriate JPCP design thickness, particularly in warmer and drier climates, where there are higher built-in negative slab temperature gradients, higher slab moisture gradients, and higher slab negative temperature gradients. Also, improving future truck volume and load spectra predictions for individual project design would result in pavement designs that would have lower fatigue transverse cracking.

- **Joint faulting:** Traffic loadings were shown to be significant in initiating transverse joint faulting in JPCP. Joint faulting on the SPS-8 test sections was very low. Faulting was greater for SPS-2 and GPS-3 sections but still generally low because all joints were doweled. Longer joint spacing resulted in greater joint faulting. Longer joint spacing tends to result in wider joints. Wider joints lose aggregate interlock, allowing higher differential deflections. Higher subgrade clay contents resulted in increased joint faulting. This finding may be related to the amount of erodible fines, which may contaminate the unbound base courses and thus lead to greater erosion and pumping beneath the joint. Greater frost penetration resulted in higher faulting. Again, colder climates will result in wider joint openings and reduced aggregate interlock throughout the year. This will lead directly to greater erosion and greater joint faulting under heavy traffic loadings, even with doweled joints.

  Recommendations to lower joint faulting include matching the dowel diameter to the slab thickness to control faulting. The traditional rule of thumb is to require a dowel diameter (in inches) that is equal to or larger than the slab thickness (in inches) divided by 8. A 12-inch slab would thus require a minimum 1.5-inch dowel diameter. For critical climatic areas (e.g., colder climates with higher clay content subgrades), the following actions should be taken:

  - Use a design procedure that considers dowel diameter and thickness in predicting joint faulting.

- Reduce joint spacing to keep joints tighter. This result was validated based on the fact that most of these sections had very low faulting after 15 years.
- For very heavy traffic, use a well-designed stabilized base course. It may be a good solution to minimize pumping and erosion beneath the JPCP.

- **Joint spalling:** Traffic was not a significant factor in joint spalling in most cases, but it did show an aggravation effect in some comparisons. The prime initiator is the in situ PCC temperature, which correlates well with other environmental factors such as freeze/thaw cycles. Many cycles of freezing and thawing of saturated concrete (as occurs near joints) can be linked mechanistically to damage at the joint.

  The lower the in situ PCC annual temperature, the greater the amount of joint spalling. Thus, cold temperatures and corresponding freezing and thawing of the PCC slab appear to correlate well with joint spalling. Thicker slabs also showed a reduced level of joint spalling. This may be explained by the fact that the frost line does not include the mid or lower portion of the slab as often (i.e., fewer freeze/thaw cycles lower into the slab).

  Recommendations to reduce the amount of joint spalling include a more comprehensive evaluation of PCC mixture design to handle saturated freeze/thaw cycles over many years. Proper entrained air content and curing are essential. Internal curing may produce a PCC that is less permeable and less susceptible to freeze/thaw under saturated conditions.

- **Smoothness (IRI):** Traffic loadings and subgrade type were the potential initiators for loss of smoothness for JPCP, similar to AC pavement. The main aggravator of smoothness loss was higher in situ PCC temperature (warmer climate). The warmer the climate is, the greater the smoothness loss or the rougher the pavement will be. This is perhaps due in part to increased slab upward curling -and increased fatigue cracking in warmer climate zones.

  Recommendations to improve smoothness include additional study into the reasons why granular subgrades would have greater smoothness loss than fine-grained subgrades. Also, the impact of traffic on smoothness loss can only be addressed by following recommendations for a reduction in fatigue cracking, joint faulting, and joint spalling.

Similar to distresses found on AC pavements, slab thickness is a critical design feature that also aggravates JPCP distress. PCC thickness was found to be significant for fatigue cracking, faulting, spalling, and smoothness loss. For these distresses and IRI, increasing PCC thickness leads to lower levels of the distresses. However, increases in slab thickness also require direct consideration of increased dowel diameter to provide adequate steel-to-concrete bearing stress for higher traffic volumes.

Table 3 summarizes the findings of environmental and design variables included in this study that initiate and aggravate JPCP distress and loss of smoothness. The findings regarding the impact of PCC thickness to mitigate distress are also provided.

Pavement Damage Due to Environmental Factors

An estimate was made of the proportion of pavement damage caused by environmental factors using comparisons of pavement damage of low-traffic SPS-8 performance with higher-traffic companion SPS and GPS sections subjected to the same environment (climate and subgrade).

AC Pavement

The performance results demonstrated that environmental factors, including climate and subgrade, are very important aspects of the initiation and progression of distress and damage in AC pavements. The analysis showed that environmental factors (from SPS-8) accounted for 36 percent of total damage (from traffic and environment) for AC pavements. Thus, about 1/3 of all damage to typically loaded flexible pavement

Table 3. Environmental and design factors that initiate and aggravate JPCP distress.

Distress Type	Initiators (Mechanistic Basis)	Aggravators (Increasing Distress)	Impact of PCC Thickness in Mitigating Distress
Fatigue cracking.	Higher AADTT.	• Lower precipitation (in a drier climate). • Higher in situ PCC temperature (in a warmer climate). • Coarser subgrades.	Significant. (Thinner PCC pavements experienced increased fatigue cracking.)
Joint faulting.	Higher AADTT.	• Longer joint spacing. • Higher subgrade clay content. • Greater frost penetration (in a colder climate).	Magnitude of faulting difference was very small. Increased thickness must be accompanied by increased dowel diameter to prevent faulting.
Joint spalling.	Lower PCC temperature (and higher freeze/thaw cycles).	• Longer joint spacing. • Higher AADTT.	Significant. (Thicker slabs exhibited lower joint spalling.)
Smoothness (IRI).	• Coarse-grained subgrade. • Higher AADTT.	Higher in situ PCC temperature (in a warmer climate).	Significant. (Thicker PCC slabs had lower loss of smoothness over time.)

was attributable to subgrade and climate factors. Key climate and subgrade factors that initiate and aggravate AC pavement distress are described as follows:

- **Climatic zone:** AC pavements located in warmer no-freeze climates exhibited significantly greater fatigue cracking and materials-related distress. This was more pronounced for the thin AC sections than for the thicker AC sections. Therefore, warm climates are especially critical for AC fatigue cracking and materials-related distress, and significant efforts (including design and materials selection) are needed to reduce these distresses. Pavements in colder climates were more likely to exhibit higher levels of transverse cracking and smoothness loss, although, surprisingly, significant amounts of transverse cracking are also present in warmer climates.

- **Freeze/thaw cycles**: Higher numbers of freeze/thaw cycles resulted in significantly greater smoothness loss over 15 years. More freeze/thaw cycles also led to increased transverse cracking. However, materials durability distress was much lower in areas of with more freeze/thaw cycles.

- **Precipitation**: Both wet days per year and base/subgrade moisture content were significant variables. Thin AC sections had significantly higher fatigue cracking levels (27.5 percent higher) when subjected to high precipitation. Thick AC sections showed no increase in fatigue cracking when subjected to high precipitation. Total rutting was also significantly affected by precipitation, with more rutting occurring in locations with higher numbers of annual wet days. Full consideration is needed of unbound materials softening when near saturation to minimize this distress. Materials durability distress was also greater with increased precipitation. Therefore, in areas of higher precipitation, the structural design (to account for reduced unbound material modulus in wet seasons), subdrainage design (stabilization to remove potential problems), and materials selection (to account for low moisture susceptibility) are critical.

- **Subgrade soil:** Subgrade-related factors showed significant impact on all but two distresses examined (AC materials durability and rutting). Changing specific subgrade characteristics was found to significantly change AC fatigue cracking and transverse cracking as follows:
    - The higher the percent fine sand content (coarser grained material), the less AC fatigue cracking.
    - The higher the percent clay content, the greater the AC pavement smoothness loss.
    - The higher the PI, the higher the AC transverse cracking and fatigue cracking.

JPCP

The performance results have shown that environmental factors, including climate and subgrade, are very important aspects in the initiation and progression of distress and damage in JPCP. Analysis showed that environmental factors accounted for 24 percent of total damage for JPCP. Therefore, about 1/4 of all damage to normally loaded JPCP is attributable to subgrade and climate factors. Key climate and subgrade factors that initiate and aggravate JPCP distress are described as follows:

- **Climatic zone:** JPCP located in warmer no-freeze climates exhibited significantly greater fatigue transverse cracking and smoothness loss. JPCP located in colder freeze climates exhibited significantly greater joint faulting and greater joint spalling.
- **PCC in situ temperature:** The annual in situ PCC temperature (averaged over the year) had a significant impact on fatigue cracking, joint spalling, and smoothness loss. While increased PCC temperature correlates well with temperature variables such as thermal gradient, climate zone, freeze/thaw cycles, and frost depth, the following observations were made:
    - Increased PCC temperature resulted in increased fatigue transverse cracking.
    - Increased PCC temperature (warmer climate) resulted in less transverse joint spalling.
    - Increased PCC temperature (warmer climate) resulted in greater smoothness loss.
- **Freeze/thaw cycles:** Higher numbers of freeze/thaw cycles resulted in significantly greater joint faulting and joint spalling over 15 years.
- **Precipitation:** Lower annual precipitation resulted in increased fatigue cracking of JPCP. Drier climates resulted in greater thermal gradients and higher moisture gradients in concrete slabs. This contributes to higher upward curling and top-of-slab tensile stresses that, combined with load-associated stresses, cause additional fatigue damage at the top of the slab with corresponding top-down cracking.
- **Subgrade soil:** Subgrade-related variables had a significant impact on fatigue cracking, joint faulting, and smoothness loss. The only distress not affected was joint spalling.

  The coarser grained the subgrade was, the greater the fatigue transverse cracking was. This result is difficult to explain other than that coarse-grained soil typically has a higher modulus that leads to higher curling stresses at the top of the slab and increased top-down cracking.

The higher the percent clay content is, the greater the joint faulting is. This may be related to pumping and erosion of the subgrade through the unbound aggregate base course layers beneath the PCC slab.

Summary

An estimate was made of the proportion of pavement damage caused by environmental factors using comparisons of pavement damage of low traffic SPS-8 performance with higher traffic “companion” SPS and GPS. Results for flexible pavement showed that 36 percent of total damage caused when loaded under normal traffic levels was related to environment (subgrade and climate variables). Results for rigid pavement showed that 24 percent of total damage caused when loaded under normal traffic levels was related to environment (subgrade and climate variables) after 15 years of service. Therefore, additional attention to AC, PCC, aggregate base course, and subgrade layer materials durability for a specific climatic zone would provide significantly improved performance. In addition, improved thickness design for AC and PCC layers would also provide significantly improved performance. (For example, AC thickness was very significant in reducing fatigue cracking in warm climates but less so in cold climates.)

In addition, many results of interest to pavement and materials engineers were obtained through analysis of the performance of the SPS-8 and other SPS and GPS companion sections. One of many interesting findings was that the occurrence of transverse cracking of AC pavement was significantly higher for companion pavements subjected to higher traffic loadings (SPS-1 and GPS-1) than under low traffic loadings (SPS-8). Transverse cracks also frequently occurred in non-freeze climate zones where they were not expected. The final report documents some suggested findings from this study to improve pavement design and materials selection to minimize distress and to maximize performance in various critical climatic regions.

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