TECH**BRIEF**

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Evaluating The Load Capacities of Flooded Pavements: Improving Practices and Developing Data-Driven Evaluation

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This TechBrief is part 2 of a two-part series (part 1 is *The System Dynamics of Flooded Pavements* (FHWA-HRT-24-096)). The TechBrief is a technical summary of the Federal Highway Administration (FHWA) report *Developing Procedures for Assessing Flooded Pavements: Evaluating Structural Capacity and Managing Risks* (FHWA-HRT-24-104).

FLOODED PAVEMENT ASSESSMENT: PAVEMENT EVALUATION FOR STRUCTURAL CAPACITY

Incorporation of flood resilience in road infrastructure is urgently needed to reduce economic losses. Flooded roads may undergo rapid deterioration after being reopened to traffic. Thus, transportation agencies must develop pavement design and management practices and methodologies that account for the likelihood and impacts of flooding, using prior experiences in similar situations and nondestructive testing (NDT) as resources. Furthermore, uncertainties in expert judgment and testing must be managed to reduce assessment risks and should be quantified, especially when pavement design information and/or NDT is unavailable. Additionally, a consistent set of standardized guidelines adopted by agencies may improve implementation.

Currently, agencies primarily base pavement evaluations and decisions regarding opening roads to various types of traffic after a flood on field observations and past experiences; additionally, some agencies may include NDT in the decisionmaking process. However, agencies need specific guidelines regarding how field observations, experience, and NDT can be effectively integrated to evaluate the postflooding structural capacity of pavements and make reliable, cost-effective decisions. In other words, further guidance is needed on how to optimize all the involved parameters to benefit decisionmakers and users.

This TechBrief summarizes some important findings from the report, which was prepared for the Flooded Pavement Assessment project funded through FHWA Project No. DTFH61-13-C00022.(1) The report addresses the load-carrying capacity of pavements affected by flooding to provide decisionmakers with quantitative tools to rationally assess and strategize opening roads to traffic after floodwater recedes, considering flooding hydraulics and pavement structural aspects. The TechBrief presents highlights from two major efforts of the research—laboratory material characterization and pavement performance evaluation.

Organization

The TechBrief highlights the various aspects of the research effort in two parts, as follows:

- Laboratory materials testing and characterization that can be conducted in a flooded pavement assessment effort.
- Modeling pavement behavior using mechanistic and empirical models to assess the impact of moisture on various pavement parameters. This effort also covers validating results with field pavement surface deflections and recommending some stress- and moisture-dependent resilient modulus (M_R) models.

The research in this TechBrief summarizes the results of a research program that was conducted in two phases. Phase 1 included a thorough literature review and the collection of information from previous work on flooded-pavement assessments to build and develop the phase 2 work plan. Phase 2 included establishing the methodology and developing a tool for assessing flooded pavements and conducting postflooding operational decisionmaking.(1)

LABORATORY MATERIALS CHARACTERIZATION

The presence of moisture is a major cause of hot mix asphalt (HMA) pavement deterioration. (See references 2 through 6.) This presence initially manifests through deterioration of mechanical properties and premature loss of surface ride quality; subsequently, the pavement loses structural strength. Materials characterization in the laboratory is an important part of identifying and quantifying the impact of flooding on a pavement. In the study, researchers first conducted characterization to identify sample conditioning procedures and tests that were effective in recognizing moisture-induced deterioration of HMA. Second, researchers developed a practical framework for quantifying the loss of pavement life due to an asphalt mixture consisting of a moisture-susceptible aggregate type (PI mix) based on probabilistic and risk analysis methods. Specifically, the two-step procedure involved the following:(1)

1. Laboratory-based quantification of material deterioration.
2. Risk-based quantification of loss of HMA pavement life due to use of PI mixes.

Ultimately, through this framework, researchers furnished a tool that State departments of transportation (DOTs) can regularly implement.

Laboratory-Based Quantification of Material Deterioration

Researchers selected two types of aggregate mixtures, the PI mix and an asphalt mixture consisting of a nonmoisture-susceptible, aggregate-type (SM) mix, meeting MaineDOT specifications.(7) Additionally, researchers selected a performance-graded (PG) 64-28 grade asphalt binder. Researchers adopted the nominal maximum aggregate size (NMAS) MaineDOT 9.5-mm mix design with 20-percent recycled asphalt pavement (RAP), having an asphalt content of 5.9 percent for PI mixes and 5.4 percent for SM mixes.

Researchers conducted retained tensile strength (American Association of State and Highway and Transportation Officials (AASHTO) T283) and Hamburg tests.(8,9) A comparison of PI and SM mixes showed the PI mix failed rut depth criterion and had a very low stripping inflection point, indicating stripping to be a major contributor to rutting. Researchers identified three parameters to investigate further based on relevant existing literature, the current findings in the study, and the overall needs for the effort: sample conditioning process, test procedure, and governing relationship between material loss and mechanical deterioration.(1)

Based on the investigative parameters, researchers devised a conditioning process that can generate cyclic water pressure and allows high saturation and sufficient moisture-ingress time. Researchers developed a test procedure that used SuperPave™ gyratory specimens and field cores.(10) Subsequently, researchers found a relationship between loss of material and deterioration

Test Procedure

Researchers selected dynamic modulus (|E^*|) and seismic modulus (E_s) tests for evaluation based on nondestructive qualities, potential for follow-up with mechanistic-empirical (M-E) analysis, high testing productivity, and relatively simple sample preparation processes.(1)

To simulate fatigue cracking conditions, researchers conducted the |E^*| test in the indirect tensile mode. This fatigue mode enables conditioning of three samples simultaneously due to thin sample size requirements. Researchers calculated the |E^*| test using testing parameters, such as loads, sample dimensions, and geometric coefficients.(15)

Researchers selected the E_s test because it is a fast and nondestructive test, which has been evaluated extensively and found to be sensitive to key properties—including HMA moisture susceptibility—and has HMA quality control guidelines.(16) The research team used a commercially available, 54-kHz ultrasonic pulse velocity (UPV) device. The method works on the basic principle that the velocity of a pulse of a compressional wave through a medium depends on the elastic properties and density of the medium. The P waves (longitudinal compressions) transmitted through the thickness of the sample are detected by sensors, and the time for travel (t_v) is displayed. T_v is used with the bulk density of the sample (d) to calculate the bulk constrained modulus and then the E_s, which can be converted to the design modulus (E_d).

A decrease in E_s due to the moisture effect can happen either due to the effect of pore pressure exerted by water into the pores or due to a loss of integrity in the mix that resulted from a loss in cohesion or adhesion. Research has indicated E_s is sensitive to both of these moisture effects.(17,18) Notably, the porewater effect will be more significant and long lasting where a relatively greater amount of water is absorbed by aggregates and where the pore sizes are small and facilitate capillary action, which helps in retaining water (i.e., finely graded mix). In mixes with higher voids or low-absorption aggregates, the effect of porewater pressure may wane quickly after the moisture-conditioning process; hence, a relatively quick test is more appropriate for detecting the loss in integrity of the material due to porewater effects.(17) Other research has reported good agreements between moduli measured by seismic methods and laboratory and field methods.(19)

Governing the Relationship Between Material Loss and Mechanical Deterioration

Modifying MIST conditioning processes slightly, researchers conditioned each specimen separately (as opposed to three specimens stacked together) and collected the effluent from the MIST. This effluent consisted of water, aggregates (broken, coated, and uncoated), and asphalt binder. The research team subjected the aggregates to sieve analysis for gradation and conducted dissolved organic carbon (DOC) analysis to detect traces of asphalt binder in the effluent and determine the content.

Findings From Laboratory-Based Quantification

Sample Conditioning Process Findings

From the phase 1 procedure, both air voids and porosity decreased after MIST conditioning for the SM and PI mixes, indicating that the impact of MIST conditioning on the samples was of a compacting nature rather than a dilatory nature, which closely simulates the stripping phenomenon. It is highly likely that the lower loss in modulus was indicated in the PI samples after MIST conditioning because, in general, a decrease in air voids leads to compaction, resulting in the overall inflation of the sample modulus. To maximize this potential, the MIST conditioning process needed to be severe enough to simulate the actual loss of material that is commonly observed in moisture-damaged pavements, which initiated phase 2 of the sample conditioning procedure. Researchers modified the MIST conditioning procedure in phase 2 by increasing the dwell period, which can simulate the water soaking period immediately after rainfall but before significant traffic is present on the roadway.

Phase 2 of the MIST conditioning procedure included mixes at high (greater than 9-percent) air voids undergoing compaction, and mixes at construction voids (6–8 percent) undergoing dilatation. Compacting samples yielded modulus increases, while dilating samples yielded decreases. At similar initial air voids, the PI mix showed a higher loss of modulus and a lower tensile strength for a smaller increase in air voids compared to the SM mix. Even after dilatation, mixes with lower initial air voids retained higher tensile strength compared to samples undergoing compaction.

Test Procedure Findings

At a 10-percent significance level, no significant difference in |E^*| was observed at 1 Hz and 10 Hz for mixtures with 6.5-percent air voids in the post-MIST- and pre-MIST-conditioned PI mixes and the SM specimens.

The $|E^*|$ test was thus unable to distinguish between the two mixtures. The E_s values of the two mixtures before and after MIST conditioning indicated a statistically significant difference for the PI mixture. A paired-sample *t*-test at the 1-percent significance level confirmed that the post-MIST values were lower; however, no such difference was found in the case of the SM mixture. The results indicate seismic testing is sensitive to the effects of moisture damage.

Governing Relationship Findings

Researchers found that the effluent material contained coated and uncoated aggregates and asphalt binder, confirming the findings of Zofka, Maliszewski, and Bernier.(20) The total amount lost per percent increase in air voids for the PI mix was 1.4 times that of the SM mix. The fineness modulus (FM) of the effluent aggregates did not show a strong correlation with indirect tensile strength; seismic modulus appeared to increase at higher FM values. At similar air voids, the PI mix showed a higher loss of seismic modulus for a lower FM value compared to the SM mix. Meanwhile, the effluent from the PI mix showed a higher DOC compared to the SM mix.

Risk-Based Quantification of Loss of HMA Pavement Life in PI Mixes

Researchers conducted linear elastic analysis (LEA) using typical pavement structures and MaineDOT materials. The Asphalt Institute fatigue cracking model was used to determine fatigue life, measured in terms of number of repetitions to failure (N_f). The loss of pavement life was estimated from the difference in N_f values using pre- and post-MIST E_d. Using the number of years to failure, researchers calculated lifecycle cost using net present value. Researchers observed, first, that State DOTs can make useful conclusions regarding the risk of loss in pavement life from using PI aggregates versus the risk of using aggregates from alternative sources with antistripping agents. Material cost, lifespan, and flood risk may be considered in reaching the most appropriate decisions. Second, State DOTs can take into consideration variability in thickness of layers and evaluate the risk of loss in pavement life.

Suggested Framework and Recommendations

Researchers proposed a framework to evaluate the moisture susceptibility of HMA mixes and developed estimates of associated risk to pavement life based on the risk assessment and material characterization study. The process is as follows. Compact a minimum of three 6-inch (150-mm)-diameter HMA samples to a 2-inch (50-mm) thickness at construction voids. Use the vacuum sealing method to determine the bulk specific gravity of the samples. Separately, determine the theoretical maximum density of the mix followed by the air voids. Test the samples with the UPV device, determine wave velocity, and record the samples' temperatures. From the obtained data, determine the values for E_s and E_d. MIST-condition the samples using 77 °F (25 °C), 20 psi (0.1379 MPa), and 15,000 cycles. Then dry the samples using a countertop fan for 8 h.

Next, conduct the procedure involving air void determination and the dried samples and determine the post-MIST values of the modulus parameters. Then, conduct a test to determine whether the difference between the pre- and post-MIST E_s is statistically significant. If this difference is significant, proceed as described in the following paragraph; if it is not significant, report the results.

If the pre- and post-MIST E_s is statistically significant, then use risk analysis software to determine the risk of loss of pavement life as follows. For each sample, calculate (pre-MIST E_d minus post-MIST E_d) and determine the critical strain at the bottom of the HMA layer using LEA. Determine N_f, the pavement life (years), and lifecycle cost, if required, and determine loss of pavement life in years. Develop a regression equation relating (pre-MIST E_d minus post-MIST E_d) to loss of pavement life. Calculate the mean and standard deviation of (pre-MIST Ed minus post-MIST Ed); a similar approach can be used for loss of lifecycle cost. Using these statistical parameters, run a Monte Carlo simulation to determine the 90-percent confidence limit for loss of pavement life.(21) If thickness variability is to be considered, then use the thickness data from the analyzed HMA layers and consider the variability established in the Monte Carlo simulations that were run in the previous steps.

The research team also recommended customizing the steps in the framework, depending on the experience of the implementing agency. Any effect of the presence of water in the samples on the measured modulus should be investigated using the UPV. Distress criteria and bottom-up fatigue cracking are required to better evaluate reduction in pavement life. Additionally, researchers recommended evaluating a shorter, combined process of MIST conditioning, in which pumping is conducted for a fewer number of cycles (i.e., damage by loss in cohesion). Subsequently, the sample is left undisturbed in the chamber to interact with the water (i.e., damage by loss in adhesion).

PAVEMENT PERFORMANCE EVALUATION

Because assessing the behavior of pavements during and immediately following extreme weather events is of utmost importance, researchers carefully investigated the structural capacity of flooded pavements and considered proactive measures to extend pavement service life. Researchers conducted the assessment to improve the understanding of flooded pavement performance.

Impact of Typical Pavement Parameters Due to Moisture Content Variations

The research team investigated a range of material types using LEA and FHWA's Long-Term Pavement Performance (LTPP) InfoPave™ database.(22) Researchers recognized catastrophic failures of pavements after flooding events, investigated pavement responses to traffic loads under different moisture conditions, and identified other parameters that affected the performance of inundated pavement. Finally, researchers assessed pavement performance using a falling weight deflectometer (FWD) and soil moisture profiling. In general, researchers studied the effects of the following three conditions on pavement structure, individually and in combination:

1. Impact of subgrade bearing capacity on pavement structure.
2. Impact of subsurface water on pavement structure.
3. Impact of layer properties and traffic on pavement structure (study involving strain ratios).

Impact of Subgrade Bearing Capacity on Pavement Structure (Catastrophic Failure of Flooded Pavements)

Researchers assessed flexible pavement failure under excessive water and postflooding using the concept of shear failure in soils in accordance with the conventional Terzaghi's bearing capacity formulation.(23) Researchers calculated bearing capacity under traffic loading by changing the soil condition from unsaturated to fully saturated (i.e., flooded) conditions. Researchers simulated flood conditions by raising the water table from an initial hydrostatic capillary pressure distribution for different cross sections over a range of subgrade soils.

Researchers evaluated three pavement sections consisting of three different asphalt course (AC) thicknesses. The base thickness was twice the AC thickness in each case, and, accordingly, researchers designated the three base layers as thin, intermediate, and thick. Researchers evaluated these pavements using three different types of subgrade soils at sites in New Hampshire (A-2-4), Texas (A-4), and Vermont (A-7-5) and varying water levels. The water level in the analysis varied from the top of the subgrade surface down to 82 ft (25 m) below the pavement surface. The subgrade below the subsurface water-level location was considered fully saturated; the subgrade material above the water level was considered unsaturated. The subgrade soil above the water level was divided into sublayers. The matric suction was set to zero for saturated soils. Researchers estimated hydrostatic capillary suction for soils above the water level, and based on these estimations, researchers estimated the degree of saturation at each sublayer from the soil water retention characteristic curve (SWRC) for the three subgrade soil types. Researchers calculated the ultimate bearing capacity (q_u) using the 1996 and 2007 models developed by Vanapalli et al.(24)

Finally, researchers calculated vertical stress on the pavement surface layer corresponding to the computed q_u of the soil layer. Researchers established allowable tire loads based on the calculated vertical stresses on the pavement surface that the road can withstand without shear failure. Researchers observed that the load-bearing capacity of the pavements on coarse-grained soils was greater than for pavements on fine-grained soils due to higher shear strengths. The pavement structure significantly changed the allowable loads as the water level dropped down to the effective depth. A crucial finding was that inundated pavements have sufficient capacity to carry most typical tire loads without shear failure in the subgrade.

Impact of Subsurface Water on Pavement Structure

When a flooding event occurs, the water level rises above the normal groundwater table (GWT), and the pavement structure becomes submerged. Over time, the floodwaters recede from the pavement surface down to the unbound material layers. The subsurface water level typically divides the unbound layer into two layers: above the water level, where the material is unsaturated (vadose zone), and below the water level, where the material is fully saturated. To incorporate the unsaturated and saturated mechanical behavior of pavement materials, researchers conducted a parametric analysis to simulate the effect of floodwater recession on the performance of pavement systems.

Researchers simulated flooded conditions using a hydrostatic pressure distribution by lowering the subsurface water level to multiple elevations in the unbound material layers. Researchers incorporated matric suction indirectly to determine the M_R of unsaturated unbound material layers. The pavement cross sections and material properties were the same as, and the matric suction and degree of saturation using SWRC were estimated the same as, what was described in the previous section titled, Impact of Subgrade Bearing Capacity on Pavement Structure. Researchers used LEA to estimate the pavement responses: maximum surface deflection, horizontal strain at the bottom of the asphalt layer, and vertical strain at the top of the subgrade layer. Researchers simulated FWD load to estimate maximum deflection and simulated single-axle, dual-tire load to calculate strains.(25) Researchers calculated pavement responses under different moisture conditions, ranging from unsaturated to fully saturated. Additionally, researchers calculated structural numbers (SNs) at different water levels.

When the water level was at the interface between the AC and the base course (BC), surface deflections were the highest due to the full saturation of the unbound materials. The results from this study indicate that, by lowering the water level to 6 inches below the surface of the BC for intermediate and thick pavements, the maximum deflection decreased only slightly (around 2 to 5 percent). However, the same action for the thin pavement structures resulted in more significant reductions in maximum deflection (around 20 to 24 percent).

When the subsurface water level was lowered down from 6 inches to 12 inches in thick pavement structures, deflections decreased rapidly (around 17 percent to 19 percent) due to stiffening of the base sublayers above the water level. Once the water level was moved to the interface between the BC and subgrade layer, the maximum deflection decreased around 12 to 14 percent in the thick pavements due to the relative contribution of the BC to the overall structural capacity. Other effects, such as those of layer thickness and material type, can be found in the report.(1)

Impact of Layer Properties and Traffic on Pavement Structure

Parameters, such as traffic loads and environmental factors, are not easily obtained during a flooding event; consequently, assessing the performance of inundated pavements accurately is challenging. Researchers evaluated six different parameters to investigate the structural capacity of inundated pavements: asphalt layer thickness, BC thickness, BC material type, subgrade material type, interlayer bond condition, and traffic load for low-volume roads and interstate highways.

The BC and subgrade soils represent a range of typical material types across the United States. Researchers obtained the measured material properties for subgrade soils from the LTPP database for sites in Utah (49-1017), Wyoming (56-6031), and South Dakota (46-1017).(22)

Researchers assumed unbound layers were at optimum moisture content during nonflood conditions to represent the as-designed strength of the pavement structure and were fully saturated during flooding conditions to simulate inundation scenarios when the pavement structure is at its weakest. Researchers assumed the M_R of the saturated materials (worst case scenario) was 50 percent of the M_R at the optimum moisture content.(17,26) Previous flooded-pavement research showed the reduction in subgrade M_R to be less than 50 percent of preflooding conditions. Researchers obtained the M_R values for BC materials and the Poisson's ratio for all materials used in this analysis from the *Mechanistic Empirical Pavement Design Guide*.(27) Researchers used two approaches to evaluate the structural capacity of a total of 13 pavement sections with three different types of BCs and three different subgrade soils.

Mechanistic Evaluation

In the mechanistic approach, researchers used LEA to predict stresses and strains and considered full-bond/full-slip interface conditions. Researchers broke traffic loads down as needed and conducted variance analysis using a 95-percent confidence interval to determine the influences of each of the pavement layer properties on the pavement responses. Researchers conducted a Tukey-Kramer honestly significant difference (HSD) test to determine the importance of each parameter on the response of the pavement structure.(28) More details of the mechanistic evaluation are as follows:

- Bond conditions: An assessment of interlayer bond impact condition on ratio of strain, calculated using saturated condition to strain, which is calculated using optimum moisture condition. Results showed that the full-slip condition is critical (larger increase in horizontal tensile strain under saturated conditions) for horizontal strain, and the full-bond condition is critical for vertical compressive strains. Researchers found a statistically significant difference between the ratio of horizontal tensile strains at the full-bond and full-slip conditions (p-value < 0.05). (The p-value is the probability under the assumption of no effect or no difference (null hypothesis) of obtaining a result equal to or more extreme than what was actually observed.(29) Researchers found no significant difference for the ratio of vertical compressive strain between full-bond and full-slip conditions for low-volume and interstate cross sections (p-value > 0.05).

- Traffic type: Impact of five different truck types (FHWA class 3, FHWA class 5, FHWA class 6, FHWA class 9, and loader) on ratios of horizontal strain at bottom of the AC surface and vertical strains on the subgrade for saturated to optimum moisture conditions.(30) Results indicated a significant difference in the ratio of horizontal strains and exhibited no significant difference in the ratio of vertical strains. The Tukey-Kramer HSD test showed the loader impact on the ratio of horizontal strains was significantly different than the loader impact for other traffic-loading types. Thus, researchers identified the loader as the critical truck type for fatigue performance in pavement structures under saturated conditions. Researchers found no statistically significant difference for rutting performance due to different truck types on pavement structure response. This finding may have occurred because researchers used the maximum vertical strains under different tires in each truck type in the analysis.
- Saturation and strain ratios: Saturated conditions almost always had a larger impact on vertical strain at the top of the subgrade layer. Type of BC and subgrade had the most influence on the change in vertical strain with moisture content. For fatigue performance (related to horizontal strain), the ratios were most sensitive to interlayer bond conditions and BC thickness for low-volume roads and asphalt and base-layer thicknesses and interlayer bond conditions for interstate sections. Type of loading had a significant impact only on the horizontal strain ratios.

Empirical Evaluation

Researchers used the traditional AASHTO SN in the empirical approach and two modified structural number approaches, which included the subgrade material in the structural number calculation (modified structural number (SNC) and the alternate modified structural number (MSN)).(31) In SNC computation, researchers added the contribution of the subgrade structural number (SN_{sg}), which was considered to be a function of subgrade California Bearing Ratio (CBR), to the traditional SN. In MSN computation, researchers divided the subgrade into two layers.

Researchers considered the upper layer to be a 3-m- (9.84-ft)-thick subbase layer, based on the sensitivity analysis, and the second layer to be an infinite subgrade layer. For the latter modified structural number approaches, the SNC and MSN showed the percentage of reduction under fully saturated conditions due to the contribution of the subgrade soil (table 1).

Table 1. Structural number modifications required to withstand same level of traffic loads as under optimum moisture conditions over varied road types during full saturation.

Structural Number Type	Road Type	Structural Number Outcome
SN	Low volume	30–40 percent increase
SN	Interstate	20–30 percent increase
SNC	Low volume	10–40 percent decrease
SNC	Interstate	6–22 percent decrease
MSN	Low volume	35–73 percent decrease
MSN	Interstate	28–61 percent decrease

The ratio of the subgrade M_R at various moisture contents to the MR at optimum moisture content is related to the change in the number of equivalent single axle loads (ESALs).(1) This relationship holds for any cross section and shows the percentage of load reduction required under saturated conditions to maintain the same structural capacity as under optimum moisture conditions. For example, if the moisture content of the subgrade increases so that the M_R is 80 percent of the value at optimum moisture content ($M_R = 0.8\ M_R$ at a reference condition (M_{Ropt})), the pavement structure will reach failure at approximately 60-percent of the design ESALs.

Regression-Based Pavement Response Models

Researchers recommended a regression-based, mechanistic-empirical, deterministic model for incorporation into a risk-based decisionmaking tool to support road operations after flooding. Researchers performed a regression analysis for the 13 pavement cross sections with three different BCs and three different subgrade types at both optimum moisture and fully saturated conditions using a stepwise analysis regression function to develop the models. In the JMP® statistical software tool, researchers predicted the pavement response models using horizontal strain at the bottom of the asphalt layer; vertical strain at the top of the subgrade layer; and layer thickness, material stiffness, and moisture contents in the unbound materials.(32) Additionally, researchers developed a regression equation to compute pavement surface deflection and included only statistically significant variables (p-value <0.05) in the models. Researchers developed the three models under a single tire load of 9,000 lb (40 kN) at 120-psi (0.8274-MPa) tire pressure.

Validation of Moisture-Based Layer Subdivision Using FWD

To determine the structural capacity of the postflooded pavement, researchers developed a cost-effective alternative to assess pavement response without conducting an FWD test. Even though layered elastic models are accepted and implemented for predicting deflection in pavements, evaluation of pavement performance and comparison with FWD data require estimation of input parameters, such as subgrade M_R. Selection of the representative subgrade modulus can be challenging because the subgrade modulus varies as the soil moisture content changes in depth.

Researchers developed four different methods (A, B, C, and D) with different layer division strategies to incorporate the soil-moisture profile, measured using a time-domain reflectometer (TDR), into a flexible pavement evaluation and investigated how the change in the GWT affected pavement deflection. In method A, researchers divided the subgrade layer into several sublayers from the top of the subgrade to the GWT, based on TDR location depths. In method B, researchers considered the subgrade layer one layer above the water table. In method C, researchers considered the subgrade layer both one layer above and one layer below the water table. In method D, the subgrade generally corresponded to an influence zone defined to project the stresses caused by surface loading of a pavement structure.(33) Researchers defined the influence zone as above the location where the induced stress reduces to at least 10 percent of the applied surface pressure. This zone was then considered a representative subgrade layer, on which the MR was calculated based on using a weighted-average moisture content.

Researchers calculated the predicted deflection basin using the KENLAYER multilayer elastic analysis computer program and compared the predicted deflections to those measured from the FWD testing.(34) Overall, the magnitude and shape of the measured deflection basins fit reasonably well with the predicted values.

Stress- and Moisture-Dependent M_R Models by Moisture-Based Layer Subdivision

Researchers conducted a study to develop predictive models for M_R of unbound pavement materials, which are stress and moisture dependent, to investigate their effect on in situ FWD deflections. Researchers evaluated a stress-based constitutive model and a predictive model for estimating the M_R of unbound materials in conjunction with the predicted and measured soil moisture content profiles in eight different unbound material types. FWD data at four (LTPP-SMP) locations in Maine, Minnesota, Texas, and Montana were used to estimate the in situ measured deflection.(22) Five methods (A to E) were used under varying saturation, pavement geometry, and material property (i.e., M_R) conditions. The following paragraph contains a brief overview of the methods, but the full report should be referenced for complete context.(1)

Method A used a traffic loading point with Boussinesq's equations to calculate stress at the middle of each sublayer under the loading point, wherein the M_R of each sublayer was estimated from a nonlinear constitutive model in the equation at optimum moisture content. Method B was like method A, except researchers used values for predicted degree of saturation in place of measured values. Method C varied from methods A and B on the basis that the M_R at each sublayer was independent from its value at optimum moisture content; researchers treated each sublayer individually based on the applied stresses and moisture content. Method D used CBR and the Witczak model to predict moisture condition and a constant optimum MR for all sublayers.(35) Method E was like method D, except researchers used the predicted degree of saturation instead of the measured values.

Overall, for nonplastic soil materials, the findings show that using the presented CBR empirical predictive model to estimate M_R for the unbound materials and implementing LEA is adequate to predict FWD deflection basins. In contrast, based on this experiment, drawing a firm conclusion for plastic soil materials is difficult, since the predicted deflection basins from the iterative and approximate stress-dependent methods and CBR empirical models overestimated the measured FWD deflection basin. The approach of incorporating the predicted moisture content from the hydrostatic pressure distribution in the CBR empirical model seems appropriate for predicting the furthest deflection points, which define the stiffness of the subgrade layer for coarse-grained soils.(1)

SUMMARY OF FINDINGS

The laboratory material characterization effort led to a significant change in the testing sample conditioning process and informed test procedure applicability. The MIST conditioning process led to sample compaction and overall inflation of sample modulus; researchers thereby determined this process did not accurately simulate the stripping phenomenon. Subsequently, researchers modified the conditioning process by increasing the dwell period to simulate soaking during flooding, after flooding, and before traffic plying. Pre-MIST and post-MIST testing indicated the E_s test was sensitive to moisture damage, but the $|E^*|$ test was not. These results indicate the testing agency can evaluate the risk of loss in pavement life, taking into consideration variability in thickness of layers. Based on the laboratory material characterization findings, researchers suggested a framework to assess moisture susceptibility together with the associated risk to pavement life.

Researchers evaluated the load-bearing capacity of inundated pavements using multilayer elastic analysis. Researchers used matric suction as an indirect way to determine the M_R of unsaturated unbound material layers, divided into sublayers above the water table. Researchers calculated pavement responses—maximum surface deflection, horizontal strain at the bottom of the asphalt layer, and vertical strain at the top of the subgrade layer—under different moisture conditions, ranging from unsaturated to fully saturated (i.e., flooded). Researchers investigated the sensitivity of pavement response to variations in different parameters to determine which parameters had the largest impact on change in expected pavement response under saturated conditions. Agencies can use these results to inform the allocation of time and resources when assessing pavement. Additionally, researchers developed and tested alternative ways to estimate in situ FWD deflection for a set of pavements from the LTPP database for further use as firsthand evaluation of pavement structure performance.(22)

The shear failure theory, matric suction, and soil water characteristic curve can be used to predict variations in flooded pavement. During periods of inundation, pavements can carry most practical tire loads without experiencing shear failure; hence, subgrade bearing capacity failure was not a concern. However, subsurface water impacts pavement structure, as identified through pavement surface deflections. Researchers saw a significant reduction in structural capacity in the fully saturated condition when the water level was at the interface between the asphalt and BC layers; structural capacity was regained when the subsurface water level dropped below the BC layer.

Researchers studied strain ratio, considering the effect of layer properties and traffic on pavement structure. These findings indicated the most critical factors in evaluating horizontal strain at the bottom of asphalt layer for predicting fatigue-cracking performance are layer thicknesses, traffic type, and interlayer bond condition. Empirical analyses involving the AASHTO SN revealed that the required SN, SNC, and MSN to withstand the same level of traffic loads as under optimum moisture conditions changed under saturated conditions and was dependent on the road type.(31) Furthermore, the ratio of the subgrade M_R at various moisture contents to the M_R at optimum moisture content was related to the change in the number of ESALs. See the main report for additional details and findings related to this discussion.(1)

Finally, researchers developed a regression equation to compute pavement surface deflection. The most appropriate alternative method to estimate in situ FWD-measured deflection was to divide the soil layer above the water table into several layers in the LEA. The most suitable predictor to estimate the in situ FWD deflection for nonplastic soil materials was the predictive model from CBR. In contrast, drawing a firm conclusion for plastic soil materials was difficult because the predicted deflection basins from the constitutive stress-based and empirical models overestimated the measured FWD deflection basin.

The work described in this document and discussed in more detail in the report can provide a cost-effective method to evaluate the performance of pavements. The presented methods can advance understanding of the structural performance and capacity of flooded pavements at different moisture conditions. This information can be used and adapted to develop an evolvingly comprehensive, engineering-based approach to evaluating the load-bearing capacity of flooded pavements, potentially helping agencies avoid flood-related damage in the future.(1)

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