Accelerated Pavement Testing Validation of the Response and Distress Models for New Flexible Pavements in the Mechanistic – Empirical Design Guide

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ABSTRACT**:** The paper presents a summary of the research work conducted to validate the response and distress models in the Mechanistic Empirical Design Guide (MEPDG) using Accelerated Pavement Testing (APT). Twelve pavement sections were constructed in the Civil Infrastructure Systems Laboratory (CISL) of Kansas State University with six different Superpave asphalt mixes. Each section was loaded by an APT machine up to 2,000,000 load repetitions of a 99.8kN single axle. Six sections were tested in a rutting experiment conducted at 35ºC and six sections were tested in a fatigue experiment conducted at 20ºC. The pavements were instrumented with strain gages, stress cells and displacement sensors to measure pavement response under APT loading. An extensive laboratory testing program was conducted to determine the properties of the materials used in the construction of the experimental sections. It was found that the revised Witczak model predicts reasonable the dynamic modulus of asphalt concrete mixes. The MEPDG structural response model under-predicted the longitudinal strains at the bottom of the asphalt concrete layers while the MEPDG over-predicted the permanent deformation in the asphalt layer. The comparison between the results of the laboratory rutting tests performed at 35°C indicate that the results of the Hamburg Wheel Rut Test (HWRT) correlate the best with the results of the APT experiment, followed by those from the Asphalt Pavement Analyzer (APA).

KEY WORDS: Permanent deformation, asphalt mixes, mechanistic-empirical design guide, accelerated pavement testing, material characterization.

1 THE MECHANISTIC EMPIRICAL PAVEMENT DESIGN GUIDE

In the United States, the *AASHTO Guide for the Design of Pavement Structures* is the primary document used by 80% the state highway agencies to design new and rehabilitated highway pavements. The Guide employs empirical performance equations developed using AASHO Road Test data from 1950's. In recognition of the limitations of earlier Guides, the AASHTO Joint Task Force on Pavements (JTFP) initiated an effort in the late 1990's to develop an improved Guide by 2002.

The National Academy of Science through its National Cooperative Highway Research Program (NCHRP), specifically Project 1-37A, has dedicated significant resources to develop a user-friendly procedure capable of executing mechanistic-empirical design while accounting for local environmental conditions, local highway materials, and actual highway traffic distribution by means of axle load spectra. Since the resulting procedure, the mechanistic-Empirical Pavement Design Guide (MEPDG), is very sound and flexible and it considerably surpasses any currently available pavement design and analysis tools, it was adopted by AASHTO as an interim design method for pavement structures.

The products of the NCHRP Project 1-37A are the design software and the documentation supporting the design guide. They were released first to the pavement engineering community in June 2004. An extensive literature describing the development of MEPDG framework, model components, the software, as well the implementation and calibration to local conditions, is available to the public. For the sake of brevity, no detailed description of various aspects related to MEPDG development and calibration is provided in this paper. The interested reader is suggested to consult at least the following references as a good starting point:

- The MEPDG website (NCHRP, 2004)
- The MEPDG Manual of Practice (AASHTO, 2008)

An important component of the calibration of MEPDG to local conditions is the verification of the component models. This research work aimed to verify the material characteristics prediction models, mechanistic structural models and pavement performance models by conducting full-scale Accelerated Pavement Tests at the Civil Infrastructure Systems Laboratory (CISL) of Kansas State University. Due to the limited number of pavement sections that can be constructed and tested at CISL, the research work focused on the verification of the NCHRP 1-37A models for twelve flexible pavement structures, four for each of the three Midwestern states: Iowa (IA), Kansas (KS), and Missouri (MO).

The major benefit of the APT as a research tool is that the performance of road materials and structures can be evaluated at a reduced cost and in a short period of time, since the damage induced by the traffic passing on an in-service road section in ten or more years is generated only in several months. The authors are aware of only two other efforts in the United States for the verification and calibration of MEPDG using accelerated pavement testing (APT): the structural experiment at the 2003 Test Track at the National Center for Asphalt Technology (NCAT) (Timm, 2008) and the calibration done with the data assembled in the California APT program (Ullitz et al, 2008); some other efforts may be under way.

2 THE FULL-SCALE ACCELERATED PAVEMENT TESTING EXPERIMENT

2.1 The Accelerated Testing Facility at CISL

The Kansas State University, in cooperation with Kansas Department of Transportation (KDOT) has developed the CISL Laboratory in 1997. The indoor facility allows the development of full-scale accelerated tests on pavement structures, by using the CISL machine as the loading device. The machine, consisting of a steel frame anchored to the concrete floor of the building and a bogie, is placed on full-scale road structures constructed in three pits. A full-size truck axle passes over the pavement at about every five seconds, applying a total axle load between 80 and 130 kN. Single and dual tires, single and tandem axles can be accommodated in this system. The ATL facility allows the control and monitoring of the temperature at the surface and in the pavement layers.

2.2 The APT Experimental Pavement Sections

In this experiment, twelve experimental pavement structures were constructed in CISL, in pits that are 4.87 m wide, 6.0 m long and 1.8 m deep; they were built in six pairs. Three pairs were ‘fatigue cracking’ sections and aimed to study the fatigue cracking behavior of flexible pavements. The remaining three pairs were ‘rutting’ sections and aimed to study the rutting behavior of asphalt concrete pavements. In total, six hot asphalt mixes were used, two for each of the three states. One ‘fatigue cracking’ and one ‘rutting’ pavement were built for each mix.

The pavement sections were constructed in three layers: an asphalt concrete surface layer, a 150 mm unbound granular base course and a 1.5 m of A-7-6 clayey soil subgrade. The ‘fatigue cracking’ sections had a 100 mm nominal thickness for the asphalt concrete surface layer and were loaded at a pavement surface temperature of 20°C. The ‘rutting’ sections had a 177mm nominal thickness for the asphalt concrete surface layer and were loaded at a pavement surface temperature of 35°C.

The sections were loaded with a 99.8kN single axle applied at the uniform travel speed of 11 km/hr. Lateral movement was provided by a lateral wandering device that moved the entire frame of the APT machine in the lateral direction with a maximum lateral wander of ±0.61 m. Transverse profiles at the pavement surface were measured periodically during APT loading.

The APT machine is equipped with a temperature chamber that allows testing at controlled temperatures within $\pm 1.0^{o}$C. Strain gauges were used to measure horizontal and vertical strains at the bottom of the hot mix asphalt layer. Linear Variable Differential Transducers (LVDTs) were used to measure the dynamic and permanent vertical deformation in each layer. Stress cells were used to measure the vertical stress below the base layer. Thermocouples were used to measure temperature at the surface and two additional depths in each pavement structure. Moisture in subgrade soil was measured using Time Domain Reflectometry (TDR) moisture probes. Transverse profiles were measured periodically to evaluate the evolution of rut depth with number of load repetition (Romanoschi et al., 2010).

2.3 Asphalt Mix Designs

The Departments of Transportation (DOTs) of Kansas, Missouri and Iowa provided the asphalt mix designs of the six asphalt mixes (two per state) used for verification of mechanistic prediction models. A local contractor was used to construct the pavement sections at CISL with materials transported from the three states. The six asphalt mixes comprised: a Kansas course mix (KS1) with 19 mm Nominal Maximum Aggregate Size (NMAS); a Kansas fine mix (KS2) with 12.5 mm NMAS; two 12.5 mm NMAS Missouri mixes with different binders and two 12.5mm NMAS Iowa mixes with the same binder but slightly different fine aggregate content and design ESALs. Mix IA1 was designed for 30 million ESALs and mix IA2 for 3 million ESALs. The mix designs information including aggregate gradation, PG binder grade, gravimetric binder content and in-situ measured air void content are not given here for the sake of brevity; they are given elsewhere (Romanoschi et al., 2010).

It is important to note that the in-situ air voids of the compacted mix varied from one mix to the other and from the desired value of 7.0 percent. In addition to this, the in-situ binder content for the IA1 and IA2 mixes was higher than the design binder content. Therefore, the results of the APT and laboratory tests should not be used to compare the mix design or derive any conclusions on the mix design practice used by the three state DOTs.

2.4 Laboratory Tests on Asphalt Mixes

An extensive laboratory testing program was conducted to determine their engineering properties of the six asphalt mixtures. Cores were taken after construction, and the field percent air voids were measured. The contractor provided information on asphalt mix quality control which included the binder content of the plant produced mix. This information was used to fabricate the laboratory samples.

To obtain the asphalt concrete samples for laboratory testing, cylinders having 150 mm diameter and 170 mm height were compacted using the Superpave gyratory compactor. The cylinders were compacted such as to obtain samples with the same air void as those measured in the APT tested pavements. Only the samples having the air void content within ± 0.5 percent of the in-situ air voids were retained for testing.

The laboratory tests conducted to determine the properties of the asphalt mixes were:

- Dynamic modulus at 35°C and 20°C at six load frequencies – AASHTO TP 62-03
- Static creep at 35°C - NCHRP Report-465
- Dynamic creep test at 35°C - NCHRP Report-465
- Triaxial repeated load test at 35°C - NCHRP Report-465
- Uniaxial strain test (unconfined) 35°C and at five strain rates and - ASTM D 4123
- Hamburg Wheel Rut Tester at 35°C and 50°C - AASHTO TP 63
- Asphalt Pavement Analyzer (APA) at 35°C and 50°C - AASHTO TP 63
- Repeated Shear at Constant Height (RSCH) at 35°C - AASHTO TP7-01
- Frequency Sweep at Constant Height (FSCH) at 35°C - AASHTO TP7-01
- Flexural Beam Fatigue at 20°C and three strain levels - AASHTO T321

2.5 Accelerated Pavement Testing

The twelve test sections were loaded in pairs in bi-directional mode with a 98 kN single axle that passes over the pavement once every 6 seconds. The ‘rutting’ sections were loaded until more than 19 mm of rutting was observed in each section, as follows: KS – 300,000 passes; MO – 700,000 passes and IA – 100,000 passes. All the ‘fatigue cracking’ sections were loaded with 2,000,000 cycles. None of these sections exhibited any cracks; they all failed due to excessive rutting. Due to time and monetary constraints it was decided that APT loading should not continue beyond the already applied 2,000,000 cycles.

Permanent deformation in each layer, longitudinal and transverse strains at the bottom of the asphalt layer, the vertical stress at the top of the subgrade layer, the temperature in the HMA layer and the moisture content in the subgrade layer, along with the applied axle load, were measured periodically during the experiment. For all sections, the APT loading started at least two months after their construction. A detailed description of the APT experiment including construction process, the response instrumentation, material testing, accelerated loading, pavement response and performance, is provided by Romanoschi et al. (2010).

3 VERIFICATION OF MEPDG MODELS

3.1 M-E PDG Simulations of the APT Experiment

In order to validate some of the response and distress models in MEPDG for flexible pavement structures, the APT loading of each of the twelve experimental sections was simulated using the MEPDG software, Version 1.0. for a design period of one year, the minimum value allowed by the software, and at 50% reliability level. The simulation was done at Level 1 and Level 3 analysis. In the Level 3 analysis the parameters from the mix design of each of the six mixes were used as input values. In the Level 1 analysis, the laboratory measured dynamic modulus of the asphalt concrete and shear modulus and phase angle of the asphalt binder were used as input values.

The APT trafficking was modeled by considering that all trucks passing over the pavement have the same configuration, with one front axle of 99.8 kN axle load and one back single axle of 99.8 kN axle load. For each APT tested pavement, the traffic volume was selected such that the total number of trucks passing in one year, be equal with the total number of passes of the axle in the corresponding APT experiment.

A virtual climatic file was created to simulate the indoors loading of a pavement under a controlled, constant temperature by modifying an existing file. The water table level was set to 9.0 meters such it will have no significant effect on the properties of the granular base and subgrade soil layers. The average layer thickness measured during the construction of the APT sections was selected as input data. A more detailed description of the MEPDG simulations is given elsewhere (Romanoschi, 2010).

3.2 Verification of Dynamic Modulus Prediction Model

The NCHRP 1-37A mechanistic-empirical design methodology has a hierarchical approach for specifying design inputs. The dynamic modulus values for Level 1 analysis must be obtained from testing of the asphalt mixtures. However, for Level 2 and Level 3 analysis the dynamic modulus is predicted using the Witczak model (NCHRP, 2004) and with the revised Witczak model (Bari and Witczak, 2006). The later model is preferred since the shear modulus and phase angle of the asphalt binder, values more commonly measured in the United State, are used. The dynamic modulus values can be predicted over a range of temperatures and rates of loading using (Bari and Witczak, 2006):

$$\log_{10} E^* = -0.349 + 0.754\left(|G_b^*|^{-0.0052}\right)\begin{pmatrix} 6.65 - 0.032\rho_{200} + 0.0027\rho_{200}^{\;2} + 0.011\rho_4 + 0.0001 - 0.011\rho_4^{\;2} \\ + 0.006\rho_{38} - 0.00014\rho_{38}^{\;2} - 0.08V_a - 1.06\left(\dfrac{V_{bef}}{V_a + V_{bef}}\right) \end{pmatrix}$$
$$+ \left(\frac{2.558 + 0.032V_a + 0.713\left(\dfrac{V_{bef}}{V_a + V_{bef}}\right) + 0.0124\rho_{38} + 0.0001\rho_{38}^{\;2} - 0.0098\rho_{34}}{1 + e^{(-0.7814 - 0.5785\log|G_b^*| + 0.8834\log\delta_b)}} \right) \quad (1)$$

where:

E^* = Dynamic modulus, *psi*

G_b^* = Asphalt/Bitumen shear modulus, *psi*

V_a and V_{bef} = Volume of air void and , the effective volume of binder, *%*

ρ_{200} = % passing the # 200 (0.075 mm) sieve, by weight

ρ_4, ρ_{38} and ρ_{34} = % retained on the # 4 (4.75 mm), 3/8” (9.5 mm) and ¾” (19 mm) sieves

δ_b = Phase angle of asphalt binder /Bitumen, *degrees*

The revised Witczak model was used to predict the dynamic modulus at five loading frequencies and two temperatures (20^{o}C and 35^{o}C), and the obtained values were compared to the dynamic moduli measured in the laboratory. The comparison, illustrated in Figure 1, clearly demonstrates that the predicted moduli were reasonably close to the measured moduli, the difference being less than 20% for almost all cases. Therefore, the laboratory test results validate the revised Witczak model for dynamic modulus (Equation 1).

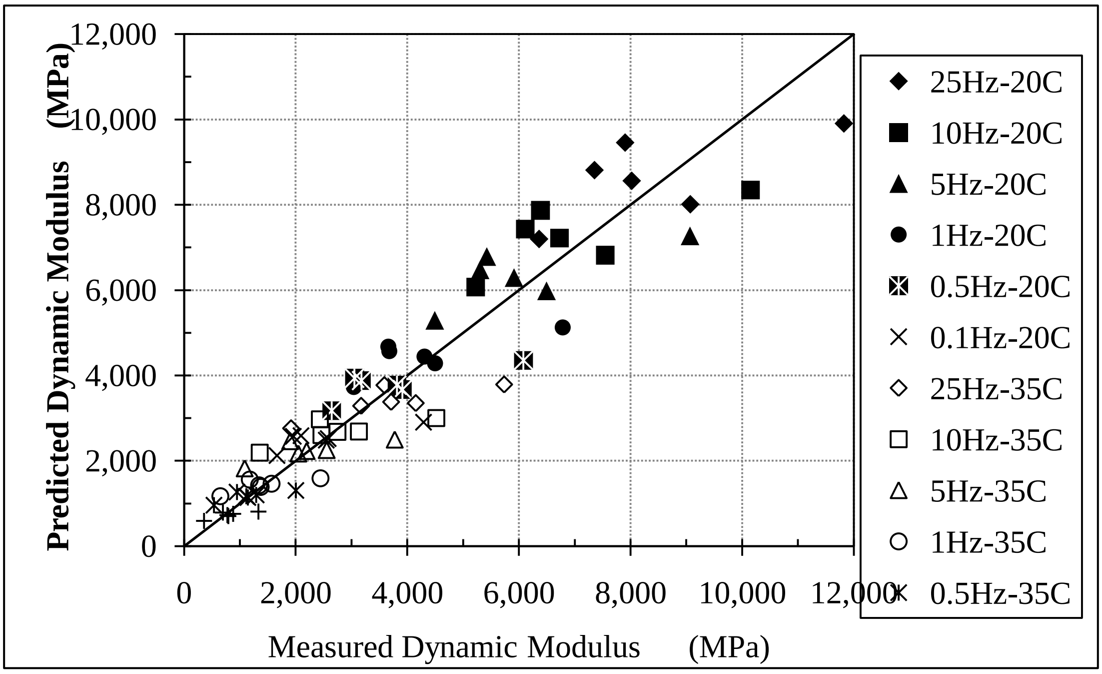

Figure 1: Predicted vs. Measured Dynamic Moduli

3.3 Verification of Pavement Response Model

The model that calculates the stresses and strains that develop in the pavement structure under truck wheel loading is a component of paramount importance in the MEPDG model since distresses and thus, pavement performance, are estimated based on the computed stresses and strains. The MEPDG software does not output the computed stresses and strains. However, the output of the software contains the accumulated fatigue damage parameter for the bottom-up fatigue cracks, the cracks that initiate at the bottom of the asphalt concrete surface layer and then propagate upward.

The fatigue damage is calculated from the value of the longitudinal strain computed at the bottom of the asphalt concrete layer in incremental fashion using Miner's law (NCHRP, 2004). The fatigue model calculates the allowable repetitions to failure as:

$$N_f = 0.00432 * k_1^{'} * C(1/\varepsilon_t)^{3.9492}(1/E)^{1.281} \quad (2)$$

where:

ε_t = longitudinal strain at the bottom of the asphalt concrete layer

E – stiffness of the asphalt concrete

$C = 10^M$ and $M = 4.84*[V_b / (V_a+V_{bef}) – 0.69]$

V_a and V_{bef} = air voids and effective binder volumetric content (%).

$k_1^{'}$ = a parameter that depends only on the thickness of the asphalt layers.

For each of the 12 months, the total duration of the simulated APT trafficking, the MEPDG output obtained for the simulated of the APT test lists the fatigue damage in percentage, the number of trucks passing over the designed pavement structure and the estimated stiffness of the asphalt concrete layers. Since the number of trucks in the simulations was the same as the number of axle passes in the APT experiment, it was possible to compute the damage calculated by the MEPDG model for a single pass of the APT axle for each month and then, to back-estimate the longitudinal strain at the bottom of the asphalt concrete with Equation 2.

Figure 2 shows the correspondence between the measured longitudinal strains and the corresponding values computed by the MEPDG software in the Level 1 and Level 3 analysis. They suggest that, for the thicker, 'rutting' sections, the measured strains were between two and three times higher that the computed strains, at both Levels 1 and 3. For the thinner sections the computed strains were closer to the measured strains in some cases, but in many cases were two to three times higher that the measured values. This suggests that the algorithm for computing the response in the MEPDG model should be revised and further validated. The under-prediction of strains can results in under-designed pavement structures.

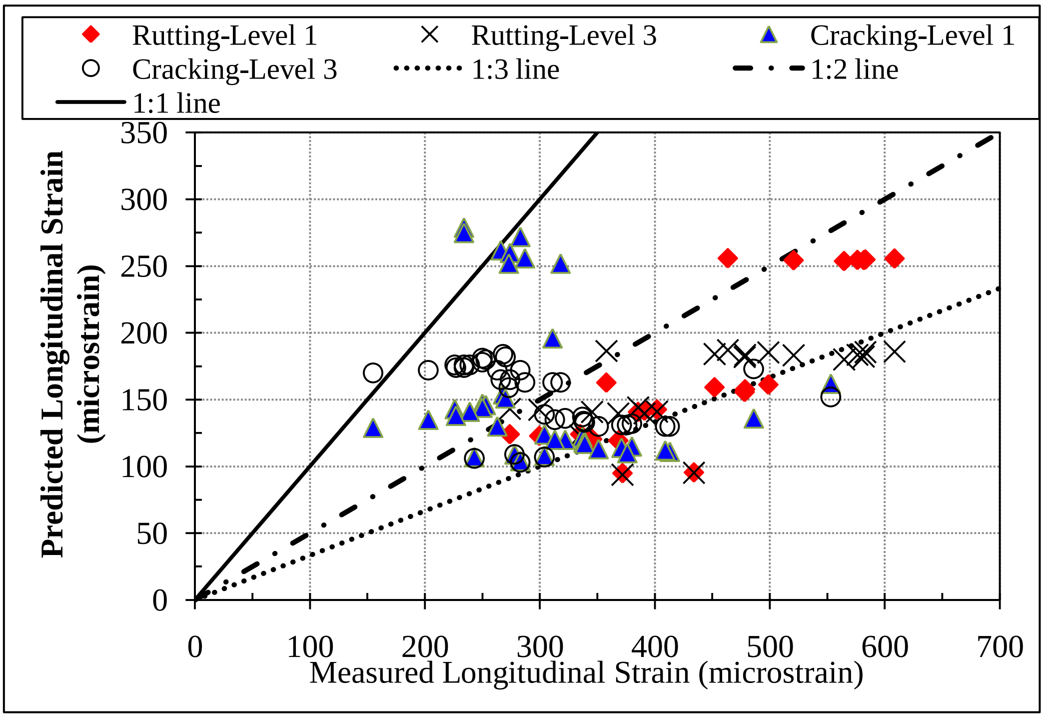

Figure 2: Measured and Computed Longitudinal Strains – 'Rutting' Sections

3.4 Verification of Permanent Deformation Prediction Model

The APT experiment allows the evaluation of the model for predicting the permanent deformation in the flexible pavement structures. For each experimental section, measurements of the permanent deformation recorded by the Single Layer Deflectometers (SLD) and of three transverse profiles were conducted periodically during the APT testing.

Figure 3 plots the evolution of the total measured and the computed permanent deformation in the Missouri (MO) pavement structures. The R and F that follows the mix code indicate the 'rutting' or the 'fatigue cracking' section for that mix. It can be easily observed from the chart that the permanent deformation predicted by the MEPDG model for Level 1 analysis is always higher that the measured permanent deformation, typically more than twice the corresponding measured deformation. This suggests that the MEPDG model may over-predict the permanent deformation and thus, lead to conservative designs.

At Level 3 analysis, the MEPDG model indicated the same rutting performance for the two Missouri mixes. However, the mix with polymer modified binder (MO1) had a much better performance in the APT rutting experiment than the mix with unmodified binder (MO2). This suggests that the Level 3 analysis cannot capture the effect of binder stiffness on the rutting performance of the mix, especially between unmodified and polymer modified binders, since these mixes had the same aggregate structure.

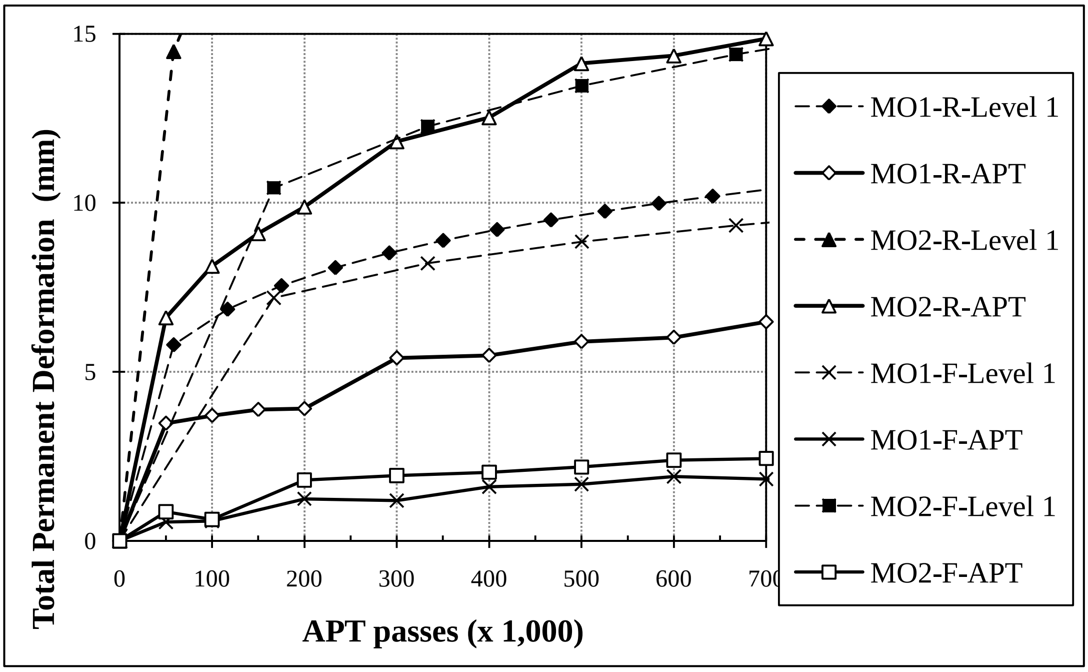

Figure 3: Measured and Computed Total Permanent Deformation in the MO Sections

4 OTHER FINDINGS FROM THE APT EXPERIMENT

4.1 Verification of Mechanistic Models for Permanent Deformation in Asphalt Concrete

The APT experiment offered the opportunity to validate three mechanistic models that estimate the permanent deformation in asphalt concrete layers: the creep, Drucker-Prager, and elasto-visco-plastic models. These models were retained because the laboratory tests they require could be done at Kansas State University and they could be integrated into the Abaqus finite element software (Abaqus, 2004). A detailed description of the FEM model, including model implementation, surface profile calculation using finite elements and laboratory material properties is given by Onyango (2009). The following conclusions were drawn regarding the validation of the permanent deformation prediction models:

- The Drucker-Prager model over-predicted the permanent deformation.
- The elasto-visco-plastic models predicted lower permanent deformations than those measured. The average ratio between the predicted and measured deformations in the asphalt layer ranged from 37% to 58%.
- The average ratio between the permanent deformations predicted by the creep model and measured permanent deformations ranged from 19% to 72%.

4.2 Comparison with Ranking from Laboratory Rutting Tests

The Hamburg Wheel Rut Tester (HWRT), the Asphalt Pavement Analyzer (APA) and the Repetitive Shear at Constant Height (RSCH) tests were conducted to evaluate in the laboratory the rutting performance of the six asphalt mixes. These tests are used by several state agencies in the United States to screen out the mixes with high rutting susceptibility.

A summary of performance ranking of each test is presented in Table 1. The ranking suggests that the results of the Hamburg Wheel Rut Test (HWRT) correlate the best with the results of the APT experiment, followed by those from the APA. A poor correlation can be observed between the results from the RSCH test and the results of the other three tests.

It is important to note here that the conclusions on the comparison with the laboratory rutting tests are valid only for 35°C test temperature since the APT experiment and all the laboratory rutting tests were performed at this temperature to obtain a direct comparison. All three laboratory tests are typically done at higher temperature: HWRT at 50^{o}C and APA at 55^{o}C.

Table 1: Rutting Performance Ranking of the Six Asphalt Concrete Mixes

Mix ID	Repeated load tests, all performed at 35^{o}C				Ranking			
	APT Perm. Def. (mm) @ 100,000 passes	HWRT depth (mm) @ 20,000 cycles	APA depth (mm) @ 8,000 cycles	RSCH g_{perm} (mm) @ 50,000 cycles	APT	HWRT	APA	RSCH
KS-1	4.8	4.69	1.08	0.79	2	4	1	1
KS-2	5.5	4.21	1.59	2.47	3	3	2	6
MO-1	3.7	3.47	1.71	1.72	1	1	3	3
MO-2	8.1	3.96	2.15	1.68	4	2	4	2
IA-1	31.1	10.15	2.27	2.31	6	6	5	5
IA-2	11.8	5.31	3.18	2.03	5	5	6	4

5 CONCLUSIONS AND RECOMMENDATIONS

The paper presents a summary of the research work conducted to validate the response and distress models in the Mechanistic Empirical Design Guide using Accelerated Pavement Testing (APT). Twelve pavement sections were constructed with six different Superpave asphalt mixes. Each section was loaded by an APT machine having a 99.8 kN single axle load. Six sections were tested in a 'rutting' experiment conducted at 35ºC and six sections were tested in a 'fatigue cracking' experiment conducted at 20ºC. The pavements were instrumented with strain gages, stress cells and displacement sensors to measure pavement response under APT loading. An extensive laboratory testing program was conducted to determine the properties of the materials used in the construction of the experimental sections. Simulation of the APT testing was conducted with the MEPDG software for Level 1 and 3 analyses, at 50% reliability level. The materials properties, loading and climatic conditions during the APT test were used in the MEPDG input and the results of the simulations were compared to the results of the APT test.

The major findings of this research work are:

- The revised Witczak model (Bari and Witczak, 2006) predicts with adequate accuracy the dynamic modulus of asphalt concrete mixes at the studied range of loading frequency (0.1 to 25 Hz) and temperatures (20 to 35ºC)**.**
- The MEPDG structural response model under-predicts the longitudinal strains at the bottom of the asphalt concrete layers. The computed strains were two to three times smaller than the measured stresses.
- The MEPDG model predicted higher total permanent deformations than the measured permanent deformations. The model must be revised to avoid over-designed flexible pavement structures.

- The laboratory rutting tests performed at 35°C indicate that the results of the Hamburg Wheel Rut Test (HWRT) correlate the best with the results of the APT experiment, followed by those from the Asphalt Pavement Analyzer (APA).

It is recommended that the MEPDG structural response and performance models be further revised, evaluated and validated with results from instrumented APT and in-service pavement sections since the accuracy of the response model is critical for achieving an efficient design of flexible pavement structures. The detailed database of material properties and response and performance of full-scale asphalt pavement structures under accelerated testing was assembled in this research should be used for the validation of other models for predicting the response and distresses in flexible pavements.

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