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Evaluation and Verification of the VESYS–3–A Structural Design System for Two Test Sites in Nebraska

ROY V. SNEDDON

VESYS–3–A, a mechanistic design system for asphalt pavements, was field verified for three pavement sections at two test sites in Nebraska. Predictions of present serviceability index (PSI) were in good agreement with field measurements for a 20-year-old three-layer pavement located near Elmwood, Nebraska. Field-measured PSI-values for an 8-in. full-depth pavement also agreed with predictions for the study period. Rut depth estimates from the model were small and were in general agreement with field measurements. Cracking estimates were poor and tended to underestimate the time required to develop observable fatigue cracking in the field. Asphalt, base course, and subgrade materials were tested in a 4.0-in.-diameter modified triaxial cell. Dynamic conditioning and rest periods were used to simulate service conditions. Indirect tensile tests of asphalt gave creep compliances and permanent strain parameters similar to those reported in the literature. Indirect tensile test fatigue characterization greatly underestimated pavement fatigue life compared with wheel-tracking test data and back-calculated AASHO Road Test data. Incremental creep tests of unbound materials tended to underestimate permanent strain parameters.

Research efforts in mechanistic design of asphalt concrete pavements have resulted in two computer simulation programs, the FHWA VESYS–3–A and an NCHRP program called PDMAP *(1)*. PDMAP does not appear to have found wide acceptance in either the academic community or at the state DOT level at this time (1985). These programs model the pavement structural system as either linearly elastic or linearly viscoelastic layers composed of materials that have probabilistic characterizations. Traffic volume can vary over time and axle load distributions within the traffic can be simulated. The effect of environmental changes is accounted for by defining temperature "seasons" during which material properties can be changed. The output of a typical pavement simulation run includes the following types of information: *(a)* stresses and strains in the pavement, *(b)* pavement deflections, *(c)* estimates of fatigue cracking, *(d)* rut depths, *(e)* roughness, and *(f)* present serviceability index (PSI).

Department of Civil Engineering, University of Nebraska-Lincoln, Lincoln, Nebr. 68588-0531.

Rationally, such software tools are attractive for pavement management, design, and rehabilitation. Their actual use in a state highway department or DOT, however, must await successful field testing and verification. Field verification of earlier versions of the VESYS model by the state of Utah and other agencies *(2-4)* has produced encouraging results.

In general, pavement materials have been characterized in accordance with methods described by Kenis *(5)* or ASTM *(6)*. The indirect tensile test *(7, 8)* of asphalt has been used in some cases and has the advantages of simplicity and ease of fabrication of test specimens.

The objectives of this study are *(a)* to report the results of field verification of VESYS–3–A for three test sections located in east central Nebraska and *(b)* to describe methods of materials characterization using the indirect tensile test and the triaxial test both of which were performed wholly within a 4.0-in.-diameter triaxial cell.

FIELD VERIFICATION

Test Sections

Three test sections at two different sites were selected by the Nebraska Department of Roads for field verification of the predictive capabilities of VESYS–3–A using criteria developed by the state of Utah *(2)*. These two test sites contain pavement cross sections that are typical of much of the secondary road system in Nebraska. The 3.0-in. pavement section at Site 1 is of special interest because it is representative of thousands of miles of rural Nebraska pavements. Current AASHTO design procedures indicate that such thin sections should perform poorly; however, state experience indicates relatively good performance.

Site 1, called Elmwood-Manley, is a short spur that connects the town of Elmwood and NE–50. Site 2 is located on NE–14 north of Central City, Nebraska. The geographic locations of these sites are indicated by the circular insets in Figure 1.

Site 1 contains two pavement sections, a 3.0-in. section between Mileposts 3 and 7 and a 5.0-in. section between Mileposts 8 and 10. The surficial soil is typically Marshall silty clay loam, an AASHTO A–7–6 soil. These soils mantle the gently rolling farmland typical of this area except near a few creeks and ditches where the soils are of fairly recent alluvial origin. The subgrade is considered well drained and is probably not affected by the groundwater table. A considerable log of performance data is available for this site. Construction was completed in the fall of 1962.

Site 2 is a full-depth asphalt section 8.0 in. thick. The surficial soils are typically of the Lex series and represent poorly drained soils of the bottomland near the Platte River. Their AASHTO classifications are A–6 and A–7. Significantly fewer performance data are available for this site. The pavement was completed in the fall of 1975.

Model Calibration

Austin Research Engineers (ARE) *(9)* was able to develop a good fit between the pavement simulation and data for field performance of I–80N near Snowville, Utah *(2)*; however, asphalt and unbound material property data differed from the original laboratory data. These changes involved a 50 percent reduction in creep compliance in the asphalt as well as 20 percent reductions for the base course and subgrade. Back-calculated fatigue data based on the AASHO Road Test *(9)* replaced Utah's laboratory data. Finally, pavement temperatures were significantly higher than those based on mean ambient temperatures at Snowville corrected for the effect of pavement heating *(10, 11)*.

Pavement material properties determined using the procedures described in the section entitled Materials Characterization required some adjustment to achieve reasonable correlations with field performance. The permanent deformation variable (GNU) was increased to be consistent with values reported by others, and AASHO back-calculated fatigue factors (K_1 and K_2) were also used. To weight the effects of daytime traffic more heavily, mean monthly ambient temperatures were increased 10°F before pavement temperature was determined. A similar approach was used by Thower *(12)*. Early simulation runs predicted fatigue failures in the 3.0-in. pavement in 2 years, a time completely inconsistent with field experience. Therefore the ZCRACK depth was changed from 3.0 to 2.30 in. thus reducing the values of radial strain used in predicting fatigue failure. These adjustments were made to obtain good predictions of PSI and resulted in generally satisfactory performance of the model in predicting cracking and rut depth as described later. The final values for all input variables for each test section as they were input to the model can be found elsewhere *(13)*.

Results

PSI is the principal tool used in determining need for rehabilitation of asphalt pavements in Nebraska and thus the primary basis on which satisfactory model performance was judged. Pavement evaluations are principally based on road meter data

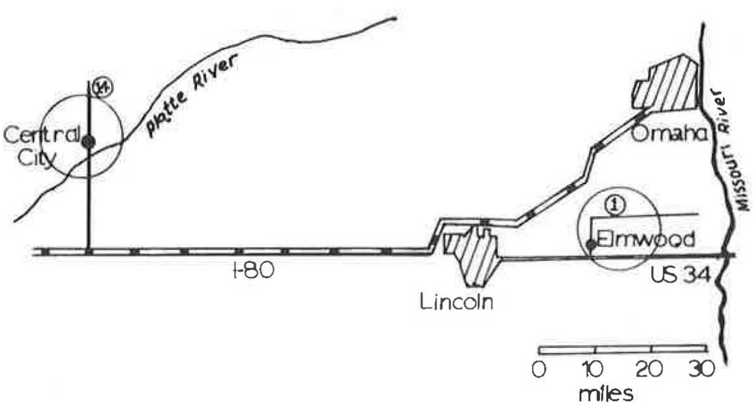

FIGURE 1 Location of test sections.

supplemented by rut depth measurements and crack surveys. Predicted PSI as a function of time is plotted for each test section in Figures 2–4. A band representing the 95 percent confidence level of the predictions is also shown as an aid to interpretation. Plotted on these same figures are mean PSI values based on field measurements. One standard deviation of the field data is plotted as a vertical line above and below a data point. Good correlation between the model and field data is indicated in all cases. The "kink" in the model prediction for Site 1, which occurs in 1974, corresponds to rapid increases in predicted fatigue cracking and appears to match field behavior.

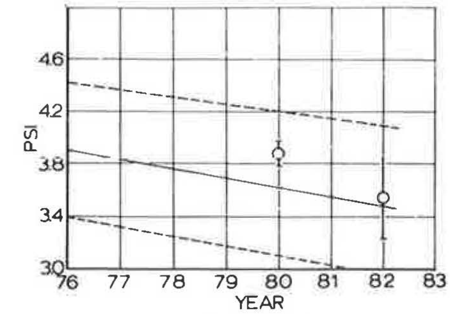

FIGURE 4 Predicted and measured PSI, Central City.

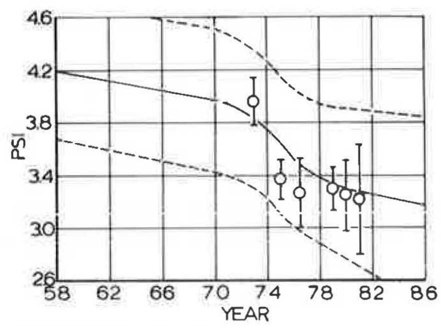

FIGURE 2 Predicted and measured PSI, Elmwood 3-in. section.

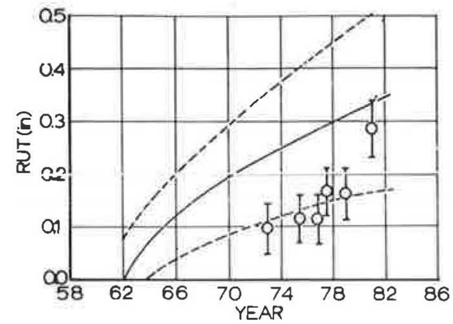

FIGURE 5 Predicted and measured rut depth, Elmwood 3-in. section.

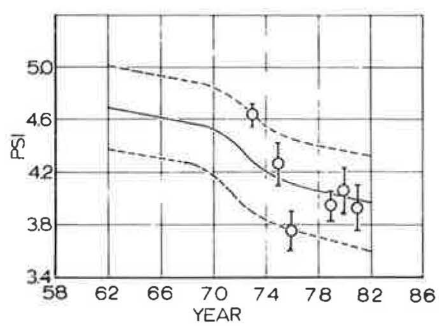

FIGURE 3 Predicted and measured PSI, Elmwood 5-in. section.

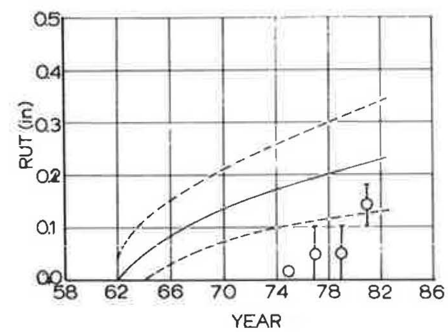

FIGURE 6 Predicted and measured rut depth, Elmwood 5-in. section.

Rut depth predictions are plotted in Figures 5–7 together with the 95 percent confidence level band. Measured rut depths and their standard deviations are plotted for comparison. The model generally overpredicts rut depth when input data are chosen to "best fit" PSI. It should be noted that, with the exception of data for Site 1 in 1981, rather crude techniques are used to measure rut depth. Because both the measured and the predicted rut depths are small, however, the model predictions are considered reasonable. It is possible to further improve the model's performance by slight adjustments of GNU and α, which control the accumulation of the plastic strain developed after each axle load.

Previous attempts at field verification of the predicted extent of fatigue cracking have generally been poor. The results shown plotted in Figures 8–10 are slightly better. Using ZCRACK = 2.30 improved the prediction for the 3.0-in. pavement at Site 1. The predicted values are reasonable; however, the 5.0-in. section is poor. No cracking is predicted by the model for Central City and very little was found; however, because only 7 years of simulation and field experience are involved at Central City, no definitive conclusion can be drawn.

Field cracking estimates are difficult to make. During site inspections many areas thought to be uncracked were found to be cracked when examined with a magnifying glass. Verification of cracking suffers from model, laboratory-testing, and field-measuring deficiencies. Laboratory testing exhibits the single greatest deficiency.

CHARACTERIZATION OF MATERIALS

Practical implementation of mechanistic design in a state DOT requires significant simplification and speedup of materials-testing procedures. The repeated load, indirect tensile test

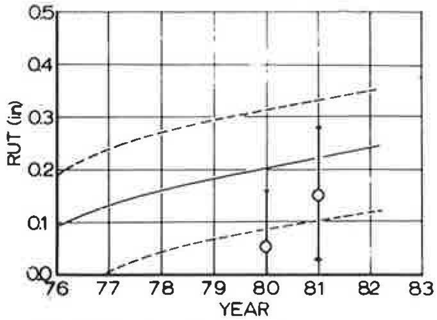

FIGURE 7 Predicted and measured rut depth, Central City.

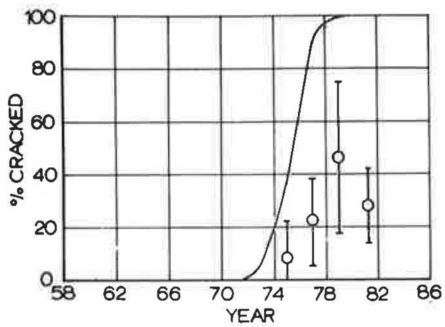

FIGURE 8 Predicted and measured cracking, Elmwood 3-in. section.

(7, 8, 14) using Marshall test specimens was selected for characterization of bituminous mixtures. It represents a good compromise between simplicity and incorporation of field loading conditions. Marshall samples were tested in a modified 4.0-in.-diameter triaxial cell that also acted as a temperature-controlled bath (±0.2°F) during testing. The 8.0-in. × 4.0-in.-diameter samples of the base course and subgrade were tested in the same cell. A pneumatic servo-controlled loading system was used for all materials testing *(13)*.

Pretest Dynamic Conditioning of Asphalt Samples

The use of static creep compliance data in field verification of VESYS has been questioned. Predicted field cracking and rutting are often much larger than predicted by the model *(2, 15)*. During sensitivity analysis ARE *(15)* suggested and

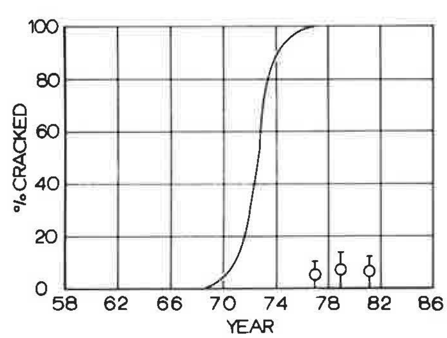

FIGURE 9 Predicted and measured cracking, Elmwood 5-in. section.

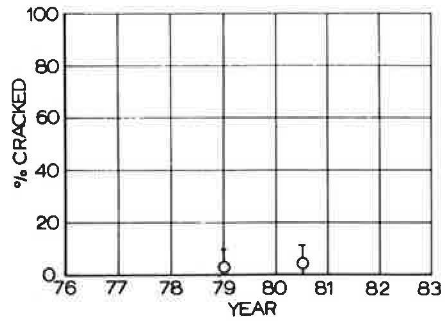

FIGURE 10 Predicted and measured cracking, Central City.

verified that dynamic conditioning before the static creep test would decrease creep compliance and thus improve these predictions. Furthermore, the inverse of creep compliance after conditioning was found to approximate the resilient modulus when the loading time was between 50 and 100 msec.

Another example of the need for conditioning is the test results from VESYS–3–A. Utah test data *(2)* for I–80N (Snowville) were used for initial familiarization runs with the model. Snowville climatological data for the study period were used to obtain pavement temperature estimates. Model predictions greatly overestimated measured rut depths and fatigue cracking. In a subsequent familiarization run, results were significantly improved when creep compliances of the asphalt were reduced 50 percent. ARE calibrations of VESYS–3 *(9)* produced good comparisons with field measurements. However, ARE departed significantly from the laboratory data reported by Utah as well as from Snowville climatological data. These results indicate the importance of conditioning when using laboratory test data as well as the potential of the model to predict field performance.

A conditioning effect was found for two Marshall specimens formed from Nebraska Type-B mix. The dynamic moduli for the two tests were 250,000 and 500,000 psi, an increase from 100,000 psi. The values of dynamic modulus for the conditioned specimens were consistent with values reported in the literature *(15)*.

Rest periods increase fatigue life up to a ratio of rest period to load duration of 10 *(16)*. Therefore the dynamic conditioning adopted for testing sought to incorporate this finding. The load duration used was 50 msec, which represents the integrated effects of truck speed and truck length. However, the respone of the pneumatic controller was such that the rest period-to-load duration ratio obtained experimentally was only 9. Typically, 15,000 cycles of haversine conditioning load with a 50-msec load duration and a 450-msec rest period were used.

Measurement of Creep Compliance

In a viscoelastic material at constant stress, strains increase over time at a decreasing rate. Therefore creep compliance can be considered the inverse of Young's modulus at various times of loading (t). Using this definition, creep compliance of a Marshall sample can be shown to be given by *(13)*

$$D(t) = C \cdot Y(t)/P \quad (1)$$

where

$Y(t)$ = vertical deformation at time t,
P = vertical load,
C = 0.693 when $\nu = 0.0$, and
C = 0.698 when $\nu = 0.5$.

Before they were tested all samples were sealed in microcrystalline wax to prevent climatic conditioning *(17)*. A sample was then conditioned with 15,000 cycles of 100-lb haversine loading at a temperature of 70°F. The sample was then held at a constant small seating load and brought to the final test temperature before creep compliance was measured. Samples were tested at 100°F, 70°F, and 50°F using 1,000-sec square-wave pulse loads of 33, 100, and 300 lb, respectively, in accordance with generally accepted procedures *(1, 6, 9)*.

Permanent Deformation Properties

An alternative to dynamic testing for the determination of permanent deformation properties *(5, 18–21)* is an incremental static creep test. The creep test procedure offers the potential for multiple tests on a single sample at different temperatures as well as reduced testing times; it was therefore used in this study.

Specimens were dynamically conditioned at 70°F before the incremental static creep test. After conditioning, samples were brought to the specified test temperature and a square-wave pulse was applied and held for 100 msec. The load was then removed and the permanent horizontal and vertical deformations were recorded after 2 min of rebound. This same process was repeated for load duration times of 1 sec and 10 sec. The 100-sec and 1,000-sec tests were given 4 min of rebound before the plastic deformation was recorded. Data from the incremental creep test were reduced in accordance with procedures given elsewhere *(13, 18, 19)*.

Fatigue Properties

Laboratory fatigue tests have been used to estimate the fatigue life of asphalt pavement in several studies *(2, 8, 15, 16)*. However, in general the predicted fatigue life greatly underestimates the measured field performance. Various reasons have been suggested for the observed differences [e.g., *(a)* failure to include the effect of rest periods *(16;* 22, p.176; *23)*; *(b)* lateral distributions of wheel loadings across the pavement *(16, 23, 24, 25)*; *(c)* inappropriate testing technique for the application such as controlled stress, controlled strain *(16)*; *(d)* time required for crack propagation *(26, 27)*; *(e)* temperature effects *(12, 16)*; and *(f)* convergence problems in the mathematical model *(28)*].

Wheel-loading tests *(25)* and a reevaluation of the AASHO Road Test fatigue data *(15, 29)* have also been used in drawing these conclusions. Finn *(30)* indicated that it was necessary to adjust laboratory constant strain fatigue data 10- to 13-fold to achieve correlation with AASHO Road Test fatigue data. Brown and Pell *(31)* suggest a fatigue design curve displaced from the laboratory curve that gives fatigue lives 20 times laboratory values determined from controlled stress tests.

Using Dijk's work *(16, 26)*, multipliers of fatigue life to account for these affects are rest periods (6 to 10X), lateral distribution of wheel loads (2.5X), and time required for crack propagation (3 to 5X). Therefore adjustments ranging from 45 to 125X are possible. Ullitdz *(27)* allowed a factor of 100 for the effect of rest periods and the time for crack propagation.

The samples used in fatigue tests were conditioned at the fatigue test temperature and at load levels that would have a neglible effect on expected fatigue life. However, the ratio of rest period to load duration was maintained at 9 as in creep testing. Response time of the loading system limited the maximum loads that could be applied in 50 msec for various load shapes. To obtain the maximum dynamic loads, square-wave loading was used rather than haversine loading. This difference in load mode should have a minimal effect on fatigue life.

Laboratory results from the indirect tensile test *(3, 8)* are typically expressed in terms of tensile strain at the center of the sample after 200 load cycles. In the fatigue test series, 200 cycles were counted after 15,000 cycles of conditioning load were applied. The tensile strain was estimated from the resilient modulus measured at 200 cycles using an assumed value of Poisson's ratio of 0.4 based on the work of Vila and Terrel *(17)*.

Simulation Requirements of Unbound Materials

The dynamic properties of unbound materials (i.e., base course and subgrade soil) used in a simulation of the as-built pavement system are influenced by the following factors: *(a)* thixotropy, *(b)* method of compaction, *(c)* confining pressure, *(d)* magnitude of applied stress difference, *(e)* long-term in situ unit weight and water content, *(f)* intrinsic properties such as granulometry and plasticity, and *(g)* as-constructed variability. Therefore, in developing methods for materials characterization, each factor should be considered in a rational way during sample preparation and testing.

Seed et al. *(32)* tested AASHO Road Test subgrade soils using field cores and laboratory-compacted samples. The effects of thixotropy were removed after 40,000 cycles of loading. Modulus of resilience also stabilized after 200 load repetitions and remained essentially constant up to 100,000 cycles of loading. Resilient moduli measured on field-compacted cores taken from untrafficked loops and laboratory kneading-compacted samples compared favorably. Samples from the trafficked loops also agreed well, but the resilient strains were less than for kneading-compacted samples.

Confining pressures within the pavement section are produced by superposition of the lateral components of overburden and axle loads. Typical triaxial confining pressures used are 3.0 psi for subgrade soil and 8 to 10 psi for base course materials *(2, 5)*.

The stress difference (deviator stress) produced by axle loads decreases with depth through the pavement section and depends to some degree on the stiffness of the overlying materials. A precise determination of the amount requires a computer model of the pavement and the surface loading. This can be readily done using VESYS. However, typical values suggested are 20.0 psi for base course and 6.0 psi for subgrade soil.

Chu et al. *(33)* suggested allowing laboratory-prepared samples to come to equilibrium with a simulated in situ water table. This procedure reproduces normal ambient moisture conditions rather than the much more severe soaking or saturated conditions sometimes advocated.

Subgrade materials selected for testing should represent the range of possible plasticity and grain size distributions in the study area. This will provide a range of material responses and thus bound the simulation. Because VESYS requires the expected mean and variance of as-built material responses, Kenis *(5)* suggests building in variability during sample compaction.

Preparation, Conditioning, and Testing of Samples

Samples 8.0 × 4.0 in. in diameter were prepared by kneading compaction to moisture contents and dry unit weights representative of field-measured, as-constructed, dry unit weights and water contents and their standard deviations. Field water table conditions were produced in some of the samples tested following the procedure of Chu et al. *(33)*. The rest of the samples were tested in an as-compacted condition.

The effects of thixotropy were removed by conditioning all samples with 50,000 cycles of haversine stress equal to the test stresses given in Table 1. After conditioning, creep compliance was determined following the procedures suggested by Kenis *(5)*. An incremental static creep test *(5, 18)* was used to determine α and GNU, the permanent deformation properties.

TABLE 1 TRIAXIAL TEST STRESSES FOR UNBOUND MATERIALS

Sample Type	Confining Stress (psi)	Conditioning Stress (psi)	Stress Difference (psi)
Subgrade	3.0	6.0	6.0
Base course	10.0	20.0	20.0
	8.0	20.0	20.0

Test Results

Asphalt creep compliances for Elmwood and Central City together with those for AASHO Test Section 266 and I–80N in Utah are given in Table 2. The values of D(t) obtained for conditioned asphalt samples from Elmwood and Central City are quite similar to those found by others *(2, 14)*. However, the AASHO data were determined using dynamically conditioned triaxial samples. The Utah tests were on unconditioned samples using the indirect tensile test. Compliances for the unbound materials are quite similar in all cases.

Table 3 gives a comparison of α- and GNU-values determined in the study and those found by others. Test results for Elmwood using incremental creep tests on conditioned, indirect tensile samples compare well with those of the repeated load tests reported for tests when the number of cycles of loading is less than 100,000. The Brampton test for 300,000 to 700,000 cycles is significantly different. The increase in GNU and, to a lesser degree, in α is significant. This has been reported *(14)* and was the basis for adjusting these values by ARE. Increasing them alters the VESYS model response. Rut

TABLE 2 COMPARATIVE CREEP COMPLIANCES OF BOUND AND UNBOUND MATERIALS ($psi^{-1} \times 10^{-5}$)

	Load Duration (sec)					
Source	0.001	0.01	0.10	1.0	10.0	100.0
Asphalt						
AASHO No. 266	0.065	0.12	0.33	0.80	1.50	2.60
Utah I–80N	–	0.38	0.54	0.78	1.09	1.61
Elmwood	0.21	0.34	0.55	0.90	1.45	2.30
Central City	0.021	0.095	0.18	0.36	0.70	1.40
Subgrade and Base Course						
AASHO No. 266						
Base	–	3.30	–			
Subgrade	–	14.0	–			
Utah I–80N						
Base	–	13.7	–			
Subgrade	–	7.32	–			
Elmwood						
Base	–	3.60	–			
Subgrade	–	3.70	–			
Central City						
subgrade	–	3.03	–			

Note: Dashes = data not applicable.

TABLE 3 COMPARATIVE PERMANENT DEFORMATION PARAMETERS α AND GNU FOR BOUND AND UNBOUND MATERIALS

Source	Material	Test Type	α	GNU
Asphalt				
AASHO No. 266 *(15)*	Cores	RLT	0.67	0.16
Brampton *(15)*	–	RLT		
10,000–30,000 cycles			0.61	0.076
300,000–700,000 cycles			0.90	0.51
Utah I–80N *(2)*	6.5% asphalt/gravel	RLT	0.52	0.064
Elmwood	4% asphalt/gravel	IT–IC	0.576	0.048
Subgrade and Base Course				
AASHO No. 266 *(15)*	Base course	RLT	0.93	2.65
	Subgrade	RLT	0.63 to 1.0	<0.1
I–80N Utah *(2)*	Base course	RLT	0.743	0.065
	Subgrade	RLT	0.635	0.040
Elmwood	Base course	T–IC	0.593	0.0004
	Subgrade	T–IC	0.479	0.0031
Central City	Subgrade	T–IC	0.459	0.0026

Note: RLT = repeated load triaxial, IT–IC = indirect tensile incremental creep, T–IC = triaxial incremental creep, and dash = data not available.

depths increase during the early years, but the rate of increase is less at later times, which improves the model's long-term predictive capacity although short-term rut depths are overestimated. Short-term overestimates of rut depth are also shown in Figures 5–7. GNU-values for the unbound Elmwood and Central City base course and subgrades are approximately one order of magnitude too small. These samples were all dynamically conditioned before testing, which significantly reduces the incremental strains observed at load times less than 100 sec. This substantially decreases GNU because it is initial strain dependent.

Interpretation of the fatigue characterizations (K_1 and K_2) given in Table 4 is much less clear. The Elmwood data are similar to Pell's data for a rotating beam test. K_1 is much smaller than the back-calculated AASHO data that are considered to represent a low fatigue life mix. The wheel-tracking data that are thought to best represent actual field performance have large values of K_1. Strains in the Elmwood samples were estimated at 200 cycles using dynamic modulus values. This probably contributed to a substantial reduction in K_1. Adedimila and Kennedy *(8)* used static moduli in their fatigue strength characterizations based on indirect tensile tests. The effect of crack propagation time is only included in the wheel-tracking tests. In conclusion, present laboratory tests are indicative of mix quality but do not appear to provide reasonable parameters for the VESYS model.

CONCLUSIONS

VESYS–3–A predicted PSI in three pavements with good agreement between field-measured values and model predictions when the depth of cracking (ZCRACK) was reduced. A comparison of field-measured rut depths and the simulation from the model is reasonable. Rut depths estimated early in the pavement's life exceeded measured values. Fatigue-cracking estimates were in fair agreement with field data. However, the AASHO Road Test back-calculated values of K_1 and K_2 can be used on an interim basis for Nebraska Type-B mixes.

Ambient temperatures were increased 10°F before pavement temperatures were estimated in order to weight daylight traffic's contribution to pavement damage more heavily. The sensitivity of the model to pavement temperature suggests the need for a data base of pavement temperatures in Nebraska.

Although satisfactory model predictions resulted from using Nebraska's W–4 tables for the three test sites evaluated, these data should be improved. The VESYS–3–A damage models are extremely sensitive to the heavier axle loads in the traffic load distribution.

The materials characterized had creep compliances in agreement with values found in the literature. Plastic strain characterizations α and GNU were reasonable for the asphalt tested. The values of GNU were too small for the base course and subgrade soils tested. Dynamic conditioning possibly reduced the initial plastic strains thus decreasing GNU. Fatigue factor K_1 was somewhat smaller than expected, possibly because of the small strains computed when the dynamic modulus was used to estimate the strain after 200 load cycles. Wheel-tracking test data or AASHO-estimated fatigue values should be used in the VESYS–3–A model in the interim.

Characterization of Nebraska pavement materials requires additional research effort to enlarge the data base. α and GNU for unbound materials from incremental static creep tests require further evaluation to improve GNU data. Repeated-load creep tests may be required. The indirect tensile fatigue test is not expected to provide good VESYS–3–A input data but can be used rationally to improve mix design.

TABLE 4 COMPARATIVE FATIGUE VALUES (K_1 AND K_2) FOR DIFFERENT TESTING METHODS

Source	Material	Test Type	K_1 STRNCOEF	K_2 STRNEXP
Shell *(25)*	California medium crushed aggregate	WTT	8.8×10^{-4}	2.64
ARE *(15)*	AASHO Road Test	Back-calculation	6.18×10^{-13}	5.00
Washington	AC	BF	6.52×10^{-5}	2.50
Monismith in Adedimila and Kennedy *(8)*[a]	40–50 penetration asphalt/granite	BF	1.03×10^{-10}	4.01
Utah I–80N, Anderson et al. *(2)*	6.5% asphalt/gravel	IT	0.349	1.55
Pell *(8)*[b]	7.7% asphalt	RB	2.5×10^{-17}	5.8
ARE *(8)*[c]	6% asphalt	IT	9.3×10^{-11}	3.49
Elmwood	4% 100–120 penetration/gravel	IT	1.16×10^{-18}	5.81

Note: WTT = wheel tracking, BF = beam flexure, RB = rotating beam, and IT = indirect tensile.

[a]68°F.

[b]50°F.

[c]75°F.

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Thickness Design for Flexible Pavement: A Probabilistic Approach

K. P. George and S. Husain

The thickness design procedure presented in this paper makes use of the concepts of limiting subgrade strain to control permanent deformation and limiting tensile strain in the asphalt layer (or limiting tensile stress in the cement-treated layer, if applicable) to control fatigue cracking. The input variables such as traffic load, ambient temperature, and subgrade resilient modulus are considered stochastic. The design nomographs incorporate reliability in design (50, 65, 80, and 95 percent), which is a unique feature of the method adopted here. Design nomographs are prepared for structural sections that consist of an asphalt concrete surface and a base of the designer's choice (asphalt treated, dense-graded aggregate, or cement treated) placed directly on the subgrade. A rational method for selecting asphalt grade is an integral part of the design procedure. The asphalt selection criteria dictate the use of relatively low-stiffness bituminous mixtures in cold climates and high-stiffness mixtures in hot climates. The region-to-region modulus variation, however, is accounted for by the judicious use of a multiplying factor that would transform the nomograph thickness to the "true" design value. To assess the reasonableness of the proposed procedure, the design thickness has been compared with that of the revised AASHO guide and with the Thickness Design Manual (MS-1) of the Asphalt Institute.

Department of Civil Engineering, The University of Mississippi, University, Miss. 38677.

The concept of structural design of asphalt pavements that employs mechanistic models and uses the fundamental properties of the pavement materials is no longer new to pavement technologists. The mechanistic concept of pavement analysis has become a powerful tool for researchers and is being increasingly recognized by design engineers as well.

Fatigue cracking and subsequent loss of performance, permanent deformation, and low-temperature cracking in pavement systems are topics of major concern. Fatigue cracking in asphaltic or granular-base pavement is attributed to the development of tensile strains that, when repeatedly applied,