

WESTRACK—THE ROAD TO PERFORMANCE-RELATED SPECIFICATIONS

by

**J. A. Epps – University of Nevada, Reno
R. B. Leahy – Oregon State University
T. Mitchell – Federal Highway Administration
C. Ashmore – Nevada Automotive Test Center
S. Seeds – Consultant
S. Alavi – Nichols Consulting Engineers, Inc.
C. L. Monismith – University of California, Berkeley**

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WesTrack – THE ROAD TO PERFORMANCE-RELATED SPECIFICATIONS

WesTrack is a multimillion dollar accelerated pavement testing facility located approximately 100 km (60 mi) southeast of Reno, Nevada. Sponsored by the Federal Highway Administration and the National Cooperative Highway Research Program, the WesTrack project has two primary objectives: to continue the development of performance-related specifications for hot mix asphalt; and to provide early field verification of Superpave volumetric mix design. To that end 34 test sections were evaluated during the application of nearly 4.8 million ESALs. Performance monitoring was supplemented by two comprehensive laboratory testing programs: quality control/quality assurance testing; and performance testing with primary emphasis on permanent deformation and fatigue cracking. Although the performance related specification has not yet been finalized its conceptual framework and system components, including pay factors, are discussed. The WesTrack project has demonstrated the importance of supplementing full-scale testing and performance monitoring with a comprehensive laboratory testing program of component materials and analysis of pavement response to develop a performance related specification with realistic pay factors for hot mix asphalt. The paper concludes with a summary of “lessons learned” on the following topics: pavement construction; use of the ignition oven for quality control/quality assurance purposes; driverless vehicle operations; and rehabilitation techniques.

INTRODUCTION

WesTrack, a multimillion dollar accelerated pavement test facility, is located on the proving grounds of the Nevada Automotive Test Center (NATC) in the Carson River Valley approximately 100 km (60 mi) southeast of Reno, Nevada. The project, sponsored by the Federal Highway Administration (FHWA) and The National Cooperative Highway Research Program (NCHRP), has two primary objectives:

- continue the development of performance-related specifications (PRS) for hot mix asphalt (HMA) pavements by evaluating the effect of materials and construction quality control (asphalt content, aggregate gradation, in-place air void content, etc.) on pavement performance; and
- provide early field verification of the Strategic Highway Research Program (SHRP) Superpave HMA mix volumetric design procedure.

The track is a 3 km (1.8 mi) oval track, a schematic of which is shown in Figure 1. Thirty-four test sections have been evaluated including the 26 original sections (Figure 1) and 8 replacement sections.

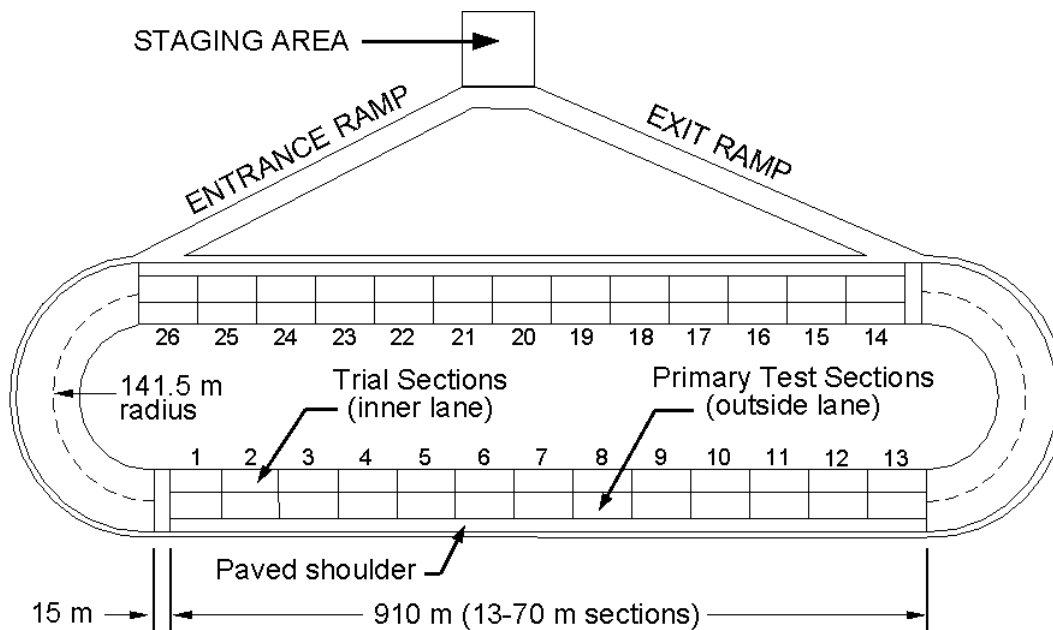


Figure 1 Layout of Test Track (not to scale)

Construction of the initial 26 sections was completed in October 1995 and trafficking, using driverless trucks, began in March 1996. In May 1997, after the application of nearly 2.8 million ESALs, excessive rutting and fatigue cracking forced replacement of 8 of the original 26 sections, and are referred to as the “replacement” sections. References (1 and 2) contain a more detailed description of the section properties and construction details.

This paper briefly describes various aspects of this accelerated pavement testing program including operation of driverless vehicles and vehicle operating costs, framework for a performance-related specification (PRS) including pay factors, performance test results and their use in performance prediction models, and a summary of lessons learned from a program of this scope.

MATERIALS, TEST SECTIONS AND PERFORMANCE MONITORING

For all test sections, original and replacement, mix variables included asphalt content, aggregate gradation and as-constructed air void content. An overview of the materials used is summarized in Table 1. Shown in Figure 2 are the aggregate gradations. More detailed information on material properties may be found elsewhere (1, 2).

TABLE 1 Aggregate and Binders Used in WesTrack Test Sections

	Original Test Sections	Replacement Test Sections
binder grade and source	PG 64-22 West coast	PG 64-22 Idaho
aggregate source and gradations	Quarry near Dayton, Nevada (partially crushed fluvial deposit) Sand from Wadsworth, Nevada coarse, fine and fine-plus	Quarry near Lockwood, Nevada (crushed andosite) Sand from Wadsworth, Nevada coarse

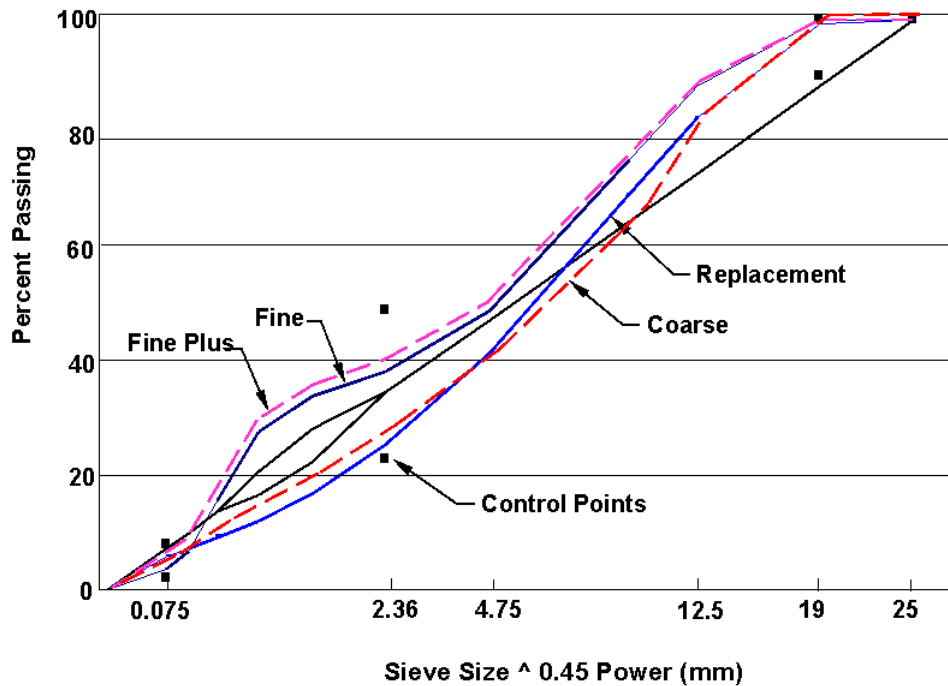


Figure 2 Mix Target Gradations

As noted previously, 26 sections were included in the original construction. Job mix formulae (JMF) were determined in accordance with Superpave mix design guidelines (3,4). The binder content for the fine-plus gradation was the same as that for the fine gradation though it contained 2 percent more bag house fines. The design asphalt content for each mix was designated the “medium”, with binder contents ~ 0.7 of the “medium” designated as “high” and “low”. Three levels of in-place air void content were selected: 4 percent, “low”; 8 percent, “medium”; and 12 percent, “high”. The resulting experiment design is shown in Table 2. Note that there were 5 replicate sections in the original construction and 1 replicate section in the replacement construction. Replacement sections are shown in parentheses.

TABLE 2 Experiment Designs Westrack Sections

Design Air Void Content	Aggregate Gradation Designation								
	Fine			Fine Plus			Coarse		
	Design Asphalt Contents								
	Low	Opt.	High	Low	Opt.	High	Low	Opt.	High
Low		04	18		12	09/21		23 (39)	25 (55)
Medium	02	01/15	14	22	11/19	13	08 (38)	05/24 (35, 54)	07 (37)
High	03/16	17		10	20		26 (56)	06 (36)	

Shaded area denotes cells not filled

Pavement Structural Section

The structural pavement section for WesTrack consisted of 150 mm (6.0 in.) of asphalt concrete compacted in two 75 mm (3.0 in.) thick lifts; a 150 mm (6.0 in.) thick dense-graded crushed aggregate base course; 300 mm (12.0 in.) of engineered fill; and a silty clay subgrade which had been scarified and recompacted to provide a relatively uniform layer. It was anticipated that this structural section would carry nearly 3.3 million ESALs before failing in fatigue.

Traffic Loading

Traffic loads were applied using four driverless tractor/triple-trailer combinations. Axle loads of 88.9 kN (20,000 lb) were utilized resulting in about 10.5 ESALs per truck passage. The trucks were equipped with 700 kPa (100 psi), 295/75R 22.5 radial tires and operated at a speed of 64 km/hr (40 mph). Instrumentation on the trucks provided continuous information for many of the trucks' operating characteristics including fuel consumption and tire pressure. Traffic wander, an integral part of the accelerated loading, is illustrated in Figure 3.

Performance Monitoring

Performance monitoring consisted of the following: visual distress surveys, transverse surface profile measurements, deflection measurements, longitudinal profile determinations, and measurements of surface friction characteristics.

The distress surveys and profile measurements were performed at 2-week intervals while the deflection measurements were obtained at 4-week intervals using a falling weight deflectometer (FWD).

A Long-Term Pavement Performance (LTPP) weather station on-site was used to collect information on temperature, frost penetration, and moisture content of unbound pavement layers.

MATERIALS CHARACTERIZATION

Extensive testing of the component materials and HMA was conducted prior to and during construction as well as throughout traffic loading. Although quality control/assurance testing was a major concern, the discussion herein is limited to that associated with performance, specifically moisture sensitivity, low temperature cracking, fatigue cracking, and permanent deformation.

Moisture Sensitivity

At the outset of the project it was decided to treat all mixes with hydrated lime to preclude or minimize water sensitivity problems. As AASTHO T283 is included in the Superpave mix design protocol, a subset of WesTrack mixes was evaluated with this protocol. Field cores taken immediately after construction (FMFC) as well as field-mixed lab-compacted (FMLC) and lab-mixed lab compacted (LMLC) samples were tested. Seventeen of

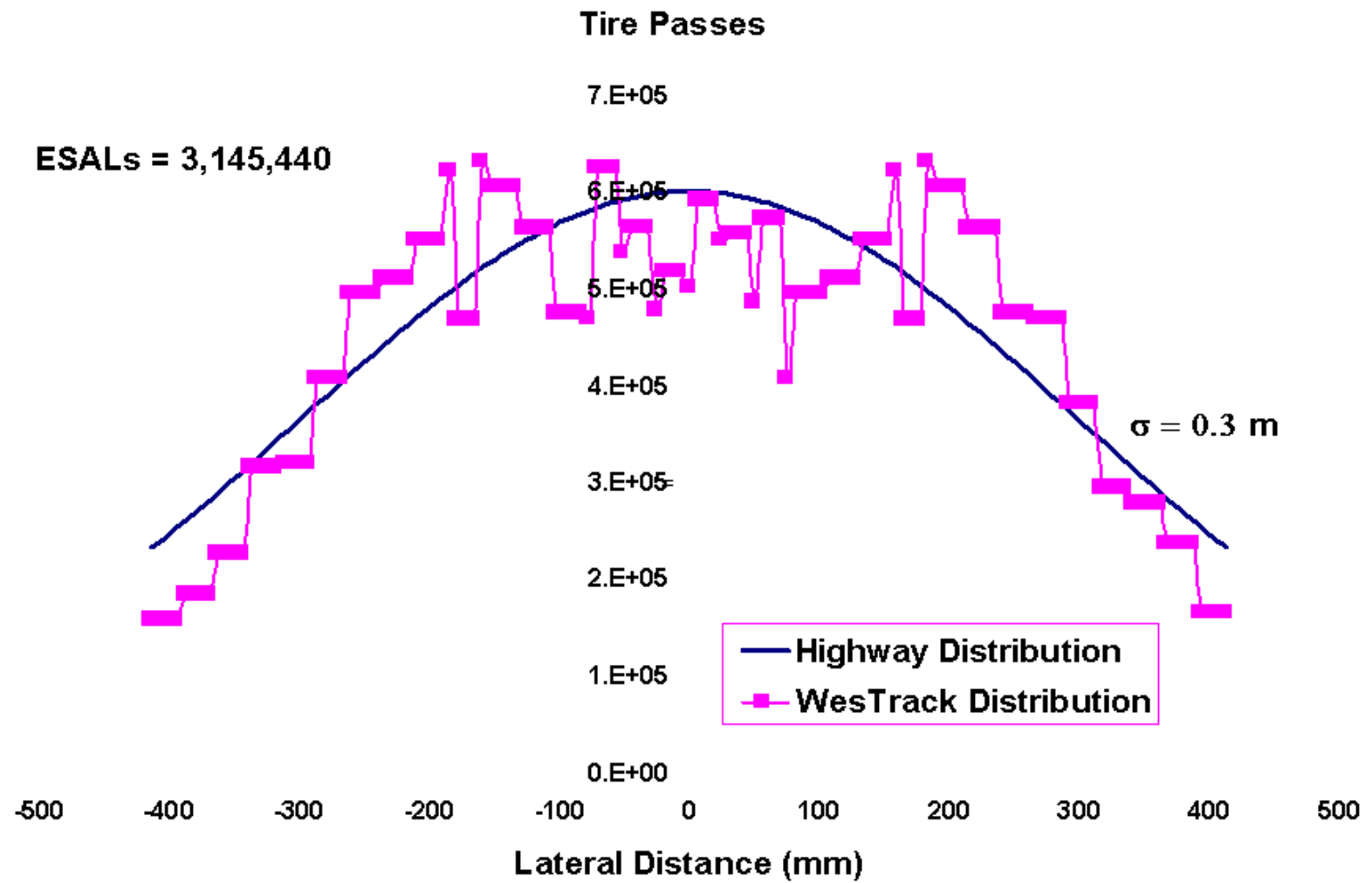


Figure 3. Distribution of Tire Passes for WesTrack @ 3,145,440 ESALs

the 34 mixes failed to meet the recommended tensile strength ratio (TSR) of 0.80, indicating that moisture damage, i.e., stripping, might be a problem. Typical data are shown in Figure 4. Thus far, no surface raveling attributed to moisture has been observed at WesTrack. Clearly, this raises concern as to the validity of the test and/or the recommended test criteria. Extensive research conducted as part of NCHRP project 9-13 tends to reinforce this concern as to the effectiveness of AASHTO T283. As to the PRS, moisture sensitivity will most likely be addressed in terms of material selection rather than in performance prediction.

Low Temperature Cracking

A similar approach was taken for low temperature cracking, i.e., by carefully selecting the materials, in this instance the binder, one might preclude or minimize low temperature cracking. Based on historical temperature data at the test site a PG 64-22 was selected. As was the case for moisture sensitivity, samples from several sources, FMFC, FMLC and LMLC, were tested using two methodologies: the Superpave indirect tensile creep and strength tests; and the thermal stress restrained specimen test (TSRST) (6,7). Typical results from the TSRST are shown in Figures 5 and 6. As shown in Figure 5, fracture temperatures, with few exceptions are equal to or less than -22°C , the low temperature grade of the binder. Similar results for short- and long-term aged LMLC samples are shown in Figure 6. Earlier research has shown that reducing the cooling rate from 10°C (that used in the lab) to 1°C (that recorded in the field) may reduce the fracture temperature by as much as 5°C . Thus, the data presented in Figures 5 and 6 provide reasonable assurance of the mixes' resistance to low temperature cracking to a temperature of -22°C . The lowest temperatures recorded at the site were -16°C and -10°C , air and pavement at a 25 mm (1 in) depth, respectively, both of which are well above the low temperature grade for the binder.

Fatigue

Flexural fatigue tests have been performed on beam specimens sawed from slabs obtained from the original and reconstructed sections. In this test, beam specimens 62.5 mm (2.5 in) wide, 50 mm (2.0 in) high, and 380 mm (15.0 in) long are loaded in four-point bending at a frequency of 10 Hz. Test temperatures for the test series ranged from 5° to 30°C with the bulk of the testing performed at 20°C .

To define the relative effect of mix variables on laboratory fatigue performance, equations of the following form were fit to the test data:

$$\ln N_f = f(V_{\text{air}}, P_{\text{asp}}, P_{200}, \bar{\epsilon}_t, T) \quad (1)$$

where:

N_f	=	load applications to a 50 percent reduction in flexural stiffness
V_{air}	=	air void content, percent
P_{asp}	=	asphalt content, by weight of mix
P_{200}	=	percent passing 0.075 mm (No 200) sieve
$\bar{\epsilon}_t$	=	tensile strain, repeatedly applied mm/mm
T	=	test temperature, $^{\circ}\text{C}$

Results of the analysis suggest that the effects of air void content and asphalt content on fatigue performance are considerably greater than that of aggregate gradation as measured by the percent passing the 0.075 mm sieve. The effect of aggregate gradation was more pronounced for the coarse mixes than for the fine and fine-plus mixes.

Although linear regression was used for the laboratory test data, it was not appropriate for analysis of fatigue cracking in-situ, because of sample bias. For the field data, two models were developed: a probit model for crack initiation and a continuous model for crack propagation in which the dependent variable is the expected value of wheel path cracking. It should be emphasized, however, that the effects of mix variables on field performance are similar to those observed for the laboratory flexural fatigue tests.

Results of both the laboratory test program and the analysis of the field data will be used to develop performance models. These developments are discussed in a subsequent section.

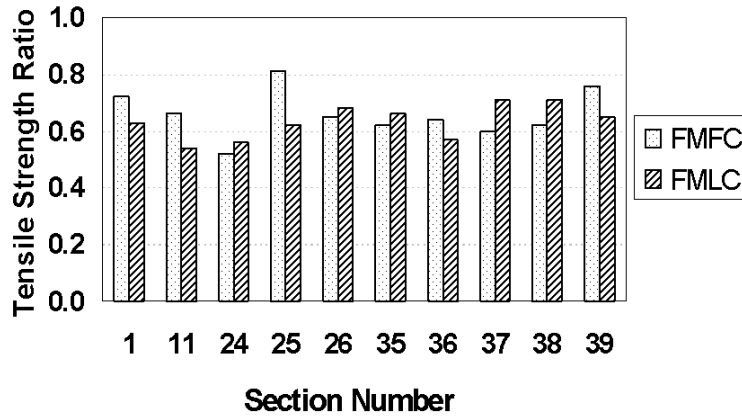


Figure 4. Moisture Sensitivity Test Results

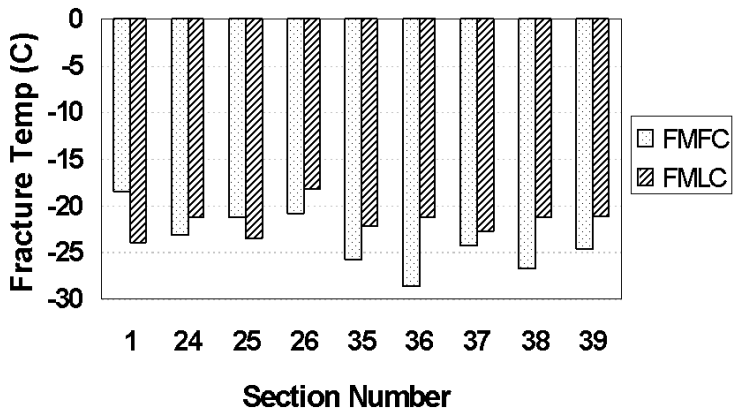


Figure 5. Low Temperature Cracking Test Results, Field Mixed Specimen

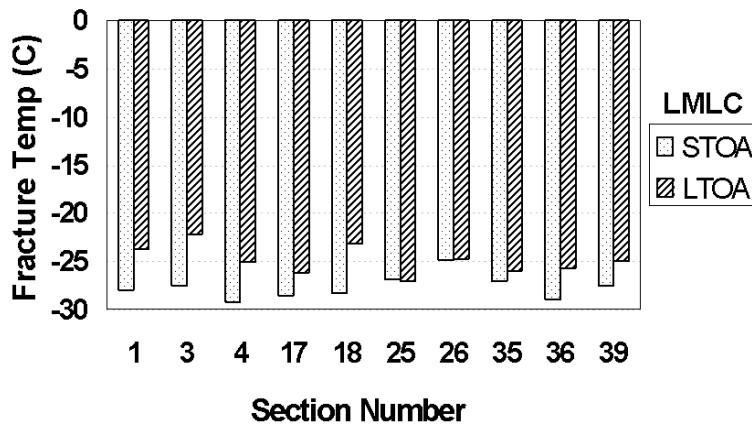


Figure 6. Low Temperature Cracking Test Results, LMLC Specimens

Permanent Deformation/Rutting

Permanent deformation characteristics of the various mixes have been measured on FMFC and LMLC specimens at this time. A limited test series is planned for FMLC specimens later in the test program. Tests have been performed at 40°, 50° and 60° on LMLC specimens. The SHRP developed simple shear test (9) has been used with the shear stress repeatedly applied while the specimen is maintained at constant height. This test is termed the repeated simple shear test at constant height (RSST-CH). For the test results reported herein, a shear stress of 70 kPa (10 psi) has been used with a time of loading of 0.1 sec applied as a haversine waveform and a time interval between loadings of 0.6 sec. A total of about 5000 shear stress repetitions is applied unless the specimen reaches a permanent shear strain of five percent prior to this number. Typical test results are shown in Figure 7.

As with the fatigue cracking investigations, direct regressions have been used to quantify the influence of mix variables on observed rutting. Both the results of the regression analyses of the field data and the results of the laboratory shear tests on the FMFC specimens are being used to develop performance models.

FRAMEWORK, PERFORMANCE-RELATED SYSTEM

The conceptual framework of the PRS is shown in Figure 8. Components of the system include the following: test procedures and sampling plans, performance prediction models, maintenance and rehabilitation decision trees, a life cycle cost (LCC) model, stochastic variability considerations, and pay factors. In the following narrative two key aspects of the PRS are addressed: development of the models for fatigue and permanent deformation, and use of these performance prediction models to develop pay factors. Note that these are only a part of the overall PRS. Figure 9 illustrates the process used to develop pay factors considering these two aspects of mix performance.

PERFORMANCE PREDICTION

While the effects of water sensitivity and low temperature cracking are of significance, the mixes at WesTrack were designed, as noted earlier, to eliminate or minimize these effects. Accordingly this section briefly describes factors needed only for predicting fatigue cracking and rutting.

Fatigue Cracking

Two models are being evaluated for fatigue cracking. One is based on a regression analysis between material properties and field performance. The other makes use of a mechanistic-empirical analysis to predict performance based on laboratory measured fatigue response and stiffness of the pavement layers.

Regression Model

The regression model, as noted earlier, consists of two parts; one to reflect crack initiation and the other, crack propagation.

For crack initiation a probit model is used. This type of model has been selected since it permits the use of observed field performance data for all 26 test sections. In the model the dependent variable is the indication of cracking termed INDCR. For each condition survey if cracking is observed, INDCR = 1; otherwise it has a zero value.

The model has the following form:

$$Prob (INDCR = 1) = f (ESALs, P_{asp}, V_{air}, P_{200}) \quad (2)$$

Figure 10 illustrates the probability of cracking in the section containing the mixes with the fine grading.

For crack propagation a continuous regression model is utilized in which the dependent variable is the expected value of wheel path cracking (CRX), that is:

$$E = [\log(CRX) | INDCR = 1] \quad (3)$$

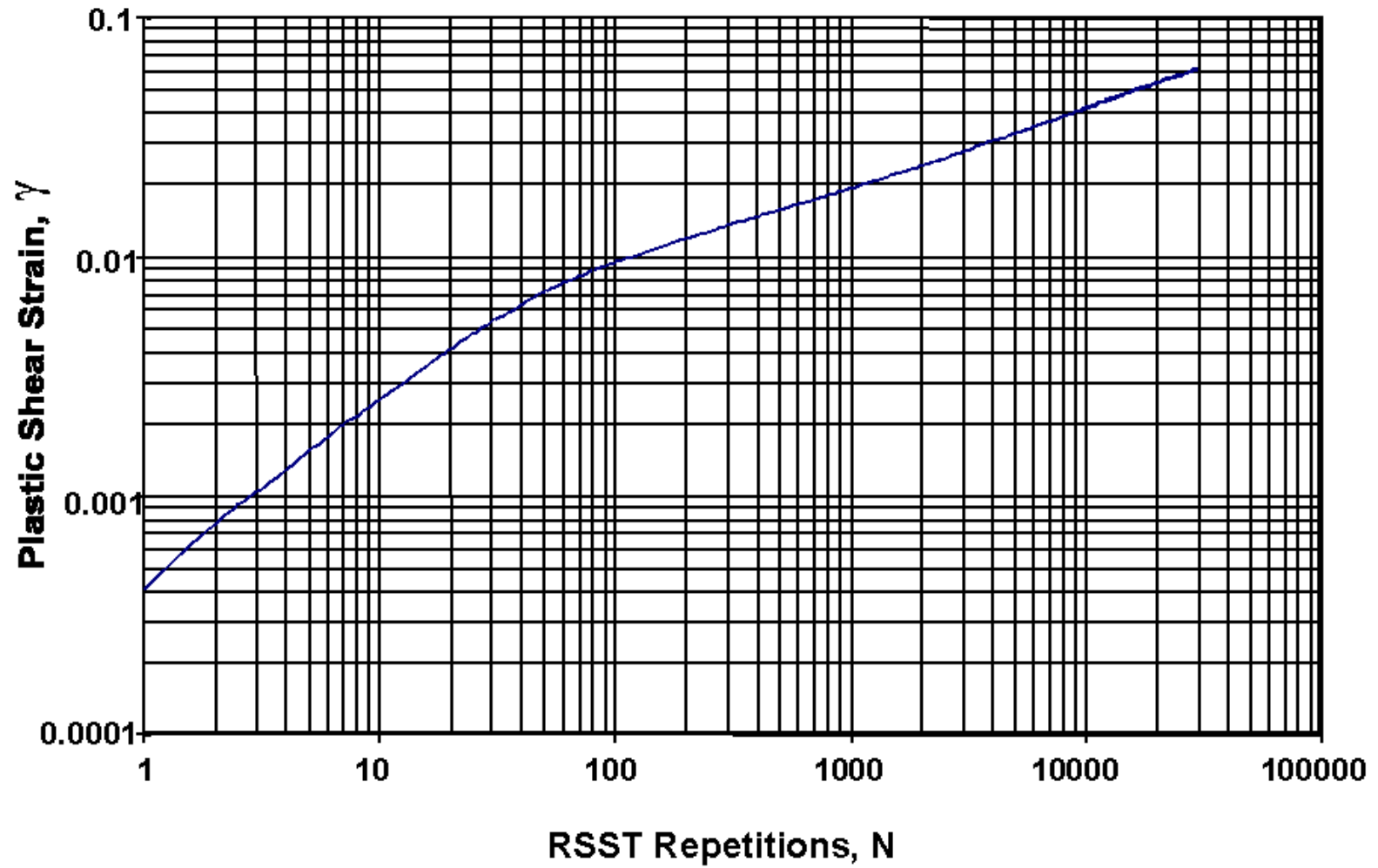


Figure 7. Results of the RSST-CH Performed at 50°C on a Specimen Obtained from the Top Lift of Section 2

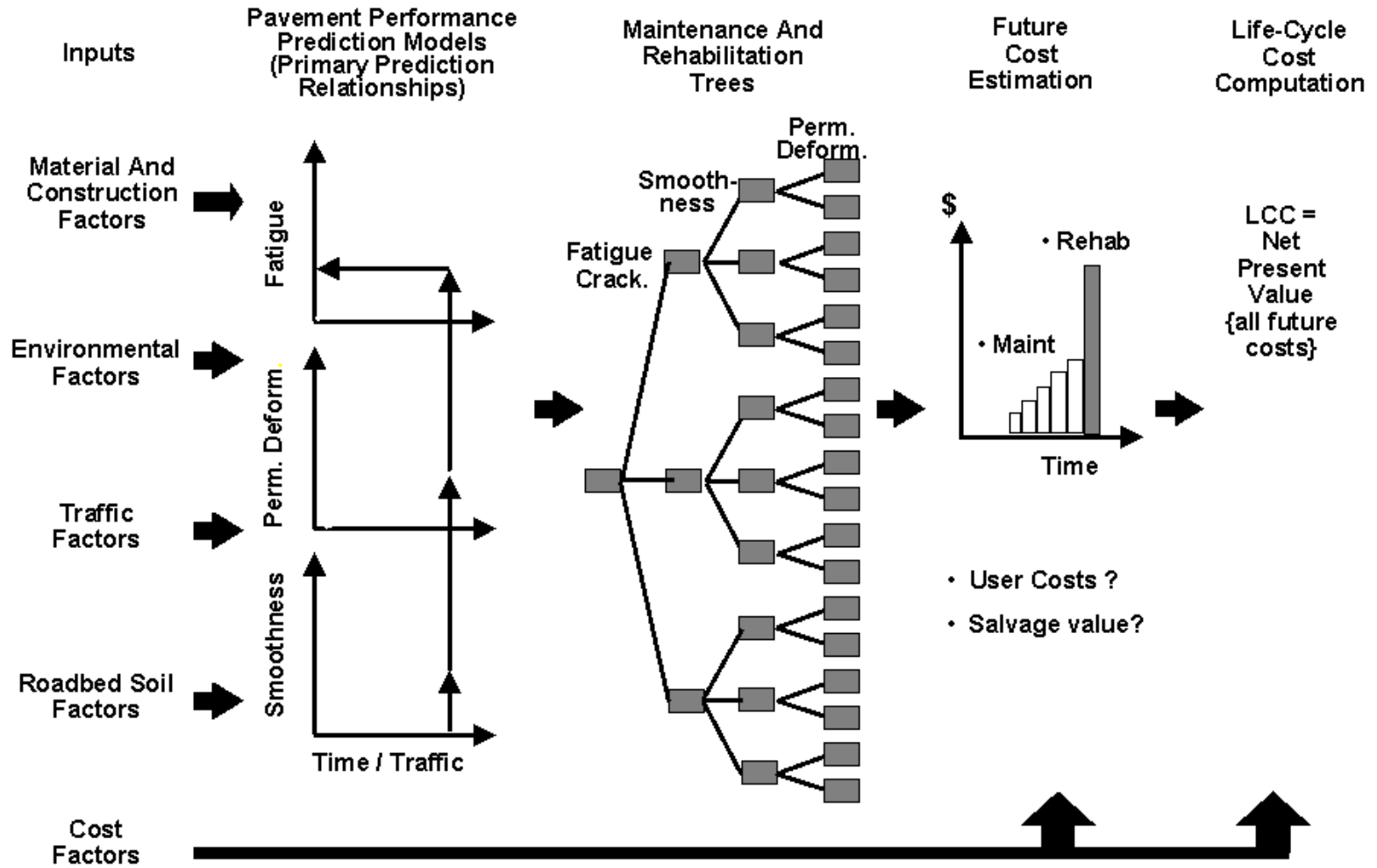


Figure 8. Framework for Performance-Related System

Framework for PRS

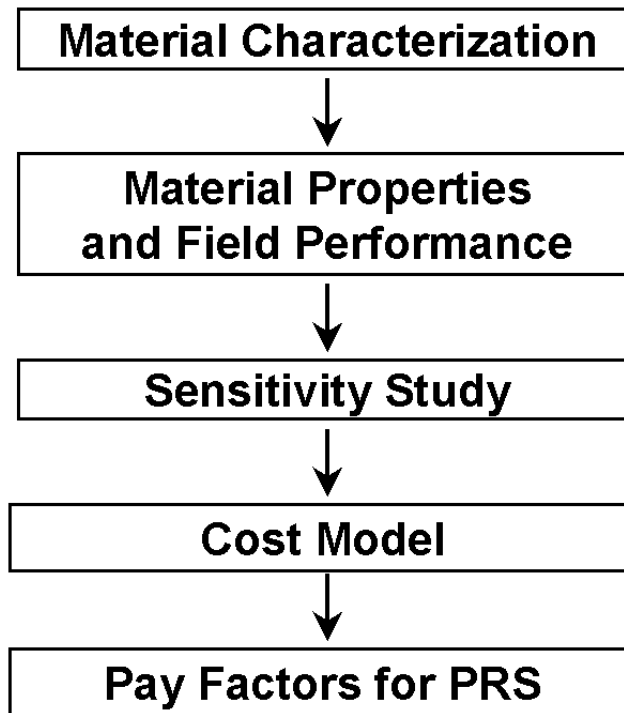


Figure 9. Example of a Framework for the Development of Pay Factors

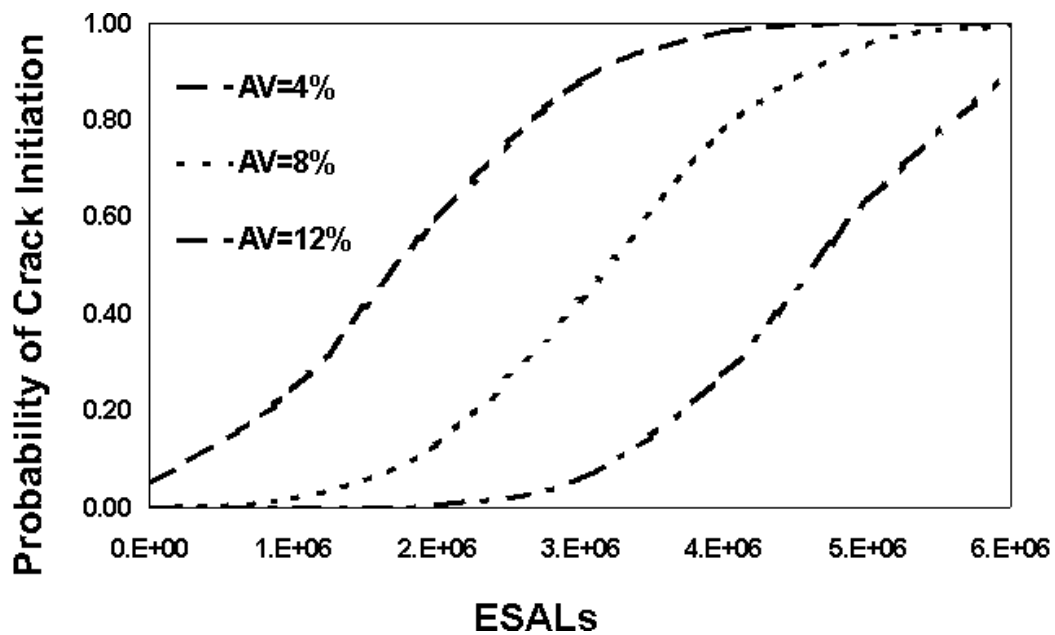


Figure 10. Probability of Crack Initiation vs ESALs, Fine Mix; $P_{asp} = 5.4$ percent, $P_{200} = 5$ percent

This equation is a function of the same variables as the model for crack initiation and includes a correction term for selectivity bias.

Analyses are currently underway using these models to determine pay factors considering the effects of asphalt content, degree of compaction, and aggregate gradation.

Mechanistic-Empirical Model

Predicted responses of the WesTrack pavements to traffic loading are also being determined using multilayer elastic analyses. The pavement structure representative of the WesTrack pavement is shown in Figure 11. Representative moduli are based on FWD measurements as well as on laboratory determined stiffness values. To reflect the effects of temperature variations with depth in the asphalt concrete, this layer is subdivided into three layers and the modulus is determined from the expression:

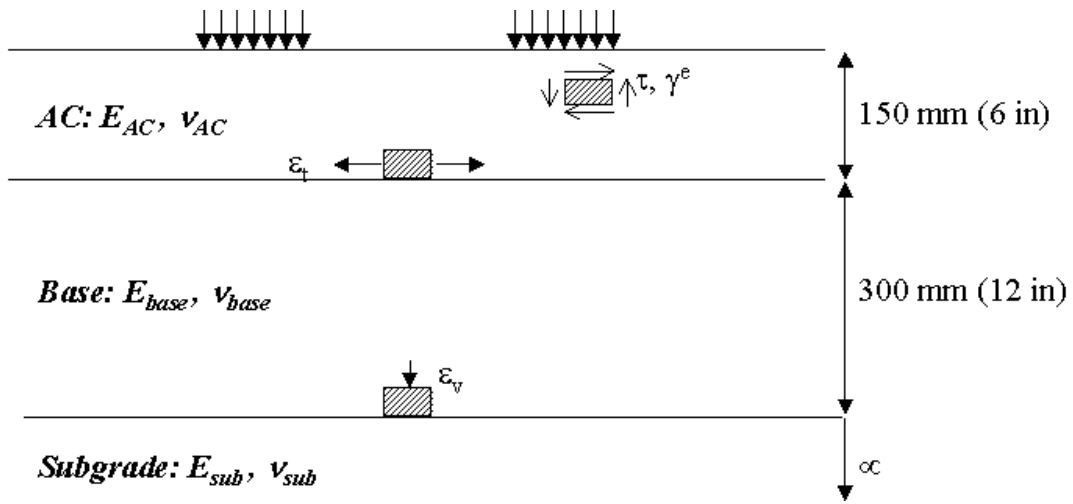


Figure 11. WesTrack Pavement Representation for Mechanistic-Empirical Modeling

$$E_{AC} = \exp(A_0 + A_1 \cdot T) \quad (4)$$

where:

A_0 = value determined from flexural fatigue tests

A_1 = value determined from FWD measurements

T = pavement temperature

In the analyses completed thus far, the modulus of the granular base is assumed to be constant throughout the year (based on FWD measurements). Moduli of the engineered fill and foundation soil (subgrade) are determined from the expression obtained from FWD measurements:

$$E_{\text{subgrade}} = D_0 + D_1 \sin(\text{day} - D_2) / 365 \cdot 2\pi \quad (5)$$

where:

D_0, D_1, D_2 = calibration coefficients

day = day of the year

Figure 12 illustrates the variation of the subgrade stiffness for the south target for a one year period. The continuous curve depicts equation (5) while the data points represent FWD determined values. The north target values follow the same pattern but the stiffnesses are greater than those for the south target.

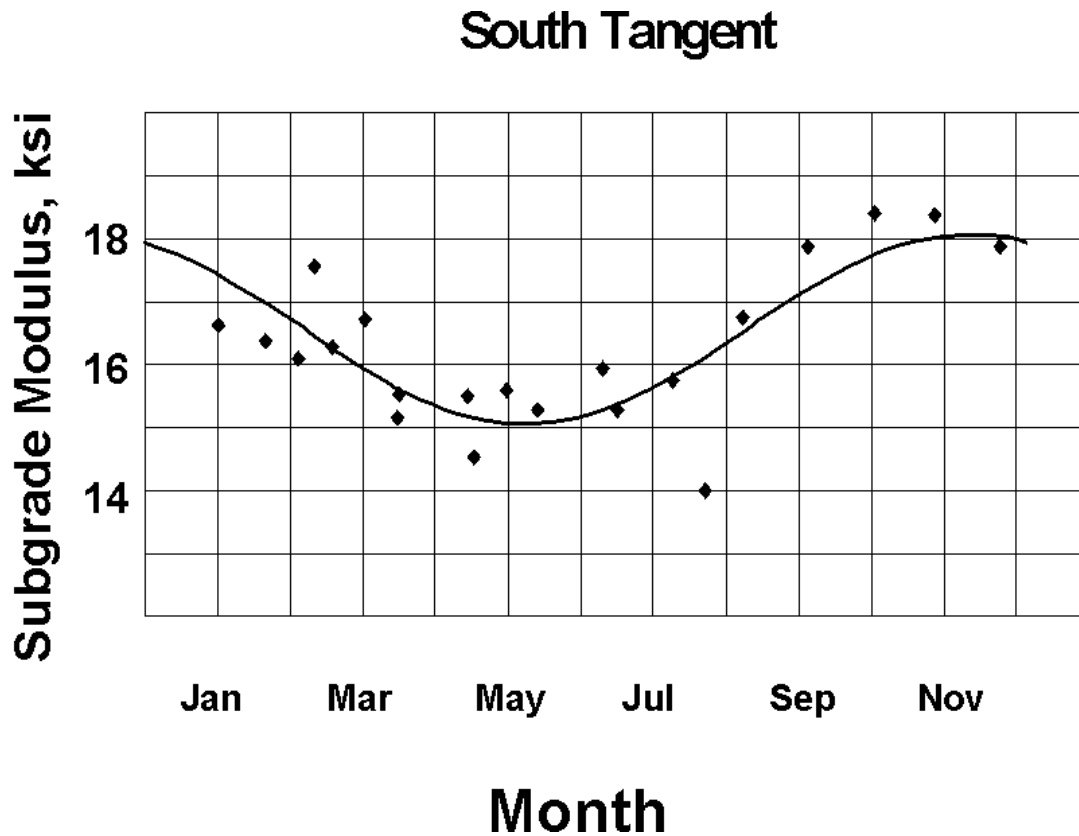


Figure 12. Variation in Subgrade Stiffness Over a One Year Period; South Tangent, WesTrack

The approach to predict fatigue cracking is summarized in references (10,11). The system specifically considers the mean and variance of the following mix construction quantities: asphalt content, air void content, and AC layer thickness. Results of WesTrack also will allow aggregate gradation effects to be included if determined to be a factor. Damaging strains under traffic loading are determined using multilayer elastic theory. The performance model computes the distribution of pavement fatigue lives using a Monte Carlo simulation.

The Monte Carlo process is outlined schematically in Figure 13. Central to this process is the random selection of air void content, asphalt binder content, and asphalt concrete thickness for each simulation. Although not shown in Figure 13, a random selection is also made of the foundation modulus representing the composite effects of base, and underlying layers in an “equivalent” two-layer system.

These random selections assume normally distributed random variables with known or assumed means and variances. Of particular significance are the variances that might be expected under normal construction operations. Estimates of these variances were obtained from several sources: literature review, moduli back calculations from FWD measurements, and data collected as part of the WesTrack project (11).

A multilayer elastic program is used to simulate the stress and strain states within the simulated pavement structures. Loading consists of a dual-tire assembly representative of the trucks used at WesTrack. Stiffness and fatigue response for mixes in each of the test sections has been developed for use in the analyses.

Each Monte Carlo simulation produces an independent estimate of the laboratory fatigue life, N . The corresponding simulated in-situ life, *in-situ reps*, is computed by applying a shift factor, SF , and a conversion factor, CF , representing the combined effects of temperature and subgrade stiffness variations as follows:

$$\text{In-situ reps} = (N \cdot SF) / CF \quad (6)$$

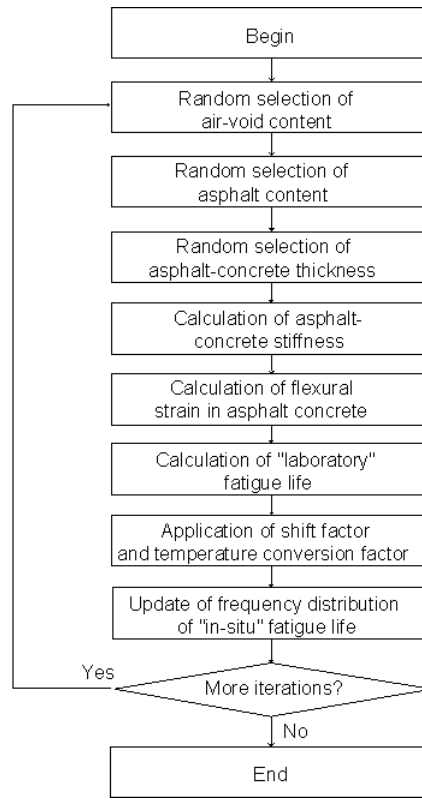


Figure 13. Outline of Fatigue Performance Simulation

The shift factor is an empirically derived factor that accounts for differences between the laboratory and the in-situ pavement in the rate at which fatigue damage accumulates with each load application. Observed cracking in the various test sections will permit the development of this factor for the WesTrack environment.

Permanent Deformation

A series of models are being evaluated for rutting including the following:

- relationship between material properties and field performance using a direct regression between mix properties (asphalt content, air void content, aggregate grading) and traffic (ESALs) to a specific rut depth.
- mechanistic-empirical analysis and performance prediction using:
 - model coefficients developed from measured rutting and RSST-CH test data
 - model coefficients developed from measured rutting and mix properties
 - model coefficients developed exclusively from RSST-CH test data

Regression Model

For the direct regression, an expression of the following form has been used:

$$\ln(ESALs_{0.40}) = a_0 + a_1 P_{asp} + a_2 V_{air} + a_3 P_{asp}^2 + a_4 \cdot V_{air}^2 + a_5 \cdot P_{asp} \cdot V_{air} + a_6 \cdot fines + a_7 \cdot finesplus + a_8 \cdot coarse \quad (7)$$

where:

$ESALs_{0.40}$ = number of ESALs to a rut depth of 10 mm (0.4 in.) and the terms fines, fines plus and coarse assume values of 1 when sections containing specific mix are analyzed, and 0 otherwise.

For example, equation (7) reduced to:

$$\ln(ESALs_{0.40}) = 48.19 - 9.43P_{asp} - 0.169V_{air} + 0.639P_{asp}^2 \quad (8)$$

for the fine gradation with an $R^2 = 0.993$ at a significance level of 0.05. This equation is shown graphically in Figure 14.

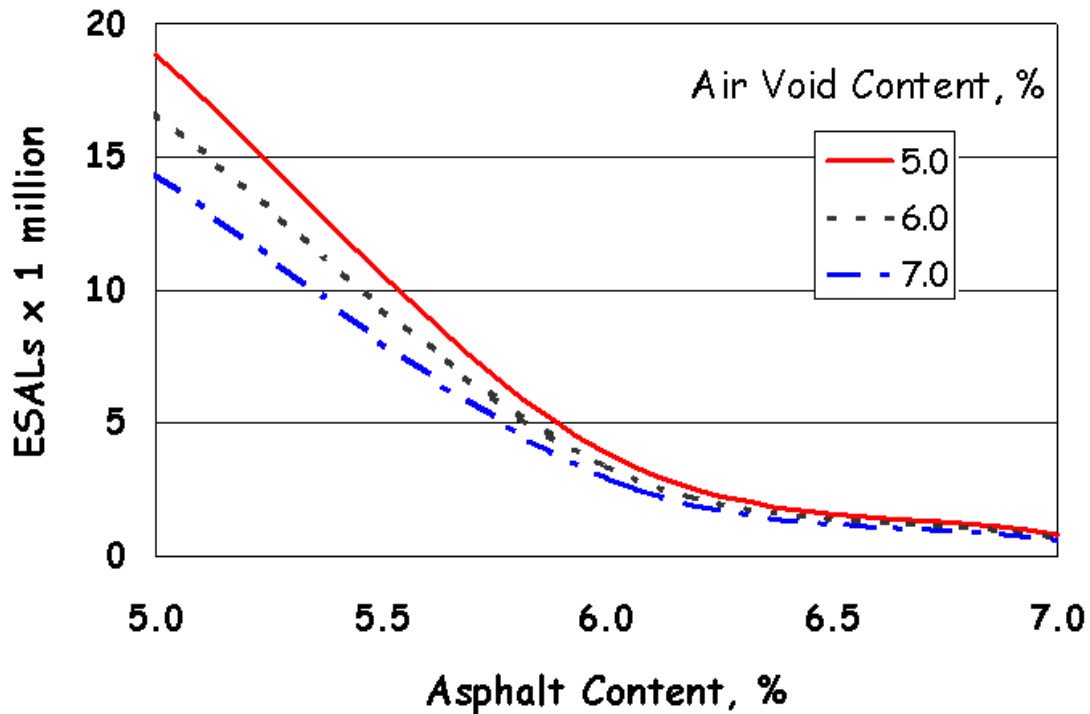


Figure 14. Relations Between ESALs to 10 mm (0.4 in.) Rut Depth, Asphalt Content, and Air Void Content, Fine Gradation

Mechanistic-Empirical Model

In the mechanistic-empirical modeling, rutting in the AC is assumed to be controlled by shear deformations. Computed elastic shear stress and strain (τ , γ^e) at a depth of 50 mm (2 in.) beneath the edge of the tire are used for rutting estimates (9), Figure 11. Densification of the asphalt concrete is excluded in the rutting estimates since it has a comparatively small influence on surface rutting.

In simple loading, permanent shear strain in the AC is assumed to accumulate according to the following expression:

$$\gamma^i = a \cdot \exp(b\tau) \gamma^e n^c \quad (9)$$

where:

γ^i = permanent (inelastic) shear strain at a 50 mm (2 in.) depth

- τ = shear stress determined at this depth using elastic analysis
 γ^e = corresponding elastic shear strain
 n = number of axle load repetitions
 a, b, c = regression coefficients

The time-hardening principle is used to estimate the accumulation of inelastic strains in the asphalt concrete under in-situ conditions. The resulting equations are as follows:

$$a_j = a \cdot \exp(b\tau) \gamma_j^e \quad (10)$$

$$\gamma_1^i = a_1 [\Delta n_1]^c \quad (11)$$

$$\gamma_j^i = a_j [(\gamma_{j-1}^i/a_j)^{(1/c)} + \Delta n_j]^c \quad (12)$$

where:

j is the j^{th} hour of trafficking

γ_j^e is the elastic shear strain at the j^{th} hour, and

Δn_j is the number of axle load repetitions applied during the j hour.

The concept is illustrated schematically in Figure 15.

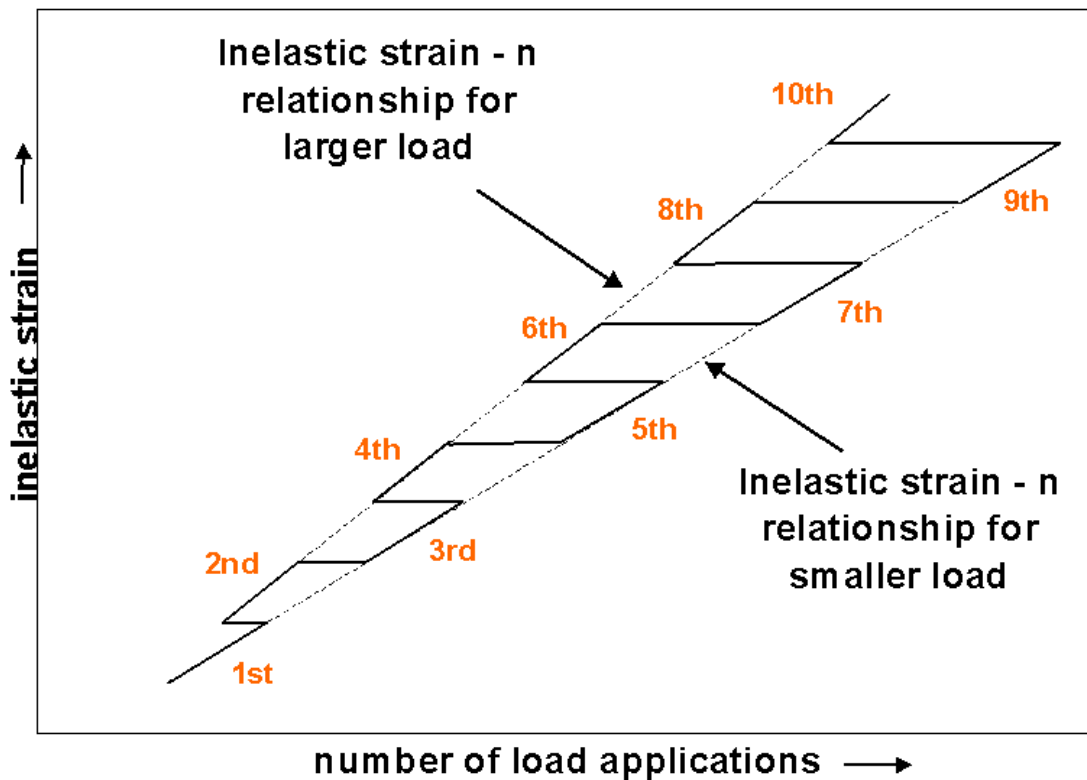


Figure 15. Time Hardening Procedure for Plastic Strain Accumulation Under Stress Repetitions of Different Magnitudes in Compound Loading

Rutting in the AC layer due to the shear deformation is determined from the following:

$$rd_{AC} = K\gamma_j^i \quad (13)$$

For a 150 mm (6 in.) layer the value of K is 5.5 where the rut depth (rd) is expressed in inches (9).

To estimate the contribution to rutting from base and subgrade deformations, a modification to the Asphalt Institute subgrade strain criteria (12) is utilized. The equation expressing the criteria for 13 mm (0.5 in) of surface rutting is:

$$N = 1.05 \times 10^{-9} \check{z}_v^{-4.484} \quad (14)$$

where:

$$\begin{aligned} N &= \text{the allowable number of repetitions} \\ \check{z}_v &= \text{the compressive strain on the top of the subgrade} \end{aligned}$$

Since the Asphalt Institute criteria do not address rutting accumulation in the pavement structure, rut depth (rd) contributed by the unbound layers was assumed to accumulate as follows:

$$rd = dn^e \quad (15)$$

Least squares analyses suggest that the value for d in equation (15) is as follows using the Asphalt Institute criteria:

$$D = f \cdot fi [1.05 \times 10^9 \check{z}_v^{04.484}]^e \quad (16)$$

with $f = 0.14$ rather than 0.5 and $e = 0.372$.

Using the time hardening principle, as for the asphalt concrete, an expression for rut depth accumulation similar in form to equation (12) can be obtained, i.e.:

$$rd_j = d_j \left[(rd_{j-1} / d_j)^{1/0.372} + \Delta n_j \right]^{0.372} \quad (17)$$

The framework for rut depth estimation using equations (9), (12) and (17) is illustrated in Figure 16. This approach has a distinct advantage over the direct regression approach; it predicts rut depth development as a function of traffic and environment as well as a function of the mix parameters.

Using the above approach and correlations to mix properties and RSST-CH measurements, a value of $b = 0.071$ for use in equation (9) was obtained with values of \underline{a} and \underline{c} for the 13 sections referred to earlier. Figures 17 and 18 illustrate computed values for the accumulation of rutting for sections 1 and 9 determined by this methodology. Also shown in the figures are the measured values.

Although this model is quite useful in quantifying the progression of permanent deformation and in developing appropriate construction pay factors, it is not useful more generally because it is applicable to the specific WesTrack mix components (asphalt and aggregate) and aggregate gradations.

Accordingly, work is underway using results of the RSST-CH tests to capture the effects of mix variables. Calibrations are being developed using RSST-CH test results as independent quantities instead of asphalt content, air void content, and aggregate gradation used in the above approach.

PAY FACTORS

Results presented in the performance models section provide a basis for establishing penalties/bonuses (pay factors) related to the quality of construction and which are an integral aspect of PRS.

The approach illustrated in this section focuses on economic effects on the specifying agency. It assumes that an appropriate penalty for inferior construction should be the added cost to the agency. It also assumes that the bonus for superior construction should be no greater than the added savings to the agency.

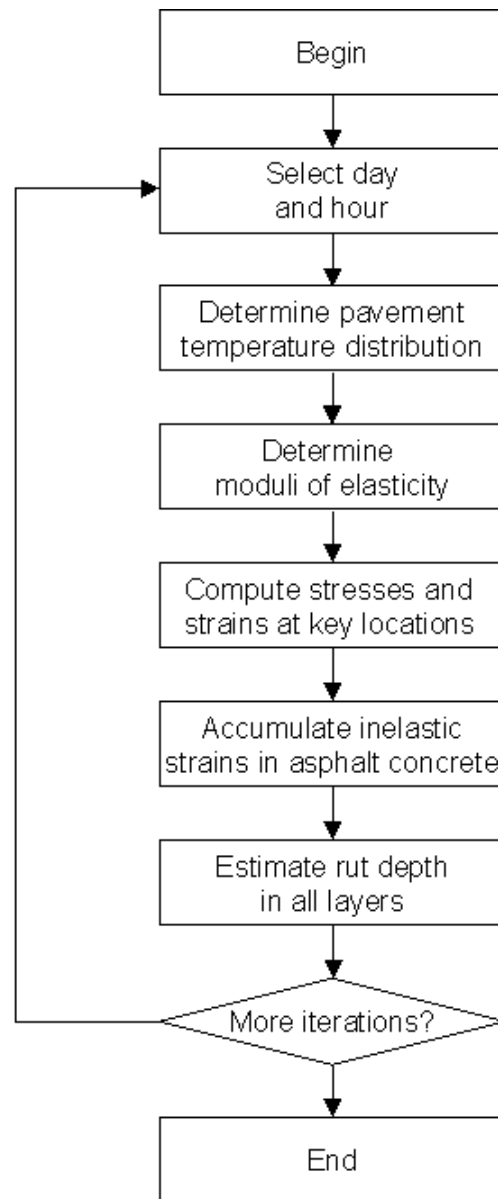


Figure 16. Framework for Rut Depth Estimation

For new construction, these agency costs/savings are associated primarily with subsequent pavement rehabilitation. Inferior construction hastens future rehabilitation and may increase the cost of rehabilitation as well. As a result, inferior construction increases the present worth of future rehabilitation costs. Superior construction, on the other hand, reduces the present worth of these costs, largely by deferring the future rehabilitation. The difference in present worths of rehabilitation costs, i.e., as constructed versus as specified, provides a rational basis for setting the level of penalty/bonus for inferior/superior construction quality.

For fatigue the model considers the means and variances of the following HMA construction quantities: asphalt content, air-void content, and AC thickness. Although AC thickness was not a variable in the WesTrack experiment, it is an important factor in fatigue performance and has been included in the analysis for pay factors. The influence of aggregate gradation is still under investigation at this time. To estimate damaging strains under traffic loading, the model treats the pavement as a multilayer, elastic system. The performance model computes the

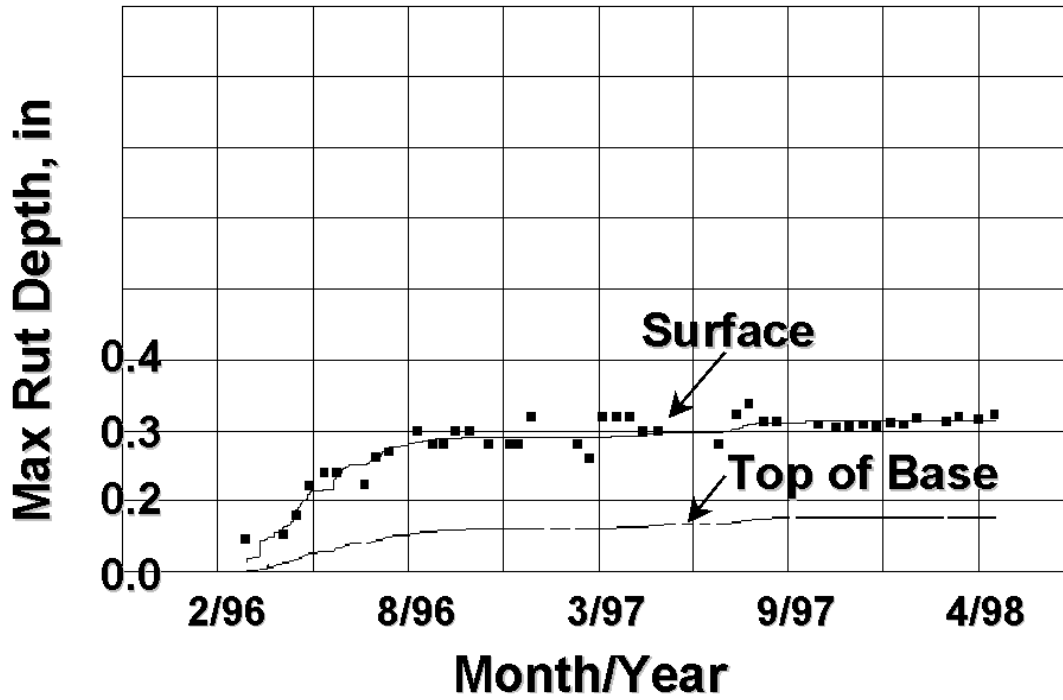


Figure 17. Comparison of Rut Depth Estimates and Measured Values as a Function of Time/Traffic Section 1

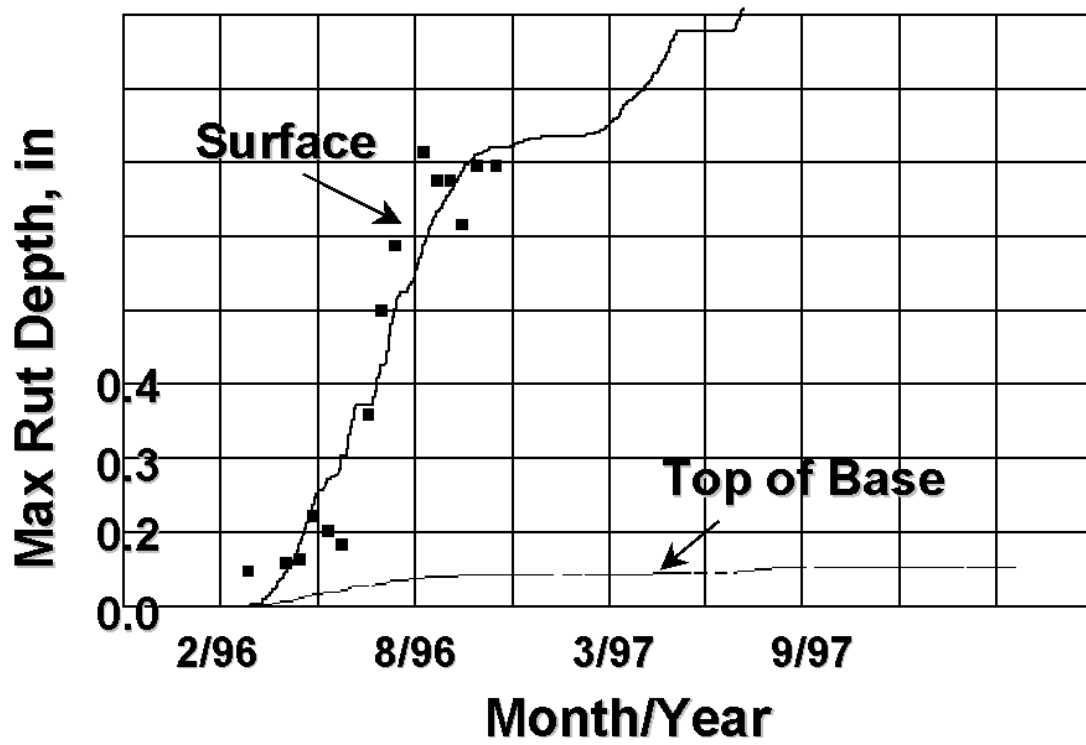


Figure 18. Comparison of Rut Depth Estimates and Measured Values as a Function of Time/Traffic, Section 9

distribution of pavement fatigue life, expressed as ESALs, using Monte Carlo simulation techniques as outlined in Figure 13.

For permanent deformation, the procedure is similar, as shown in Figure 16. Thus far only the model represented by equation (7) has been utilized.

The cost model used as an example considers only the time to the next rehabilitation activity. It understates agency costs by ignoring possible effects of construction quality on future rehabilitation costs. Also, it ignores future rehabilitation activity beyond the first cycle. It requires an estimate of future rehabilitation costs (in current-year dollars) and considers annual inflation of rehabilitation costs, traffic growth, expected years of new pavement life, and a discount rate representing the time value of money.

Table 3 summarizes the quantities used to represent reasonable estimates of materials/construction variability associated with conventional construction practice (11). The equations for estimating the standard deviation of asphalt-concrete thickness were developed as an approximation to handle multilift construction. Among the assumptions made in their development was that the coefficient of variation of thickness in single-lift construction is about 14 percent (11).

TABLE 3 Variation of Mix and Structural Characteristics for Monte Carlo Simulations

Parameter	Total Standard Deviation	Percentage of Variance Due to Materials/Construction	Materials/Construction Component of Standard Deviation
Asphalt content	0.30%	40	0.19%
Air-void content	1.6%	60	1.2%
Surface thickness	$0.200 \cdot T^{0.69}$ (cm)	80	$0.173 \cdot T^{0.69}$ (cm)
Foundation modulus	30% (coefficient of variation)	70	25%

T = thickness

Since the analyses of the WesTrack fatigue results have not been completed at this time, the computations for the pay factors reflecting fatigue performance are based on data presented in Reference (13). The 10th percentile fatigue life was used as the basic performance estimate. This corresponds to approximately 10 percent fatigue cracking in the wheel paths. With the performance model, ESALs for both on-target and off-target construction could be estimated.

For permanent deformation the traffic (life) to a rut depth of 10 mm (0.4 in.) has been used as the performance estimate. This particular rut depth was selected since the performance model represented by equation (7) was calibrated at this depth of rutting for the WesTrack data.

The off-target pavement life in years, OTY, that results from the simulated performance differential, assuming that traffic grows geometrically, was computed as follows:

$$OTY = \frac{\ln\left(1 + RP\left[(1 + g)^{TY} - 1\right]\right)}{\ln(1 + g)} \quad (18)$$

g is the annual rate of traffic growth expressed as a decimal; TY is the number of years of pavement life resulting from on-target construction activity; and RP is the ratio of off-target ESALs to on-target ESALs.

The cost model assesses the present worth of moving the first rehabilitation cycle from its on-target position, TY , to its off-target position, OTY . The net present worth, expressed as a percentage of the rehabilitation costs (in current-year dollars), is computed as follows:

$$\Delta PW = 100 \left(\frac{1+d}{1+r} \right)^{TY} \left(\frac{1+r}{1+d} \right)^{OTY} - 100 \quad (19)$$

ΔPW is the percentage change in the present worth of the cost of the first rehabilitation cycle, r is the annual rate of construction-cost inflation expressed as a decimal, and d is the annual discount rate expressed as a decimal. Applying this percentage to the expected rehabilitation cost yields the agency cost increment due to off-target construction.

Following this methodology the effects of off-target construction on future agency rehabilitation costs can be determined. In the approach used herein bonuses for superior construction were set at 50 percent of the agency savings while penalties for inferior construction were set at 100 percent of the added agency costs.

For equations (18) and (19) an on-target pavement life of 20 years was used and the following parameters were assumed:

- annual rate of traffic growth, $g = 2.5$ percent
- annual rate of inflation, $r = 2.0$ percent
- discount rate, $d = 5.0$ percent

To determine the effects of rutting, only data for the mix containing the fines gradation was utilized. Figure 19 illustrates the effects of asphalt content and a range in standard deviations of that parameter on pavement life. Similar computations were done for the effects of air void content, as shown in Figure 20.

From these simulations it was then possible to estimate the effects of off-target construction. Figure 21 illustrates effects of off-target asphalt content on future agency costs expressed as a percent change. For this example the target asphalt content was 5.4 percent and a standard deviation of asphalt content of 0.19 percent was considered representative (see Figure 19). From this information simplified tables were then constructed with bonuses and penalties, expressed to the nearest 5 percent, which allowed the generation of Figure 22.

Similar computations were accomplished for fatigue. Figure 20 illustrates the results of a simulation showing the effects of as-constructed air-void content and standard deviation on simulated fatigue life to the 10 percent fatigue cracking. In this example the target air void content was 7 percent and the representative standard deviation was selected as 1.2 percent. Figure 23 illustrates the pay factors, based on relative compaction. Pay factors which account for the effects of asphalt content and pavement thickness have also been developed.

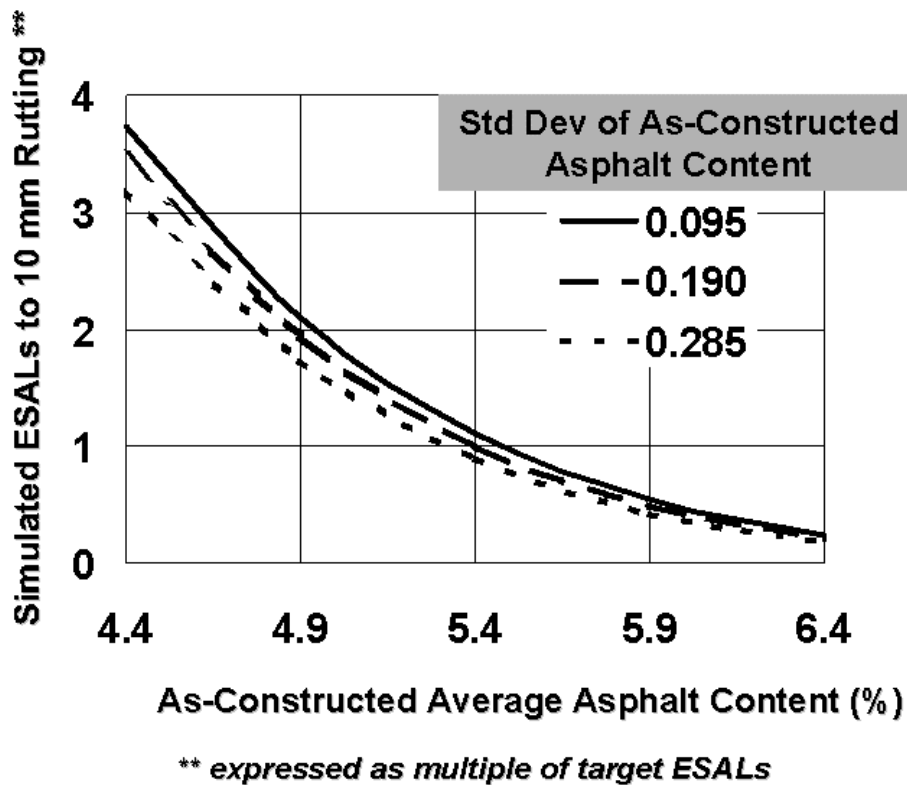


Figure 19. Relations Between ESALs to 0.4 in. (10 mm) Rut Depth and Asphalt Content, V_{air} of 7 Percent

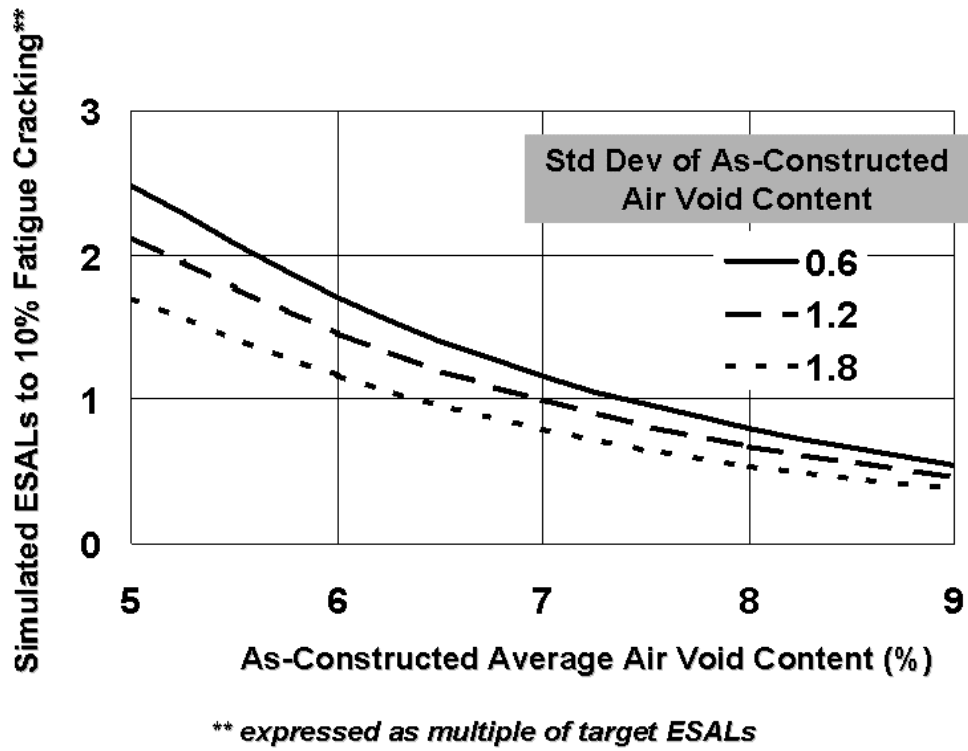


Figure 20. Effects of As-Constructed Air-Void Content on Pavement Fatigue Performance

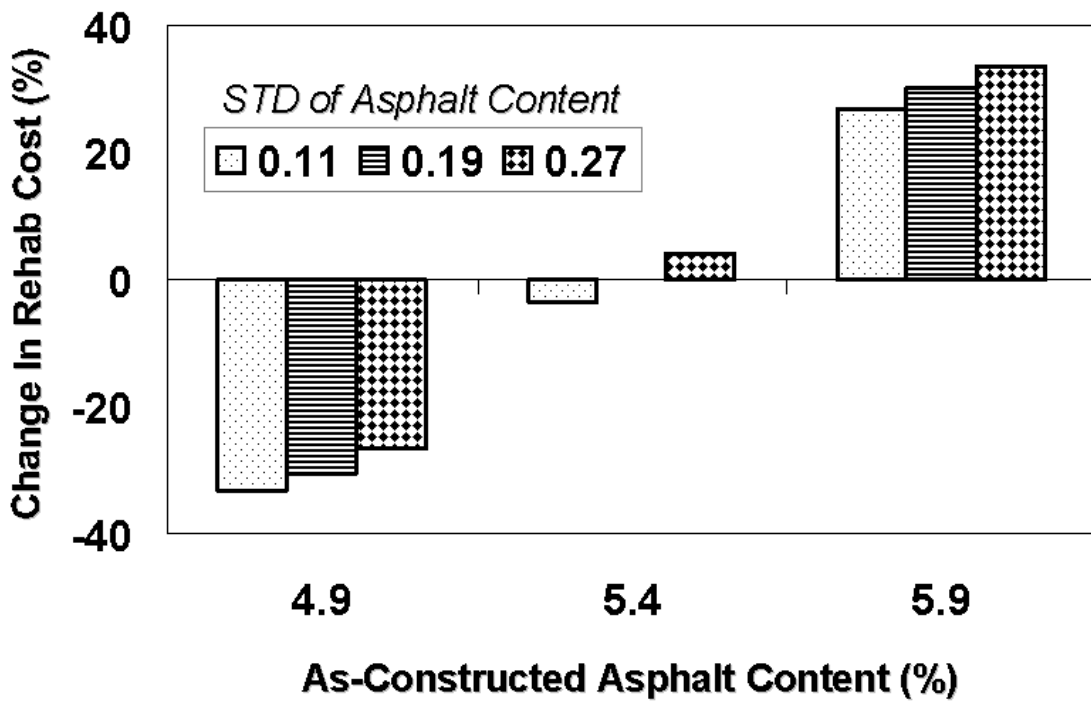
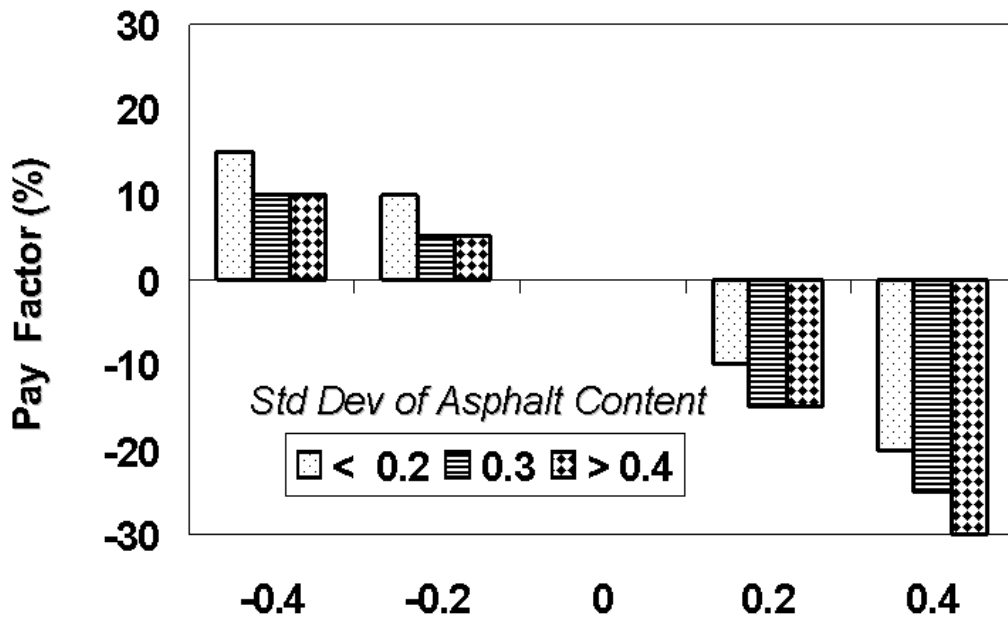


Figure 21. Effect of Off-Target Asphalt Content on Future Agency Rehabilitation Cost (Percent Change)



Difference Between Measured and Design Asphalt Content

Figure 22. Rutting Pay Factors for Asphalt Content
(Percentage of Future Rehabilitation Cost in Current-Year Dollars)

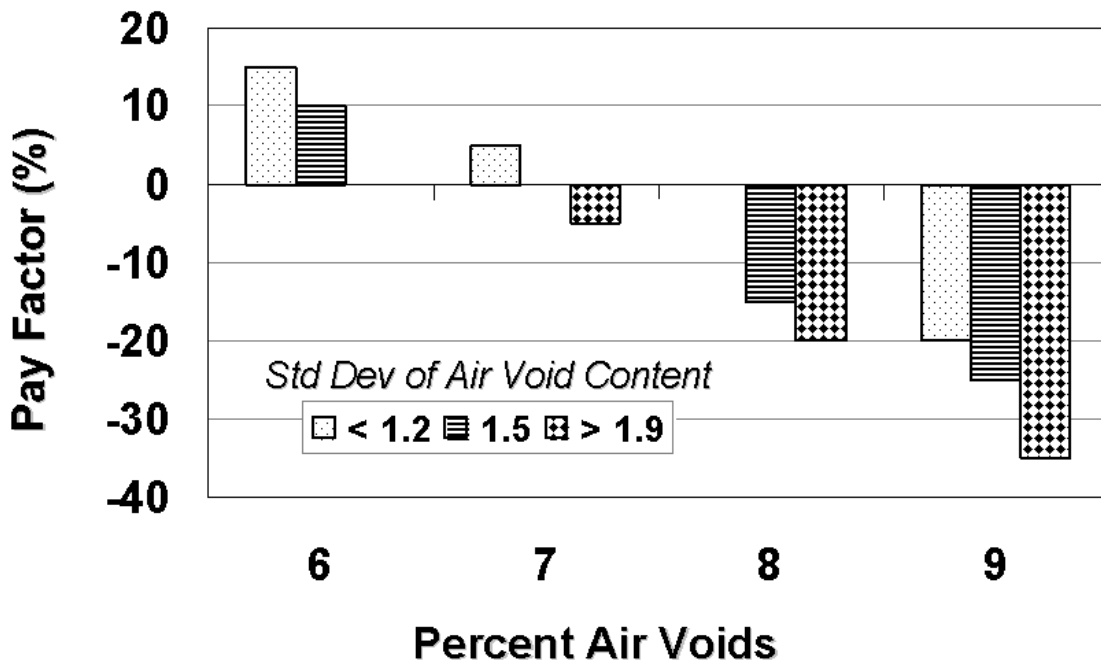


Figure 23. Fatigue Pay Factors for Relative Compaction
(Percentage of Future Rehabilitation Cost in Current Year Dollars)

A set of pay factors which shows the effect of asphalt content on both rutting and fatigue is shown in Figure 24. This combination is based on the assumption that the cost of repairing premature rutting is the same as repairing premature fatigue cracking. Obviously, if these costs are different, it would be necessary to consider the distresses separately to compute bonuses/penalties.

Rational pay factors calculated from these analyses were then combined to produce the combined pay factors. These were computed from the following expression:

$$CPF = (1 + pf_{av})(1 + pf_{ac})(1 + pf_t) - 1 \quad (20)$$

where pf_{av} , pf_{ac} , pf_t = pay factors for air-voids content, asphalt content, and asphalt concrete thickness, respectively. The results of this computation are illustrated in Figure 25. The basis for the use of equation (20) is described in Reference (13).

LESSONS LEARNED

In addition to supplying the information to continue the development of performance-related specifications, WesTrack also provided useful information in the following areas: pavement construction; quality control/quality assurance (QC/QA) during construction; vehicle operations; materials specifications; and pavement rehabilitation. Each area is briefly described.

Pavement Construction

As a part of the experiment it was necessary to compact each mix type to specific air void contents, i.e., 4, 8, and 12 percent. The experience at WesTrack indicated that this is achievable within close limits. Establishing roller patterns and calibrating nuclear gauges for each mix type by the QC crew are key items. The most important aspect of pavement construction is close coordination among the engineers responsible for construction, roller operators, and the QC crew. Daily meetings prior to the start of construction resulted in an operation in which all parties involved worked together to achieve the desired degree of compaction in each section. With the roller operators understanding what was to be achieved and the QC crew confident in the calibrations of the nuclear gauges (which was checked daily), the target density/air void content compaction was achieved by controlling the number of roller passes at specific mix temperatures.

Quality Control/Quality Assurance (QC/QA)

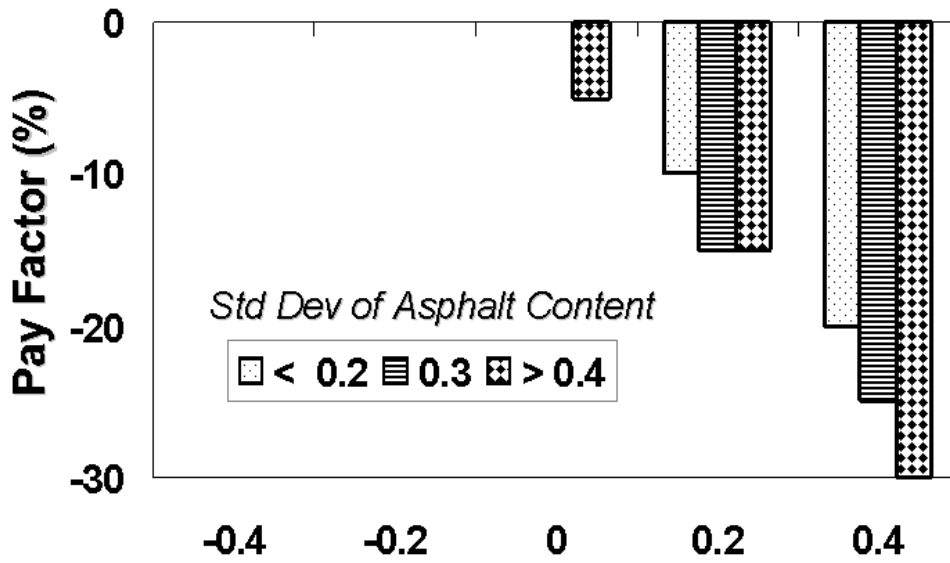
The ignition oven, which has been heralded as a device which can expedite the QC/QA process during construction, was used at WesTrack for this process. While the oven does hold promise for the QC/QA process, the lesson learned from WesTrack experience is that *careful calibration* of the equipment is critical. For each mix, calibration is required over a range of binder contents. Extreme care must be taken when hydrated lime is used as an additive. Because of its particulate nature, it is likely to be emitted in the exhaust draft of the oven. This will necessarily yield an erroneous determination of binder content (14).

Vehicle Operations

As the roughness of the pavements increased due to structural damage from traffic loading, there was an opportunity to study vehicle operating costs due to increased roughness.

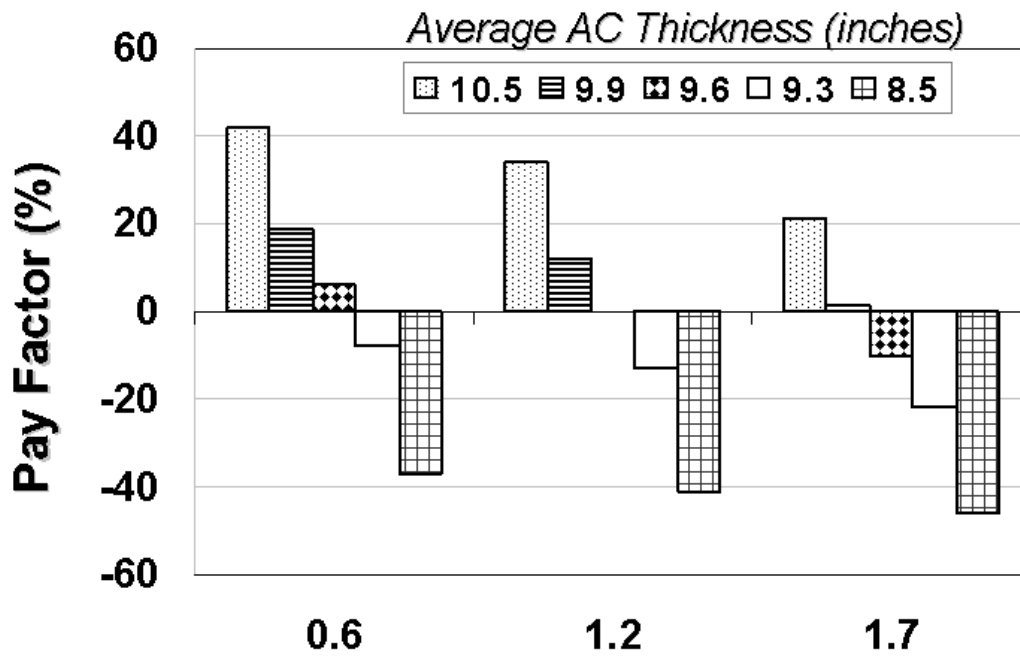
In January/February 1998, after 1.5 years of continuous loading, the track had reached its roughest condition. The track was so rough that measurements at the driver's location indicated that a driver would not be able to tolerate the ride for more than a few hours. Accordingly the track was rehabilitated in early March 1998 resulting in a significant reduction of roughness. This period of time (i.e., prior to and after rehabilitation) provided a unique opportunity to evaluate truck operating costs versus pavement roughness. During this time frame the pre- and post-rehabilitation IRI were 150+ inches/mile and approximately 75 inches/mile, respectively.

During a 3-month period, 60 days prior to and 60 days after rehabilitation, fuel consumption was measured in two of the trucks. Average fuel consumption before rehabilitation was 4.2 mpg, while afterwards it was 4.4 mpg. This difference amounts to a 4.5 percent change. For the average truck travelling 1,000,000 miles, this translates to a savings of nearly 10,300 gallons as a result of the "smoother" pavement. Obviously this would result in significant cost savings and reduction of emissions to the environment.



Difference Between *Measured & Design* Asphalt Content

Figure 24. Interim Recommendation for Pay Factors for Asphalt Content (Percentage of Future Rehabilitation Cost in Current-Year Dollars)



Std Dev of Air Void Content

Figure 25. Recommended Combined Pay Factors (Percentage of Future Rehabilitation Cost in Current-Year Dollars)

The increased roughness was also manifested by failure of truck/trailer component parts including the fracture of trailer beams and spring failures. Pavement roughness forced more frequent replacement of suspension springs.

Superpave Volumetric Mix Design

The rutting performance of mixes at WesTrack suggests some difference in behavior between the coarse and fine mixes at high temperatures. In addition, it was observed that the rutting rate increases beyond some critical high temperature. Rutting data suggest that this is true regardless of mix type.

The results underscore the importance of a performance test which quantifies resistance to shear deformation at a *critical* high temperature.

Rehabilitation Techniques

As pavement roughness typically accompanies distress, maintenance and rehabilitation were ongoing to insure a reasonably smooth surface, and in turn these activities minimize dynamics loads which would confound interpretation of the performance results. Two procedures which proved successful and may be useful for in-service highways are briefly described in this section.

For pavement rutting which affects vehicle operations, milling to a depth of 50-75 mm (2-3 in.) and replacing it with new HMA was an effective technique for carrying traffic during the winter months. This maintenance strategy allows traffic to be safely carried until the usual construction season begins in late spring or summer.

To repair extensive fatigue cracking, the “deep T-patch” shown in Figure 26 was very effective. If the section was long enough this procedure could be accomplished with two passes of the milling machine. For smaller areas, hand excavation is more practical.

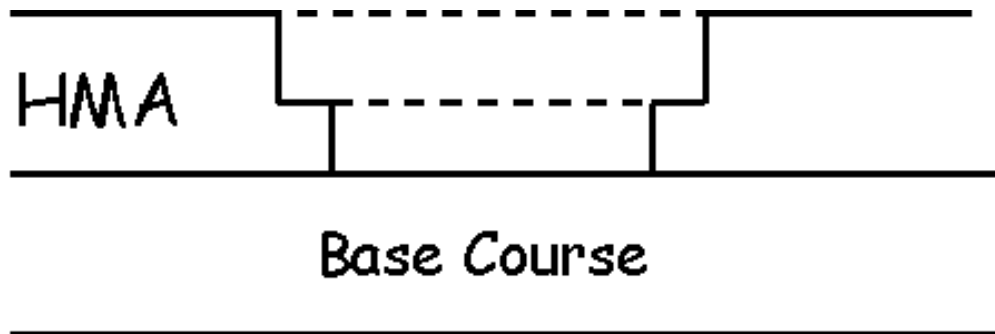


Figure 26. Schematic Representation of a Deep “T-Patch” for Remediation of Fatigue Cracking

SUMMARY

WesTrack, a 14.5 million dollar accelerated pavement test to further the development of performance related specifications for asphalt concrete mixes, has provided much useful information in terms of the design, construction, performance and rehabilitation of asphalt concrete pavements. While the performance related specification has not been completed at this date many of the objectives of the program have been achieved.

The project has demonstrated that asphalt concrete mixes, through proper construction quality control, can be built to close tolerances in terms of asphalt content, aggregate gradation, and compaction. It does, however, require close cooperation between the engineer-in-charge, the inspection team, and the equipment operators performing the construction operations.

While the ignition oven can be a useful device for QC/QA, careful calibration of the equipment is required for each mix. Moreover, with mixes containing hydrated lime, careful interpretation of the data is critical.

The use of driverless vehicles has proved to be an effective way to conduct an accelerated pavement test program. Moreover, through extensive instrumentation of the vehicles, much useful information has been gained on vehicle operating costs, particularly with regard to fuel consumption.

Low temperature cracking test results suggest that the probability of the mix cracking at a temperature of -22°C is low. No low temperature cracking has been observed at the test site thus far, although the temperatures at the site have not reached the -22°C level to date.

Moisture sensitivity test results for the WesTrack mixes are generally below the recommended TSR of 0.8. After nearly 4.9 million ESALs, moisture damage was not evident. While it might be argued that the test was relatively short term and that water damage may occur later in the life of the pavement, Nevada DOT experience with lime treatment of the type used at WesTrack on similar materials suggests otherwise. Thus, the criteria for the TSR or the test itself should be considered suspect.

For fatigue cracking, both field performance and laboratory test results have shown the effects of compaction and asphalt content. With low air void content or medium to high asphalt content the mixes showed much better fatigue resistance. Also, aggregate gradation was significant, particularly for the coarse gradation. The most important mix parameter, however, is compaction. As the degree of compaction is increased, fatigue life is significantly improved.

SHRP-developed technology for defining fatigue response of mixes can be used to quantify the effects of material properties on pavement performance and to develop realistic pay factors for a PRS as described herein.

For permanent deformation (rutting), field performance and laboratory RSST-CH results have demonstrated the effects of asphalt content, compaction, pavement temperature and, to some extent, the effects of aggregate gradation. The SHRP developed RSST-CH and associated technology can be used to quantify the effects of these variables on pavement performance and can be used to develop realistic pay factors for a PRS as well.

A methodology is also briefly described illustrating how the pay factors for fatigue and permanent deformation can be combined to develop a realistic set of factors reflecting the effects of asphalt content, degree of compaction, and asphalt concrete thickness.

To keep traffic operating during the application of the 4.9 million ESALs, periodic maintenance and rehabilitation were required to repair the expected early distress. Two expedient repair procedures developed for WesTrack have potential application for service pavements were described. The procedure for rutting involves milling the rutted areas and replacing the milled-out sections with a rut resistant mix. The other, to repair sections with extensive fatigue cracking, utilizes a patching procedure referred to as a "T-patch."

Finally, this large accelerated pavement testing experiment has illustrated the importance of combining the results of full-scale testing, an extensive laboratory test program of materials utilized in the pavement sections, and analysis of pavement responses to develop an improved performance-related specification with realistic pay factors for asphalt concrete construction.

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