Permanent Deformation: Field Evaluation

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Permanent deformation testing in the laboratory and rutting measurements on the highway continue to present complicated situations to the engineer attempting to understand mixture performance. The development of new testing procedures promises to provide a better understanding of material behavior. Although this increasingly complex technology continues to provide more information, a vast amount of information available today is not being analyzed in a fundamentally sound manner. Accurate rutting comparisons are needed to help the highway engineer today while the new technology undergoes development, testing, and validation. These procedures must provide data that are applicable to field studies and consistent for use in the new Strategic Highway Research Program testing procedures. Field measurements of permanent deformation indicating that previous modeling attempts using field measurements may have been fundamentally flawed are discussed. Predictions of rut depth development in the field are not always adequately presented to truly represent the interaction of mix parameters with performance. Previous models have not considered the developmental phases of rutting. The result is that different materials are not compared consistently. These misapplications produce comparisons of mixtures that cannot accurately indicate the true performance potential of the various mixtures. Correct procedures that provide representative comparisons of mix quality are presented.

Debates are not uncommon about how pavements can best be evaluated to develop material properties indicative of performance potential of the various materials used in their construction and how best to predict in-service performance of slightly different materials using the properties derived from the study. The permanent deformation testing of asphalt concrete is no exception and perhaps best represents the dilemma currently facing pavement engineers. A number of test procedures are available for laboratory characterization of mix performance. For instance, investigators are using static creep testing, dynamic creep testing, confined and unconfined testing of both types, and incremental static testing of the VESYS program. Thin-walled torsional testing has been conducted to provide more accurate constitutive relationships for asphalt concrete mixtures, and the Strategic Highway Research Program (SHRP) has developed another device using simple shear to provide constitutive equations for the asphalt concrete mixes. These laboratory procedures provide a very confusing picture for characterizing permanent deformations.

Evaluation of a mix after placement in a pavement is the best way to compare permanent deformation resistance between different mixes. Before a new and improved laboratory testing procedure is accepted as more accurately depicting mixture behavior, it is imperative to fully understand and characterize field behavior of the mixture. The comparisons of mixtures on the basis of field measurements of permanent deformation can be erroneous if the necessary precautions are not taken. Field measurements to provide comparisons of mix quality are being reported with no regard to how rutting or permanent deformation develops in an asphalt concrete mixture. Such representations produce inappropriate comparisons and allow erroneous conclusions, such as that one mix has more rutting resistance than another. These representations are not acceptable, given the recent advancements in laboratory testing and their potential use for comparison of field performance.

This paper considers procedures that have compared field development of rutting in different asphalt concrete mixtures. Development of these techniques has not been appropriate for obtaining all the information available from the rutting measurements, and there are deficiencies that result from their use. The discussion of the measurement of rut depths on existing pavements illustrates an appropriate analysis procedure to develop reliable performance comparisons for the asphalt concrete mixes. This procedure is necessary as laboratory and field measurements must be reconciled before judgments are made about the suitability of different mixes.

PERMANENT DEFORMATION

General Development

Permanent deformation, that is, how it develops in a mixture, and how rutting develops in a pavement require a fundamental examination. Figure 1 shows the generally accepted response of an asphalt concrete mixture to repeated loadings. The three stages in the permanent deformation of a mix include

1. Primary—initial densification,
2. Secondary—stable shear period, and
3. Tertiary—rapid unstable shear failure.

Two criteria to judge the long-term performance of the mixture are (a) how quickly a critical rut depth is reached in the mixture and (b) the rapidity with which the mixture reaches the failure point for Stage 3. These two criteria are not mutually inclusive. A mixture can reach critical rutting before the mixture becomes unstable, or it may become unstable before it develops a critical rut depth. It is vital to separate these two occurrences and describe how they develop in the field.

The onset of unstable failure has been related to both a void condition in the mixture and a level of permanent strain. Figure 2 shows these general trends between voids and permanent deformation. The strain criterion proposed for the onset of unstable deformation is typically 2 to 3 percent. The assumption of an arbitrary permanent strain level for failure

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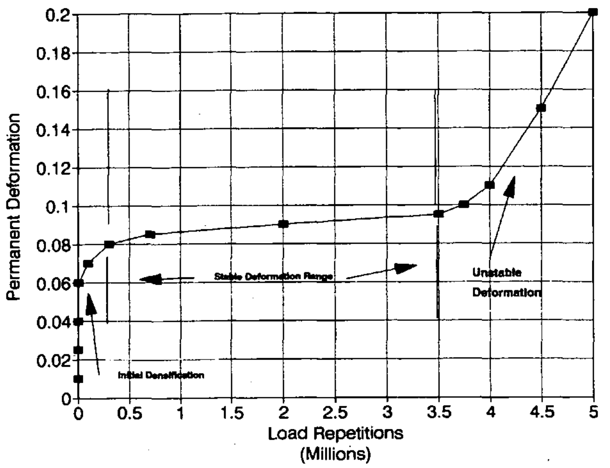

FIGURE 1 **Stages in permanent deformation development.**

ignores the initial composition of the mixture, however, and is not recommended when quality comparisons of field measurements are being made. A good mix will not densify to the point at which voids reach 2 percent, whereas a poor mix will densify to and beyond this value quickly and fail rapidly under relatively low permanent strain levels. The mix parameters produced during initial construction will influence how much permanent strain occurs when the limiting voids develop. This consideration of the onset of unstable behavior is important to a full understanding of field behavior relations with laboratory testing but is beyond the scope of this paper.

Form of Permanent Deformation

The phenomenological relationship for permanent deformation curves shown in Figure 1 is the log-log relationship

$$e_P = A(N)^B \tag{1}$$

where

A, B = material properties from the best-fit line to the rutting data,
N = number of load repetitions, and
e_P = permanent strain.

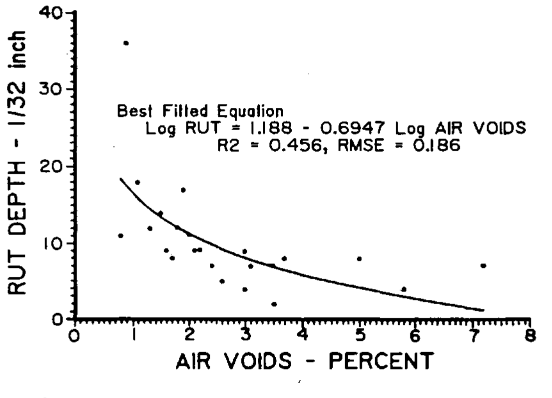

FIGURE 2 **Relationship between air voids and rut depth in Arkansas (*1*).**

Work by Khedr extended the form of this relationship using plasticity and fracture considerations to provide excellent material property relationships (*2*). The relationship derived is of the following form:

$$e_P/N = A(N)^m \tag{2}$$

where the variables are as previously defined and m is equal to $B - 1$.

The shape of permanent deformation curves determined in the laboratory and field consistently follows the trends indicated by these equations. Although more complicated constitutive-type equations can be applied, it is the form of the curves that is critically important and not the number of parameters in the equation. Previous field work has often ignored the form of the curve entirely, which is where problems arise. In this discussion these simple equational forms provide the most consistent relationships with material behavior.

Initial Densification

The expressions for rut development or rutting rate provide sound material property relationships. The most useful of these is the relationship between A and the stress state (*2,3*). The A-parameter is the intercept of the log-log curve at 1 load repetition. As such, it represents the initial densification potential of the mixture. The relationship between A and the stress state as indicated by the modulus/stress ratio is excellent, as shown by Khedr (Figure 3) and in a comprehensive study by Leahy, as shown in Figure 4 (*3*). This material property indicates that densification potential is evident in comparing data between a mix possessing little or no densification potential and a traditional dense-graded mixture. Such a comparison between the new stone matrix asphalt (SMA) mixes and the traditional hot mix clearly illustrates this behavior. The limited tests available today show clearly that the SMA mixtures considerably reduce the A-parameters associated with the development of permanent deformation in these mixes. Figure 5 shows these data from testing performed in the laboratory on SMA in Ontario, Canada (*4*). A recent SMA placed in St. Louis, Missouri, in 1991 developed 3 to 6 mm (⅛ to ¼ in.) rutting almost immediately after placement, but no further rutting has occurred since that time (*5*).

Stable Shear Development

The slope of the log-log permanent deformation trace has shown the least variation with mix type, loading type, and temperature. Khedr concluded that this value was a constant ($m = -0.78$) (*2*). Mahboub and Little (*6*) conclude that it is relatively constant in the range of -0.75 to -0.85. In a study of various aggregates, asphalt cements, and mix designs Leahy (*3*) could not statistically differentiate between the slopes of the different materials tested. The average slope, B, for all asphalt cements and crushed stone aggregate was -0.80 in the Leahy study. It may well be that various testing configurations, sample sizes, and end conditions have an impact on this slope value determined from these laboratory data, but

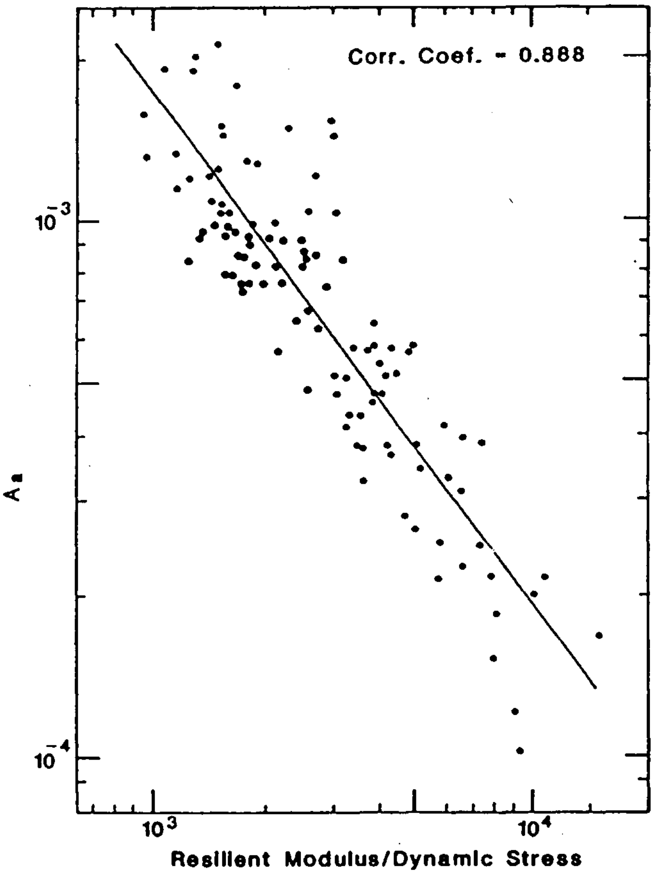

FIGURE 3 Relationship between initial densification parameter (*A*) and stress state (*2*).

the relationship between testing conditions and resulting slopes has not been established. Current developments in the constitutive testing of asphalt mixes being produced by the SHRP effort will provide more data in the areas of defining values such as *A*- and *m*-parameters for mixes, although perhaps not in this exact form. Field measurements of rut depths may not show significant differences in slope because the loading and boundary conditions are relatively uniform and constant.

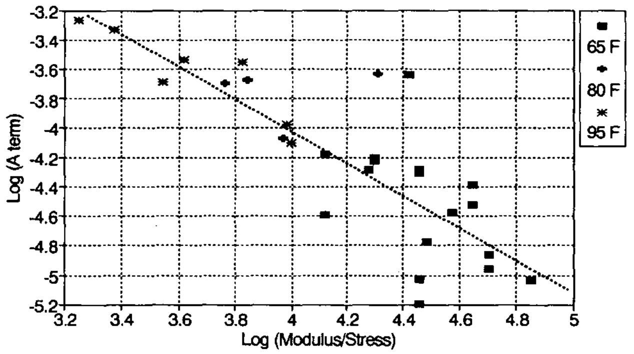

FIGURE 4 Densification parameter (*A*) and stress state according to Leahy (*3*).

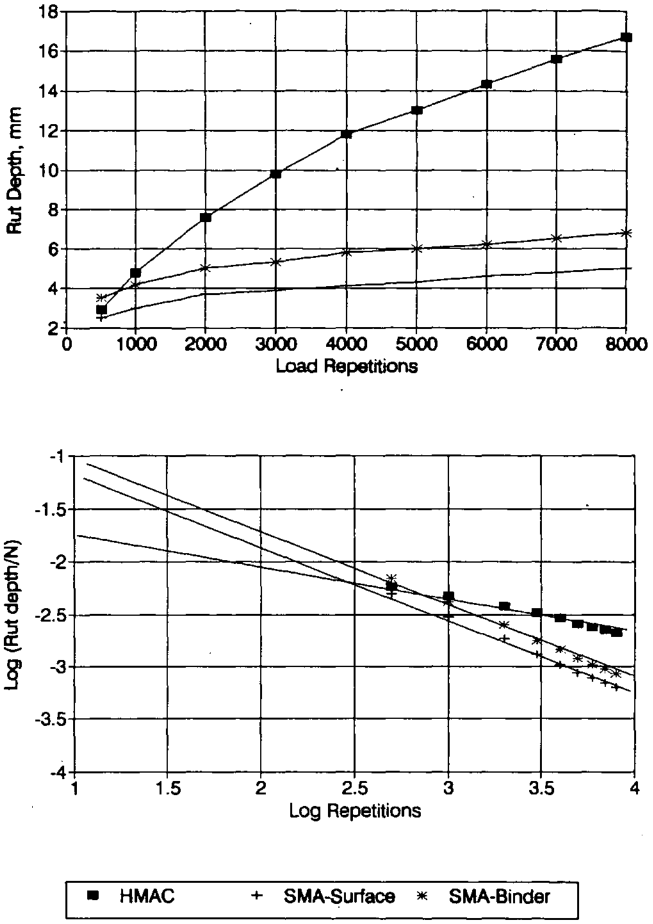

FIGURE 5 Ontario wheel tracking on hot-mix asphalt concrete and SMA (*4*).

Interpretation of Field Measurements

Permanent deformation measurements taken on various pavements illustrate a mixture's potential for rutting. Different mixes with differing *A*- and *m*-parameters complicate the measurement of permanent deformation in the field and the ability to correlate these field measurements with laboratory rankings of mixture potential for permanent deformation. Because the behavior of an asphalt concrete mixture in the laboratory should be no different from what it is in the field under the same inputs, the three phases observed in the laboratory testing on any one mixture should be observable in the field. In an analysis to determine mix quality comparisons it is important to use a procedure appropriate for the manner in which the permanent deformation develops in the mixture. Time-sequenced measurements are necessary for correct interpretation of field performance when comparing mixture quality.

Time-Sequenced Measurements

The three mixes shown in Figure 6 demonstrate the three deformation phases discussed earlier, but they exhibit ex-

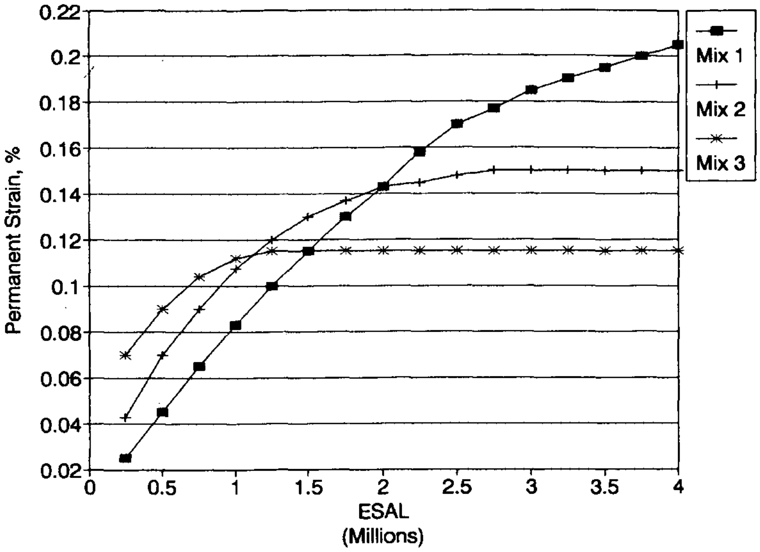

FIGURE 6 Typical hypothetical rutting curves.

tremely different overall performance levels that are not unrealistic for field behavior. The differences can arise from different, but not unexpected, *A*- and *m*-parameters for the mixture. Given these different performance parameters, different conclusions result about rutting performance of these mixes, depending on when the rutting measurements are taken and how they are compared.

The simplest form of comparison reported in the literature to form rut prediction models is to take a rut measurement on a pavement at a specific time and then calculate the number of equivalent single-axle loads (ESALs) that have used the pavement since placement of the mix. Next, use these values in a model to predict rut depth as a function of traffic ESALs with the corresponding material property relationships. Some investigators calculate a rut depth per ESAL value, or some derivative thereof, to use in the comparisons of various mixes. Assuming that the example mixes shown in Figure 6 were placed on the same pavement and that the ESAL values were consistent for all mixes, a one-time measurement conducted at a life of 1 million ESALs would show that Mix 3 was the worst performer. This is followed by Mix 2, with Mix 1 having the best resistance to rutting by this simple measure.

Time sequence readings alone do not guarantee an appropriate indication of permanent deformation potential. In Figure 6, rut depth readings taken at 0.5 million and 1 million ESALs provide much the same indication of performance comparisons between mixes when examining the simple measure of rut depth or rut depth per ESAL as previously discussed. This is the most common procedure used to establish regression equations for different mixes. However, plotting the two values of rut depth in the form of log rut versus log ESAL or log ESAL versus log rut/ESAL gives a different comparison of rut resistance, as shown in Figure 7. Figure 7 shows the rut rate versus ESAL plot. Using just these two time-sequenced readings, the rutting parameters *A* and *m* for Equation 2 will accurately characterize the various potentials for the three mixes.

These rutting parameters are significantly different for each mixture because they truly represent the development of permanent deformation in each mixture. The use of this form of equation to predict rut development provides a true indication of the overall performance of these mixes over time. This comparison of permanent deformation parameters avoids the inaccuracy of one-time sequence comparisons or the errors resulting from a simple linear comparison of rutting as a function of ESALs for various mixes measured at the same time. A correct comparison shows the quality of the mixes in their correct order: Mix 3 better than Mix 2, which is better than Mix 1. This is the only appropriate method to compare field data to use in judging mixture quality. Regression equations, such as those developed by Carpenter and Enockson (*7*) or those used in MICHPAVE (*8*) and others that derive from field measurements with regression against material properties, can provide interesting trends in the data that illustrate important material properties. These equations are not suitable for use as an accurate predictor of permanent deformation accumulation as a function of time or traffic. In addition, they cannot accurately compare different mixes for rating quality, and finally they do not include the required physical form of the data in the regression. Even with thousands of one-time or multitime data points, a regression will not produce the proper relationship.

INTERPRETATION AND APPLICATION OF FIELD DATA

The early history of loadings on a newly placed mixture describes the stable development of permanent deformation in a pavement. The densification phase and development of stable deformation properties are evident very quickly, if described by the appropriate sequence of measurements. The early permanent deformation history of a mixture cannot, however, accurately indicate the onset of unstable perfor-

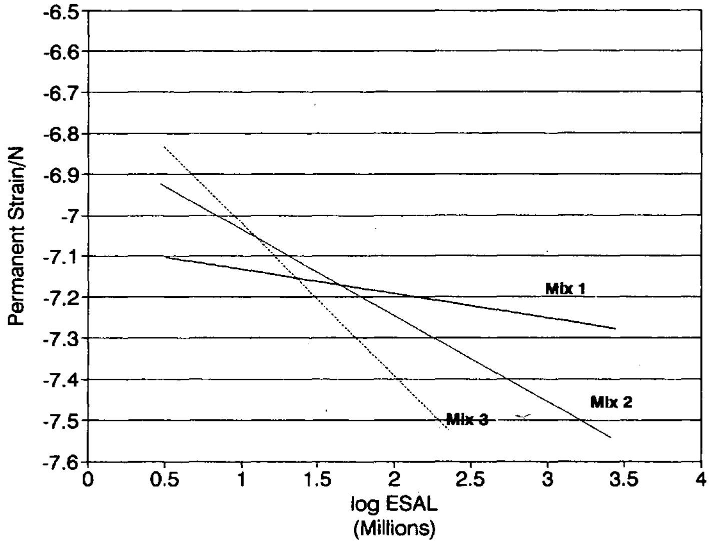

FIGURE 7 Rutting curves derived from two time sequence points.

mance; although a higher slope, m, may indicate the potential for early onset of unstable behavior. Several sets of field rutting measurements presented here illustrate the potential for misuse.

AASHO Road Test

A mixture in the stable portion of its life will have a rut rate curve with a constant slope as rutting develops. A monitoring of void data or rut data provides early indications that a mix is approaching its unstable phase. Voids approaching 2 percent or dropping below the laboratory design value indicate that a problem is developing. The rutting measurements in the field will deviate from the straight-line portion of the stable rut rate curve when unstable behavior begins. The rut rate curve flattens markedly as the mixture becomes unstable and then reverses slope dramatically as the mix fails, as shown in Figure 8 from the AASHO Road Test, Loop 4, cement-treated base sections (*9*). The data presented here represent a thick section not exhibiting base failure. The rutting for the single 80-kN (18-kip) axle load and for the tandem 142-kN (32-kip) axle load is shown.

The measurements for the 80-kN (18-kip) single axle indicate a stable mixture for the number of axle load repetitions studied. The onset of unstable behavior is clearly exhibited for the tandem axle loads by the flattening out of the curve. These data clearly indicate that the asphalt concrete mixture used during the AASHO Road Test did not have the stability to withstand the limited number of tandem axle repetitions used at the facility. The 400,000 tandem axle loads convert to approximately 1.2 million ESALs (*9*). It is unreasonable

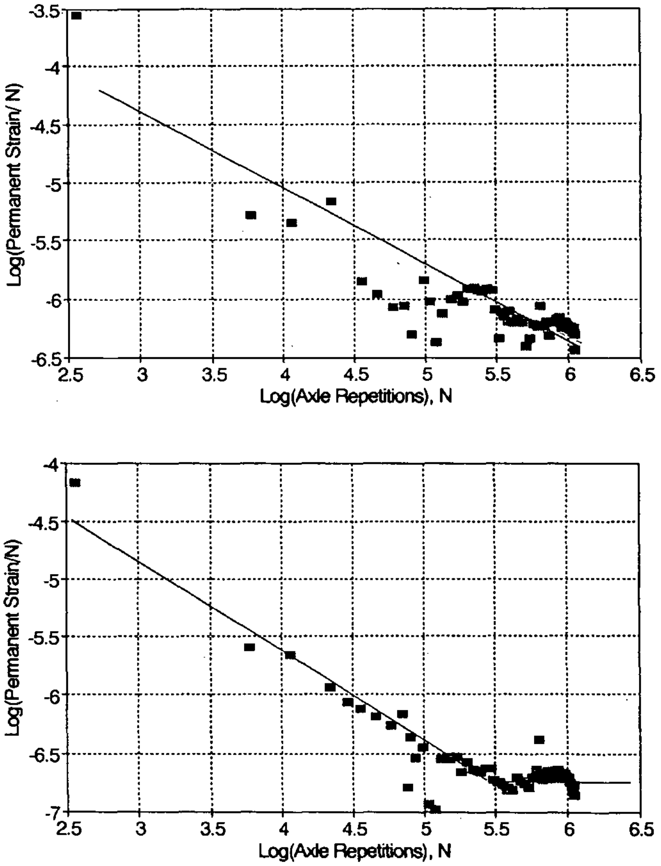

FIGURE 8 AASHO Road Test rutting data: single (*top*) and tandem (*bottom*) axles.

to expect any mix prepared to the specifications used for the road test mixture to give satisfactory service under the extreme loads and repetitions existing on today's highways. These mix designs have not performed satisfactorily, and the development of new rut-resistant mixes is a hot topic at various state highway agencies.

Illinois Department of Transportation Overlays

The Illinois Department of Transportation (DOT) periodically collects rutting measurements of overlays on their Interstate pavements. The data base currently contains rutting measurements of first overlays of concrete Interstate pavements constructed with a new mix, specified in 1984. The data base contains survey data from 1985, 1987, 1989, and 1991. These data provide an excellent means of comparing mixture performance in the AASHO mixture and in designs used before 1984. A previous survey in 1982–1983 on overlays of concrete Interstate pavements made with the previous mixture was analyzed by Carpenter and Enockson (7) in their analysis of rutting performance of this mixture.

Pre-1984 Overlays

The study by Carpenter and Enockson analyzed the rutting performance of asphalt concrete overlays of Interstate concrete pavements and developed a regression equation relating material properties to the development of rutting over time (7). In these situations, the rut measurements were attributed entirely to the asphalt mixture. However, although it provides some good qualitative indications of mix influences, this analysis is an illustration of an inappropriate evaluation of mixtures for comparisons of rutting potential. This study lumped together all mixtures from the various districts and used the past traffic to calculate a rut depth (or rut strain) per ESAL. A regression analysis using this parameter relates the influence of the mixture properties on the development of rutting and the relationship with traffic. As discussed, this approach is not correct for comparing different mixes. The trends in various material properties affecting rut development are generally correct, but the degree of rutting developing cannot be relied on for direct comparisons. The equation derived from these data, keeping the units as derived, was

$$\begin{aligned}\mathrm{RUT} = {} & -0.040930187(-40+80)^{1.0849} \\ & - 0.0002569715(\mathrm{STAB}) + 0.083705(\mathrm{DIFFS40}) \\ & + 0.0523817(\mathrm{AVEHOT}) \\ & + 0.313578(\mathrm{ESAL})^{0.045565} - 1.27458(-200)^{-1.24927} \\ & + 0.00041937(\mathrm{D}) + 0.0106828(\mathrm{RDEN}) - 1.38669 \qquad (3)\end{aligned}$$

where

RUT = rut depth (in.),
$-40 + 80$ = percent passing the No. 40 sieve, retained on the No. 80 sieve of the surface mix (%),
STAB = Marshall stability of the surface mixture (lb),
DIFFS40 = hump in the FHWA 0.45 power gradation curve on the No. 40 sieve in the surface mixture (%),
AVEHOT = average of the maximum monthly temperature during June, July, and August (°C),
ESAL = cumulative 18-kip ESALs using the overlay since placement (millions),
-200 = percent passing the No. 200 sieve in the binder level mix (%),
D = theoretical maximum density (pcf), and
RDEN = relative density of the surface mixture (%).

The combined performance of these overlays within a district only approximates the characterization of an individual mixture. The plots of district data in Figure 9 illustrate the log-log relationships of permanent strain and ESALs for the districts in the analysis. Although somewhat limited, the curves indicate some striking similarities that lead to a conclusion that they are developing stable shear; in addition, the mixes within a district appear to perform similarly, even though similarity is not directly determinable from these data. The data from District 8 could indicate either an upturn in the rut rate plot beyond approximately 3 million ESALs (log = 6.5) or the performance of completely different mixtures. The data for District 1 indicate very different mixes; the two points with the large A value had significantly lower relative density at the time of construction. Because of the nature of the data points, however, any validation of these assertions is uncertain, illustrating the inadequacy of analyzing data from a one-time survey. Determination of individual mix behavior from these data is questionable.

The behavior of the data shown in Figure 9 and the general agreement with published data indicate that mix performance within a district is similar for these overlay mixes. The slope of 0.78 established by Khedr fits the data quite well, and on a statistical basis the data do not allow for separation into individual mixes. Each data point represents an average rut depth on individual pavements constructed with potentially different mixes. The similarity of these measurements with expected values indicates that the performance represented by these curves should accurately model rutting as a function of traffic in a general form for the district.

The errors that result from the application of Regression Equation 3 could be considerable. Figure 10 shows the rutting curve for the AASHO Road Test mixture for 80-kN (18-kip) single-axle loads, the rutting curve for the rut rate Equation 2, assuming $m = 0.78$ for District 3 (average $A = 1.3951 \times 10^{-3}$), and the above regression curve Equation 3 using the average material properties for District 3 (*8*). The regression curve for District 3 predicts development of a large rut depth early and very little increased rutting at later stages. This is in direct disagreement with the rut rate curve for District 3, from Figure 9, which predicts the rutting quite well but adds more stability at the earlier loading times (lower A value). The mixtures in District 3 are clearly performing better than the original AASHO mixture. The excessively high rut depth early on from regression Equation 3 is caused by the limited one-time nature of the data that do not allow accurate extrapolation of performance to lower traffic levels. The regression equation is good only for predicting rut depths at a specific level of traffic, nominally 3 million ESALs, and not for predicting development over a range of traffic or over the life of a mixture.

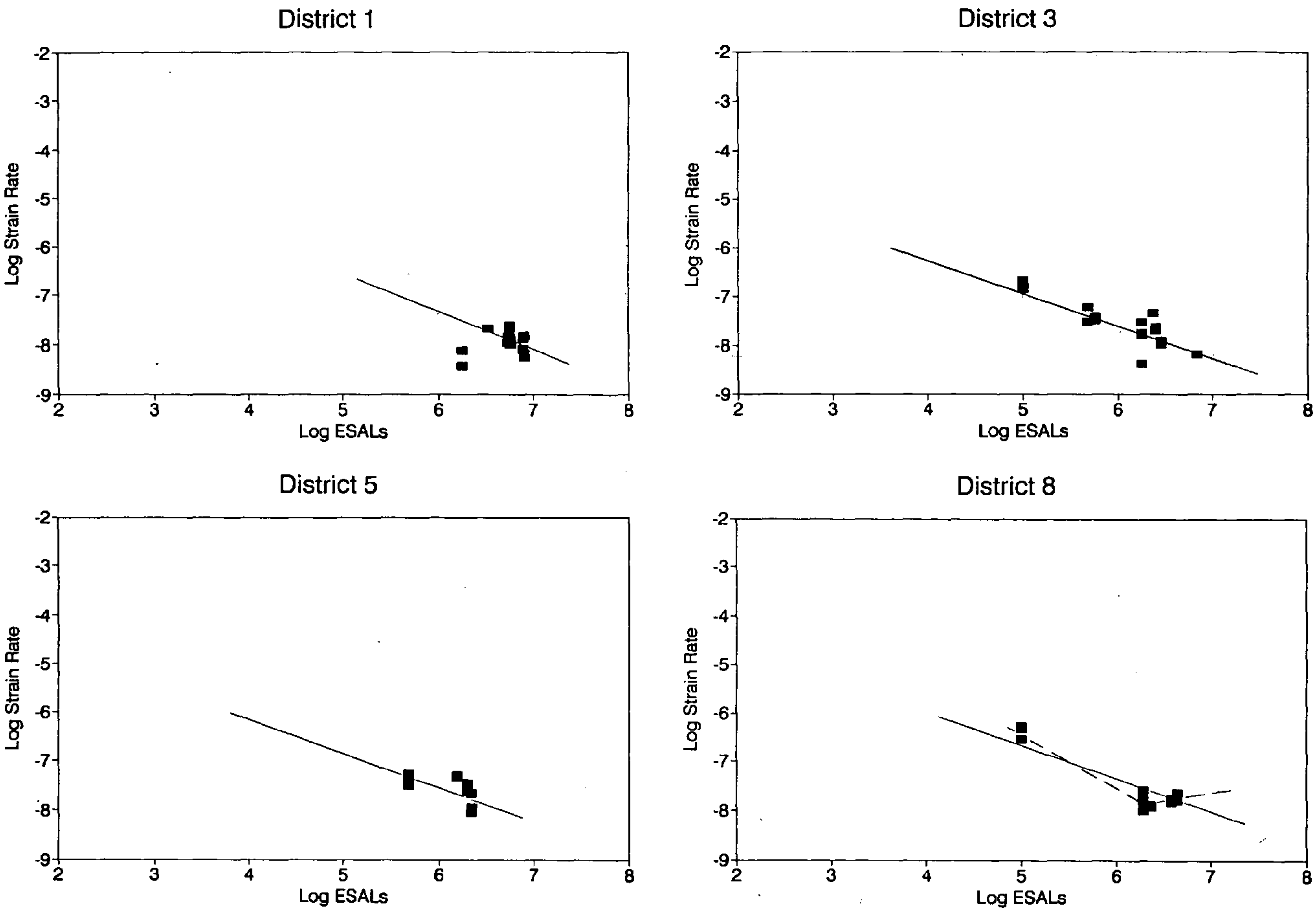

FIGURE 9 Rutting data from 1982 survey correctly plotted.

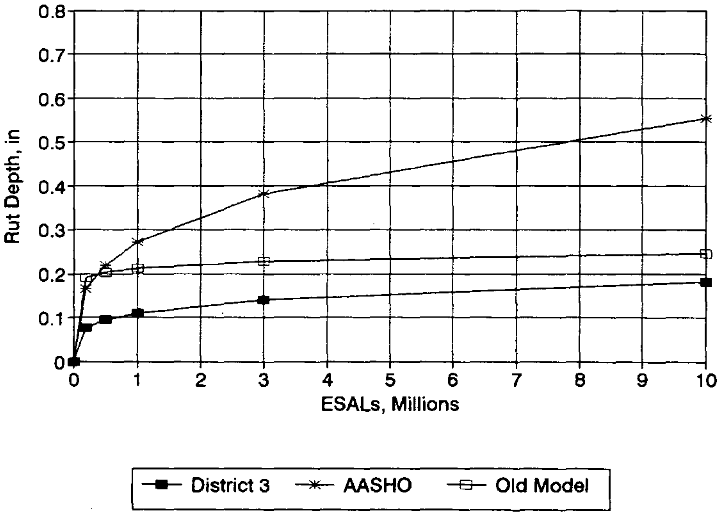

FIGURE 10 Comparison of rutting data from different models (District 3).

These data reinforce the need to use the form of the equation to analyze the resulting deformation. Using such data collected on a mix-by-mix basis, a regression analysis will relate the A- and possibly m-parameters to mixture properties. The mixture relations established by Equation 3 do not provide a means of differentiating quality and comparing long-term performance because there are no individual mixture curves to provide individual A- and m-values for each mixture. The level or type of traffic (stress history level) will also have an impact on the A-values obtained from measurements on a pavement, thus producing different parameters on different pavements containing the same mixture.

Illinois Pavement Feedback System Data Base of Post-1984 Mixes

Placement of the new mix designed by Illinois DOT for overlays of concrete Interstate pavements began in 1984. At this time periodic surveying of these pavements continued, resulting in periodic collection of rut measurements. Presently there are data available for 1985, 1987, 1989, and 1991. These data provide the necessary information to perform an adequate analysis of mixture performance because there have been measurements taken on the same pavements from the time of construction to the current time at regular intervals. Figure 11 shows these data for several contracts placed in District 3, on I-55, I-57, and I-74.

The data in Figure 11 represent rutting measurements on individual contracts, that is, one mixture in the inner and outer wheelpath of the travel lane in both directions of travel. A regression analysis on these data provided the following rutting parameters:

- I-57—$A = 0.0000641$, $m = -0.650$, and $R^2 = 0.91$;
- I-74—$A = 0.006321$, $m = -0.873$, and $R^2 = 0.67$; and
- I-55—$A = 0.000895$, $m = -0.748$, and $R^2 = 0.58$.

Using these regression coefficients, comparisons between calculated rut depths and the data presented earlier from the 1982 survey of District 3 reveal true differences. The comparisons in Figure 12 indicate that the new mixes in this district are developing rutting at a lower rate than is the older pre-1984 mixture. The rut data analyzed and presented in the format of these figures provide a sound basis for extrapolating future rutting development and comparing performance of different mixes on different pavements. This analysis of the data can differentiate the various mixture capabilities to resist rutting.

SUMMARY

With the increased investigations into rutting behavior of mixes, the ability to quantify and compare field and laboratory data on a common basis takes on greater importance. Contemporary studies of field measurements of rutting have not adequately considered the form of rutting development. The result has been a series of comparisons of various mixes and the development of regression equations containing mixture properties that are inconsistent and improperly formulated. The resulting comparisons of mixture quality have little validity because there is no consideration of how far along in the normal development of rutting the mixes were when the rut measurements were taken.

This paper presents comparative data indicative of the errors that could result from an incorrect analysis of rut depth information. With these errors field-generated comparisons bear no relation to laboratory-generated rutting information. These errors prevent a systematic evaluation of mix performance that is necessary for the next generation of performance-based specifications.

Field data can accurately compare the quality of various mixtures in pavements only when they include the form of the development of rutting in the analysis of the collected data. Data analyzed as shown here provide a means of readily comparing mixture behavior. Predictive models developed with a minimum of data collection can accurately indicate mixture variable influences on rutting. Early-life measurements of field rutting, however, cannot provide an indication

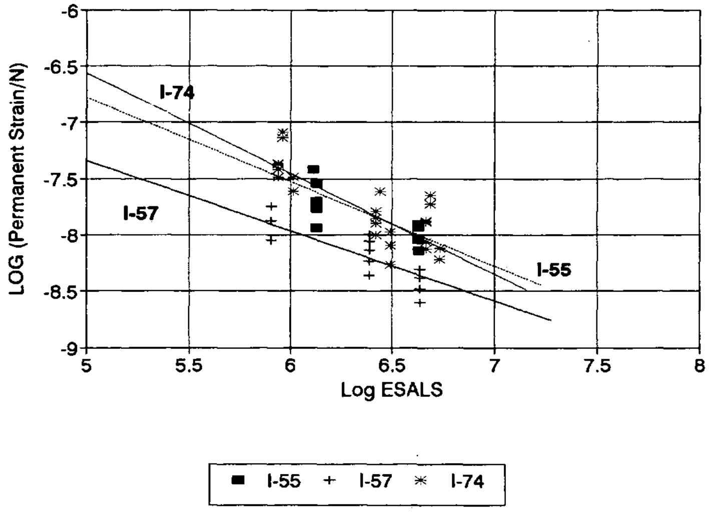

FIGURE 11 Rut survey data for post-1984 mixtures, District 3.

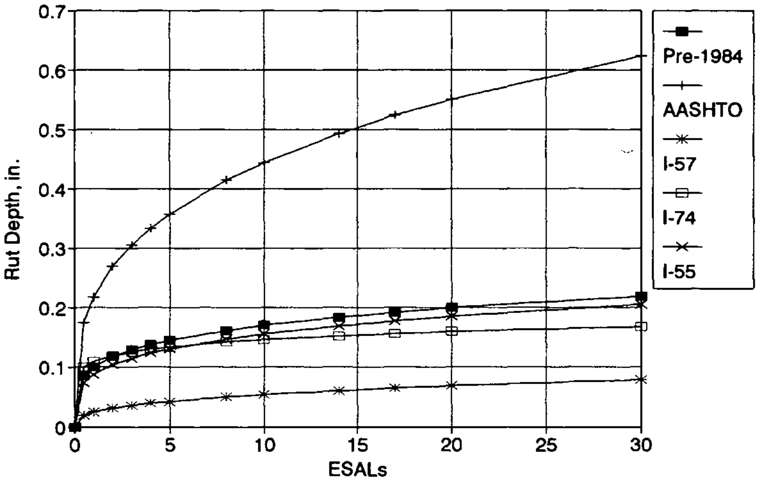

FIGURE 12 **Comparison of pre- and post-1984 mixtures, District 3.**

of the length of stable rut life for a mix. There is a requirement for combining long-term measurements with a coordinated laboratory study. The need to combine laboratory and field data reemphasizes the need to use appropriate characterization methods to ensure data compatibility and consistency.

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