Data Acquisition for Mechanistic-Empirical Overlay Design Equations for Reflection Cracking in Flexible Overlays

P. W. JAYAWICKRAMA, R. E. SMITH, R. L. LYTTON, AND M. R. TIRADO

This paper describes a mechanistic-empirical design procedure developed to assist pavement engineers in determining when flexible overlays of flexible pavements will develop reflection cracking. A mechanistic equation based on fracture mechanics was developed to predict when reflection cracking was expected to occur. Data on in-service pavements were collected for six environmental regions. The equations were used to predict the occurrence of reflection cracking. The performance data were then used to calibrate the mechanistic equations to three different damage levels. The final design equations were placed in a user-friendly microcomputer design program. This paper tries to demonstrate the data collection requirements and problems associated with developing mechanistic-empirical design equations. This approach to developing design equations has great promise; however, the data must be complete and accurate for the approach to be used fully. Some of the problems encountered are described, along with the approaches used to solve these problems.

Asphalt concrete overlays are one of the most common rehabilitation treatments applied to asphalt concrete pavements. Design procedures for these overlays have traditionally been empirical (*1*). In recent years, several mechanistic design approaches have been developed that use the strain at the lower surface of the asphalt layer as a fatigue related design criterion (*1*). This approach relies on the relationships developed between the calculated strain in new pavements and fatigue damage due to traffic loadings.

Reflection cracking is a common form of asphalt concrete deterioration in overlaid pavements, caused by cracks in the original pavement propagating through the new asphalt layer. These cracks in the overlay deteriorate over time, leading to failure of the overlay (*2*). The need for design procedures to address the problem of reflection cracking of asphalt concrete has long been recognized. Such a design methodology, using principles of fracture mechanics to predict overlay life against reflection cracking, was presented by Jayawickrama and Lytton (*3*). This work demonstrated how the mechanistic model could be calibrated using in-service overlay performance data to obtain design equations. The data used in that study were collected from the state of Texas and, therefore, represent the environmental conditions prevailing only in that part of the United States. This paper describes a recently completed project that expanded this effort by collecting data from 11 different states so that all six of the climatic regions shown in figure 1 and described in table 1 are represented.

The boundary between the wet and dry zones is the Thornthwaite Index contour 0, which indicates the moisture balance between annual rainfall (+) and the potential evapotranspiration (−). The boundary between the no-freeze and the freeze-thaw cycling zones represents the contour along which freezing temperatures will penetrate the pavement to a depth no greater than 5 inches (130 mm) (*4*). The boundary separating the freeze-thaw cycling and the hard freeze-spring thaw zones represents the contour along which freezing temperatures persist in the ground for more than 60 days continuously each year (*5*).

Environmental data adequate to define these boundaries were collected from participating state highway agencies, county soil maps, and the National Atmospheric Bureau. Data describing the properties and condition of the pavements over time were collected for use in developing mechanistic-empirical design equations for asphalt concrete overlays on flexible pavements for each climatic region. These results were then integrated into a microcomputer-based design program described elsewhere (*6*).

To develop a mechanistic-empirical design equation, a mechanistic equation is selected or developed that accurately models known forms of failure in the pavement; however, it is generally impossible to model all factors influencing the pavement failure mode. The mechanistic model is calibrated using performance data collected on pavements to reflect the influence of these factors. Data used in the mechanistic model must be available on the pavement sections used for the calibration process.

This paper briefly describes the process of selecting an appropriate mechanistic equation and the empirical calibration process. The model defined the data required for the calibration process. The problems encountered in collecting and using data from in-service pavements is described. A complete and detailed description of the design method is presented elsewhere (*3*, *6*).

REVIEW OF MECHANISTIC MODEL DEVELOPMENT

The mechanisms generally thought to lead to reflection cracking are the vertical and horizontal movement of the underlying layers. These damaging movements may be caused by traffic

P. W. Jayawickrama, R. E. Smith, and R. L. Lytton, Texas Transportation Institute, College Station, Tex. 77843. M. R. Tirado, ERES Consultants, Inc., P.O. Box 1003, Champaign, Ill. 61820.

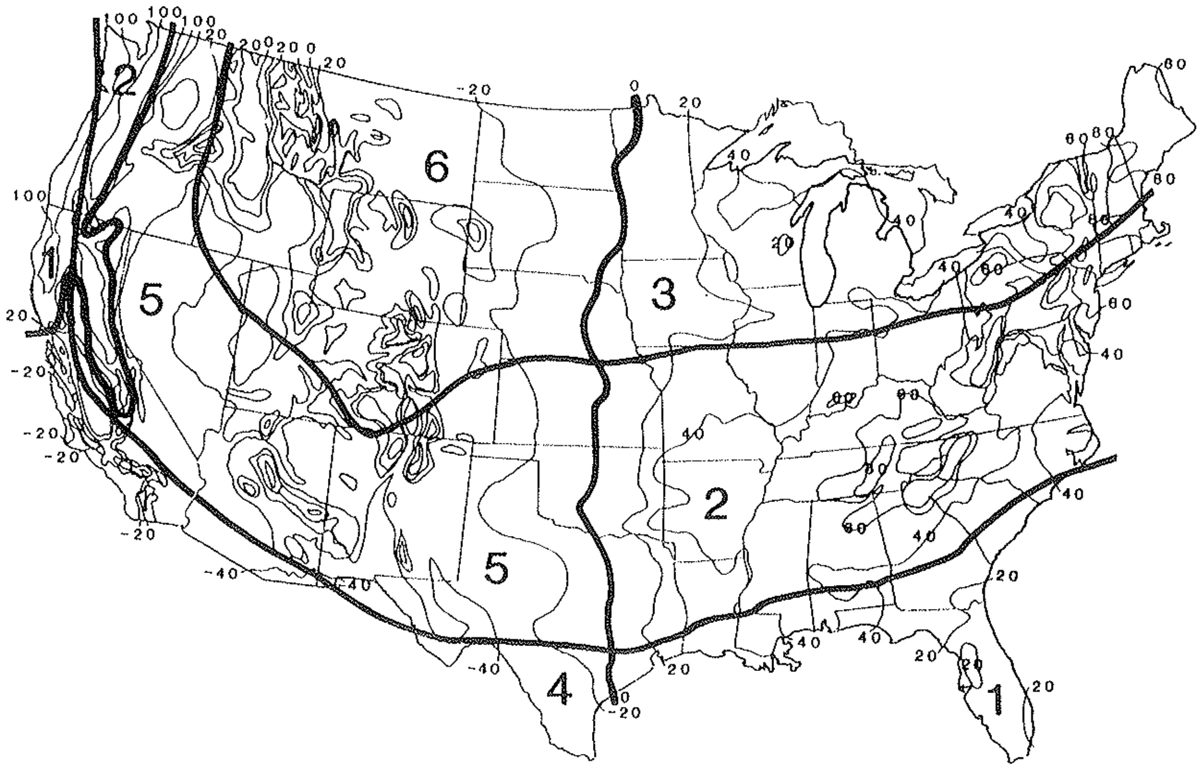

FIGURE 1 The six climatic regions in the United States (*1*).

loading, thermally induced contractions and expansions, or a combination of these mechanisms.

Figure 2 illustrates the changes in bending and shear stresses that occur within an overlay as a wheel load passes over a crack in the original pavement. These stress conditions cause the crack to propagate into the overlay, due to shearing movement in one direction followed by a bending movement and again by shearing movement in the opposite direction. In addition to the influence of the traffic loads, contraction and expansion of the pavement and the underlying layers with changes in temperature also contributes toward the growth of reflection cracks. In these three mechanisms of crack growth, the stresses generated cause a crack to form in the overlay and grow with repeated application. The principles of fracture mechanics are used to determine the rate of crack growth due to these mechanisms. In this process each crack growth mechanism is treated independently, and their influence is combined in a final design equation.

The recent developments in linear elastic and viscoelastic fracture mechanics concepts have enabled a rational design approach to the problem of reflection cracking of overlays. Experimental investigations carried out at Ohio State University (*7–9*) and Texas A&M University (*10–12*) have verified the applicability of fracture mechanics principles in predicting fatigue life of asphalt concrete mixes. The results indicate that the rate of crack propagation in asphalt concrete can be predicted by using the empirical power law relation developed by Paris (*13*).

$$\frac{dc}{dN} = A(\Delta K)^n \qquad (1)$$

where

ΔK = stress intensity factor amplitude,
A,n = fracture parameters of the material,
c = crack length, and
N = number of load applications.

Integrating Equation 1 we obtain,

$$N_f = \int_0^h \frac{dc}{A(\Delta K)^n} \qquad (2)$$

where

N_f = number of load applications to failure
h = thickness of the overlay

The use of Paris' crack growth law to determine the overlay life requires a knowledge of the stress intensity factor, K, and the material constants, A and n, within the in-service overlay. The stress intensity factor, K, in the overlay due to each of the crack growth mechanisms was determined by using a formulation that combines beam-on-elastic foundation theory and the finite element method. In the beam-on-elastic foundation analysis the original surface layer and the overlay are modeled as a beam. The base course and the subgrade are

TABLE 1 DESCRIPTION OF CLIMATIC REGIONS

Region	Character of the Region
1	Wet, No-Freeze
2	Wet, Freeze-Thaw Cycling
3	Wet, Hard Freeze, Spring Thaw
4	Dry, No-Freeze
5	Dry, Freeze-Thaw Cycling
6	Dry, Hard Freeze, Spring Thaw

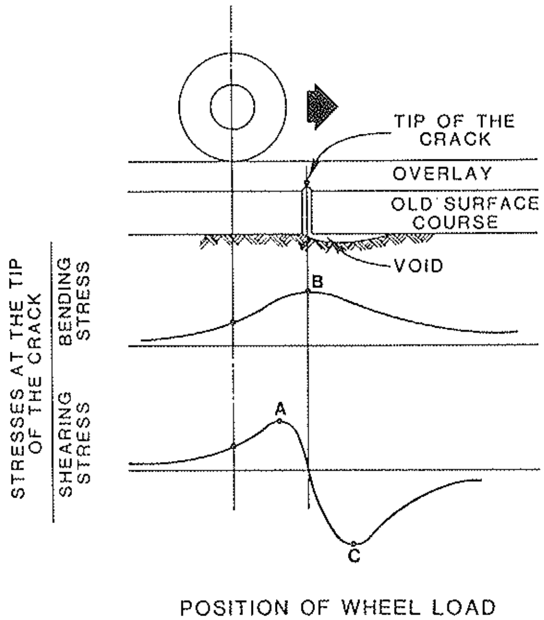

FIGURE 2 Stresses induced at a cracked section due to a moving wheel load.

represented as a homogenous elastic medium supporting the beam. In order to calculate the stress intensity factors accurately and determine their variation with the crack length, a finite element method was used (*6*).

The use of the mechanistic model for the analysis of crack propagation through an overlay requires a knowledge of overlay stiffness as well as fracture parameters, A and n. The mix stiffness is determined using the nomograph procedure outlined by Van der Poel (*14*) and Mcleod (*15*). In this study, computerized versions of the nomographs were used. In addition, the computer programs profile the slope, m, of the log of the mix stiffness versus log of the loading time curve which is used to determine the exponent, n, in Paris' equation as shown below:

$$n = 2/m \tag{3}$$

Theoretical justification for equation 3 can be found elsewhere (*16*). This relationship has been verified for asphalt concrete mixes by Germann and Lytton (*10*) and Molenaar (*17*).

The following empirical relationships, developed based on the crack growth tests of asphalt concrete mixes, were used to determine the parameter, A:

For traffic associated cracking:

$$n = -2.2 - 0.5 \log A \tag{4}$$

For thermal cracking:

$$n = -0.92 - 0.42 \log A \tag{5}$$

The propagation of reflection cracks is the result of all three failure mechanisms (bending, shearing, and thermal) acting simultaneously. However, in the integration of the Paris' equation the three failure mechanisms are treated independently.

It is recognized that this idealized model may not provide accurate estimates of the stress intensity factors induced by the different loading mechanisms in the various mixes. However, the model can be used to establish the form of the equation that reflects the correct influence trends of the variables. The form of the regression model in the empirical calibration was selected to incorporate the influence of the combined action of the three mechanisms into the final design equation. The in-service performance data is then used in the regression analysis, which compares the mechanistically calculated time-to-crack formation with recorded crack development to develop equations that reflect the expected performance in each of the six climatic regions.

DATA NEEDS

The data required by the mechanistic equation to calculate the time until the pavement develops a reflective crack must be available for the in-service pavement sections used in this process. This same data will be required for use in the design program. The following information is required for calculating the overlay life using the mechanistic equations in this project:

- Laboratory data on the bitumen and the mix—to characterize the asphalt material used in the overlay,
- Deflection test data—to characterize the existing pavement structure,
- Environmental data pertaining to the location, and
- Traffic data.

In order to combine the influence of the three different mechanisms, the mechanistically computed overlay responses are regressed against crack development rates in the overlays. Therefore it is also necessary to collect data on overlay performance.

DATA ACQUISITION

Previous studies indicated that sufficient data were not available to develop one overlay design equation for the whole United States, primarily because of the excessive amount of data required to account for climatic and regional differences. However, they did indicate that sufficient data were available to develop regional equations (*18*). Considerable effort is required to collect data adequate for use in calibrating mechanistic empirical design equations. Many state highway agencies have some of the data needed to develop mechanistic-empirical equations; however, very few have all of the data needed.

DATA SOURCE LOCATION

The information on available data (*18*, *19*), along with other sources, were used to begin the search for in-service data. Many of the agencies stated that they did not have all such data for their pavements. Others were reluctant to participate in the project because the data required were not readily available or retrievable. Those agencies that did have the needed data generally did not have all required data in one file set.

In many instances during the data collection effort, it was found that the required data on a desirable in-service pavement section was missing from the files. So an agency would often start with 30 to 40 candidate in-service pavement sections on which the researchers expected to collect data only to end with 5 to 15 sections with adequate data for use in the project. As a result, the researchers never knew the number of sections on which data could be collected until they were on site at the agency. In some instances, it was not possible to be sure that the data were usable until after the data was collected and reduced into common-analysis units. When the data were normally stored in several different files, each file would often have a different referencing or cataloguing scheme, making it difficult to cross reference the data elements. So even when data could be found, it was not always possible to identify corresponding data sets, such as which asphalt properties corresponded to a given section of pavement.

DATA REDUCTION

Raw data were collected from several different agencies, as shown in table 2. In many instances the data gathered by the research team were not measured or collected in the same form by the various highway agencies from which it was gathered. When data in different forms are used, they must be reduced to similar forms of material and response characteristics before they can be used in developing the desired mechanistic-empirical design equations.

Asphalt Material Characterization for the Overlay

The stiffness of the asphalt-concrete overlay must be known in order to determine the fracture properties and was calculated using the Van der Poel or Mcleod method (*14, 15*). To use the Van der Poel method, the following properties of the bitumen and the mix must be known:

- Penetration at 77°F,
- Ring and ball softening point,
- Asphalt percentage in the mix or volume concentration of aggregate,
- Time of loading, and
- Age of mix or time in service.

Many of the pavement sections did not have ring and ball softening point data. In those cases, the McLeod procedure was used which requires the following data.

- Penetration at 77°F,
- Viscosity at 275°F or viscosity at 140°F,
- Service Temperature,
- Time of Loading,
- Asphalt percentage in the mix or volume concentration of aggregate, and
- Percent of air voids.

Any set of data that could be used in either of these two procedures was accepted. These data were generally determined from laboratory test results found in construction records. In some cases they were the result of many specific tests made for the project, which was the original intent; however, in other cases, asphalt properties were from asphalt sources tested over the period of time during which the project was constructed.

Mix design properties were taken from quality control records in the construction records in most cases. When these were not available, the mix design parameters were taken from standard mix design requirements in effect at the time of the overlay construction; however, this may add error to the results. Time of loading was selected to represent a moving wheel load of a truck; service temperature was selected based on environmental information for the areas; and age of mix was based on construction date. Availability, or locating, the asphalt cement and mix design properties for the overlay were major problems of this data collection effort.

Characterization of the Existing Pavement Structure

The mechanistic model represents the existing pavement prior to the overlay as a beam on elastic foundation. The stiffness characterizing the surface and foundation support can be determined from deflection testing data on the existing pavement prior to the time of the overlay, in conjunction with layer thickness. A record of construction history was obtained for each section used in this analysis to determine the thickness of each layer and its date of construction; in some cases this was supplemented with coring reports. It would have been beneficial to have had deflection data across a series of cracks in the pavement prior to the overlay to determine the load transfer level; however, those data were not available. Many projects with otherwise usable data were discarded from this project when deflection data could not be located for them.

Climatic Data

The temperature and moisture information defining the climatic zone in which the pavement section is located were described earlier. The 24-hour temperature drop and average monthly temperature were the other two climatic data elements required. They were found in the same sources.

Traffic

Traffic data regarding the average number of 18,000-lb equivalent single-axle loads (ESALs) per day over the life of the overlay were collected from the highway agencies. Where they had some other measure of traffic such as average daily traffic (ADT), their conversion system of converting ADT to ESAL was used. It was then converted to average ESAL per day. Several of the agencies expressed reluctance at providing traffic data because they were not sure of its accuracy.

Performance (Distress)

The mechanistically computed development of cracking is compared to the observed crack development in the regression process. To determine the amount of reflection cracking that developed over time, distress data regarding reflection

TABLE 2 DISTRIBUTION OF PAVEMENT SECTIONS ON WHICH DATA WERE COLLECTED AND USED

STATE	CLIMATIC ZONE 1 AC	1 PCC	2 AC	2 PCC	3 AC	3 PCC	4 AC	4 PCC	5 AC	5 PCC	6 AC	6 PCC	Total AC	Total PCC
Arizona							03 / 06		34 / 43				37 / 49	
Arkansas			-- / 03	03 / 03									-- / 03	03 / 03
California	02 / 02		06 / 07				10 / 14		02 / 04				20 / 27	
Florida	-- / 09	-- / 03											-- / 09	-- / 03
Georgia			-- / 01	03 / 03									-- / 01	03 / 03
Idaho											11 / 14		11 / 14	
Illinois				20 / 24				14 / 15						34 / 39
Minnesota					10 / 10	06 / 08					03 / 03	-- / 01	13 / 13	06 / 09
Texas	01 / 01		08 / 08				03 / 03		24 / 24				36 / 36	
Utah									03 / 03		10 / 11		13 / 14	
Washington	07 / 07		35 / 36	05 / 05									42 / 43	05 / 05
TOTAL	10 / 19	-- / 03	49 / 55	31 / 35	10 / 10	20 / 23	16 / 23		63 / 74		24 / 28	-- / 01	172 / 209	51 / 62

Note $\frac{\#\#}{\#\#} = \frac{\text{No. Pavement Sections Used}}{\text{No. Pavement Sections Collected}}$

cracking after the application of the overlay is required. Since the performance used in the mechanistic approach considered damage that varied from zero to one, the distress data had to be transformed into equivalent levels of damage (*18*). Even had this not been required, the data would still have had to be transformed into a common set. Each agency collects distress data in its own form, and virtually no two agencies used the same distress identification system. The distress identification system from each agency was used to develop a conversion similar to that used in the initial program (*3*). The transformations used to convert the distress from each data set into a common damage function are presented elsewhere (*6*).

DEVELOPMENT OF PERFORMANCE CURVE

The observed damage levels over time and traffic were used to develop a mathematical equation to describe the growth of damage, or overlay reflection cracking, with increasing time and increasing number of load passes for each pavement section included in the project. By comparing the mechanistic crack development time with observed time to reach various levels of damage, design equations could be developed for different amounts of allowable reflection cracking.

Two forms of reflection cracking were considered: transverse and longitudinal. It was hoped to use both distress area and severity; however, only distress area was available for many of the in-service pavements. As a result, only area was used for the final equations.

Different forms of equation have been used to fit the observed pavement distress data over increasing time or axle load applications. The following equation was selected for use in the present analysis since it is in accordance with the physical boundary conditions (*18*):

$$g = e^{-(\rho/N)^{\beta}} \qquad (6)$$

where

g = the damage rating of the pavement
N = the number of load applications in 18-kip ESALs
ρ, β = characteristic parameters

An equation that relates the damage level of the distressed pavement to the number of load applications is commonly referred to as a structural performance curve. The damage rating of the pavement is a variable that ranges between 0, representing a smooth riding or undistressed surface, to 1, representing a severely damaged pavement structure. Therefore, the performance curve of a pavement will be bounded by 0 and 1. Pavement distress observations show that the performance curve starts out horizontally, bounded from below by a rating of 0. As the number of load applications increases, the curve will asymptotically reach the damage rating of 1. These boundary conditions imply that the functional performance curve should be sigmoidal, or *S*-shaped.

Nonlinear regression analysis techniques were used to develop the performance cures to define a relationship between damage and the number of load applications, N_{18}. This allows the number of applications to be determined at any desired level of damage. Several problems were encountered in using these programs. The nonlinear regression procedures are not always straightforward, especially if the data are not well defined through the entire area defining all parameters in a curve. Thus, there is not always one unique curve that will fit the data points and meet the convergence criteria. Since many of the data sets contained data with damage levels only to levels of 0.1 or less, several sets of regression parameters could be fit through those points and still meet the convergence criteria. Luckily, the major differences in predicted values are above damage levels of 0.5 and have little impact on the results used in this project.

Because some of the distress identification procedures report distress in condition categories, for example, 5 to 15 percent equals distress rating of 2, some of the distress data had plateaus, as illustrated in figure 3. When regression was conducted, parameters could be calculated to define the curve shown as A in figure 4, or another set could be calculated to define the curve shown as B in figure 4. The performance curves for this type of data were forced to follow the shape identified as Curve B in figure 4 because it was believed that the observed data was in the earliest stages of distress development. Allowed to develop further, it is expected that they would develop the *S*-shape defined by Curve B in figure 4.

In some of the in-service pavement sections, no distress had developed at the time of data collection resulting in all zero damage levels. These sections could be ignored; however, ignoring pavements that were performing well would bias the data. To use these data, average ρ and β values for the non-

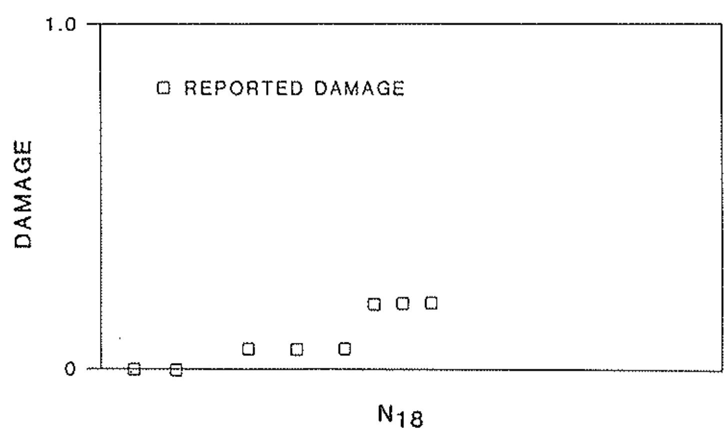

FIGURE 3 Distress data with plateaus.

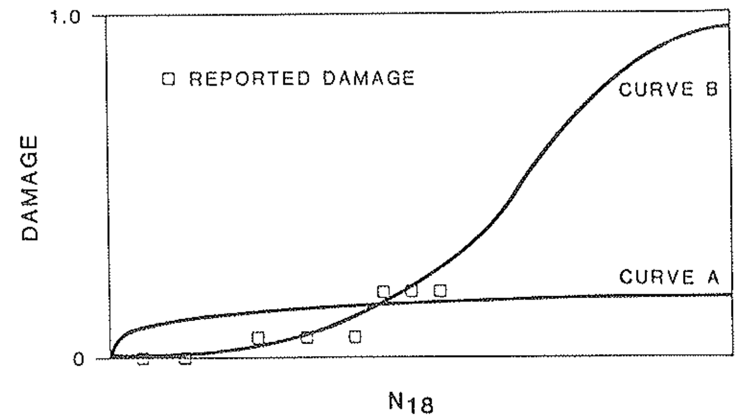

FIGURE 4 Curves fitting data with plateaus.

zero data sets within each climatic/pavement type group were determined. Those values were used to define the curve through the all zero data points, as illustrated in figure 5. If the all-zero points extended to the right of the curve from the average values, the ρ values were increased until the curve extended through all of the reported zero points as shown in figure 5. This allowed the influence of the all-zero points to be included in the analysis.

RESULTS

A final set of design equations to address reflection cracking were developed that allow the designer to select a damage level of 0.33 for a moderate amount of reflection cracking, 0.50 for a high amount, and 0.44 for an intermediate amount. They have been placed in a user-friendly microcomputer program that can be used by highway engineers to determine when reflection cracking is expected to develop in an overlay of desired thickness for different asphalt cement and mix properties. This research has extended the work that began in NCHRP Project ZO-7, Task 17, Phase II, and includes design equations for six climatic regions for asphalt overlays.

This is a major step forward in developing design equations that address the performance problems of asphalt concrete overlays. The best available data was used to calibrate the mechanistic equations; however, they would be more reliable if the data used to calibrate the mechanistic equations were more complete and comprehensive. They can be improved by using more accurate in-service data when it becomes available.

The data used to calibrate the mechanistic equations were collected from agencies with data on pavements of the type needed in the desired climatic zones. The data did not come from a designed experiment, and all the problems inherent in using this type of data are incorporated into these design equations. One of the biggest problems with this type of data is that unknown biases exist, making it impossible to determine the true reliability of the resulting data. In addition, the variability and reliability of the data collected were generally unknown. This does not mean that the equations are unreliable, but it does mean that the reliability of the design equations developed using this type of data cannot be accurately defined.

The mechanistic empirical approach to overlay design has been shown to be feasible and practical. It has also shown the need for collecting accurate data with variability and reliability information included for use in developing mechanistic-empirical equations. The mechanistic empirical approach provides an excellent means to develop design equations that are soundly based on mechanistically correct concepts with a limited number of parameters. However, they will only be as

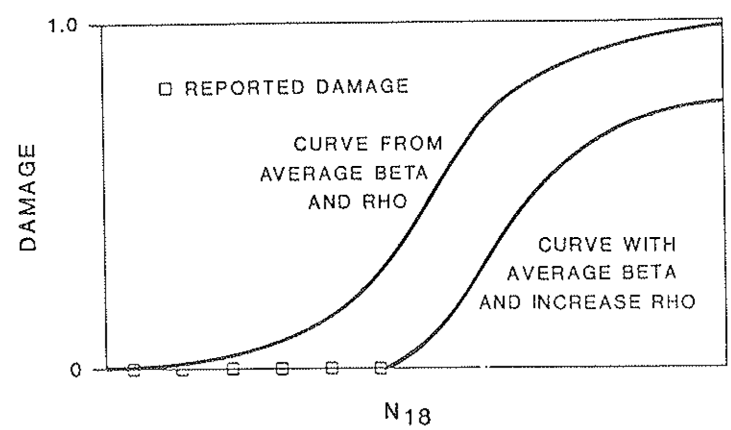

FIGURE 5 Using all zero data points.

good as the data used to calibrate them. Until accuracy of available data is known, accuracy of the resulting design equations will be unknown.

RECOMMENDATIONS

The data collection problems in this and other projects demonstrate the need for a comprehensive centralized data collection effort if mechanistic-empirical procedures are to be used in the pavement engineering field. The data required to calibrate these and other mechanistic empirical design equations should be collected in the Strategic Highway Research Program (SHRP). These data should be collected in a manner to avoid the problems of possible bias and uncertainties that occur in using available data to calibrate mechanistic equations. These data can then be used to update this first set of design equations.

ACKNOWLEDGMENTS

This paper is based on work completed by ERES Consultants, Inc., and the Texas Transportation Institute. The work was sponsored by the Office of Research and Development, Federal Highway Administration. The contracting officer's technical representative was Peter Kopac. The assistance of the several state highway department personnel is gratefully acknowledged.

REFERENCES

1. R. E. Smith, R. P. Palmieri, M. I. Darter, and R. L. Lytton. *Pavement Overlay Design Procedures and Assumptions, Volume I, Analysis of Existing Procedures*. FHWA/RD 85/006, FHWA, McLean, Va., 1986.
2. R. E. Smith, M. I. Darter, and S. M. Herrin. *Highway Distress Identification Manual*. FHWA-RD-79-66, FHWA, Washington, D.C., 1979.
3. P. W. Jayawickrama and R. L. Lytton. Methodology for Predicting Asphalt Concrete Overlay Life Against Reflection Cracking. *Proceedings, Vol I, Sixth International Conference on Structural Design of Asphalt Pavements*, Ann Arbor, Mich., July 1987, pp. 912–924.
4. *Frost Action in Roads and Airfields. Special Report No. 1*, HRB, National Research Council, Washington, D.C., 1951, p. 123.
5. *Report on Frost: Investigation, 1944–45*. New England Division, U.S. Army Corps of Engineers, U.S. War Department, Boston, Mass., April 1947.
6. P. W. Jayawickrama, R. E. Smith, R. L. Lytton, and M. R. Tirado. *Development of Asphalt Concrete Overlay Design Equations, Vol. I, Development of Design Procedures*. FHWA, Washington, D.C., 1987.
7. K. Majidzadeh, C. Buranarom, and M. Karakouzian. *Application of Fracture Mechanics for Improved Design of Bituminous Concrete*. Report No. FHWA-RD-76-91, Vol. I, June 1976.
8. K. Majidzadeh, D. V. Ramsamooj, and T. A. Fletcher. Analysis of Fatigue of Sand Asphalt Mixtures. *Proceedings, Association of Asphalt Paving Technologists*, Vol. 30, 1969.
9. K. Majidzadeh and D. V. Ramsamooj. *Development of Testing Procedures and a Method to Predict Fatigue Failures of Asphalt Concrete Pavement Systems*. The Ohio State University Research Foundation, Project RF 2873, March 1971.
10. F. P. Germann and R. L. Lytton. *Methodology for Predicting Reflection Cracking Life of Asphalt Concrete Overlays*. Report No. FHWA/TX 79/09/207-5, March 1979.
11. R. L. Lytton and U. Shanmugham. *Fabric Reinforced Overlays to Retard Reflection Cracking*. Report RF-3424-5, Texas A&M Research Foundation, February 1983.
12. R. L. Lytton and K. H. Tseng. *Laboratory Evaluation of Overlays Reinforced with Fabrics*. Texas Transportation Institute, Texas A&M University, College Station, Tex., May 1983.
13. P. C. Paris and F. Erdogan. A Critical Analysis of Crack Propagation Laws. Transactions of the ASME, *Journal of Basic Engineering*, Series D, S5, No. 3, 1963.
14. C. Van der Poel. A General System of Describing the Viscoelastic Properties of Bitumens and Its Relation to Routine Test Data. *Journal of Applied Chemistry*, Vol. 4, May, 1954.
15. N. W. Mcleod. Asphalt Cements:aPen-Vis Number and Its Application to Moduli Stiffness. *Journal of Testing and Evaluation*, Vol. 4, No. 4, 1976.
16. R. A. Schapery. *A Theory of Crack Growth in Viscoelastic Media*. Report MM-2764-73-1, Mechanics and Materials Center, Texas A&M University, College Station, Tex., 1973.
17. A. A. A. Molenaar. *Structural Performance and Design of Flexible Load Constructions and Asphalt Concrete Overlays*. Ph.D. thesis, Delft University of Technology, The Netherlands, May 1983.
18. R. L. Lytton and A. Garcia-Diaz. *Evaluation of AASHO Road Test Satellite and Environmental Studies*. NCHRP Project 20-7, Task 17, Texas Transportation Institute, Texas A&M University, College Station, Tex., 1983.
19. R. L. Lytton, and G. L. Kohutek. *Evaluation of AASHO Load Test Satellite and Environmental Studies*. Phase II Final Report, NCHRP Project 20-7, Task 17, Texas Transportation Institute, Texas A&M University, College Station, Tex., 1983.

Publication of this paper sponsored by Committee on Pavement Rehabilitation.