Evaluating Structural Damage of Flexible Pavements Using Cracking and Falling Weight Deflectometer Data

PETER SEBAALY, NADER TABATABAEE, RAMON BONAQUIST, AND DAVID ANDERSON

The relationship between surface cracking and the structural capacity of both thin and thick pavement structures was investigated using field data from the FHWA Pavement Testing Facility test sections. The test sections were loaded with the Accelerated Loading Facility. Surface cracking was evaluated in terms of lineal cracking and AASHO Class 2 and 3 cracking; structural capacity was evaluated in terms of peak deflections and back-calculated moduli of the asphalt concrete layer under falling weight deflectometer testing. The field data indicated a definite lag between the loss of structural capacity and the appearance of surface cracking for both thin and thick pavements. Because a structural capacity loss may exist before cracks appeared on the surface, the use of surface cracking to indicate structural condition may be misleading in several cases. Field data on peak deflections indicated that the deflection ratio may reach a value of 2 before any surface cracking appears and a value of 3 before any AASHO Class 2 and 3 cracking appears on the surface. The back-calculated moduli of the asphalt layer were reduced by 50 percent before any lineal cracking or AASHO Class 2 and 3 cracking appeared on the surface.

The failures of flexible pavements under traffic loading are classified under two categories: functional and structural. The functional performance is usually evaluated through subjective measurements conducted at the pavement surface. Manual surveys (such as crack mapping and visual observations) and automated photographic techniques (such as the Pasco and ARAN systems and the laser survey system) have been extensively used in various pavement management systems (PMS).

The structural performance of pavement is seldom evaluated at the network level. The majority of the techniques available to evalute the adequacy of pavement structure are used at the project level. The functional performance surveys at the network level are often used as catalysts for more sophisticated structural adequacy evaluations at the project level. This process of pavement performance monitoring would be acceptable if a direct relationship existed between surface distresses and the structural capacity of pavements. For example, the lack of alligator cracks on the surface of a pavement structure may not be interpreted as a guarantee of the structural adequacy of the pavement. On the other hand, the first appearance of alligator cracking may be the result of the total loss of the structural capacity of the pavement. Therefore, indicators that have been used as triggering devices in various PMS practices may not be appropriate.

The research presented in this paper examines the relationship between the structural and functional performance parameters. Two pavement structures were tested using the FHWA Accelerated Loading Facility (ALF). Among the various performance parameters studied were the surface cracking and load-deflection response of the pavement structures under falling weight deflectometer (FWD) loading. The correlation between the amount of surface cracking and the actual structural loss of various pavement sections was investigated.

BACKGROUND

Surface distress surveys play a primary role in pavement management systems used throughout most state and local agencies. The findings of the AASHO Road Test have been used to recommend that riding quality as expressed by the present serviceability index (PSI) would suffice as an indicator of pavement performance (*1*). However, little weight was given to the presence of surface cracking and the actual fatigue of the asphalt concrete materials. The PSI is still commonly used, and the most recent versions of the equation do not include any contribution from cracking or surface fatigue (*2*, p. 224).

Many PMS use surface cracking as an indicator of the structural condition of a pavement. Various levels of cracking serve as triggers for determining maintenance and rehabilitation needs. By using surface cracking to indicate structural condition, these systems assume a relationship exists between surface cracking and loss of structural capacity. The remainder of this paper investigates the reliability of this assumption.

DATA COLLECTION

Pavement Testing Facility

The data for this evaluation were obtained during the first phase of research at the FHWA Pavement Testing Facility (PTF). This facility is an outdoor, full-scale pavement testing laboratory that includes (a) the ALF testing machine, (b) two instrumented, asphalt concrete test pavements, and (c) a computer-controlled data-acquisition system.

P. Sebaaly, N. Tabatabaee, and D. Anderson, Pennsylvania Transportation Institute, Research Building B, University Park, Pa. 16802. R. Bonaquist, Office of Research, Development, and Technology, FHWA, 6300 Georgetown Pike, HR-20, McLean, Va. 22101.

The ALF is used to simulate traffic loading. It models one-half of a dual-tire, single axle and can apply loads ranging from 9,400 to 22,500 lb. The test wheels travel at 12 mi/hr over 40 ft of pavement. To simulate highway traffic, the loads are applied in one direction and are normally distributed over a 48-in. wheel path.

Each test lane is divided into four sections for a total of eight test sections. Lane 1 consists of 5 in. of asphalt concrete over 5 in. of crushed aggregate base. Lane 2 consists of 7 in. of asphalt concrete over 12 in. of crushed aggregate base.

Test Conditions and Failure Modes

Data from six of the eight test sections were used in this study. Table 1 presents the load, tire pressure, testing period, and number of applied-load repetitions. The test section was considered to have failed when the average rutting reached a value of 0.5 in. or the lineal cracking reached a value of 50 in./ft^2. After each test section failed, a postmortem evaluation was conducted to determine the mode of failure. This evaluation consisted of excavating the pavement layers; obtaining transverse profiles, density measurements, and samples for laboratory testing; and documenting the cracking and rutting through a cross section of the pavement.

If the section showed an average rutting of 0.5 in., the failure mode was considered to be rutting; however, if the section showed a lineal cracking value of 50 in./ft^2, the failure mode was considered to be fatigue. Fatigue of the asphalt concrete was the predominant failure mode for the tests used in this evaluation. Lane 1, Section 3 failed prematurely as a result of cracking that emanated from two core holes in the test section. Portions of the test section, however, showed little distress when trafficking was stopped; had the test continued, these areas would probably have failed as a result of fatigue. Excessive rutting in the subgrade was the primary failure mode only for the thin pavement trafficked with heavy loads.

TABLE 1 TEST CONDITIONS

Test Section	Load, lb	Tire Pressure, psi	Start Date	End Date	Load Applications	AASHO Equivalence Factors
Lane 1, Section 1	14,100	100	3/24/88	4/04/88	37,033	5.49
Lane 1, Section 2	11,600	100	12/14/87	2/18/88	147,696	2.53
Lane 1, Section 3	11,600	100	9/04/86	2/23/86	66,523	2.53
Lane 1, Section 4	16,400	100	3/01/88	3/08/88	14,240	10.50
Lane 2, Section 2	19,000	140	6/18/87	1/24/87	578,142	11.5
Lane 2, Section 3	19,000	100	1/08/87	6/04/87	502,662	11.5

Pavement Performance Monitoring

Routine performance monitoring at the PTF included periodic measurements of cracking, rutting, slope variance, FWD deflections, and strain at the bottom of the asphalt layer. For this study, only the cracking and FWD deflection data were considered.

A manual procedure was used to measure cracking. On a regular schedule, a clear plastic sheet was placed over the test section and the cracks were traced onto the plastic, using different color markers each time a crack survey was performed. The test section was then divided into eight 4-ft-long by 6-ft-wide subsections. The total length of all cracks in each subsection was measured with a map wheel, and the surface area of AASHO Class 2 and Class 3 cracking was estimated.

Surface deflections were measured periodically with a Phonix Model ML 1,000 FWD. Loads ranging from 7 to 14 kip were applied through a 5.9-in.-diameter plate. Surface deflections were measured with geophones at six radial offsets ranging from the center of the loading plate to 50 in., and FWD tests were conducted in each of the eight subsections used for the crack survey.

DATA REDUCTION

Cracking

In most distress surveys, load-associated cracking is measured using a procedure similar to that developed during the AASHO Road Test. At the road test, three severity levels were identified for load-associated cracking: *Class 1* cracking was defined as disconnected hairline cracks running parallel to each other; further development of cracking to form a pattern of blocks was defined as *Class 2* cracking; and *Class 3* cracking was defined as Class 2 cracking that has progressed to the point that the blocks have become loose and rocked under traffic. The area of pavement surface exhibiting each class of cracking was measured and normalized with regard to 1,000 ft^2. Only the areas of AASHO Class 2 and 3 cracking are considered in most distress surveys.

Because the test sections at the PTF are only 32 ft long, it was possible to track cracking more closely than described above. Each time a crack survey was conducted, the total length of all cracks within a test section was carefully measured using a map wheel. Because the surface area over which the cracking was measured remained constant, the total crack length represented crack density. The average accumulation of total crack length and AASHO Class 2 and 3 cracking as a function of cumulative 18-kip equivalent single-axle load (ESAL) is presented in Figures 1 and 2 for typical tests on Lanes 1 and 2, respectively. From these figures, it is apparent that any small changes in the cracked surface would appear in the measurement of crack length long before they would appear in the measurement of AASHO Class 2 and 3 cracking. An example of the increased sensitivity is presented in Figure 3, which shows two areas with the same surface area of AASHO Class 2 cracking. It is obvious, however, that these areas have different total crack lengths.

FWD Deflections

FWD deflections were used in two approaches to monitor the structural performance of the test sections. In the first, the variations of the peak deflections were compared at various

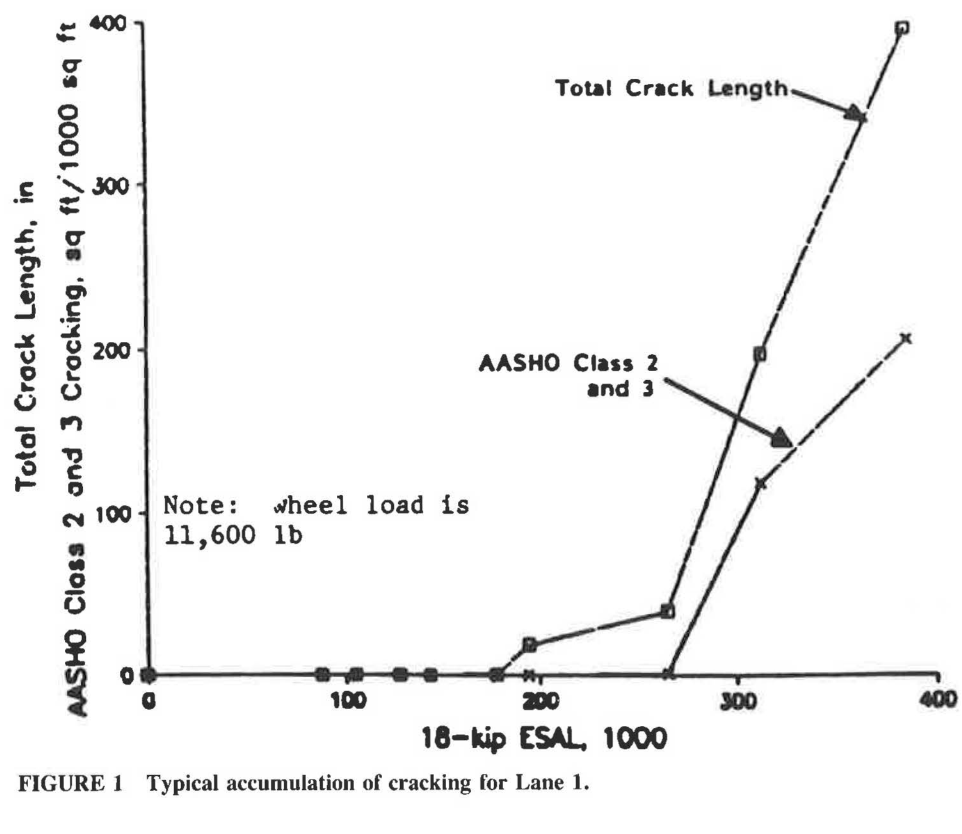

FIGURE 1 Typical accumulation of cracking for Lane 1.

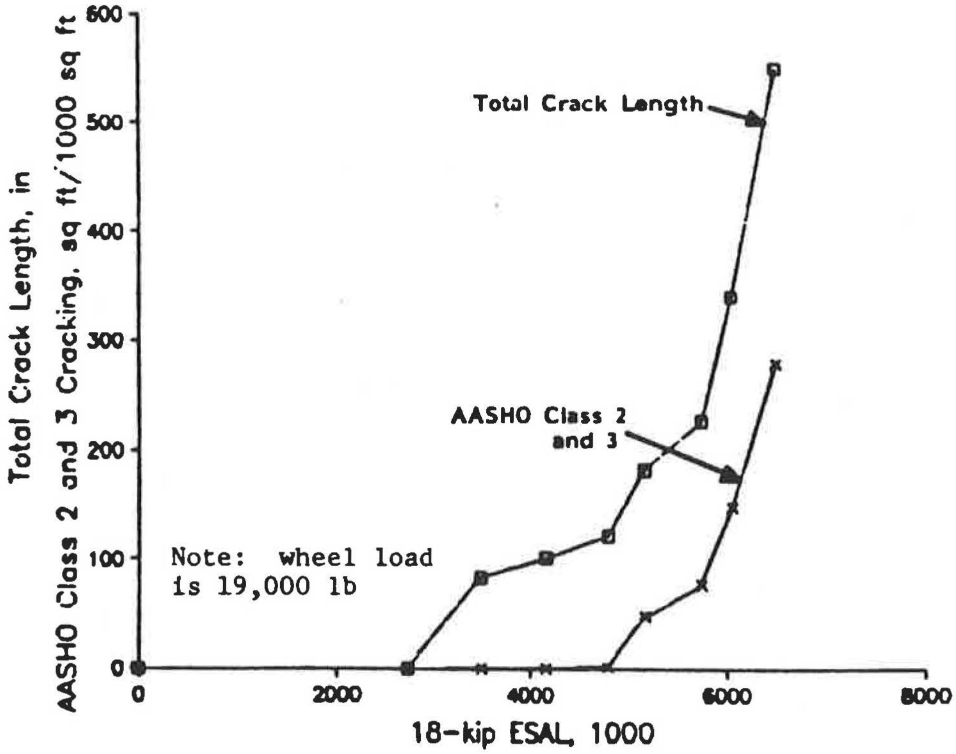

FIGURE 2 Typical accumulation of cracking for Lane 2.

ESAL values. In the second, the FWD deflection basins were used to back-calculate the pavement layers' moduli. The back-calculated moduli were compared at various ESAL intervals throughout each test period.

The significance of both approaches in evaluating pavement actual structural capacity depends on the accuracy and precision of the FWD equipment in collecting the surface-deflection basins. To minimize any potential error from the FWD measurement, a testing scheme was implemented by which three replicates of the FWD deflections were obtained at each point. The average deflection basins were then used in the analysis of both approaches.

The FWD testing periods were spaced throughout the loading life of each test section in order to evaluate the section's capacity at various ESAL levels. The pavement temperature changes from one test period to another, which greatly affects the response of the asphalt concrete layers. Consequently, it was necessary to measure the temperature throughout the asphalt layer and correct the peak deflections and the back-calculated moduli to a base temperature.

There are various methods by which the deflections and moduli values could be temperature corrected. This study used the method recommended by the new *AASHTO Pavement Design Guide* (*3*). The variations of temperature throughout the asphalt concrete were monitored by thermocouples embedded at various depths. The thermocouple temperatures were read at the beginning and at every hour during each FWD testing period. The average pavement temperature was calculated as the average of the various thermocouple temperatures at the hour nearest the time the FWD test was conducted. Using the average pavement temperatures, the temperature correction factors for the peak deflections and the back-calculated moduli were obtained from the corresponding AASHTO curves (*3*). The correction factors were used in the following equations:

$$Fd = \frac{d_1(70°\mathrm{F})}{d_1(T)}$$

$$Fe = \frac{E_{70°\mathrm{F}}}{E_T}$$

where

Fd = AASHTO adjustment factor for peak deflection,
$d_1(70°\mathrm{F})$ = FWD peak deflection at 70°F,
$d_1(T)$ = FWD peak deflection at test temperature,
Fe = AASHTO adjustment factor for back-calculated moduli,
$E_{70°\mathrm{F}}$ = resilient modulus of the asphalt layer at 70°F, and
E_T = resilient modulus of the asphalt layer at test temperature.

Peak Deflection and Back-Calculated Moduli

Because the peak FWD deflections were measured at slightly different load levels, the deflections must be adjusted to a common load before they can be compared. The linearity of the FWD load-deflection response of the PTF test sections was investigated by Anderson et al. (*4*, p. 111), who recommended that the assumption of linearity is valid for the given range of FWD loads (from 8,000 to 14,000 lb). In this study, the FWD peak deflections were adjusted to a 12,000-lb. load.

The back-calculated moduli for certain stations were not calculated because the measured deflections were greater than

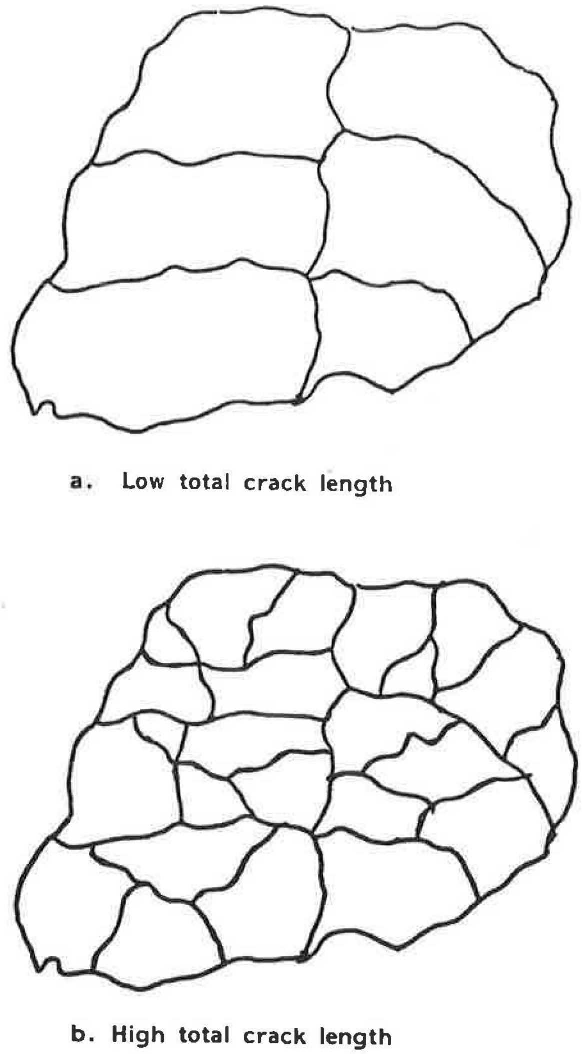

FIGURE 3 Sensitivity of crack length procedure to changes in cracking.

80 mils. With deflections greater than 80 mils, the measuring capacity of the FWD sensors is exceeded. Also, deflections as large as this imply a cracked pavement, which violates the assumption that the asphalt concrete is a continuous medium.

The back-calculated moduli were evaluated using the BACKCHEV program (*5*). This back-calculation technique uses a constrained search where the moduli of each layer are bonded within reasonable limits. The percentage of allowable total error between the measured and calculated deflections for all six sensors was 10, which is equivalent to an average error of 1.5 percent at each sensor.

The back-calculated moduli for all FWD tests in this research were evaluated under the same initial moduli, deflection tolerance, and upper and lower bounds of each layer's moduli. This back-calculation approach minimized the effect of non-uniqueness of the back-calculated moduli on the final results.

ANALYSIS

Fatigue Cracking

Surface cracking is, perhaps, a good indicator of the structural condition of a pavement section for use in PMS. Most pavement engineers agree that load-associated cracks initiate near the bottom of the asphalt layer, where tensile strains are highest. Repeated traffic loads then propagate the cracks to the surface, eventually forming the block or alligator pattern characteristic of fatigue cracking. The rate of crack propagation through the asphalt depends on combinations of various factors: (a) the thickness of the asphalt layer, (b) the maximum size of aggregate in the asphalt mix, (c) environmental conditions, and (d) the magnitude and frequency of loading. Therefore, no general rate of crack propagation can be identified for any pavement system.

Peak Deflections

When a crack initiates, the structural capacity of the pavement section is reduced. The crack decreases the section of the asphalt layer available to resist tension, resulting in higher pavement deflections. Figures 4, 5, and 6 show this increase in deflection as a function of 18-kip ESAL for FWD tests conducted on Lanes 1 and 2, respectively. The data are presented as a deflection ratio, defined as

$$D_{\text{ratio}} = \frac{d_{l(x)}}{d_{l(0)}}$$

where

D_{ratio} = deflection ratio,
$d_{l(x)}$ = FWD deflection at the middle of the loading plate at x number of 18-kip ESALs adjusted to a 12,000-lb load, at 70°F, and
$d_{l(0)}$ = FWD deflection at the middle of the loading plate before trafficking adjusted to a 12,000-lb load, at 70°F.

Also shown in these figures is the accumulation of total crack length and area of AASHO Class 2 and 3 cracking as a function of 18-kip ESAL. Figures 4 and 5 represent data from Lane 1, Section 1 and Lane 1, Section 2 tests, respectively. The data from these two tests were not combined because each test showd a different mode of failure.

The failure of Lane 1, Section 1 was a combination of fatigue failure of the asphalt layer and rutting of the subgrade, whereas the failure of Lane 1, Section 2 was a total asphalt fatigue failure. Comparisons of the deflection ratio and cracking show the deflection ratio can increase to 2 before any cracking appears at the pavement surface, and to 3 before significant AASHO Class 2 cracking occurs. In the case of Lane 1, Section 1 (rutting and fatigue failure), the cracking appeared at a deflection ratio of 1.5.

Because the PTF test sections model one-half of a 12-ft-wide lane and the wheel path is 48-in. wide, AASHO Class 2 and 3 cracking of 100 ft^2/1,000 ft^2 represents approximately 15-percent wheel path cracking. At this level of cracking, the deflection ratio was approximately 2. Figure 6 represents data from Lane 2 tests, which show that the deflection ratio can increase to between 2.5 and 3.0 before any cracking appears at the pavement surface.

Back-Calculated Moduli

In layer theory analyses, it is assumed that the reduction in structural capacity from fatigue cracking results from a decrease

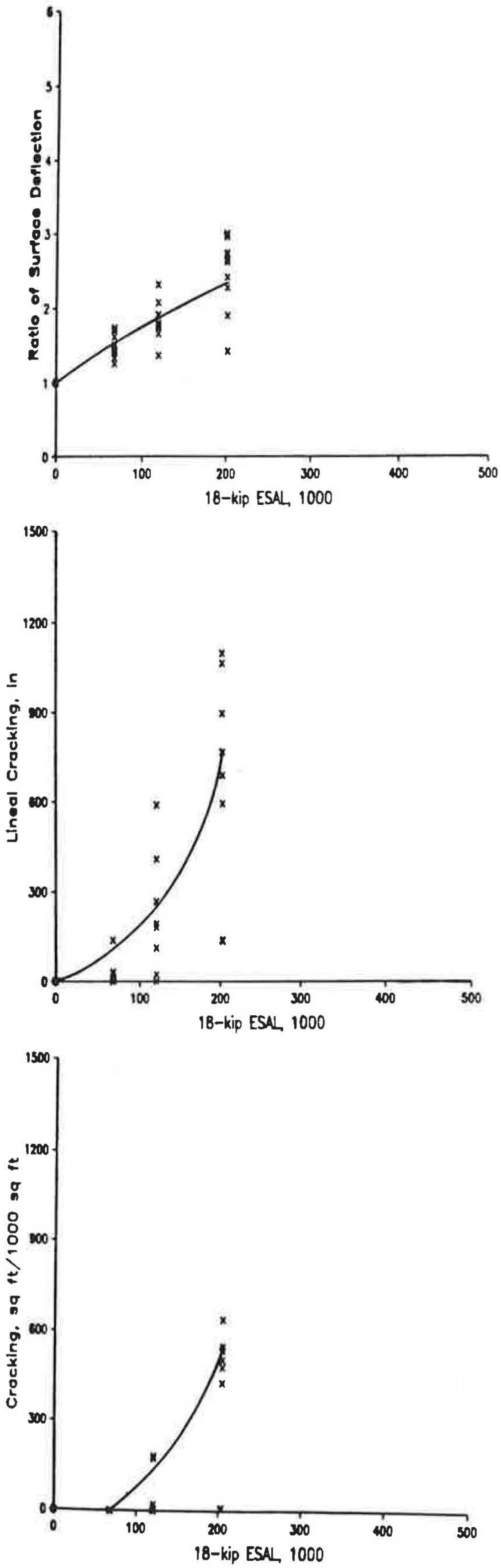

FIGURE 4 Variations of ratio of surface deflection, lineal cracking, and AASHO cracking as a function of 18-kip ESAL repetitions for Lane 1, Section 1.

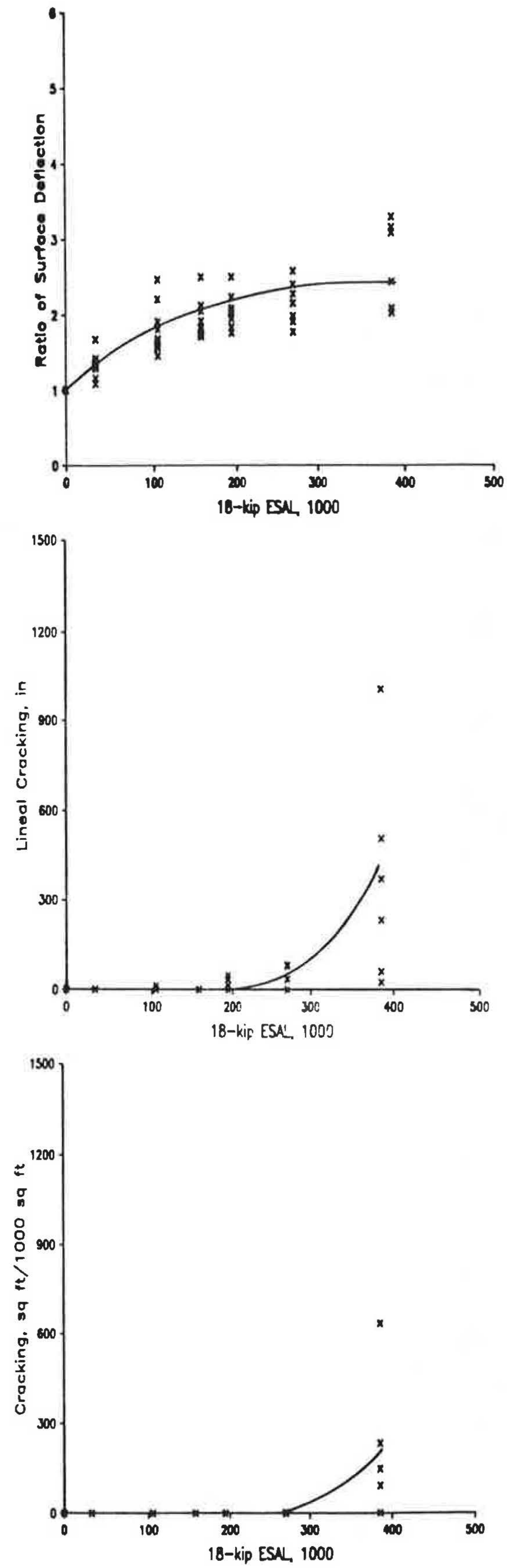

FIGURE 5 Variations of ratio of surface deflection, lineal cracking, and AASHO cracking as a function of 18-kip ESAL repetitions for Lane 1, Section 2.

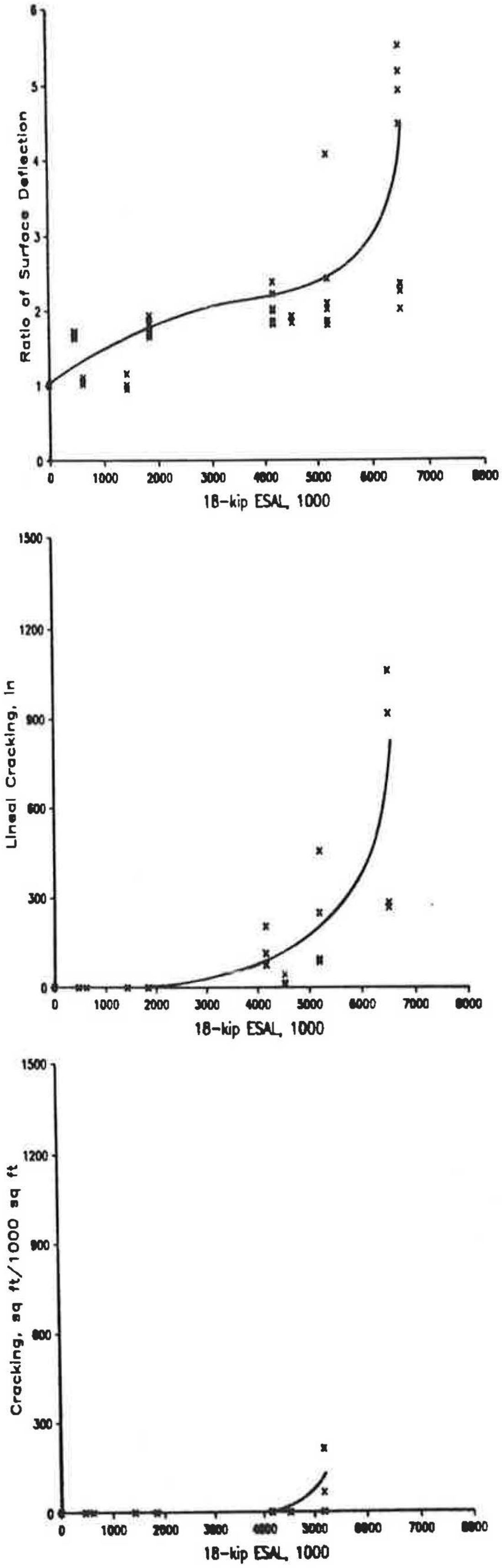

FIGURE 6 Variation of ratio of surface deflection, lineal cracking, and AASHO cracking as a function of 18-kip ESAL repetitions for Lane 2 tests.

in the modulus of the asphalt concrete layer. Figures 7, 8, and 9 show the decrease in the modulus of the asphalt concrete layer as a function of 18-kip ESAL for Lanes 1 and 2, respectively. The data are presented as modulus ratio, defined as

$$M_{\text{ratio}} = \frac{M_{r(x)}}{M_{r(0)}}$$

where

M_{ratio} = modulus ratio,
$M_{r(x)}$ = back-calculated asphalt concrete modulus at x number of 18-kip ESALs, adjusted to 70°F, and
$M_{r(0)}$ = back-calculated asphalt concrete modulus before trafficking, adjusted to 70°F.

Also shown in these figures is the accumulation of total crack length and area of AASHO Class 2 and 3 cracking as a function of ESAL. Comparisons of modulus ratio and cracking show the modulus ratio can decrease to 0.50 before any cracking appears at the pavement surface, and to 0.30 before significant AASHO Class 2 cracking occurs. With 15-percent wheel path AASHO Class 2 and 3 cracking, the modulus ratio was 0.5.

Laboratory-Resilient Moduli

To ensure that the increased deflections and decreased back-calculated moduli presented in the previous sections resulted from load-associated damage, rather than moisture damage or other environmental effects, laboratory-resilient modulus data were analyzed. Cores were cut from the PTF test sections shortly after construction in September 1986 and again during each of the postmortem evaluations. Laboratory-resilient modulus data were obtained from indirect tensile tests on these cores. Complete analysis of the data is documented in Anderson et al. (*4*). The data did not show a definite decrease in modulus with time, as would be expected if the damage were purely environmental.

In addition, the resistance of the wearing and binder mixes to moisture damage was estimated by measuring the tensile strength and resilient modulus of selected cores before and after conditioning. The conditioning consisted of vacuum saturation with tap water at room temperature. (The results of these tests are also documented in Anderson et al.) The saturation caused no significant decrease in the tensile strength or modulus of the cores. The tensile strength and modulus actually increased for some of the cores, which is a common occurrence for moisture-resistant mixes.

SUMMARY AND CONCLUSIONS

Field data from the PTF sections have indicated a time lag exists between the appearance of surface cracking and the reduction in structural capacity of flexible pavement systems. The use of surface cracking as a catalyst for maintenance and rehabilitation needs may not be justified. The study shows that the peak deflections and the back-calculated moduli of the asphalt layer from FWD measurements may reach critical levels before any type of cracking appears on the surface. Even though some of the PTF sections showed different fail-

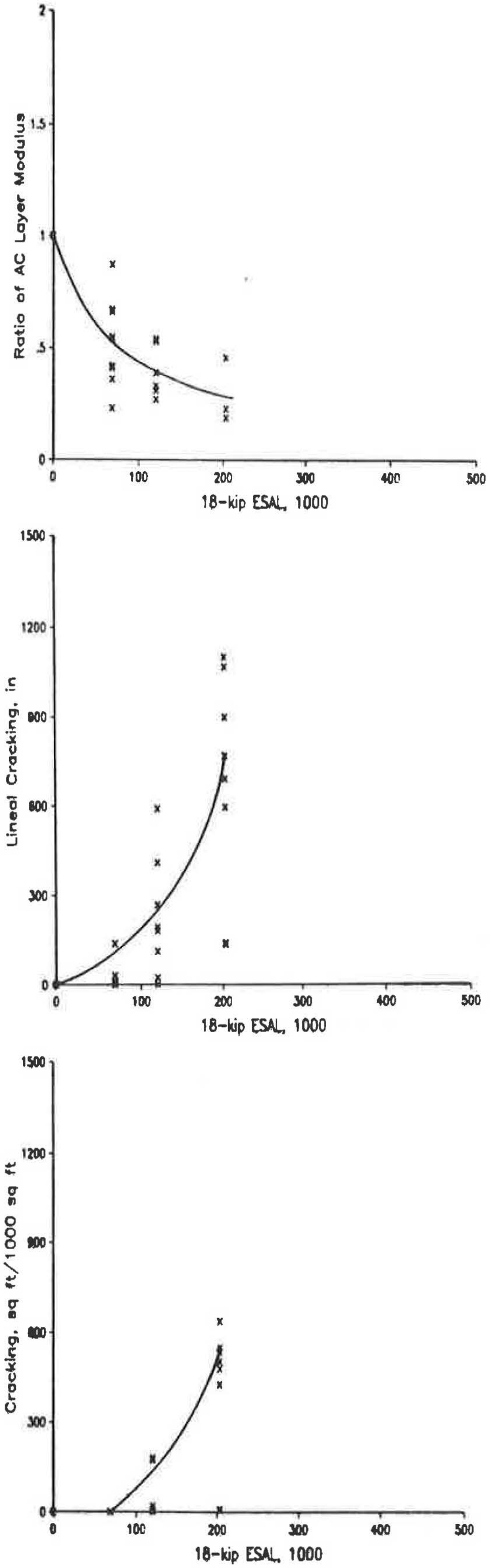

FIGURE 7 Variation of ratio of AC layer modulus, lineal cracking, and AASHO cracking as a function of 18-kip ESAL repetitions for Lane 1, Section 1.

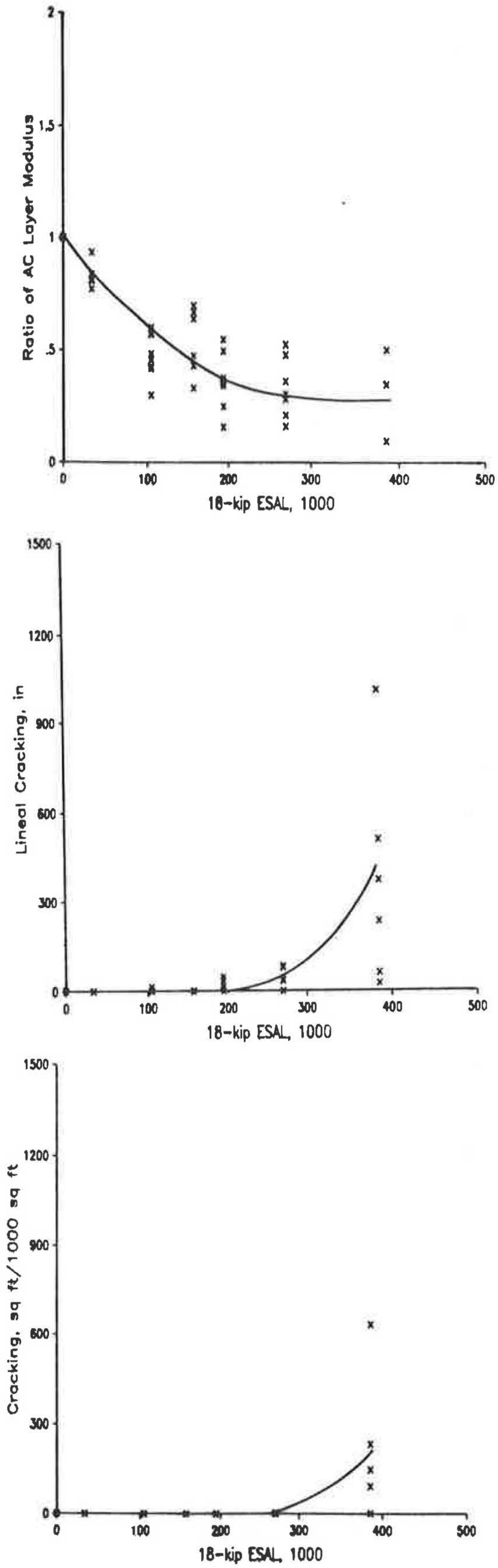

FIGURE 8 Variation of ratio of AC layer modulus, lineal cracking, and AASHO cracking as a function of 18-kip ESAL for repetitions for Lane 1, Section 2.

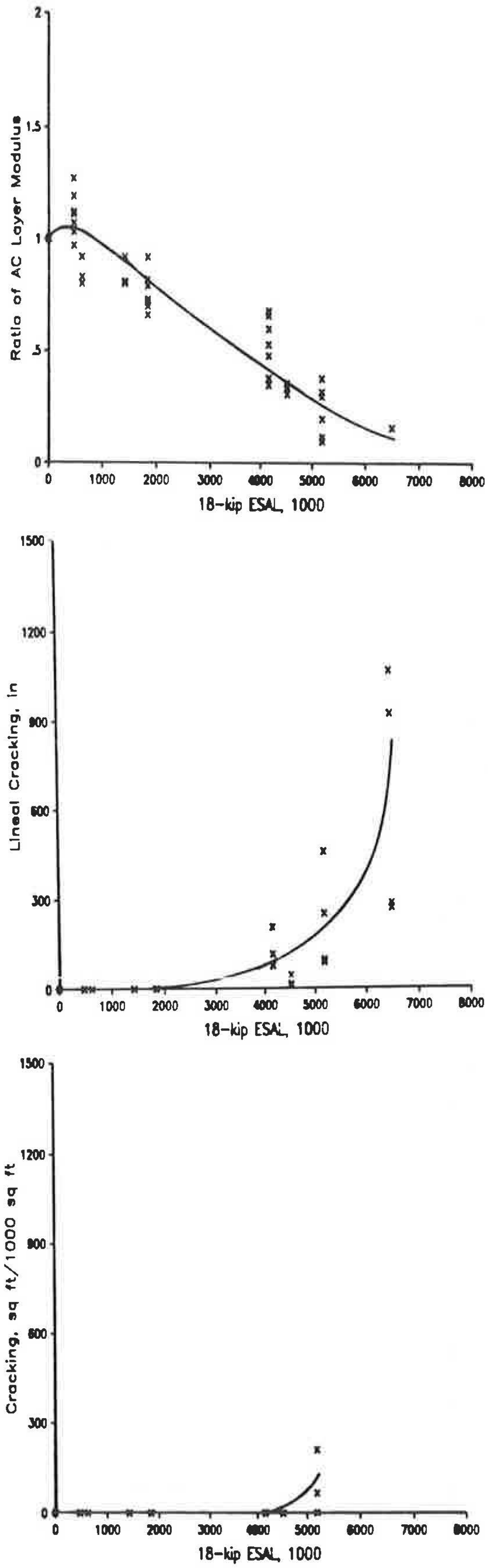

FIGURE 9 Variation of ratio of AC layer modulus, lineal cracking, and AASHO cracking as a function of 18-kip ESAL repetitions for Lane 2 tests.

ure modes (fatigue or rutting), field data indicated that the lag between structural capacity reduction and surface cracking exists at all test sections. Based on field data from tests on thin (Lane 1) and thick (Lane 2) pavement structures, the following conclusions were drawn:

- Good correlation is shown between the reduction in the back-calculated moduli of the asphalt layer and the increase in peak deflection as a function of 18-kip ESAL repetition, given that both parameters are corrected to a common base temperature.
- Small changes in the cracked surface would appear in the measurement of crack length long before they would appear in the measurement of AASHO Class 2 and 3 cracking.
- The field data show a definite lag between the reduction in the structural capacity of the pavement and the appearance of surface cracking. The lag is even longer if the AASHO Class 2 and 3 cracking is used in the measurement procedure.
- The ratio of the existing asphalt layer moduli to the initial moduli may reach a value of 0.5 before any cracking appears on the surface. If the AASHO Class 2 and 3 cracking is used, the ratio may become as low as 0.3.
- The ratio of the measured peak deflection to the initial peak deflection may reach a value of 2 before any cracking appears on the surface. If the AASHO Class 2 and 3 cracking is used, the ratio may reach as high as 3.
- In the case of thin pavements, the lag between the structural capacity reduction and surface cracking may be in terms of a couple hundred thousand 18-kip ESAL repetitions. However, in the case of thick pavements, the lag may be in terms of 2 to 3 million 18-kip ESAL repetitions.
- The use of 10 to 15 percent AASHO Class 2 and 3 wheel path cracking, which represents 100 $ft^2/1{,}000\ ft^2$ at the PTF sections, is not justified for structural capacity evaluation. A reduction of 50 percent in the modulus of the asphalt concrete layer and an increase of 200 percent in the peak deflection may occur before the 100 $ft^2/1{,}000\ ft^2$ cracking is reached.
- Field data from the PTF sections show no definite relationship between deflection under load and surface cracking. Consequently, deflection measurement is a better indicator of the structural capacity of the pavement than any other crack measurement technique.

REFERENCES

1. Highway Research Board. *The AASHO Road Test*. Special Reports 61A-61G, HRB, National Research Council, Washington, D.C., 1962.
2. D. R. Luhr, D. A. Anderson, and E. G. Fernando. *Development of Material Structural Coefficients and Evaluation of Material Behavior*. Final Report, FHWA/PA 84-028, Volume 6, December 1984.
3. *AASHTO Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1986.
4. D. A. Anderson, P. Sebaaly, N. Tabatabaee, R. Bonaquist, and C. Churilla. *Pavement Testing Facility—Pavement Performance of the Initial Two Test Sections*. Final Report, FHWA/RD-88/060, February 1988.
5. P. Sebaaly and M. S. Mamlouk. Typical Curves for Evaluation of Pavement Stiffness from Dynaflect Measurements. In *Transportation Research Record 1070*, TRB, National Research Council, Washington, D.C., 1986, pp. 43–53.

Publication of this paper sponsored by Committee on Flexible Pavement Design.