The following paper was prepared by Mr. Kingham for presentation at the Third International Conference on the Structural Design of Asphalt Pavements while he was a member of the Asphalt Institute staff. Since then, he has joined the Highway Research Board staff. Because Mr. Witczak, in an earlier paper in this Special Report, uses the fatigue criteria developed by Mr. Kingham, this paper in included for information and is reproduced from the conference proceedings with permission of the Executive Committee of the Third International Conference on the Structural Design of Asphalt Pavements.

FAILURE CRITERIA DEVELOPED FROM AASHO ROAD TEST DATA

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ABSTRACT

Theoretical models of pavement deformation behavior such as elastic-layered theory can only be used for design purposes when failure criteria are specified. Although such models can be used to predict stress and strain states, they in no way indicate whether the material in the pavement can withstand the predicted deformations. For elastic-layered theory, limiting values of strain or stress need to be defined before the theory can be used to assist practicing engineers in the design of asphalt pavements.

There is general agreement in the literature that horizontal tensile stress or strain at the bottom of a thick asphalt layer is the controlling criterion for design to prevent repetitive load cracking. Although such strains were not measured at the bottom of the asphalt layer at the AASHO Road Test, they can be inferred from a knowledge of the material characteristics and the measured deflections. Repetitive load cracking was observed to be the predominant mechanism of initial failure at the Road Test. Since the bituminous base sections provided a complete range of performance, from failures to survivors of over 1 million load repetitions it was possible to describe the strain history of these test sections in terms of performance.

The bituminous base sections fell into three performance classifications, depending upon whether they failed the first spring of testing, survived the testing period with a low serviceability rating or survived the testing without any change in serviceability. The horizontal tensile strain, horizontal tensile stress and vertical strain on top of the subgrade data were computed for each test section in each performance classification. Asphalt moduli for a wide spectrum of deflection measurements were input into the stress and strain computations. Moduli values were determined from dynamic loading in compression. Subgrade moduli were inferred from the deflection measurements.

The results of the elastic-layered computations showed that there were indeed large differences in horizontal tensile strain, horizontal tensile stress and vertical strain in the subgrade, depending upon the performance classification. Secondly, the level of strain or stress for each performance classification was a function of the asphalt base stiffness at the asphalt layer bottom. From the horizontal strain results it was apparent that asphalt pavements can tolerate higher strains at lower stiffnesses.

The horizontal tensile strain and stress relationships with asphalt stiffness were converted into "load repetition to failure" relationships by relating two performance classifications to the number of load repetitions to failure. A log-log relationship was assumed. The resulting family of "fatigue-like" curves for a range of asphalt stiffnesses has been used by Witczak and is the subject of another paper to this conference.

INTRODUCTION

The development of failure criteria described in this paper was undertaken to complete one structural model required in a pavement management system.[1] A pavement management system has four major subsystems which in turn may be further subdivided. These major subsystems are design, construction, maintenance and the processing of information. The information subsystem is concerned with all aspects of pavement management and provides the source of feedback into the other subsystems.

The design subsystem is concerned with the material selection and thickness design of pavements and their interrelationship with the many other factors affecting road performance. To describe the pavement design subsystem, it may be further divided into subsystems that relate to mechanisms of failure. Haas, Kasianchuk and Terrel, in a paper to this conference,[2] have outlined the research needs required to develop the fatigue, rutting and thermal fracture subsystems. Fatigue and rutting are acknowledged to be load associated, whereas thermal fracture is more closely associated with cold temperatures and secondly to load. This paper is concerned with developing failure criteria for use in the fatigue subsystem. Major emphasis is given to Full-Depth asphalt pavements and thick asphalt bases.

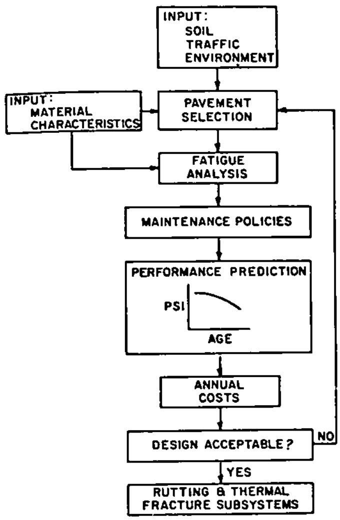

Fig. I FATIGUE SUBSYSTEM.

BACKGROUND

A major part of the fatigue subsystem shown in Figure 1 is the fatigue analysis which requires the development of a structural model. Miner's hypothesis provides such a model which can be used to predict failure or to design pavements for a given life. This hypothesis requires the computation of stress or strain from a behavior model and a knowledge of the load applications to failure for each level of stress or strain. The stress and strain computations for a given pavement can now be easily computed using one of the several available computer solutions to the elastic layered system. The Chevron Asphalt program[3] was used by this author. Finn and Hicks[4] have shown that the measured deflection and strains are reasonably close to those computed by the elastic layered system. The author has made other studies himself with data obtained from test roads in Brampton, Ontario and in Colorado to verify that deflections, vertical strains and radial strains can be reasonably computed from elastic layered theory.

For the determination of load repetitions to failure as a function of pavement deformation, Dormon and Metcalf[5] have rationalized that the horizontal stresses and strains at the bottom of the asphalt layer and the vertical strain in the subgrade are critically related to pavement performance. Deacon and Monismith[6] and Pell[7] have used a flexural test of asphalt mixtures in the laboratory to determine relationships between radial strain and load repetitions to failure. They have shown to this author that the scatter obtained from the laboratory test can be considerable and that a large number of tests are required to determine the relationship for a specific asphalt mixture. In another paper to this conference,[8] this author describes the problem of establishing a family of laboratory fatigue curves that consider the asphalt mixture stiffness. Another approach to determining the repetitions to failure as a function of stress or strain is to infer values from full-scale field tests. Although the AASHO Road Test[9] did not produce measured values of strain as a function of load repetitions to failure, it does provide a substantial number of thick asphalt base sections from which stress or strain criteria can be inferred.

Limitations of using AASHO Road Test data for the purpose of deriving failure stresses and strains were recognized at the outset. There was no check on the computed strains and stresses using measurement data. Secondly, failure at the AASHO Road Test was described by an unsatisfactory level of present serviceability index. Present serviceability index was not developed to represent the effects of any one particular mode of failure. However, from the author's observations while employed at the AASHO Road Test, failure initiated with cracking in the wheel path. Rutting and shear failure were only evidenced in advanced stages of failure after the cracking had occurred. It is believed that stress and strain failure criteria as developed from the AASHO Road Test data represent very closely failure stresses and strains for a fatigue mechanism of failure. Such curves, however, are not true fatigue curves and hence in this paper will be referred to as load repetition curves.

HYPOTHESIS

To obtain an understanding of performance and deformation behavior of the bituminous base sections, a detailed study was made of performance and deflection measurements. For each test section, present serviceability index and deflection were plotted for each measurement date to show annual trends. Figure 2 presents a typical example. It was readily apparent that the peak deflections for the bituminous base sections were to be found in the summer during periods when temperatures were at their maximum. This trend was in contrast to the granular base, where deflection measurements peaked in the spring. However, for both the granular base and bituminous base designs, failures took place predominantly in the spring. Almost no cracking occurred during the summer peak deflection periods. Some rutting, however, was measured during the summer and was considered tolerable by the Road Test staff in thicknesses adequate to resist cracking. It was hypothesized that critical strains must be a function of the asphalt layer stiffness since cracking did not occur during the summer.

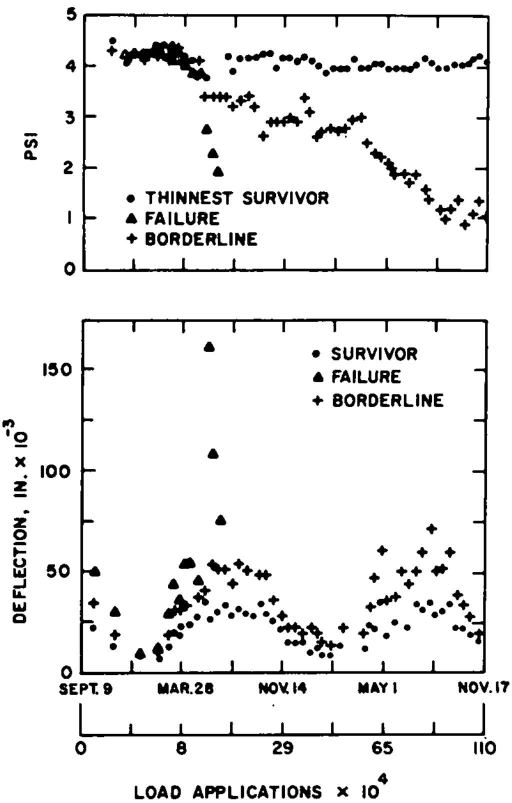

Fig. 2 TYPICAL PSI AND DEFLECTION TRENDS BY PERFORMANCE CLASSIFICATION.

The AASHO Road Test included bituminous base sections under three weights of loading -- 12,000, 22,400 and 30,000 lb. axle loads. For each load there appeared two or three trends with time as shown in Figure 2. For all loads one test section failed during the first spring of testing, having carried approximately 121,000 load repetitions throughout the previous fall and winter. These are described as "failures." For the two heavier loads, one test section exhibited significant present serviceability index decreases during the springs of each test year and was classified a "borderline" performer. Again, for all three loads one test section displayed no changes in present serviceability index or cracking. These sections were classified "thinnest survivors." It was hypothesized that since performance characteristics depicted by these curves were so completely different that the radial stresses and strains and the vertical strains in the subgrade would be different.

ANALYSIS

The input data available for stress and strain computations were as follows:

(a) complex modulus values as a function of termperature and rate of loading for the asphalt concrete surfacing (determined by Coffman).[10]

(b) complex modulus values for the asphalt concrete base as a function of temperature and rate of loading (determined in The Asphalt Institute laboratory).[11]

(c) deflection data for all periods of the year.

(d) pavement temperature data measured for the top four inches of asphalt concrete at hourly intervals during the entire testing period.

For complex modulus determinations a frequency loading of one cycle per second was chosen for use with deflection measurements. Coffman[10] describes the rationale for picking this loading frequency. Temperature data for modulus determinations were obtained from the AASHO Road Test data system 3300 for the time of deflection measurement. Deflection times were estimated from the operation schedule and the temperatures recorded with the deflection data system. Where temperatures were required at depths greater than four inches, the Southgate[12] approach was used to estimate these temperatures. The following equations were used to determine stiffness for the asphalt concrete surface and base:

Surface:

$$\log E = 6.56495 - .01178(T)^{.995}$$ Eq. 1 (Coffman data[10])

Base:

$$\log E = 6.32456 - .000012(T)^{2.51}$$ Eq. 2 (Kallas[11])

where E = modulus at 1 cps
T = temperature F.°

No test data were available to estimate the subgrade and subbase modulus values directly. Even if such values had been available it would have been difficult to estimate the condition of the base and subgrade for each of the 315 deflection measurments analyzed. Therefore, subgrade and subbase modulus values were estimated from the pavement deflection measurement using Kirk's[13] simple formula for deflection. Deflection data were selected to represent all seasons of the year and all loads, as shown by Figures 3 and 4. These represent approximately 50% of all deflections taken on the bituminous base sections. A modular ratio of subbase to subgrade of 2:1 was assumed from the work of Dormon.[14] Once the modulus values for the asphalt granular subbase and subgrade were known, it was possible with an assumed Poisson's ratio to compute the

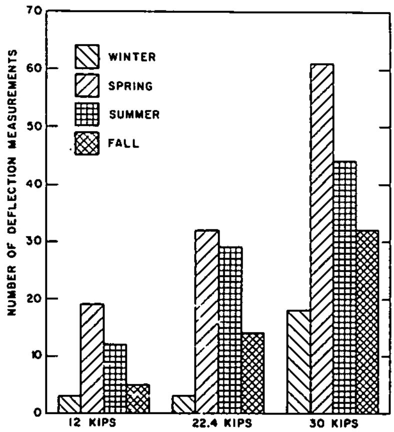

Fig. 3 DATA INPUT BY SEASON

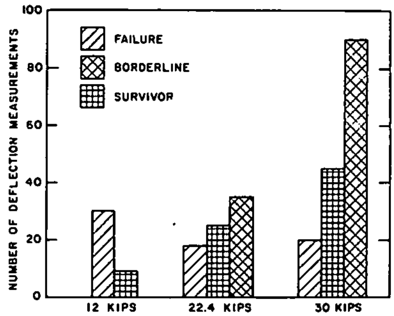

Fig. 4 DATA INPUT BY PERFORMANCE CLASSIFICATION.

strains, stresses and deflections using the Chevron elastic layer computer program. A single plate loading configuration was assumed to represent the dual wheel configuration. Hence the maximum horizontal tensile strains and stresses are radial strains and stresses. Poisson's ratios of 0.45 and 0.4 were assumed for asphalt concrete temperatures greater than and less than 70°F. A check on the computations was made by comparing computed deflections to those measured. The computed values were in all cases within .002" of those measured.

In order for the computed stresses and strains to be applied to a repeated load analysis, the performance classifications had to be identified with numbers of load repetitions. Pavements failing the first spring, "failures," carried a total of 121,000 load repetitions on the average. Of these only 57,000 were applied with no frost in the subgrade. For the "borderline" test sections, repetitions to failure were harder to define. Test sections carrying the 22,400 lb. axle load did not reach the terminal present serviceability index of 1.5 by the end of the test. Extrapolating the serviceability index trend it was estimated that 2.03 million load repetitions would have been required to reduce the serviceability index to 2.5. Test sections carrying the 30,000 lb. single axle load failed at an average of 644,200 load repetitions. A logarithmic average between the 22,400 and 30,000 single axle load results would fall close to the total number of load repetitions imposed on the test sections, 1.12 million. Therefore, this class was identified with 1.12 million load repetitions. Load repetitions to failure for the thinnest surviving test sections could not be determined.

HORIZONTAL TENSILE STRAIN (Radial Strain)

The radial strain on the bottom of the asphalt concrete determined at the time of each deflection measurement was plotted against the modulus of the asphalt concrete. Since the modulus was not a constant with depth the modulus for the bottom of the base layer was used. Figures 5 and 6 show the strain as a function of modulus on log-log scales. The top curve of Figure 5 shows the data by performance classification. The remaining curve in Figure 5 and those in Figure 6 show the data breakdown by load for each performance classification. Several conclusions can be drawn from these curves. First, the data for the three performance classifications are indeed completely separate as hypothesized. Therefore, it seems reasonable that these curves are indeed a family of curves which can be identified with two levels of load repetitions. Secondly, they do suggest that an asphalt concrete pavement can withstand greater strains when its stiffness is lowered.

The data plotted in Figures 5 and 6 excluded all data points for periods when measurable depths of frost were recorded in the subgrade. Figure 7 shows the computed curves from Figures 5 and 6 together with the "frozen" data. The data plot significantly below the curves suggesting that these points are in reality on other curves representing a much larger number of load repetitions.

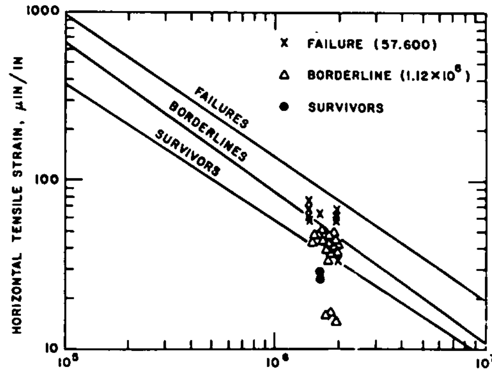

Fig. 7 COMPARISON WITH DATA FROM FROZEN PERIODS.

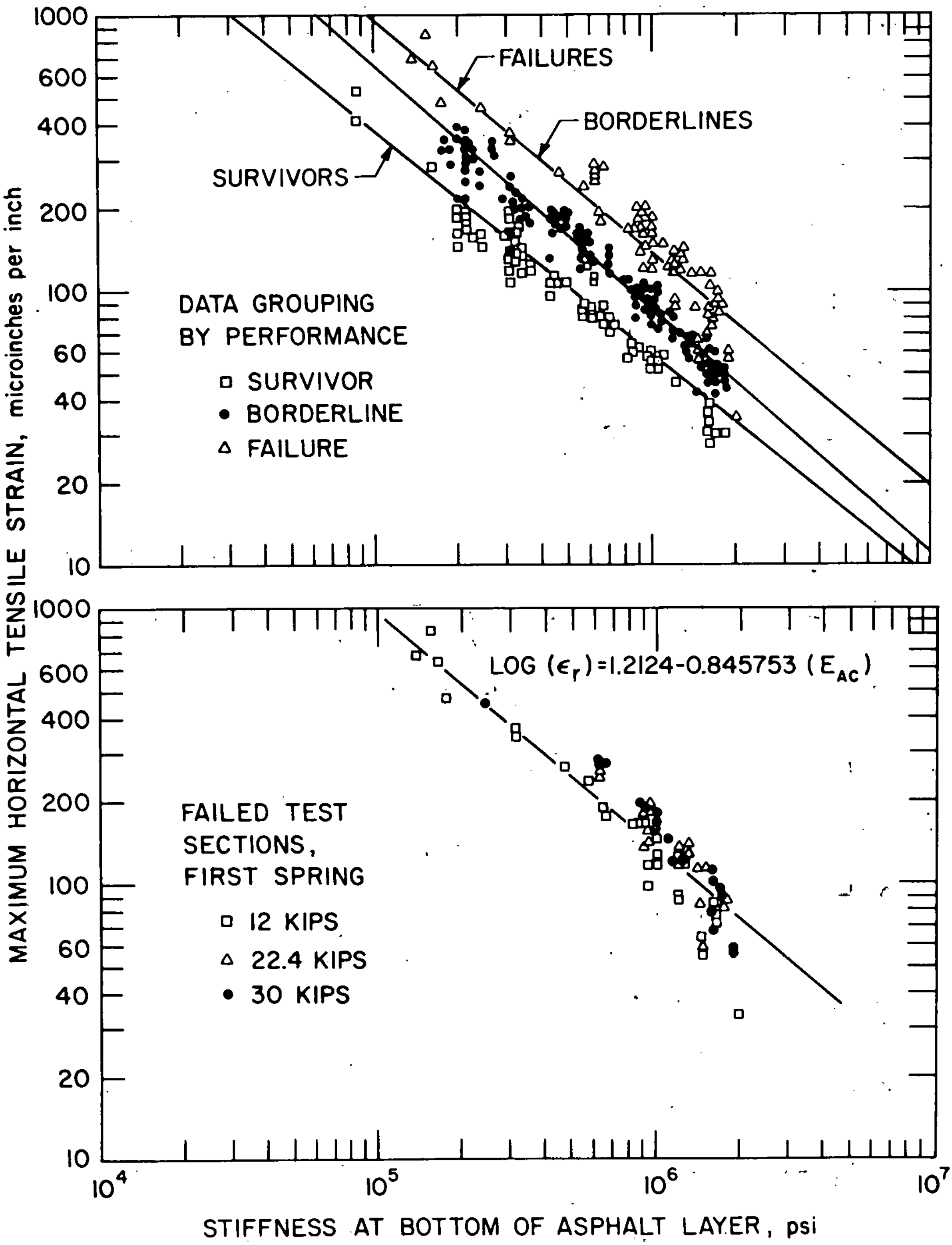

Fig. 5 STRAIN LEVELS BY PERFORMANCE CLASSIFICATION.

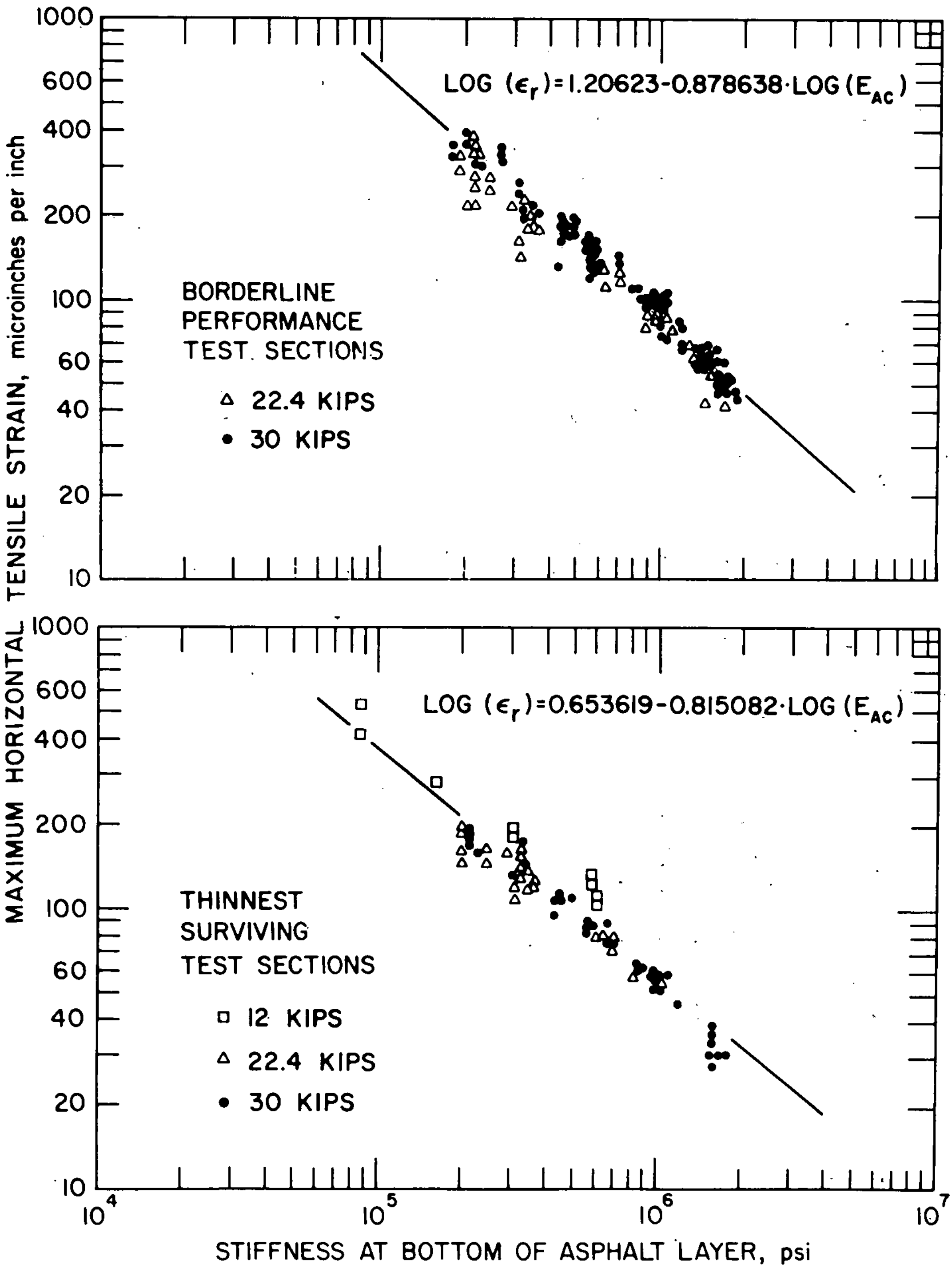

Fig. 6 STRAIN LEVELS BY PERFORMANCE CLASSIFICATION.

The plot of radial strain versus stiffness modulus can be resolved into a plot of load repetition curves showing radial strain as a function of load applications to failure. The regression analyses for two sets of curves are shown in Figure 8. To construct

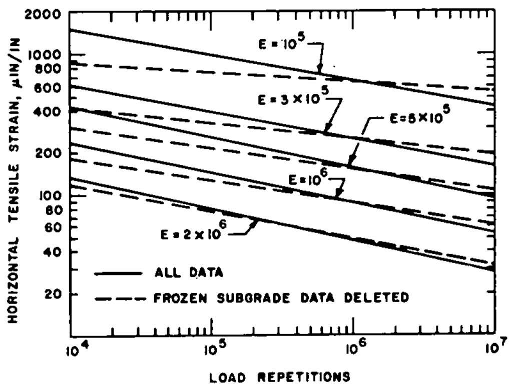

Fig. 8 LOAD REPETITION FAILURE CURVES WITH AND WITHOUT DATA FROM FROZEN PERIODS.

the curves it was necessary to assume that the relationships were linear in the log-log transformation. The solid lines represent the result from analyzing all deflection data (for frozen and unfrozen subgrades). Test sections classified as "failures" were identified as having 121,000 load repetitions to failure. The dashed lines are those determined with all strain data and load repetitions associated with the frozen periods deleted. "Failures" for this analysis were associated with 57,000 load repetitions. For both solid and dashed lines 1.12 x 10^6 load repetitions to failure were identified with the borderline performance test sections. Equations describing the two sets of curves are given below.

For all data:

$$\log e = 1.2458 - .67296 \log E - .0065461 \log N_f - .034001 \log E \log N_f$$

For deletion of data associated with frozen subgrades:

$$\log e = -1.34114 - .28646 \log E + .403893 \log N_f - .094801 \log E \log N_f$$

The solid lines are nearly parallel and have similar slopes to laboratory fatigue curves,[15] whereas the dashed lines are slightly flatter than laboratory fatigue curves. The selection of design curves from this analysis is a matter of judgment. Witczak,[16] in his paper to this conference, chose the solid curves because of their nearly parallel nature and the support from laboratory data for the slopes. As an aid to selection for design, the data scatter represented by the root mean square error is given in Table 1.

Table 1

HORIZONTAL TENSILE STRAIN FAILURE CRITERIA FOR LOG STRAIN = INTERCEPT + SLOPE (LOG E)

Performance Classification	Regression Results Intercept.	Slope	RMSE
All Data			
Failures	1.2124	-.84575	.11600
Borderlines	1.20623	-.87864	.10862
Survivors	.653619	-.81508	.12914
Frozen Subgrade Data Deleted			
Failures	.57972	-.73732	.13007
Borderlines	1.1021	-.85993	.11058
Survivors	.53188	-.79308	.12894

In translating the strain - stiffness curves to strain - load repetition curves, it is assumed that if one were to test at a given stiffness level then a unique number of load repetitions would occur for a given strain. It is possible that a data bias exists because of the single environmental locality of the AASHO Road Test. To check on the possibility of such a data bias an analysis was made to develop the load repetition curves using Miner's hypothesis and the actual distribution of load applications as a function of temperature. Details of this analysis are given in the Appendix. The result was very minor changes in the load repetition curves as shown in Figure 9, which were judged to be insignificant.

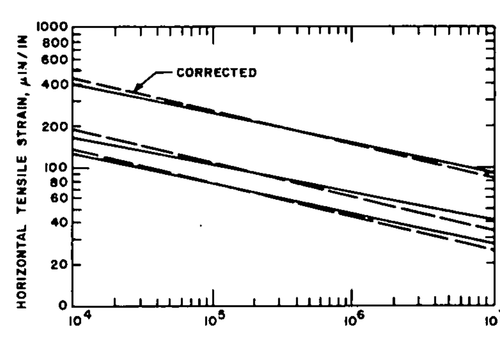

Fig. 9 COMPARISON OF FAILURE CRITERIA CURVES WHEN CORRECTED FOR ENVIRONMENTAL DATA BIAS.

An application of the load repetition curves to a 5" Full-Depth asphalt pavement carrying an 18-kip axle load for subgrade modulus values of 6000 and 15,000 psi is given in Figure 10. The plotted points are strains determined in an elastic layered analysis. These strains when plotted on the load repetition curves show that the higher asphalt layer stiffnesses are more damaging than the lower asphalt stiffnesses which is in agreement with the philosophy of some highway department engineers.

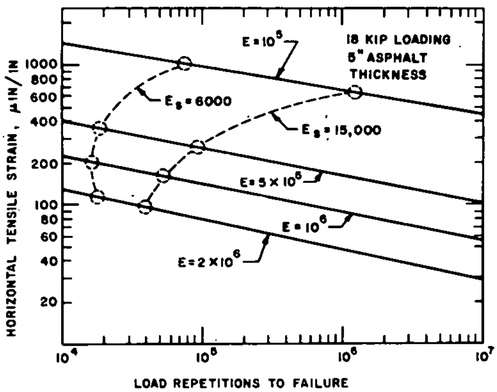

Fig. 10 COMPARISON OF DAMAGE WITH CHANGES IN ASPHALT STIFFNESS.

HORIZONTAL TENSILE STRESS (Radial Stress)

In the same manner that strain was plotted against stiffness of the asphalt layer, radial stress was also plotted. At first glance the data appeared to be much more scattered than those for radial strain. Further examination indicated that the subgrade modulus had a large effect on the data scatter. When subgrade modulus was recognized the expected curve of increasing stress with increasing stiffness was found, as shown in Figure 11. Also load differences appeared to explain some of the scatter. These plots show that a failure stress needs to be qualified by the subgrade modulus it pertains to. Failure stresses increase with decreasing subgrade modulus. Hence this design criterion is not entirely independent of other structural considerations, as was the radial strain.

Radial strain as a function of load repetitions to failure for various levels of asphalt and subgrade modulus values are given in Figure 12. Regression analysis results for the plotted curves in Figures 11 and 12 are given in Table 2. At the time of writing these criteria have not been applied to airfield or highway design.

VERTICAL STRAINS

Vertical strains were analyzed in the same manner as for radial strains and stresses. The changes in vertical strain with asphalt concrete modulus were considerable. Since rutting was not an observed failure mechanism except in instances where cracking occurred initially, the values of vertical strain at various levels of load

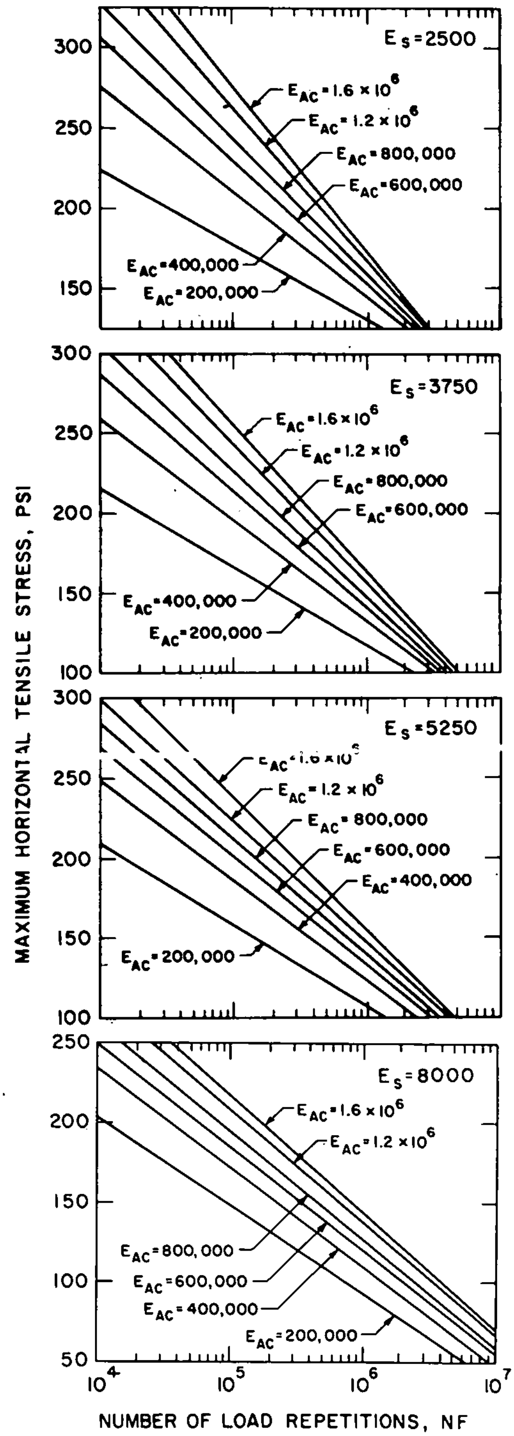

Fig. 12 LOAD REPETITION CURVES FOR HORIZONTAL STRESS CRITERIA.

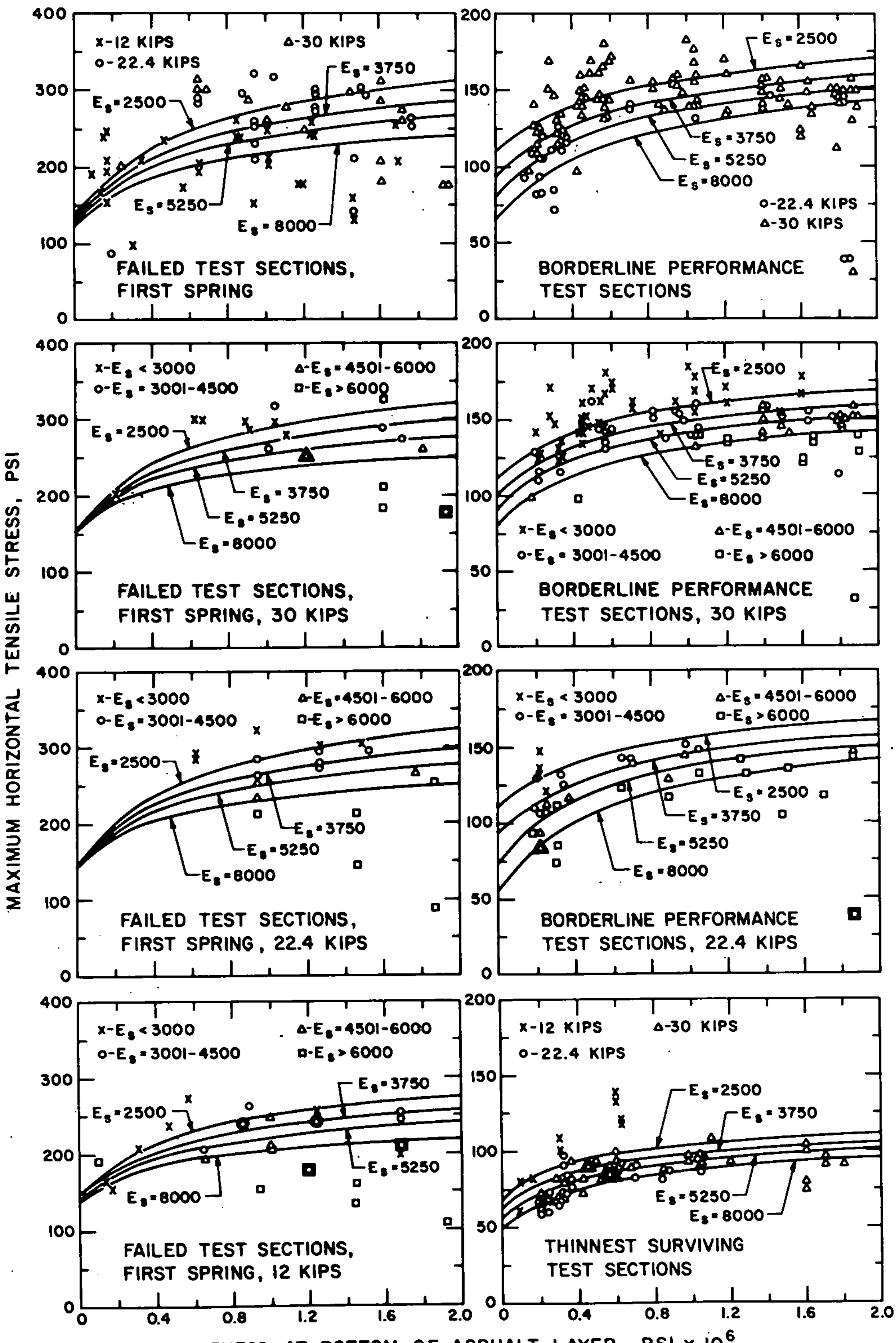

Fig. II STRESS LEVELS BY PERFORMANCE CLASSIFICATION.

Table 2

HORIZONTAL TENSILE STRESS FAILURE CRITERIA
REGRESSION ANALYSIS RESULTS*

Regression Results	Performance	Classification
Data For Frozen Subgrade Deleted	Failures (57,000 reps)	Borderline (1.12×10^6 reps)
A_0	-1878.94	590.67
A_1	422.91	-37.81
A_2	412.74	-203.70
A_3	-87.53	23.86
R^2	.885	.874
RMSE	25.1 psi	10.4 psi

$$*\text{Stress} = A_0 + A_1 \log E_b + A_2 \log E_s + A_3 (\log E_b)(\log E_s)$$

where

b = base
s = subgrade

repetition were only of interest to compare with other criteria. Table 3 presents the vertical strain results from regression analyses associated with each performance classification. Design criteria published by Dormon and Metcalf[5] are compared. The only valid comparisons are those where pavements survived a significant number of load repetitions when pavement modulus values were at 200,000 psi or lower. This excludes the failure classification since these test sections failed before the first summer of test traffic. From the valid comparison it is obvious that vertical strains in the subgrade exceeded those recommended for design by Dormon and Metcalf. Since little or no rutting was measured in the subgrade soil it is the opinion of this author that the Dormon and Edwards vertical strain criteria are conservative.

An interesting conclusion can be drawn from the subgrade vertical strain and the associated measured rut depths given in Table 3. As a function of load the rut increased from the lightest to the heaviest load for the thinnest surviving pavements. Vertical strains in the subgrade, however, decreased with increases in rut depth. Each survivor test section had 1.12×10^6 load repetitions applied to it. Hence the magnitude of vertical strain in the top of the subgrade does not explain the surface rutting observed. Other studies conducted at the Road Test[9] indicate that less than 10% of the surface rut reflected into the subgrade. Since increasing base thickness

Table 3

SUMMARY OF VERTICAL STRAIN ANALYSIS

Classification No. of Load Repetitions to Failure	Axle Load Kips	Regression Equations* Slope	Intercept	R^2	MSE	Shell Vertical Strain Criteria**	AASHO Computed Strain Values** Ave.	Ave. -2 RMSE	Measured Rut Depth (Inches)
FAILURES (57,400 load repetitions)	12	-1.07818	3.04914	.899784	.10417	1120	2400	543.6	
	22.4	-1.14834	3.61938	.625782	.125764		3700	721.4	
	30.0	-1.15021	3.61388	.825974	.117772		3700	760.7	
BORDERLINE (1.12×10^6 load repetitions)	22.4	-.808804	1.20951	.927274	.0711949	630	830	243.3	
	30.0	-.796925	1.24201	.926375	.0674619		1040	315.8	
SURVIVORS (unknown load repetitions)	12	-.730062	.735	.56954	.17563	Unknown	730	105.8	.25
	22.4	-.615682	-.0561679	.905311	.0463689		480	178.8	.38
	30.0	-.690541	.377486	.92566	.0573453		520	173.2	.50

*Model $\log e_v = a_0 + a_1 \log E$

**Values computed for a pavement modulus value of 200,000 psi above the minimum required to prevent cracking did not reduce the rutting, it is apparent that limiting the subgrade vertical strain would not prevent rutting for the Road Test asphalt base pavements. Hence it is concluded that limiting the subgrade vertical strain in design may prevent rutting in the subgrade but it will not insure the prevention of rutting at the pavement surface.

SUMMARY AND CONCLUSIONS

1. Horizontal tensile strains and stresses at the bottom of the asphalt base and vertical strains in the top of the subgrade were correlated to performance trends at the AASHO Road Test. From such a correlation, levels of radial strain, radial stress and vertical strain in the subgrade could be identified with unique numbers of load repetitions.

2. Stiffness of the asphalt concrete provided a strong influence on critical strains or stresses. By comparison with limiting horizontal tensile strain values published in the literature it is apparent that asphalt pavements can tolerate higher strains at lower stiffnesses.

3. Horizontal tensile strains at failure for given numbers of load repetitions to failure were independent of load effects and hence appeared to be entirely a function of the asphalt mix properties.

4. Horizontal tensile stresses at given load repetitions to failure were highly dependent on subgrade stiffness and hence more difficult to use as design criteria than strain.

5. Vertical strains in the top of the subgrade did not correlate to the measured rut depths. Therefore, limiting vertical strain in the subgrade may prevent deformation in the subgrade but it will not insure the prevention of rutting at the pavement surface.

APPENDIX

DERIVATION OF STRAIN-LOAD REPETITION CURVES

It is possible to derive a family of strain-load repetition curves as a function of asphalt stiffness that considers the distribution of loads with stiffness experienced at the AASHO Road Test. The resulting curves should be free of any environmental bias that imposes itself by virtue of the data base being entirely from the AASHO Road Test. In Figure A-1, the curve for 121,000 load repetitions is drawn from Figure 5 for the failed test sections. The curve designated 626,000 load repetitions represents the average life of borderline performance test sections from the 30-kip axle load test. For the third curve, the

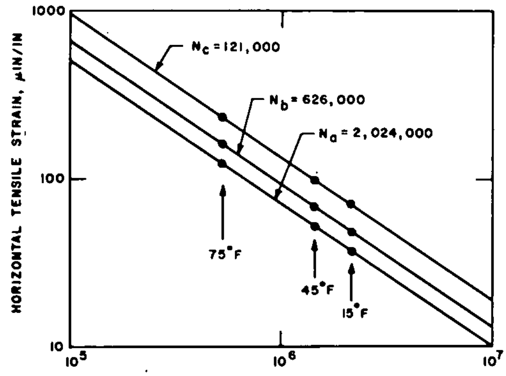

Fig. A-1 STRAIN-E DATA FOR ANALYSIS INPUT.

22.4 kip axle load test sections were assigned a value of 2.024 x 10^6 load test repetitions based on an extrapolation of their present serviceability index trends. By dividing the temperature range of 0° to 90°F into three equal parts and converting to stiffness of the asphalt concrete for 1 cycle per second loading time, three values of strain are identified for each curve, or nine values in total. For each strain and stiffness pair there exists an actual number of load repetitions applied. These are known from the loading history and are given in Table A-1.

The load repetition values were derived from the histograms given in Figures A-2 and A-3. These in turn were derived from monthly average pavement temperature - air

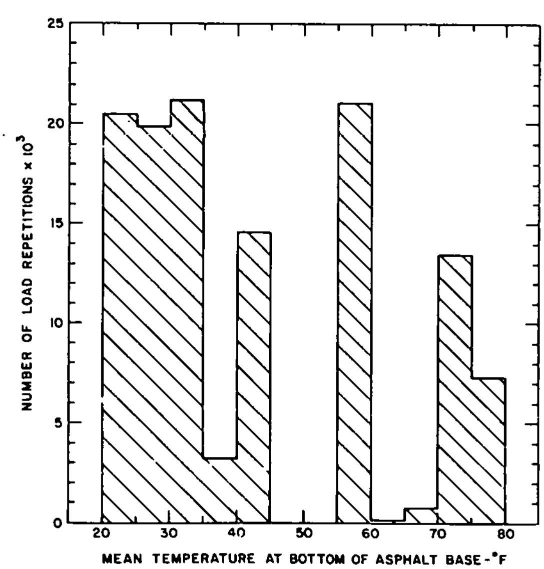

Fig. A-2 FAILURES

Table A-1

SUMMARY OF ANALYSIS INPUT DATA

Strain - Load Repetitions Pairs μ in/in - No.	Pavement E_1 530,000 psi	Pavement E_2 1,428,000 psi	Pavement E_3 2,095,000 psi	Total Load Repetitions
e_{ia}	122.5	52.3	37.5	
n_{ia}	1,021,495	783,213	219,580	2,024,000
e_{ib}	160.0	68.2	49.0	
n_{ib}	198,000	289,000	139,000	626 000
e_{ic}	237.5	100.1	76.6	
n_{ic}	26,199	52,222	52,616	121,037

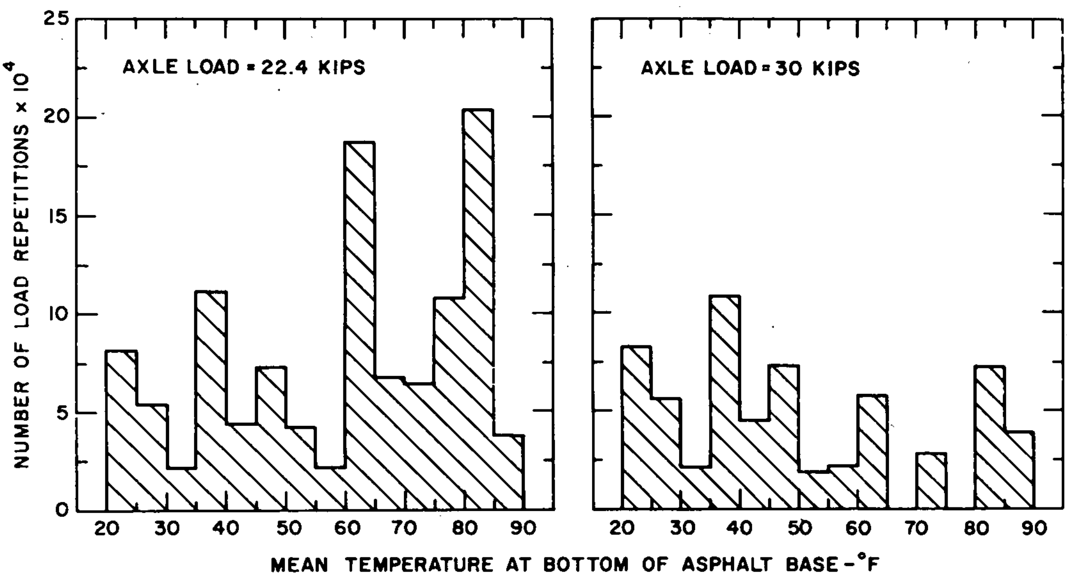

Fig. A-3 BORDERLINE SECTIONS.

temperature relationships developed by Witczak.[18]

Using Miner's hypothesis, repetitions to failure for each strain - stiffness pair was determined in the following manner:

Let n_{ij} be the actual number of weighted repetitions occurring during an average temperature range (associated with $\bar{E}_i$ for the j^{th} failure curves

$i = 1, 2, 3$
$j = a, b, c$

Let e_{ij} be the maximum tensile strain at the bottom of the A.C. layer associated with the i^{th} and j^{th} point on the failure curves

$n_{1a} + n_{2a} + n_{3a} = N_a = 2,024,000$
$n_{1b} + n_{2b} + n_{3b} = N_b = 626,000$
$n_{1c} + n_{2c} + n_{3c} = N_c = 121,000$

Using Miner's hypothesis of damage accumulation and letting

N_{f1a} = allowable rep. to failure that e_{1a} will cause at E_1 for N_a curve

N_{f1b} = allowable rep. to failure that e_{1b} will cause at E_1 for N_b curve

N_{f1c} = allowable rep. to failure that e_{1c} will cause at E_1 for N_c curve

N_{f2a} = allowable rep. to failure that e_{2a} will cause at E_2 for N_a curve

N_{f2b} = allowable rep. to failure that e_{2b} will cause at E_2 for N_b curve

N_{f2c} = allowable rep. to failure that e_{2c} will cause at E_2 for N_c curve

N_{f3a} = allowable rep. to failure that e_{3a} will cause at E_3 for N_a curve

N_{f3b} = allowable rep. to failure that e_{3b} will cause at E_3 for N_b curve

N_{f3c} = allowable rep. to failure that e_{3c} will cause at E_3 for N_c curve

$$\therefore \frac{n_{1a}}{N_{f1a}} + \frac{n_{2a}}{N_{f2a}} + \frac{n_{3a}}{N_{f3a}} = 1 \qquad \text{(Equation 1)}$$

$$\frac{n_{1b}}{N_{f1b}} + \frac{n_{2b}}{N_{f2b}} + \frac{n_{3b}}{N_{f3b}} = 1 \qquad \text{(Equation 2)}$$

$$\frac{n_{1c}}{N_{f1c}} + \frac{n_{2c}}{N_{f2c}} + \frac{n_{3c}}{N_{f3c}} = 1 \qquad \text{(Equation 3)}$$

Assuming that the true family of fatigue curves (N_f - e) are parallel, i.e., $c_1 = c_2 = c_3$ for various temperatures (stiffnesses E_1, E_2, E_3) then the following are true

$$N_{f1a} = K_1\left(\frac{1}{e_{1a}}\right)^c \qquad N_{f1b} = K_1\left(\frac{1}{e_{1b}}\right)^c$$

$$N_{f1c} = K_1\left(\frac{1}{e_{1c}}\right)^c$$

$$N_{f2a} = K_2\left(\frac{1}{e_{2a}}\right)^c \qquad N_{f2b} = K_2\left(\frac{1}{e_{2b}}\right)^c$$

$$N_{f2c} = K_2\left(\frac{1}{e_{2c}}\right)^c$$

$$N_{f3a} = K_3\left(\frac{1}{e_{3a}}\right)^c \qquad N_{f3b} = K_3\left(\frac{1}{e_{3b}}\right)^c$$

$$N_{f3c} = K_3\left(\frac{1}{e_{3c}}\right)^c$$

or $$\frac{N_{f1a}}{N_{f1b}} = \frac{(e_{1b})^c}{(e_{1a})^c} \quad \therefore \quad N_{f1a} = N_{f1b}\left(\frac{e_{1b}}{e_{1a}}\right)^c$$

(Equation 4)

$$\frac{N_{f1a}}{N_{f1c}} = \frac{(e_{1c})^c}{(e_{1a})^c} \quad \therefore \quad N_{f1a} = N_{f1c}\left(\frac{e_{1c}}{e_{1a}}\right)^c$$

(Equation 5)

$$\frac{N_{f2a}}{N_{f2b}} = \frac{(e_{2b})^c}{(e_{2a})^c} \quad \therefore \quad N_{f2a} = N_{f2b}\left(\frac{e_{2b}}{e_{2a}}\right)^c$$

(Equation 6)

$$\frac{N_{f2a}}{N_{f2c}} = \frac{(e_{2c})^c}{(e_{2a})} \quad \therefore \quad N_{f2a} = N_{f2c}\left(\frac{e_{2c}}{e_{2a}}\right)^c$$

(Equation 7)

$$\frac{N_{f3a}}{N_{f3b}} = \frac{(e_{3b})^c}{(e_{3a})^c} \quad \therefore \quad N_{f3a} = N_{f3b}\left(\frac{e_{3b}}{e_{3a}}\right)^c$$

(Equation 8)

$$\frac{N_{f3a}}{N_{f3c}} = \frac{(e_{3c})^c}{(e_{3a})} \quad \therefore \quad N_{f3a} = N_{f3c}\left(\frac{e_{3c}}{e_{3a}}\right)^c$$

(Equation 9)

The nine equations above allow the solution of the N_{fij} values which are the desired load repetitions to failure. Analyses for chosen values of C from 4 to 6 revealed that sets of positive N_{fij} values could only be determined for values of C from 4.20 to 4.23. Assuming a mid-value of 4.215 the solution is given in Table A-2.

These data are the basis of the "corrected curves" shown in Figure 9. As concluded in the main section of the paper there would appear to be little or no environmental bias in the development of the failure criteria.

Table A-2

SUMMARY OF LOAD REPETITIONS TO FAILURE DETERMINED FROM ANALYSIS

Stiffness, psi	Load Repetitions to Failure at Given Strain, μ in/in.					
	N_{f1j}	e_{1j}	N_{f2j}	e_{2j}	N_{f3j}	e_{3j}
2,095,000	131,022	122.2	694,482	52.3	2,130,078	37.5
1,428,000	122,908	160.0	651,475	68.2	1,998,830	49.0
530,000	104,858	237.5	555,801	100.1	1,705,290	76.6

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