Although considerable work has been completed on laboratory testing of asphalt concrete to determine fatigue properties, more work must be done on predicting fatigue behavior in the field. The initiation and progression of fatigue cracks in a pavement normally take on the familiar "alligator" or "chicken-wire" shape. However, their point of initiation within the pavement structure or within the life-span of the pavement is not well understood. This paper describes several projects that were developed as pavement experiments to investigate several aspects of performance. The projects selected are representative in terms of both simple field observation of fatigue cracking and complete studies that include data on materials characterization, loading history, and other aspects.

Examples of Approach and Field Evaluation: Research Applications

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Five separate road tests or experiments have been selected by the author in an attempt to illustrate 2 factors: (a) the initiation and development of fatigue or fatigue-related cracks and (b) the prediction of fatigue cracking as part of controlled experiments where knowledge of the pavements was sufficient to provide input for modeling their behavior. The Brampton and San Diego projects are included in the first category, and the Folsom and Morro Bay projects are in the second. Tests at the Washington State University test track provided an opportunity for both observation and prediction.

BRAMPTON TEST ROAD

During the summer of 1965, a full-scale test road was constructed near Brampton, Ontario (1). Although many pavement sections were included in that experiment, two were selected here to illustrate fatigue-related crack development.

The first contained 3½ in. of asphalt concrete, 2 in. of crushed-stone base, and 6 in. of sandy-gravel subbase. After an initial period of service, short transverse cracks began to develop in the outer wheelpath as shown in Figure 1. Progression to more advanced forms of alligator cracking (Figs. 2 and 3) occurred rather rapidly and is somewhat typical for that type of failure. The load-associated cracking shown in those figures is perhaps closest to the pure fatigue failure and has been observed by the author to be frequently associated with asphalt pavements overlying unbound granular bases.

The second example at Brampton illustrates that crack initiation may be non-load-associated in many instances but may eventually develop into fatigue cracking. Low-temperature cracking, as shown in Figure 4, or reflection cracking from underlying cement-bound layers, as shown in Figure 5, often occurs soon after construction. Those breaks in the pavement surface may permit initially higher than normal deflections because of free boundary conditions or because of influx of water into underlying layers or both.

How non-load-associated cracks rapidly develop into load-associated cracking is shown in Figures 5, 6, and 7. The surface crack occurred about 2 to 3 months after construction and was reflected from the underlying cement-treated base. Alligator cracks began to appear around that initial crack (Fig. 5), and additional secondary cracking in the wheelpath (Fig. 6) was further evidence of load association. In many instances, those pavements with cement-treated bases were also badly rutted as shown in Figure 7. That observation and the associated high deflection measurements suggested that the cement-bound material was breaking down and reverting to a situation analogous to a granular base. As a result, failure was markedly accelerated.

SAN DIEGO TEST ROAD

Another example of an extensive test project in which observations are still under way is the experiment on Sweetwater Road near San Diego, California (2). Constructed in the mid-1960's, the project was a cooperative study of 8 base types with 4 levels of thickness. After 4 years of in-service operation, none of the sections showed any significant distortion or permanent deformation. However, although no photographs were available, many of the pavement sections showed considerable load-associated cracking (2). Based on observations by Finn (3), about 27 percent of the test sections exhibited cracking of that type. In several instances, the cracking may have been associated with longitudinal cracks that occurred along the outer edge of the pavement and that were not associated with traffic. However, many of the sections were of full-depth design, and failure appeared to be somewhat different from that observed at the Brampton test road.

FOLSOM TEST PROJECT

Several full-scale projects in California have been reported by Monismith et al. (4), in which considerable testing and analysis were used in an attempt to predict fatigue life. The Folsom project, constructed by the California Division of Highways between Sacramento and Placerville, had a pavement cross section as shown in Figure 8. The subgrade and untreated materials in the pavement were tested in repeated load triaxial compression to obtain the resilient moduli. The asphalt concrete was tested for fatigue properties.

Two variations of the subgrade were considered; those were part of a compaction study. A range of moisture for a particular stress condition was used so that a relation such as that shown in Figure 9 could be used to represent the subgrade material under various construction, load, and environmental conditions. In that figure, isoclines of resilient modulus were developed over a range of moisture-density conditions.

The rounded-gravel subbase material was used to fabricate cylindrical specimens for repeated load tests over a range of cell pressures. For those tests, both axial and circumferential deformations were measured, so that resilient modulus and Poisson's ratio were determined as follows:

$$M_R = 7,730\ (\theta)^{0.46}$$

$$\nu = 0.13 + 0.05\ (\sigma_1/\sigma_3)$$

where

θ = sum of principal stresses,
σ_1 = vertical repeated stress, and
σ_3 = lateral cell pressure

A crushed-gravel base-course material was tested in the same manner as was material for the subbase, and modulus and Poisson's ratio relations were determined as follows:

$$M_R = 3,470\ (\theta)^{0.65}$$

$$\nu = 0.16 + 0.08\ (\sigma_1/\sigma_3)$$

Figure 1. Initial transverse cracks in outer wheelpath of Brampton test road.

Figure 2. Beginning of alligator fatigue cracks.

Figure 3. Complete alligator cracking prior to repair.

Figure 4. Non-load-associated crack that was thermally induced and may act as catalyst to fatigue cracking.

Figure 5. Initial crack that was reflected up from cement-treated base and is starting point for fatigue cracking.

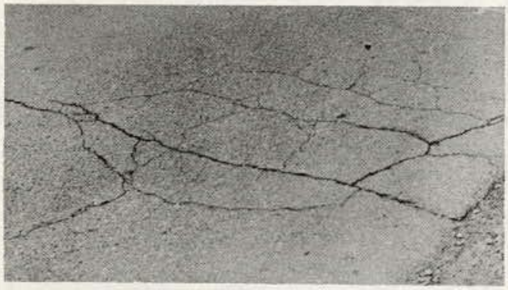


Figure 6. Cracking shown in Figure 5 that has developed to complete alligator cracking in wheelpath.

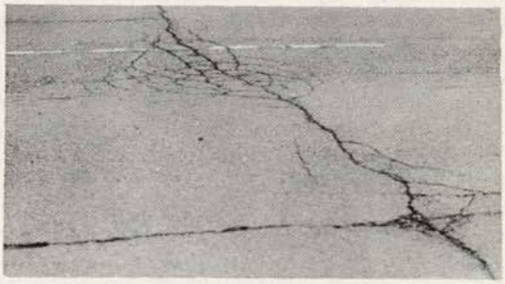


Figure 7. Section with cement-treated base showing considerable pavement deformation prior to cracking.

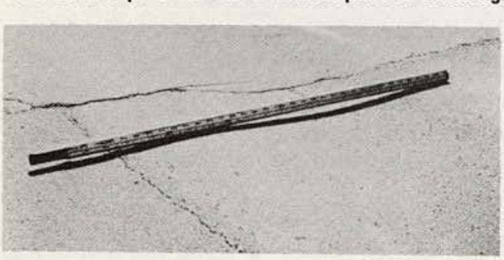


Figure 8. Structural pavement section of Folsom project.

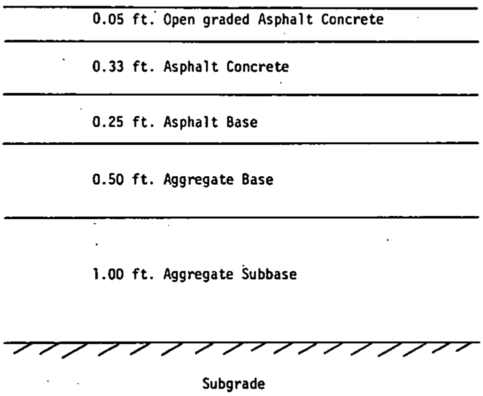
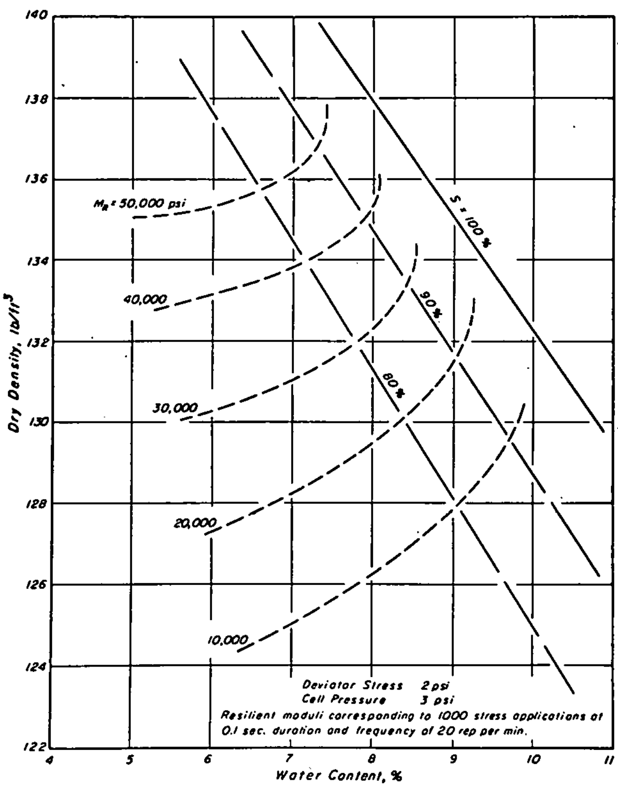


Figure 9. Water content-dry density-resilient modulus relation for subgrade soil.



The asphalt-concrete surface course was tested for flexural stiffness characteristics by the use of beam specimens over a range of temperatures. Stiffness values for 2 ranges of loading times are shown in Figure 10. For purposes of pavement response, Poisson's ratio was assumed to vary from 0.30 to 0.35.

Figure 11 shows the Folsom pavement section as well as the material characteristics for each layer. Once the pavement was characterized by the laboratory tests, it was desirable to determine how measured surface deflections compared with those calculated by the CHEV 5L program. Figure 12 shows a comparison of those deflections and also the effect of asphalt concrete stiffness and subgrade moisture (inasmuch as those 2 variables had the most influence on deflection).

In addition to stiffness modulus of the asphalt-concrete surface course, fatigue characteristics were also determined. Results of both controlled-stress and controlled-strain tests at 68 F are shown in Figures 13 and 14 for the control section. Similar relations were determined for the other test sections but are not shown.

Estimating the service life of the pavement involves systematically characterizing the materials, traffic, and environmental factors and then comparing the predicted life and cracking with that actually observed. The steps followed in that estimation are summarized below.

1. Estimate the truck traffic distribution throughout the day in hourly increments for the various axle-load groups based on several assumptions. All of the traffic variables were related.

$$AHT_{ij} = ADTT \cdot \frac{A_j}{100} \cdot \frac{HT_i}{100}$$

where

$ADTT$ = average daily truck traffic, one direction in design lane;
A_j = percentage of truck traffic of class j (2 axle, 3 axle, and so on);
HT_i = percentage of truck traffic in the hourly interval i; and
AHT_{ij} = number of operations of class j in hour i (daily).

$$AXLD_{ik} = \sum_{j=1}^{S} (AHT_{ij} \cdot WLF_{kj})$$

where

WLF_{kj} = wheel load factors to relate axle class j to axle-load group k, and
$AXLD_{ik}$ = matrix of the number of axle loads of group k in each hour i (on a monthly basis).

The $AXLD_{ik}$ values were expanded to an annual basis by incorporating climatic information as described in step 2.

2. Estimate the stiffness moduli for the asphalt-concrete layer based on climatic data for the Folsom area. Those data were used in a computer program that was modified to provide mean stiffness and temperature at the beginning and end of each hourly increment throughout the day. That approach allowed the use of a single modulus value for the full depth of asphalt concrete and simplified the analysis.

3. Compute stress and deformation by the use of the multilayer linear elastic computer solution, and estimate the bending strains on the bottom side of the asphalt bound layers. The range of those values is shown in Figure 15.

4. Estimate the fatigue performance of asphalt concrete from the road section based on data similar to that shown in Figures 13 and 14. For pavements with asphalt sections of an intermediate thickness, a mode factor (i.e., stress- or strain-controlled) should be considered. A range of mode factors that are intermediate to the limits obtained can be determined in laboratory fatigue testing depending on whether the tests are stress-controlled or strain-controlled. A comparison of mode factors is shown in Figure 16 and can be used for variable thickness pavements.

Figure 10. Computed relation between mixture stiffness and temperature.

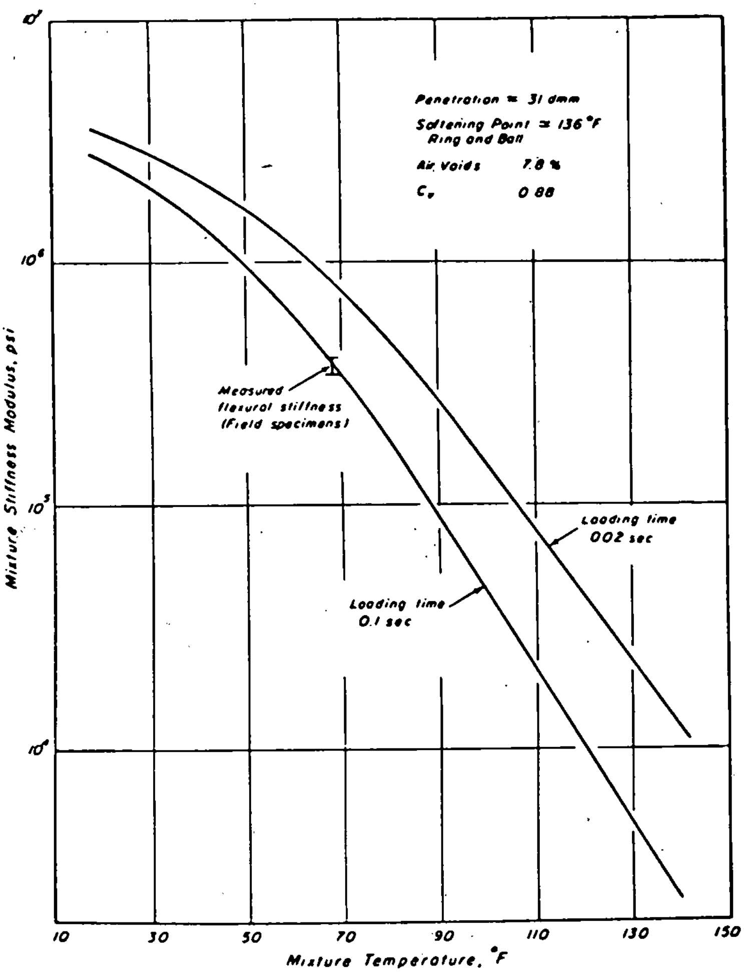


Figure 11. Pavement section used in analysis.

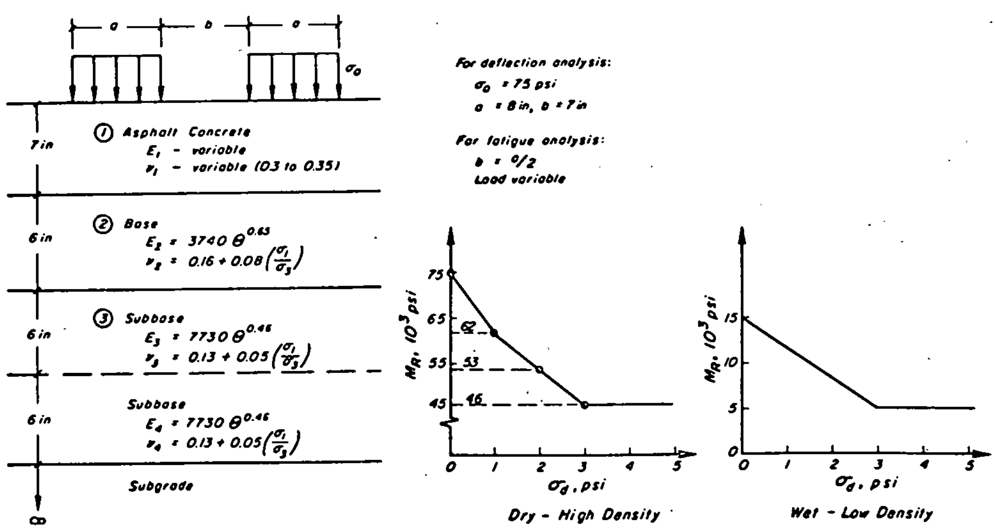


Figure 12. Computed and observed pavement deflections.

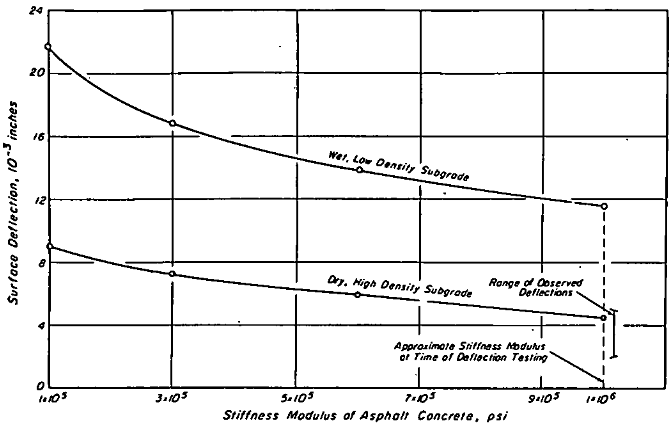


Figure 13. Initial mixture bending strain and applications to failure.

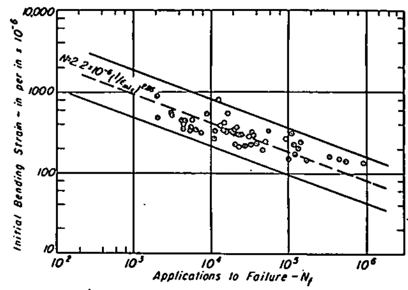


Figure 14. Mixture bending stress and applications to failure.

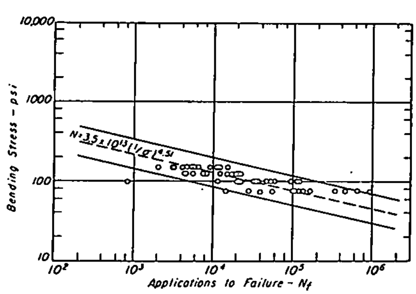


Figure 15. Bending strain on underside of asphalt layer and axle load for stiffness range.

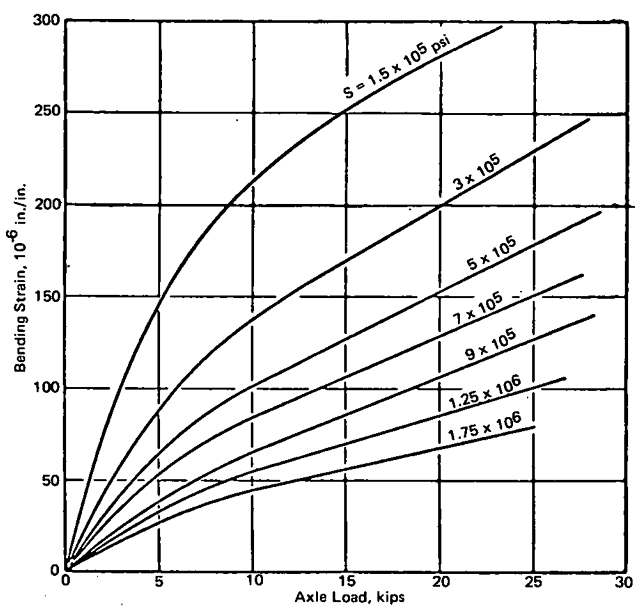
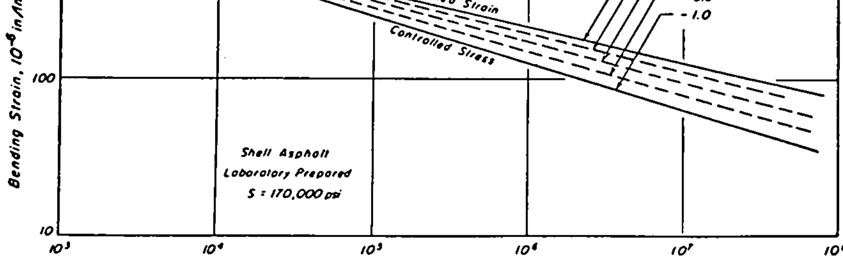


Figure 16. Fatigue curves for series of modes of loading.



5. Predict fatigue life by assembling all the required data so that, for each increment of time, a condition representing the pavement in terms of strain, mode factor, and stiffness is easily accessible. The number of repetitions to failure were designed $ENNF_{\ell k}$, where ℓ is the stiffness group and k is the axle-load group. Then,

$$\text{Annual damage} = \sum_{\ell} \sum_{k} (APL_{\ell k}/ENNF_{\ell k})$$

Traffic values were then incremented by an expansion factor (3 percent), and the process was repeated until the total damage was equal to one.

Fatigue life predictions were made by the use of 3 sets of strain-repetitions to failure relations. The relations and the predicted fatigue life are given below (4).

1. Fatigue life was based on tests of laboratory specimens prepared with the control asphalt. Individual estimated lines were linearly extrapolated to the full range of strain computed. Those data resulted in a predicted fatigue life of 9.5 years.
2. The data were the same as those used in step 1 except that the assumption was made that strains less than 70×10^{-6} in./in. caused no fatigue damage (i.e., endurance limit). The data resulted in a predicted fatigue life of 12 years.
3. A set of relations was estimated from results of tests on specimens obtained from the field surface-course layer. Strains less than 70×10^{-6} in./in. were again excluded. Those data resulted in a predicted fatigue life of 6 years.

The pavement in the Folsom project was designed for a 10-year life by the California Division of Highways using conventional techniques. Based on appropriate traffic data for 1970, suitable extrapolations, and other tests and analysis, the pavement was predicted to perform well on the basis of fatigue life. In other words, a predicted life of 9 to 12 years based on fatigue data appears to be reasonable.

MORRO BAY PROJECT

Other projects, similar to the Folsom project, were a part of the total program described by Monismith et al. (4). One of those near Morro Bay, California, was analyzed by similar techniques but was based on much less sophisticated fatigue data. One conclusion was that a single fatigue curve may not be sufficient for prediction of fatigue life when the total input is so complex.

The Folsom project was newly constructed so that sufficient time had not elapsed for actual fracture to initiate in the field sections by the time of reporting. The Morro Bay project was constructed in 1963, however, and offered an opportunity to observe field cracking. The total analysis, similar to that described above, indicated that some distress might show up in 1965. Field sampling did not show any such evidence, but resampling in 1967 revealed the apparent initiation of fatigue cracking. Figure 17 shows the pattern of observed cracks on the bottom side of several slabs of asphalt concrete removed from the pavement.

WASHINGTON STATE UNIVERSITY TEST TRACK

The special testing facility at Washington State University has provided another opportunity to study fatigue behavior in the field. That apparatus, shown in Figure 18, permits a careful control of the traffic factors, which were difficult to estimate for the in-service pavements discussed in the previous section. Details of the facility have been described elsewhere (5, 6).

Although 4 circular test rings have been completed at the track, the test series conducted from October 1968 to August 1969 was selected for analysis here. That particular test ring consisted of 12 pavement sections (Table 1). The main experiment was the investigation of the 3 main base types, all covered by a uniform 3-in. asphalt concrete surface. Loads were applied to the pavement sections by the special 3-armed loading frame at speeds varying from 5 to 20 mph. Dual tires had a total load of 10,600 lb, and a special control mechanism caused the loads to move slowly from one side to the other while all 3 sets of tires were simultaneously revolving around the track.

After the construction of the Washington test track, loading was initiated in and continued through the autumn of 1968 when weather was extremely wet but was suspended during freezing conditions throughout the winter. When testing was resumed the following March, very little additional rainfall occurred, and the temperatures were steadily increasing until the conclusion of the test in August 1969.

Performance as measured by Krukar and Cook was in 2 phases: (a) the number of load applications until the appearance of the first cracking, and (b) the applications until the section was completely destroyed and the test was stopped for repairs. In most of the pavement sections tested, surface cracks first appeared as short transverse cracks very similar to those at the Brampton test road. Figure 19 shows an example of those cracks that have been accentuated with chalk. That form of cracking was typical for pavements with untreated base courses and with thinner base sections of emulsion and asphalt cement treatment.

Figure 20 shows an example of the next phase of crack advancement. In addition to further cracks, an appreciable amount of permanent deformation has occurred in the wheelpath. That type of failure was often of a local nature and may have been associated with weak or uncompacted underlying materials. A more advanced form of alligator cracking is shown in Figure 21 and is somewhat typical for most of the thinner sections. Fatigue cracks were frequently developed during the summer and autumn months when those test pavements received the first phase of loading. Provided there was no accompanying deformation in subgrade or base courses, the number of load repetitions supported was surprisingly large. In other words, once the primary fatigue cracks appeared, no further development of failure appeared during many thousands of repetitions (note in Fig. 21, 588,000 repetitions).

During the wet fall, rainwater accumulated in the depressed areas and thoroughly soaked the untreated bases and subgrade. Intrusion of water through the cracked surface and the usual spring thaw tended to weaken the underlying material. When testing was resumed in the spring, total failure quickly resulted as shown in Figure 22. That was a result not of further fatigue distress but of subgrade failure.

Several of the thicker (up to 9.5 in.) all-asphalt-concrete and asphalt-treated base sections served considerably longer before distress began to appear. Eventually, when the typical short transverse cracks appeared they were often accompanied by evidence of pumping. Figure 23 shows small amounts of the silt subgrade being exuded at the surface. Other thick sections did not exhibit surface cracks. However, when the pavements were removed and examined, there was considerable evidence of alligator cracking on the underside of the asphalt layers as shown in Figure 24. Subgrade soil had also been pumped into that crack system. The fact that cracks were well developed at the bottom and practically nonexistent at the surface was further evidence that the failure was of the fatigue type and that cracks initiate at the bottom and propagate toward the surface.

It appears feasible to predict the advent of fatigue cracking when sufficient information and test data are available. A brief attempt at this approach (6) resulted in a reasonable relation between laboratory flexural fatigue tests and cracking in the test ring. Figure 25 shows actual points of failure (individual points) superimposed over laboratory data (solid lines) for similar surface materials, for at that time data were not available for the test track pavements. The technique used for this comparison was very similar to that described for the Folsom project. The materials were characterized in the laboratory, and computations were made to estimate or predict the actual measured field behavior. By iterative procedures, a reasonable match was obtained, and the resulting pavement was used for comparison. During the field tests, surface strain was measured under repeated loads, and an average weighted strain was estimated during the period of testing. That analysis was made for the test ring completed in the spring of 1968, and, although the test sections (Table 1) were similar, actual data and weather were somewhat different from those for the 1968-69 test.

A much more detailed analysis of the Washington test track has been provided by Kingham and Kallas (7), which in many respects parallels the approach described by Monismith for the Folsom project. After the field testing was complete, pavement samples were obtained from the untraveled portion of the track. Subgrade testing had

Figure 17. Crack patterns on bottom of slabs obtained from Morro Bay project.

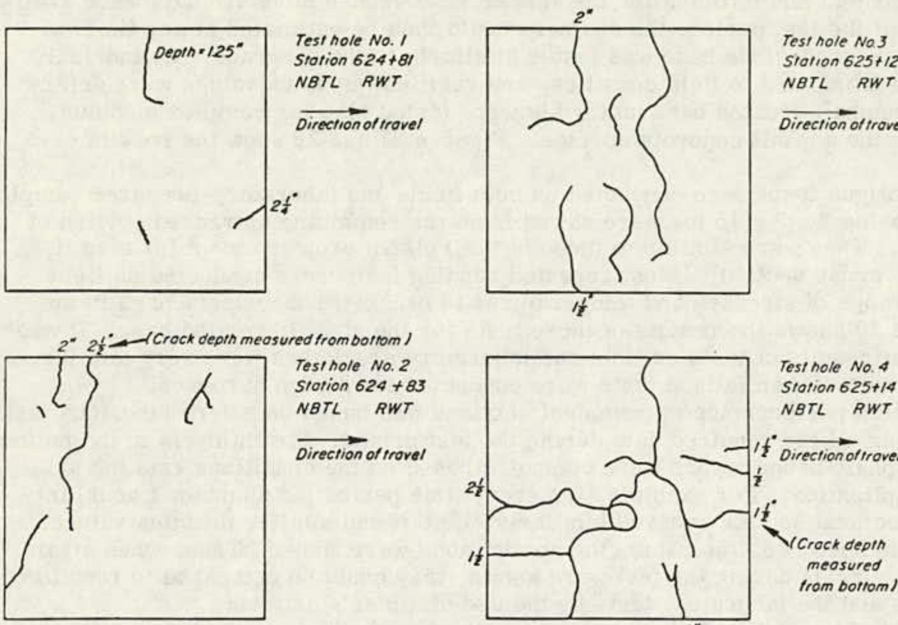


Figure 18. Loading applied by dual truck tires to Washington test track.

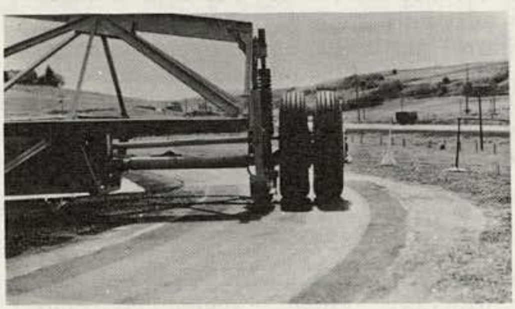


Figure 19. Typical short transverse cracks that are initial stage of more complete failure.

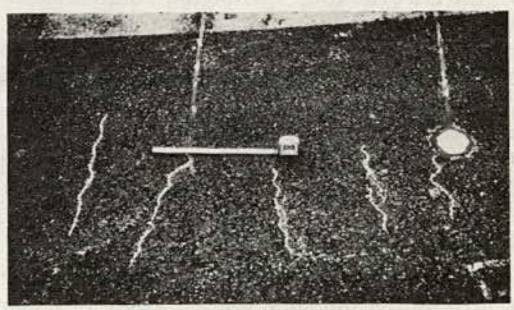


Figure 20. Further crack development and permanent deformation.

Figure 21. Ultimate form of alligator cracking covering entire trafficked area.

been completed on those materials previously (6). Figure 26 shows the relation between water content and modulus for the subgrade. Because moisture data were available throughout the test period, the stiffness could then be estimated at any time.

Untreated crushed-stone base was tested similarly to the subgrade. Cylindrical samples were fabricated to field densities, and resilient modulus values were determined. The asphalt-treated base materials were tested also for complex modulus values as was the asphalt concrete surface. Figures 27 and 28 show the results of those tests.

Flexural fatigue tests were conducted on both field- and laboratory-prepared samples. Beams measuring 3 x 3 x 15 in. were sawed from the remaining untracked portion of the pavement. They were similar to those of the Folsom project except for size (i.e., 1.5- x 1.5-in. cross section). Most repeated bending tests were conducted on field beams for a range of stresses and temperatures to bracket those experienced in the field. Figure 29 shows the results of those tests for the asphalt-treated base. It was also found that results of tests on field and laboratory specimens were very similar, an important factor when fatigue tests were conducted for design purposes.

The predicted performance of pavement sections was based on a very laborious task of accumulating all the required data during the test period. Strain levels in the bottom side of the asphalt-bound layers were computed based on the conditions existing at every load application. For example, for every time period (as short as 1 hour) in which the structural section behaved similarly, i.e., it had similar modulus values and the vehicle speed was the same, the applications were added. Then, when strain levels for all periods during the test were known, they could be compared to results of the field tests and the laboratory tests by the use of Miner's criteria.

The results of predicting fatigue failure by the procedure given above are given in Table 2. The last column in that table shows the actual count of wheel load applications to the point of cracks appearing at the surface. Both laboratory tests (stress-controlled and strain-controlled) as well as field criteria (dynamic modulus-temperature relations) were considered. Both types of laboratory tests tended to overpredict the life to initial cracking. Although comparisons were better for stress- rather than strain-controlled for the asphalt-base sections, they still were somewhat inaccurate. Comparisons for crushed stone were poor. Therefore, prediction of failure for thinner asphalt sections may be inadvisable, at least by the use of the approach described.

In summary, it would appear that prediction of pavement fatigue life is reasonable but not entirely accurate, at least with the data and techniques now available. Further work may be needed to develop criteria for pavement design with respect to prediction and prevention of fatigue distress.

SUMMARY

It would appear that much can be gained by observing the behavior of pavements in the field and through careful study of specific projects. Fatigue cracking may occur in several ways. In general, asphalt concrete surfaces on unbound aggregate bases tends to show initial distress through the development of short transverse cracks in the wheelpath. Although that is the appearance at the surface, cracks may be much more developed on the underside of the asphalt concrete.

Many pavements showing fatigue distress may have initially been affected by other factors that actually served as a catalyst to crack development. For example, cement-treated base may develop shrinkage cracks that in turn are reflected by the asphalt surface and form the beginning of a typical alligator crack system.

Most pavements tend to deteriorate rapidly once fatigue cracks develop, particularly if surface water is available to penetrate into underlying pavement materials. It is, however, often difficult to distinguish which comes first: the surface cracking that develops into a rutted or surface depression or a weak substructure that permits high strain levels to develop in the asphalt layer and thus accelerate fatigue distress. Further, it is apparent that considerable range in the service life of pavements exists after the surface has developed fatigue cracking. In some instances, the pavement structure continues to serve traffic for a considerable length of time after fatigue "failure," provided the underlying layers are not disturbed.

Figure 22. Total failure after subgrade became saturated.

Figure 23. Pumping action associated with initial short transverse cracks on pavement sections with asphalt concrete directly on subgrade.

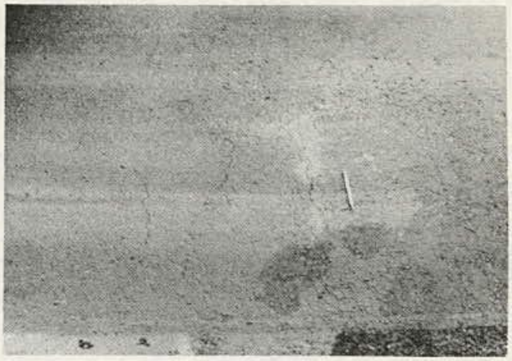


Figure 24. Well-developed crack system on underside of asphalt sections that showed little crack development at surface.

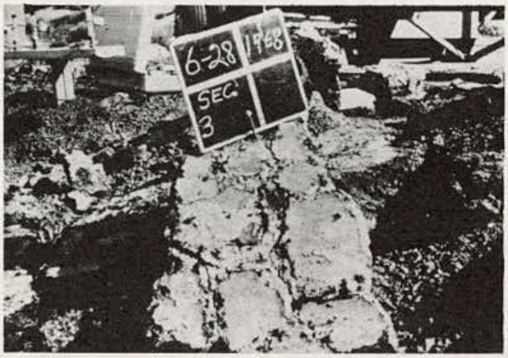


Figure 25. Laboratory fatigue data and wheel load applications.

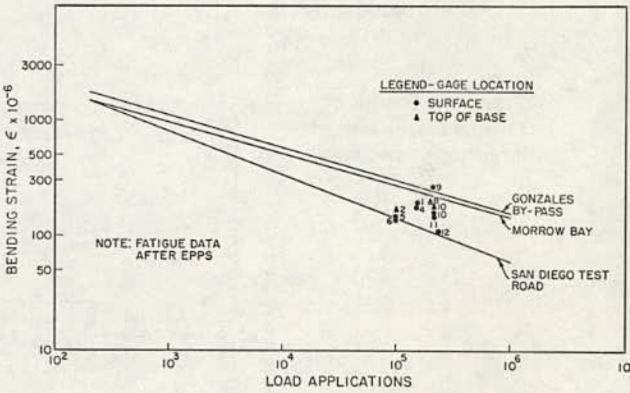


Figure 26. Variation of laboratory-measured subgrade soil stiffness.

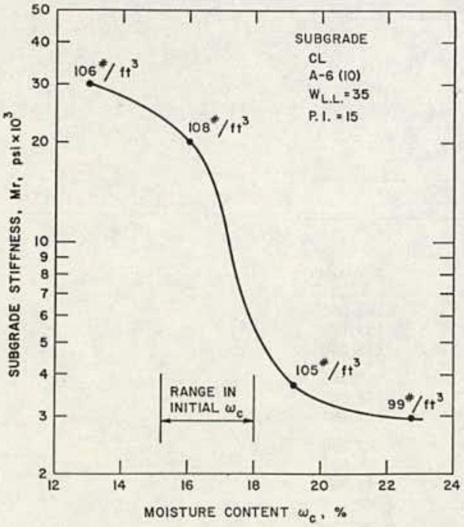


Table 1. Design of ring 4 of Washington test track.

Base	Section	Base Thickness (in.)
Sand asphalt	1	2.0
	2	4.0
	3	6.0
	4	8.0
Asphalt concrete	5	0.0
	6	2.0
	7	3.5
	8	5.0
Crushed stone	9	4.5
	10	7.0
	11	9.5
	12	12.0

Figure 27. Modulus relations for asphalt base courses.

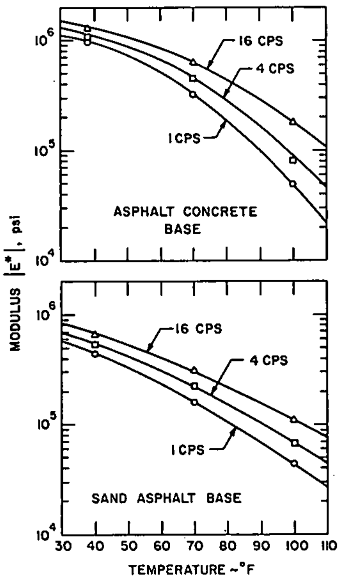


Figure 28. Modulus relations for asphalt-treated layers.

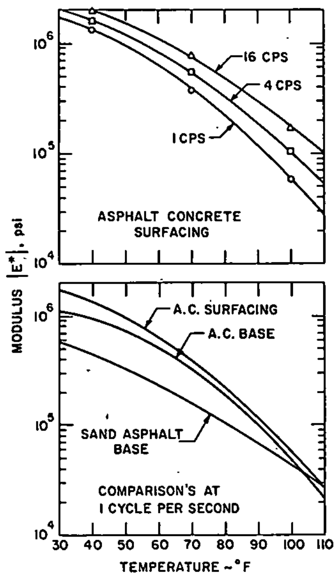


Figure 29. Results of flexural fatigue tests of asphalted-treated base.

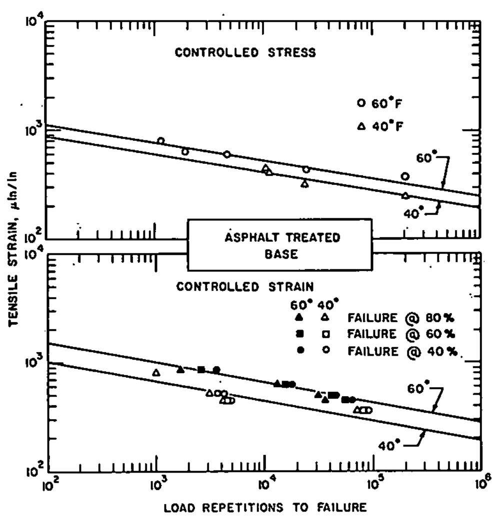


Table 2. Predicted and observed performance of pavement sections.

Base	Section	Surface and Base Thickness (in.)	Repetitions to Failure: Laboratory-Controlled Stress	Repetitions to Failure: Laboratory-Controlled Strain	Repetitions to Failure: Actual (5)
Sand asphalt	1	3 to 2	132,100	162,784*	144,660
	2	3 to 4	190,801*	190,801*	159,789
	3	3 to 6	220,189*	220,189*	175,620
Asphalt concrete	5	3.1 to 0	153,300	157,100	47,391
	6	3.1 to 2	164,800	158,137*	148,887
	7	3.3 to 3.5	174,900	170,710*	161,262
Crushed stone	9	3 to 4.5	147,000	152,700	12,000
	10	3 to 7.0	150,300	156,700	47,391
	11	3 to 9.5	153,700	158,000	48,000
	12	3 to 12	156,700	160,100	49,104

*Further analysis periods are required for the failure prediction because cycle ratios were less than 0.85 at the end of computation.

Two extensive test projects have been described that illustrate techniques for developing potential fatigue prediction procedures. One of those used an in-service pavement and the other a special test track. Both are very comprehensive in that they take into account all the variables that were feasible at the time of analysis.

The project reported by Monismith et al. was an in-service pavement that required a careful analysis of traffic loads as well as environment and materials. Characterization of the pavement structure and fatigue-life determination of the surface asphalt concrete were key factors. Once all available data were assembled, the cumulative effects of traffic on the pavement for the environmental conditions and the time period were estimated. Depending on the assumed influence of repeated traffic loads on fatigue life (in terms of strain in the asphalt-bound layer), a predicted life to failure ranged from about 9 to 12 years; the pavement was designed for 10 years according to the conventional California method. It would appear from this analysis that a reasonable estimate of design life in terms of fatigue cracking is feasible if the engineer is willing to take the time and care needed to do so.

The test pavements at the Washington State University test track were really studied from 2 standpoints: (a) observation and a limited analysis and (b) a more complete analysis based on consideration of all cumulative effects. Terrel and Krukar made a brief study in which they compared the number of load applications to initial surface cracking with failure expected by theoretically characterizing the pavements (based on modulus tests) and using fatigue data (from materials similar to that in the track). A reasonable prediction resulted but was inconclusive because of the lack of actual laboratory fatigue performance of the pavement materials used in the test track.

A more complete analysis of the Washington pavements by Kingham and Kallas probably lies somewhere between the analysis of the Folsom project and the Washington analysis discussed above. Careful characterization of the pavements and materials and also fatigue tests were provided. The traffic in terms of applied wheel loads was carefully analyzed in conjunction with changes in subgrade moisture and temperature (i.e., asphalt stiffness). Each increment of loading was accumulated as damage or distress. Predicted failure of the surface in fatigue was then compared with observed cracking in the pavements. Predictions for pavement sections with crushed-stone bases were poor; those for treated bases were somewhat better, although not so good as might have been expected.

In summary, it would appear that prediction of fatigue failure in actual pavements is feasible. However, there appears to be a basic lack of knowledge in the actual behavior of pavements under varying loads and environments. That difficulty in characterizing the pavement section, coupled with laboratory fatigue tests of the material, still leaves a gap in the understanding of all phenomena involved. Even so, more basic studies such as those described here will certainly assist the engineer to gain a better grasp of how to incorporate fatigue into a pavement design procedure.

REFERENCES

1. Phang, W. A. Four Years' Experience at the Brampton Test Road. Ontario Dept. of Highways, Rept. RR153, Oct. 1969.
2. Hicks, R. G., and Finn, F. N. Analysis of Results From the Dynamic Measurements Program on the San Diego Test Road. Proc., AAPT, Vol. 39, Feb. 1970.
3. Finn, F. N. Observation of Distress in Full-Scale Pavements. HRB Spec. Rept. 126, 1971, pp. 86-90.
4. Monismith, C. L., Epps, J. A., Kasianchuk, D. A., and McLean, D. B. Asphalt Mixture Behavior in Repeated Flexure. Univ. of California, Berkeley, Rept. TE-70-5, Dec. 1970.
5. Krukar, M., and Cook, J. C. Pavement Research at the Washington State University Test Track. Washington Dept. of Highways, Vol. 2, July 1968.
6. Terrel, R. L., and Krukar, M. Evaluation of Test Track Pavements. Proc., AAPT, Vol. 39, Feb. 1970.
7. Kingham, R. I., and Kallas, B. F. Laboratory Fatigue and Its Relationship to Pavement Performances. Proc., 3rd Int. Conf. on Struct. Des. of Asphalt Pavements, London, 1972.