File Copy

Sulfur Extended Asphalt Pavement Evaluation Test Track Pavement Performance

WA-RD 56.2

Final

January 1982

Washington State Department of Transportation
Public Transportation and Planning
In Cooperation with
United States Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
Sulfur Extended Asphalt Pavement Evaluation in the State of Washington: Test Track Pavement Performance Report	January 1982
	6. Performing Organization Code
7. Author's J.P. Mahoney, J.A. Lincoln, D.C. Christensen, R.L. Terrel, J.C. Cook, R.L. Garman	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Washington Department of Civil Engineering Seattle, WA 98195	10. Work Unit No. (TRAIS) 34G1-363 11. Contract or Grant No. DOT-FH-11-9620,WSDOT Y-2004
12. Sponsoring Agency Name and Address * Federal Highway Administration Washington State Department of Transportation	13. Type of Report and Period Covered Interim Report 14. Sponsoring Agency Code

15. Supplementary Notes

WSDOT Contract Manager - Mr. Art Peters
FHWA Contract Manager - Mr. Gary L. Henderson

This report provides an overview of the performance of sulfur extended asphalt (SEA) paving mixtures at the WSU Test Track (Pullman, WA). A brief description of the mix designs, pavement structural design, test track loading apparatus and test pavement configurations is followed by a description of selected test track data (accelerations, temperatures and strain measurements). Finally, a description of the fatigue relationships developed from the WSU Test Track data is presented. Included are laboratory fatigue results.

* U.S. Department of Transportation
Federal Highway Administration
Offices of Research and Development
Washington, D.C. 20590

Washington State Department of Transportation
Highway Administration Building
Olympia, WA 98504

17. Key Words	18. Distribution Statement
Sulfur, asphalt, pavement, sulfur extended asphalt, test track, pavement performance, fatigue	No restrictions. This document is available to the public through the National Technical Information Service Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72)

SULFUR EXTENDED ASPHALT PAVEMENT EVALUATION IN THE STATE OF WASHINGTON: TEST TRACK PAVEMENT PERFORMANCE REPORT

WA-RD 56.2

By

Joe P. Mahoney, Jeffery A. Lincoln,
Derald C. Christensen, Ronald L. Terrel,
John C. Cook, Robert L. Garman

Prepared by the
University of Washington

for the

Washington State Transportation Commission
Department of Transportation
and in Cooperation with
U.S. Department of Transportation
Federal Highway Administration

DOT-FH-11-9620
WSDOT Contract Y-2004
January 1982

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the major contributions of the following graduate students: Capt. Paul Starkey (USA), Lt. Greg Tucker (USN), Lt. Ken Vesely (USN), and Lt. Mike Donnelly (USN).

Special acknowledgement is made to the Washington State Department of Transportation, the Federal Highway Administration, the Sulphur Development Institute of Canada and the Asphalt Paving Association of Washington for their interest and support of the study.

CHAPTER I

INTRODUCTION

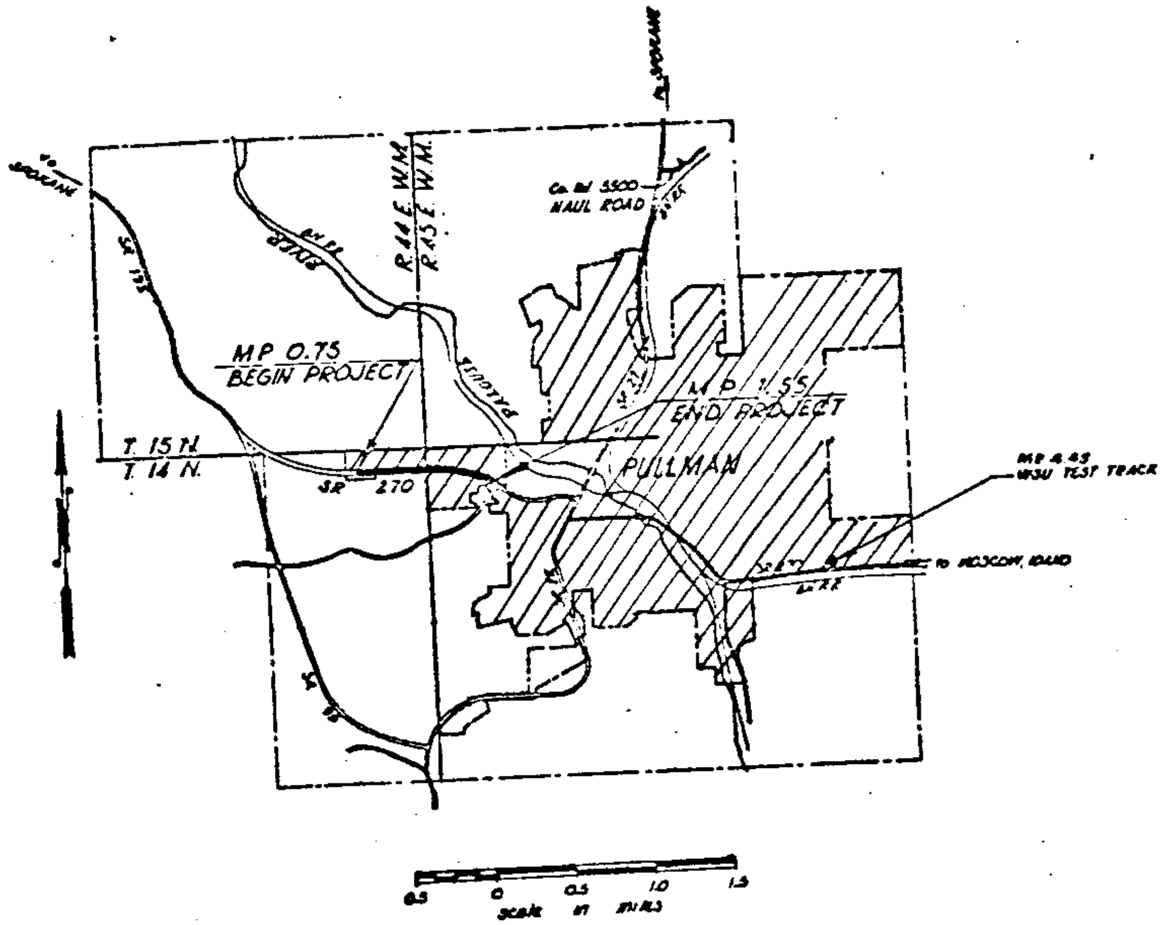
A number of laboratory-analytical studies have been conducted by various organizations to investigate the effect of combining sulfur, asphalt and various aggregates in paving mixtures. Additionally, several full-scale experimental highway projects have been built in the United States, Canada and elsewhere using various combinations of these materials.

Much of this work has been reported and some research efforts, particularly the field trials, are still in progress. It has been observed that, in general, the laboratory-analytical studies have shown the use of sulfur extended asphalt (SEA) binders to be promising, and possibly superior to conventional asphalt concrete paving materials. The results of the full-scale experimental highway projects are, at this time, somewhat inconclusive. This is not to say that compared to conventional paving mixtures SEA bound pavement materials are performing poorly under normal highway traffic and realistic environmental conditions.

The study being reported is intended to help bridge the gap between the laboratory-analytical studies and the full-scale experimental highway projects. This work comprised building full-depth pavement structures for repetitive wheel load testing at the Washington State University G.A. Riedesel Pavement Test Facility (hereafter identified as the "test track") as well as construction and evaluation of a companion highway project. Both types of test pavements were located in the immediate vicinity of Pullman, Washington (Southeastern Washington) as shown in Figure 1, and were constructed August, 1979. This experimental configuration allowed for the concurrent construction of both the test track and a highway project. Thus, the same materials and central batch plant were used for both locations.

There were a number of unique advantages involved in using the WSU Test Track. One is that a limited number of variables were monitored under controlled conditions. The use of a test track thus eliminated some of the uncertainties and variabilities encountered in constructing and evaluating experimental highway projects. It also provided a more realistic assessment of the performance of the composite pavement structure than obtained through laboratory studies. Additionally, a conventional asphalt batching plant and associated laydown equipment were used to produce and place the various mixtures and thicknesses investigated. It was considered important to simulate actual highway construction procedures to the maximum extent possible.

The sponsors for the study included the Washington State Department of Transportation (WSDOT), Federal Highway Administration (FHWA), Sulfur Development Institute of Canada (SUDIC), and the Asphalt Paving Association of Washington. The prime contractor for the conduct of the study was the University of Washington (UW) with Washington State University (WSU) as subcontractor. The Washington State Department of Transportation provided substantial funding for the study as well as participation in the construction and evaluation of the test pavements.



1 km = 0.6 miles

Figure 1. Vicinity Map of Experimental Pavements

This report is the second of three detailing the conduct and findings of the study and deals primarily with the performance of the experimental pavements at the WSU Test Track. A final report will present the final analysis and related information obtained from the SR 270 (highway) test sections.

WSU TEST TRACK

LOADING APPARATUS

The loading apparatus at the test track consists of a 15-ton structural steel frame (Figures 2 and 3) and a water tank revolving over an 85 ft (25.9 m) diameter ring. This applies approximately 11,100 lbs (5034 kg) to each of three sets of dual wheels. Each wheel has a contact width of approximately 8 in (20.3 cm).

To keep the wheels from continuously moving in the same wheel path, the center of rotation of the structure is designed so that various wheel path widths can be applied to the pavement structure. In this study, the wheel path was set at 4 ft (1.2 m) from outside to inside. This yielded a loading distribution as illustrated in Figure 4.

The loading frame is guided by a 6.5 in (16.5 cm) diameter vertical steel shaft. This shaft rotates in a self-aligning bearing mounted in a power-driven revolving frame. The frame is designed to operate in either a clockwise or counterclockwise direction at speeds of 1 to 45 mph (1.6 to 72 kph). The frame is powered by a 440 volt three-phase alternating current 200 horsepower General Electric Kinamatic Speed Variator which supplies 220 volts direct current to each of three 60 horsepower motors geared directly to the wheels. Power is supplied only to the inside wheel of each dual.

During the testing the frame rotated in a clockwise direction at a normal operating speed of less than 30 mph (48 kph). Speed was reduced when the track began to deteriorate in order to reduce excessive dynamic loading due to bouncing of the load assemblies.

TEST TRACK INSTRUMENTATION

Various types of measurements were obtained in order to characterize the performance of the test pavements. These measurements included the following:

1. Strain (vertical and horizontal)
2. Benkelman beam deflections
3. Temperature (air, pavement and subgrade)
4. Visual condition counts
5. Load repetition counts
6. Load acceleration

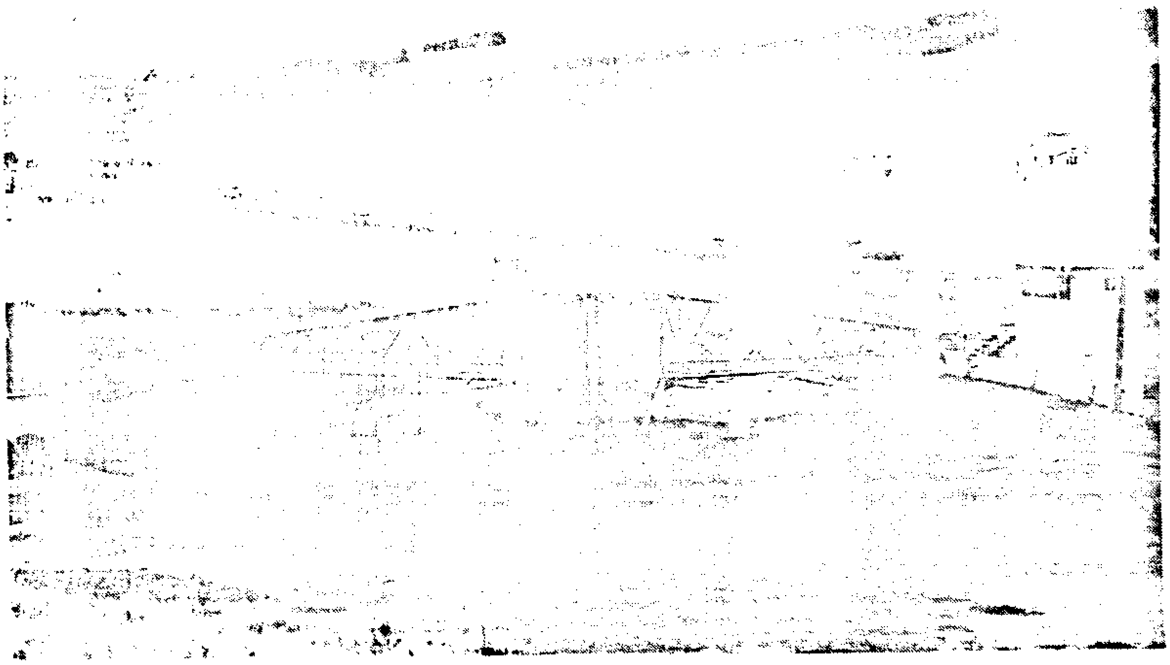


Figure 2. G.A. Riedesel Pavement Test Facility Following Construction of Test Pavements

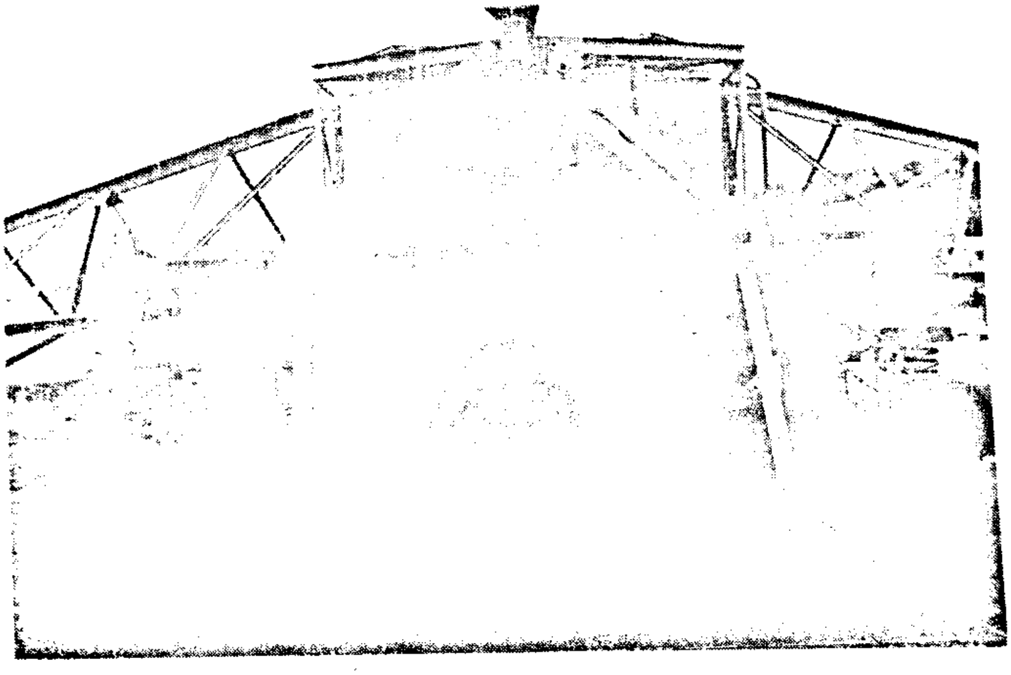


Figure 3. One of Three Sets of Dual Tires Used to Apply Loads to Test Pavements

Primarily, the instrumentation system was designed to automatically measure three variables: strain (deflections), temperature and vertical wheel accelerations. It was also designed to perform preliminary data reduction, data storage and control operations. The strain sensor system measured both the long-term (static) and dynamic strains. The transducers used to make these measurements were developed around a system of wire-wound inductance coil strain sensor pairs (manufactured by Bison, Inc.). The main advantages of these sensors are that they are independent of mechanical linkages and their relative location and initial separation can be determined after placement. They are rugged, unaffected by changes in their environment and minimize the disturbance of the material to be measured. A single strain sensor consists of a minimum of two wire-wound disk shaped coils which can be used in either a coplanar or coaxial configuration. The coil sizes used were one, two and four inch (2.5, 5.1 and 10.2 cm) diameter, respectively.

The initial coil separation can vary from less than one to four coil diameters, with the nonlinear scale factor favoring the closer spacing range to obtain maximum sensitivity. The sensors are connected to an off-the-shelf instrument package (Bison 4101A), which was modified for this study and consisted of the necessary excitation voltage, calibration system, balancing adjustments, readout and analog outputs. The Bison strain coil layout for each of the twelve test sections is shown in Figure 5.

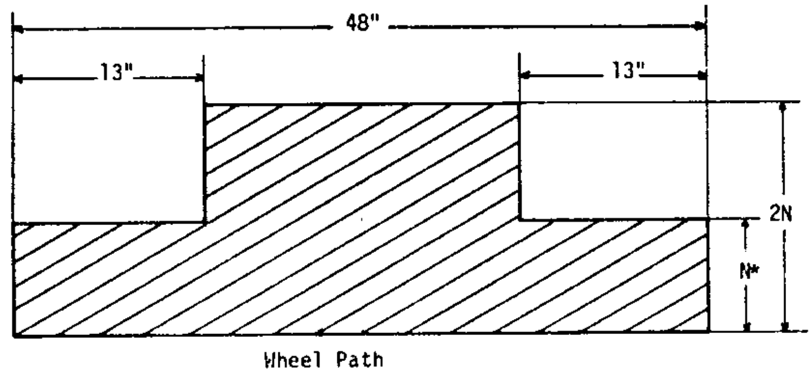
Additional information about the overall instrument system is contained in Reference 1.

TEST PAVEMENT CONFIGURATIONS AND MATERIALS

The test pavement configurations are shown in Figures 6 and 7. These figures show the final design cross sections (and SEA ratios) as well as a plan view of the twelve test sections at the WSU Test Track. The test track pavements were constructed 16 ft (4.9 m) wide (Figure 7). This width not only accommodated the wheel tracking but also provided adequate paving material for subsequent sampling (cores and saw cut beams).

The test track pavements were built on approximately 14 ft of "Palouse silt" (Unified Soil Classification: CL) over bedrock. Contaminated surface material from previous test pavements was removed and replaced with two lifts of uncontaminated subgrade fill (Palouse silt). After the subgrade was compacted to final grade, twelve separate sections of pavements were placed over the subgrade. These pavement sections include four sections each of 0/100 asphalt concrete (conventional - no added sulfur), 30/70 and 40/60 SEA concrete. Two sections for each SEA ratio were "thin" sections, nominally 2.5 in (6.4 cm) thick, and two were "thick" sections, nominally 5 in (12.7 cm) thick. All twelve sections were overlaid with a leveling surface course of 30/70 SEA concrete. Figure 8 shows the final test section thicknesses.

The paving mixtures used in the study were composed of a crushed basalt aggregate (WSDOT Class B gradation) obtained from a quarry adjacent to the WSU Test Track, AR-4000W asphalt cement produced by the Husky Oil Company and molten sulfur from Coleman, Alberta. All paving mixtures were produced



*N = Number of Wheel Loads

1 cm = 0.394 in

Figure 4. Load Distribution in Wheel Path

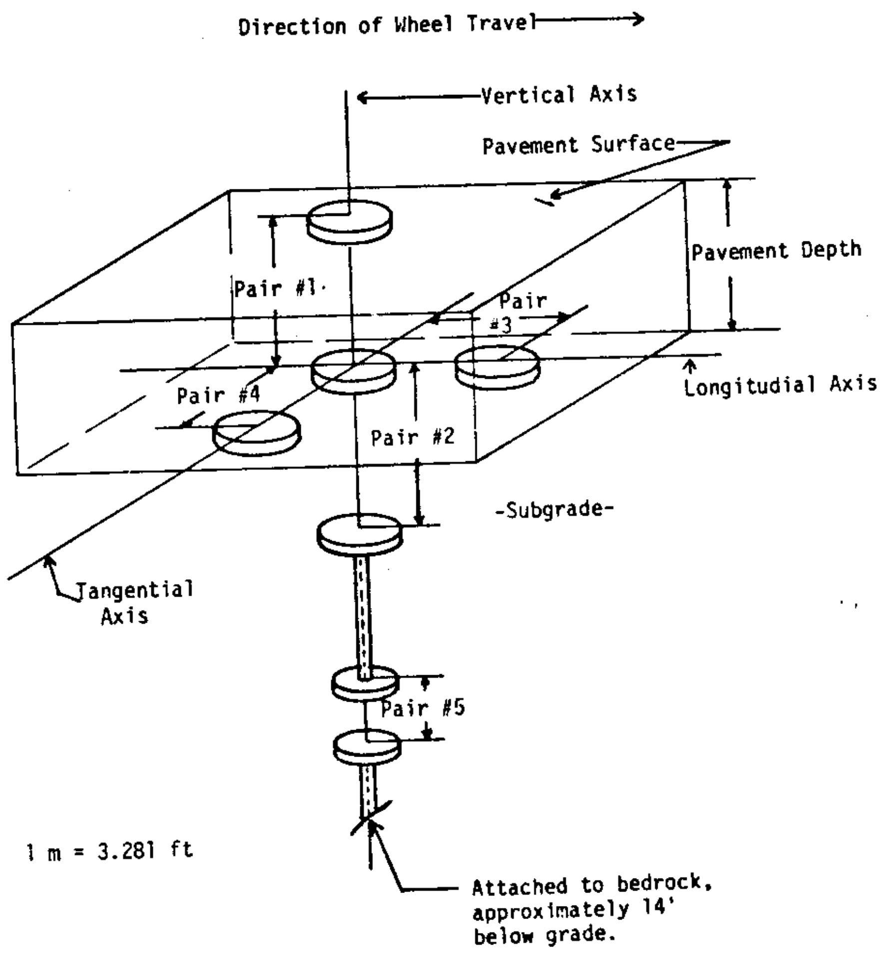


Figure 5. Bison Strain Coil Layout for Each Test Section

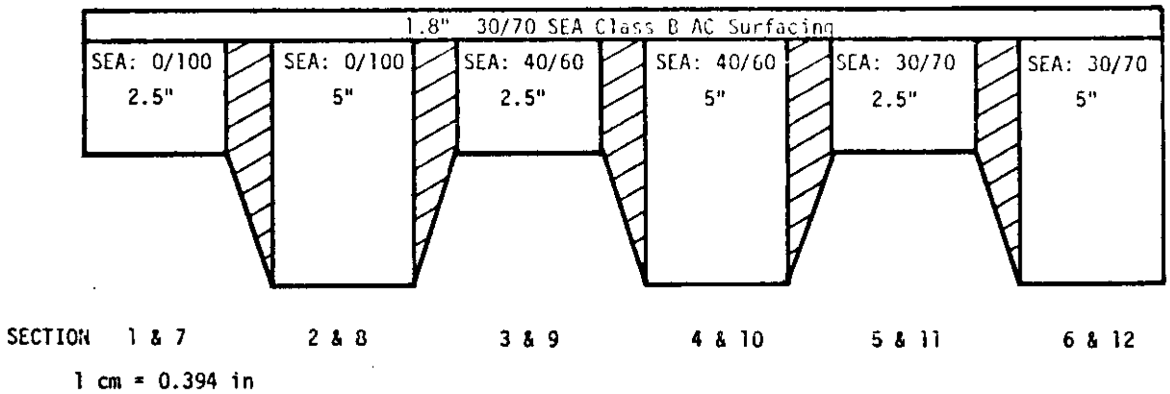


Figure 6. Schematic Profile of Test Track

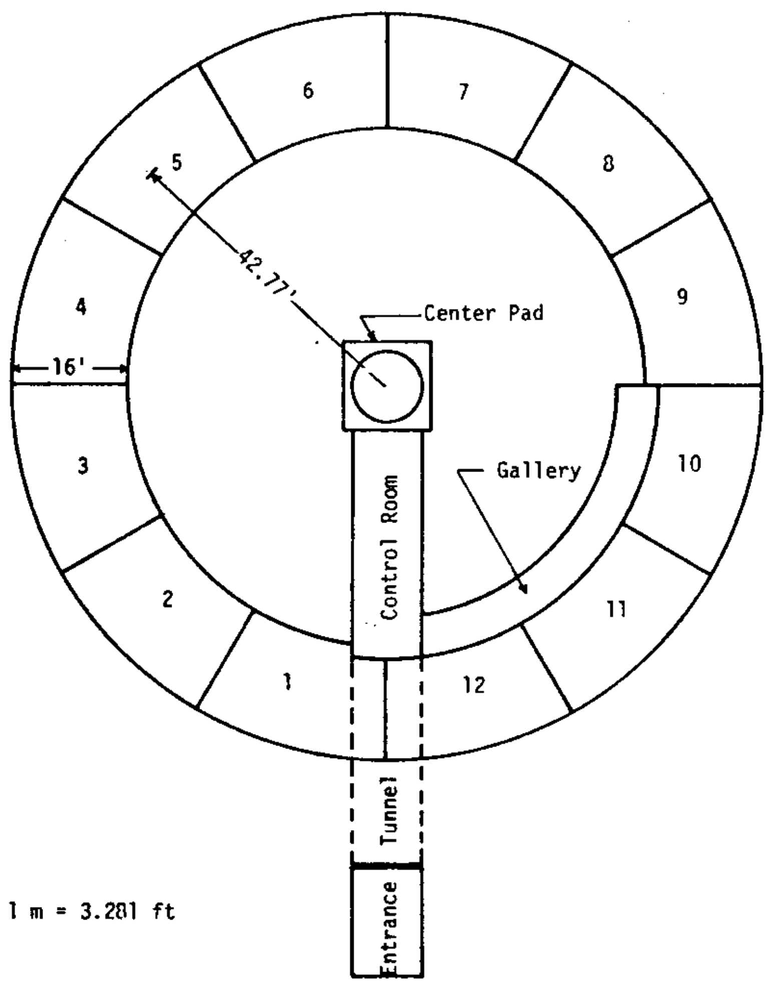
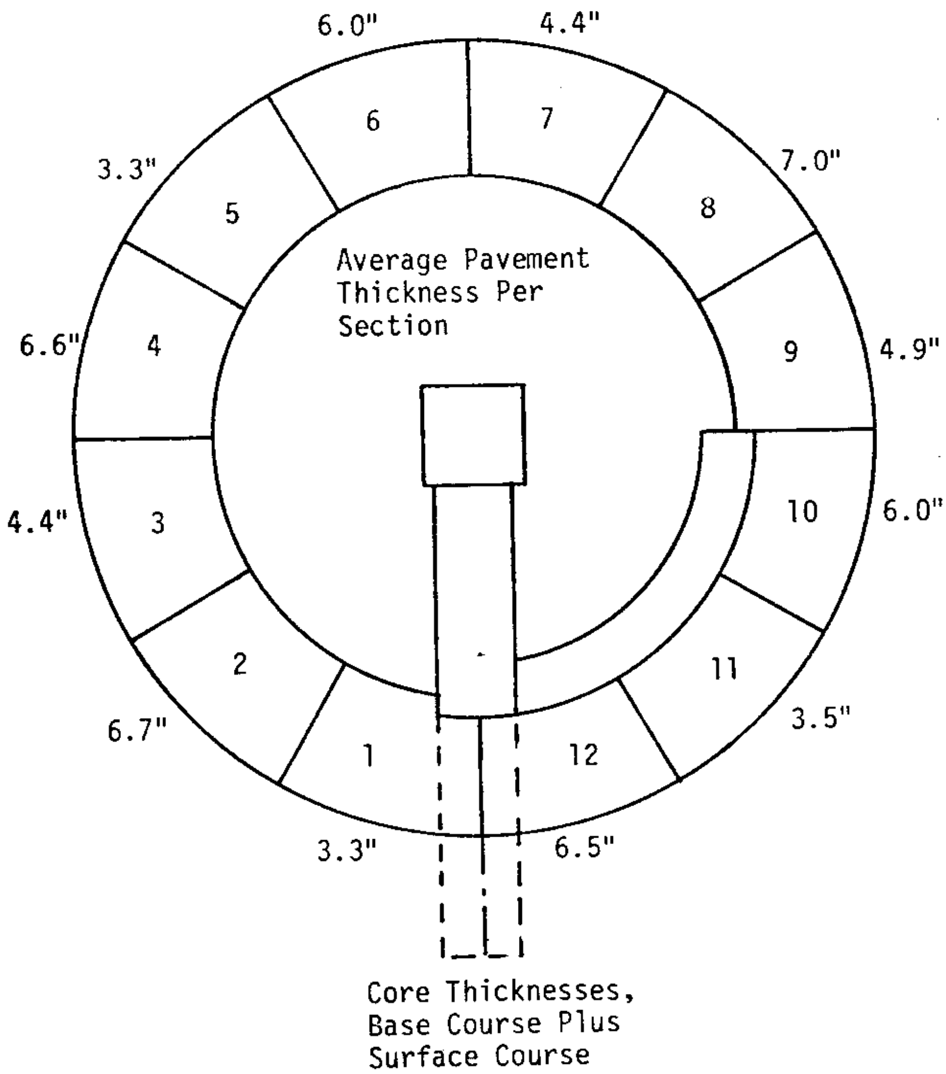


Figure 7. Plan View of Test Track

THICKNESS OF LEVELING COURSE (IN)

THICKNESS	1.1	1.4	1.4	1.2	1.1	1.9	1.6	1.6	1.1	1.7	1.5	1.5
SECTION	1	2	3	4	5	6	7	8	9	10	11	12



1 cm = 0.394 in

Figure 8. Actual Pavement Thickness at Test Track

by the United Paving Company of Pullman, Washington utilizing a standard plant with a pugmill capacity of 3000 lbs (1360 kg).

Both the Hveem and Marshall mix design methods were used in arriving at the proper binder contents for the three paving mixtures. The Hveem procedure was conducted in conformance with Washington State Test Methods 701 (Kneading Compaction) and 702 (Hveem Apparatus). For the Marshall procedure, the test specimens were prepared in accordance with ASTM D 1559.

A summary of the mix designs for both the Marshall and Hveem procedures is shown in Table 1. These results are reported for 0/100, 30/70 and 50/50 SEA ratios. Originally a 50/50 SEA ratio was planned for the field study in lieu of the 40/60 SEA ratio ultimately used. The laboratory mixture data indicated a binder content of 5.5 percent by weight of total mix was optimum for the 0/100 SEA mixture (conventional asphalt concrete). Similarly, the 30/70 and 50/50 mixtures indicated similar optimums (on an approximate equivalent volume basis) at 6.5 and 7.4 percent, respectively. It is of interest that the kneading compaction technique (Hveem) resulted in lower air void contents and slightly higher densities at the "optimum" binder contents as compared to those obtained from the Marshall compaction method. If only the Hveem mix design data had been used in selecting the binder contents for the three mixes, lower "optimum" binder contents may have been selected.

The actual binder contents used were 5.7 percent (by weight of total mix) for the 0/100 mixture, and 6.6 percent for the 30/70 and 40/60 mixtures. By equivalent volume of asphalt cement, the 40/60 SEA binder would have been approximately 0.5 percent binder content below optimum. This was not planned in the initial experimental design but provided the opportunity to evaluate a SEA mixture below the volume equivalent of the 0/100 mixture.

Table 1. Summary of the UW Marshall and Hveem Mixture Design Data at Optimum Binder Content

Data Type	Test Value at Optimum Binder Content		
	0/100 SEA	30/70 SEA	50/50 SEA
1. Marshall			
(a) Stability (lb)	3650	4800	9660
(b) Unit Weight (pcf)	154	155	156
(c) Air Voids (%)	3.5	5.0	3.8
2. Hveem			
(a) Stabilometer Value	46	52	64
(b) Unit Weight (pcf)	161	161	159
(c) Air Voids (%)	1.5	1.2	1.3
3. Optimum Binder Content (% by Weight of Total Mix)	5.5	6.5	7.4

1 N = 2.248 lbf
1 Mg/m^3 = 62.4 lb/ft^3

CHAPTER II

TEST TRACK DATA

Several types of test track data will be summarized in this chapter. These data include the following:

1. Accelerations

2. Temperatures (thermocouples)

3. Selected strain measurements

ACCELERATIONS

Acceleration measurements were made of the vertical motion of the dual wheel axles (Model 303B Sanstrand accelerometers) in an attempt to provide a measure of the true load on each individual wheel as it passed over a transducer set. These signals were averaged over a interval of approximately ±1 ft (0.3 m) either side of the track centerline. Where available, the readings were given in g's about a zero mean. Thus, a measure of -0.5 g would indicate that on the average over the interval measured the wheel was being accelerated upwards, resulting in approximately 1/2 of its mass being applied to the pavement structure. Unfortunately, the transducers operated intermittently. However, accelerations ranging between 0.5 to 1.5 g were measured after the thin test pavements began to fail (resulting from rough pavement surfaces).

TEMPERATURES

The temperature measurements were made at various locations (Table 2) throughout the test track. These measurements were made using J type thermocouples capable of measuring temperatures from below freezing to 392°F (200°C) with a resolution of approximately 0.2°F (0.1°C) and an accuracy of ±0.5 percent or ±1.8°F (±1°C) (whichever is larger). This information was tabulated, printed and stored on a floppy disc with each strain measurement summary. A record of these temperatures is included as Appendix A. A typical temperature trend is shown in Figure 9 for various locations and depths (selected day: November 13, 1979).

SELECTED STRAIN MEASUREMENTS

This section is used to demonstrate the accuracy/reliability of the Bison coils in a vertical (or parallel) configuration. The discussion of the development of fatigue relationships (Chapter III) will illustrate the accuracy of these coils in a horizontal (coplanar) configuration.

During the operation of the test track, data was recorded relating to the vertical deflections of the pavement test sections. Coil Pairs 1, 2 and 5 were designed to measure the deflections (or change in deflection) of the pavement structural layer (Pair 1), the subgrade to a depth of 4 to 15 inches beneath the pavement (Pair 2) and the remaining subgrade beneath

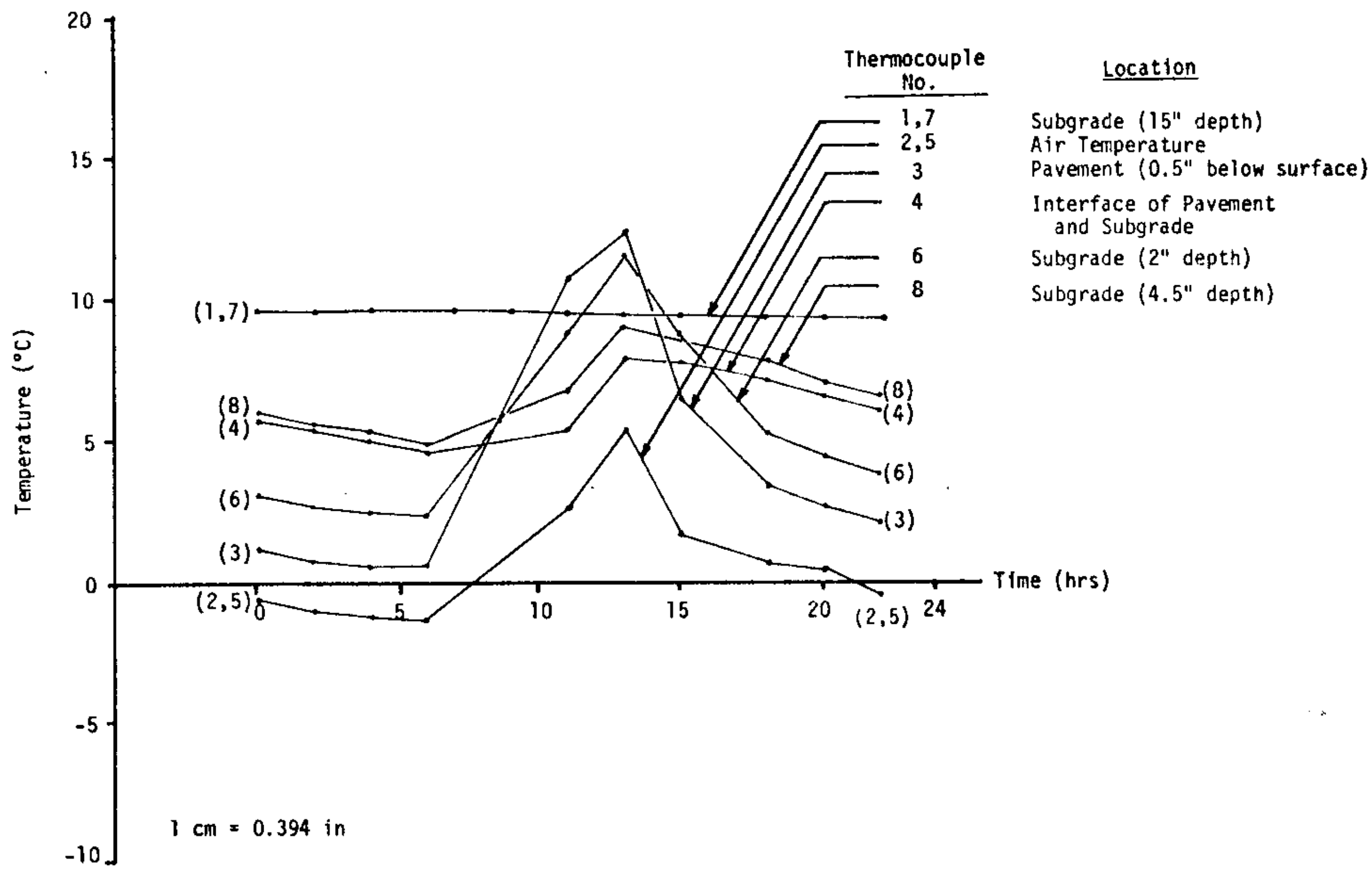


Figure 9. Typical Temperature Trends (November 13, 1979)

Pair 2 to bedrock (Pair 5).

On November 15, 1979, a set of Bison coil measurements was recorded at the same time that a Benkelman Beam was used to record deflections of the pavement surface between the center of the dual tires of Arm No. 1. Recorded were the coil spacings of Pairs 1, 2 and 5 with the coils in a load/unload configuration. On this date, approximately 230,000 loadings had been applied and all thin sections except Section 5 had failed (although this section was distressed and near failure). For this reason, only the five thick sections with operational Bison instrumentation were analyzed. From the temperature data (Appendix A), it was determined that the temperature was near 32°F (0°C). Using the resilient modulus of the pavement materials extrapolated to that temperature, the pavement sections were modeled using the BISAR layered elastic computer program (developed by the Shell Oil Co.). These temperature and material properties result in a "stiff" pavement, therefore measurements from Pair 1 are discounted since little deformation is possible within the pavement layer. Pairs 2 and 5 represent the total vertical deflection of the test sections. The results of these measurements are shown in Table 3.

There exists a consistent deflection correlation for the five test sections except Section 10. The track log (Appendix B) indicates that Section 10 failed somewhat prematurely and had experienced severe transverse cracking at 216,000 load repetitions and noticeable deformations at 249,000 load repetitions. Deterioration in the pavement structural layer in the form of cracking can cause the Bison coils to become loose and therefore unreliable. This may account for the difference between Benkelman Beam and BISAR predicted deflections. Section 10 was considered failed at 244,000 load repetitions, shortly after these measurements were recorded.

Table 2. Location of Thermocouples at WSU Test Track

Thermocouple No.	Test Section	Description of Location
1	5	15 inches into the subgrade
2	6	Exposed to the air
3	6	0.5 inch below pavement surface
4	6	Between SEA pavement and subgrade
5	9	Exposed to the air
6	9	2 inches into the subgrade
7	9	15 inches into the subgrade
8	10	4.5 inches into the subgrade

1 cm = 0.394 in

Table 3. Vertical Pavement Deflections Measured by Benkelman Beam, Bison Coils and BISAR Predicted (November 15, 1979)

Section	Benkelman Beam (in)	Bison Coils (in)	BISAR Predicted (in)
2	0.035	0.030	0.034
4	0.035	0.033	0.033
6	0.029	0.032	0.035
10	0.063	0.025	0.034
12	0.040	0.044	0.032

1 cm = 0.394 in

CHAPTER III

FATIGUE CHARACTERISTICS OF TEST PAVEMENTS

Numerous approaches have been tried in determining the fatigue characteristics of asphalt concrete mixtures. Recent investigations of SEA mixtures [2, 3] have used laboratory applied loadings to determine the fatigue parameters. Many engineers feel that laboratory derived fatigue relationships, in general, tend to underestimate the fatigue life of an in-service pavement. The use of the WSU Test Track provides a condition where field constructed pavement can be failed by use of controlled, known loads in a relatively short period of time.

In this chapter, the number of load repetitions applied to each test section will be presented followed by an analysis of this information, other material properties and laboratory tests to derive fatigue relationships.

WSU TEST TRACK REPETITIONS

The test track was constructed during late August 1979, and operation began slowly in early October. Operations increased during the late part of October with approximately 80,000 loadings complete on November 1. By November 15, when the air temperature began dropping below freezing, 216,000 loadings had been completed and by November 17 all thin sections had failed. Operation of the track continued through January and into February 1980, when operations ceased with approximately 500,000 loadings completed. A summary log of critical events and general comments is contained in Appendix B.

The wheel loads (recall that the average load for each set of duals was 11,100 lb (5030 kg)) were applied to each of the twelve test sections until failure occurred. The basis used to determine repetitions to failure (N_f) for any test section was when the section exhibited 25 percent or more of fatigue (alligator cracking)on the pavement surface. The estimated number of load repetitions to failure for each of the twelve sections is shown in Table 4. This table also contains a further summarization of the wheel loading data. For the "thin" sections, the relative performance of the three SEA mixtures based on repetitions to failure and ranked from best to worst appears to be: 40/60, 0/100 and 30/70. The 30/70 SEA sections are ranked lowest due to the large variability observed for the two 30/70 sections. For the "thick" sections, the same ranking method results in the following: 0/100, 30/70 and 40/60. Thus, from a straightforward tabulation of such data, a consistent trend is not apparent.

DEVELOPMENT OF FATIGUE CRITERIA

The determination of the fatigue characteristics for the experimental paving mixtures was accomplished by developing relationships between the initial bending strain at the bottom of each pavement base course vs. the number of load repetitions to failure. The determination of the initial bending strain was made by using two approaches. One approach used the in-situ strains as measured with the Bison strain coils (installed in each of the twelve pavement sections). The other approach used the BISAR computer program which utilized elastic moduli and the thicknesses of the various layers.

For the Bison measuring system, strip chart measurements of the voltages from the Bison coils taken on October 24 and 27, 1979, at the beginning of the test track operations, were used to estimate the tensile strains at the bottom of pavement layers. The strip chart measurements were taken with the loads at various distances from the centerline of the Bison coil; the distance being a function of the load assembly eccentricity. As the load of Arm No. 1 signaled the relay, the strip chart recorder was switched to the pair being sampled. As the load passed the coils, a change in voltage was recorded signaling a change in the coil spacing. Since the distance between loads and coils was as much as 33 in (84 cm), it was necessary to sample at another time and eccentricity in order to obtain sufficient data. The most extensive sampling (seven to eight readings per pair) was taken on October 27, 1979, and was used as the primary data source, while data from October 24 was used as required. The available results are shown in Table 5.

The measurements taken by strip chart were generally not taken with the loads positioned so as to cause maximum tensile strains in the pavement layer at the Bison coils. Since the maximum tensile strains are necessary to develop fatigue relationships, a method of modeling to relate the measured "offset" values to the expected maximum strains in the actual pavements was necessary. Additionally, it was desired to model (estimate response) the pavement sections by a method to compare measured with predicted strains. Again, the BISAR computer program was used for this purpose.

BISAR COMPUTER MODELING

The BISAR computer program is a general purpose program that is capable of calculating stresses, strains and vertical deflections that result from the imposition of the dual wheel loads.

The program uses the following input:

1. Elastic modulus; Poisson's ration and thickness of each layer.

2. Character of each load, including stress imposed, radius of loaded area and position (cartesian coordinates).

Upon request, the program can provide a wide range of expected stresses, strains and deflections in any layer and position.

Table 4. Summary of Load Repetitions to Failure for the WSU Test Track Sections

Paving Mixture	Type of Section	Section No.	Repetitions to Failure (N_f) Individual Test Section	Mean	Range
0/100	Thin	1 7	130,000 173,000	151,500	43,000
	Thick	2 8	500,000 500,000	500,000	-
30/70	Thin	5 11	246,000 84,500	165,250	161,500
	Thick	6 12	500,000 438,000	469,000	62,000
40/60	Thin	3 9	173,000 216,000	194,500	43,000
	Thick	4 10	474,000 244,000	359,000	230,000

Table 5. Initial Horizontal Strains as Measured by the Bison Instrument System

Test Section	Horizontal Strain ($X10^{-6}$) Measured		Adjusted	
	Longitudinal	Tangential	Longitudinal	Tangential
1	231	249	312	299
2*	82	-	204	-
3	234	343	369	-
4*	155	-	216	-
5	109	-	315	-
6	-	-	-	-
7	143	207	331	-
8	-	-	-	-
9	291	58	358	-
10	-	-	-	-
11	-	-	-	-
12	-	-	-	-

*Data from 10/24/79 - all other from 10/27/79

Input Data

The resilient modulus data for all layers used in the modeling is shown in Table 6. The resilient modulus of the subgrade was of particular interest since no granular base course material, such as crushed rock, was used as a structural base for the paved layers. The paved layers were placed directly on the compacted subgrade of Palouse silt. The subgrade had previously been determined to have a resilient modulus of about 4,000 psi (27,570 kPa) under optimum moisture conditions (as determined with standard laboratory compaction) and considerably less with moisture contents higher than optimum. It was also noted that the final moisture content of Section 10 through 12 was somewhat higher than the other sections resulting in a lower density. For these reasons a resilient modulus of 2,000 psi (13,780 kPa) was assumed for these sections.

Poisson's ratio was taken as 0.30 for all SEA concrete materials and 0.35 for the subgrade.

Material thicknesses were taken from the values determined from core samples removed from the test track.

The loads used in the simulations were modeled after the load of Arm No. 1, since this arm triggered the activation of the recording system and was used for all measurements. This resulted in a stress of 80 psi (550 kPa) over a loaded radius of 4.76 in (12.09 cm).

The BISAR modeling was done in two phases. During the first phase, the modeling was performed in order to adjust the Bison coil readings from Pairs 3 and 4 (refer to Figure 5). This was done by modeling the systems in a worst case situation (duals centered over coils) as well as modeling the system under the same conditions that existed when the strip chart measurements were taken, i.e. with the dual wheels located offset from the coils. Using this data, it was assumed that the ratio of BISAR offset strains to BISAR centered (worst case) strains would closely approximate the ratio of Bison coil offset measured strains to the worst case strains expected if the loads were centered over the coils. Possible inconsistencies exist in using this data since pavement thicknesses may vary slightly at the various locations and because the subgrade modulus initially was assumed in this phase as to be 4,000 psi (27,570 kPa) for all test sections.

In the second phase, BISAR was used to predict the response of the pavements using the data reported in Table 6 for pavement moduli and thicknesses, and the Poisson's ratios previously mentioned. Additionally, the subgrade resilient modulus for Sections 10 through 12 was set at 2,000 psi (13,780 kPa) while the other sections remained at 4,000 psi (27,570 kPa). Using the summary of the test track log, and photographs of the test track, the number of repetitions to failure was determined. These values were previously shown in Table 4.

FATIGUE RELATIONSHIPS

The strains determined by both the Bison coils and calculated with the

BISAR computer program were used to develop a fatigue relationship for each experimental paving mixture. This approach was used because some of the critical Bison coils malfunctioned (refer to Table 5). The resulting fatigue relationships are shown in Figures 10-13. Figures 10-12 each contain "BISAR", "Bison" and "most probable" plots for each of the SEA mixture combinations (Figure 10 (0/100), Figure 11 (30/70), and Figure 12 (40/60)). Figure 13 is a composite of the "most probable" plots for each of the SEA mixtures.

The available data was plotted and the fatigue parameters determined for the following equation:

$$N_f = K_1 \left(\frac{1}{\varepsilon}\right)^{K_2}$$

where N_f = load repetitions to failure

ε = initial bending strain

K_1, K_2 = fatigue parameters

This equation relates the expected repetitions to pavement failure to the inverse of the initial bending strain. Thus, the damaging effect of any loading condition can be evaluated for a pavement constructed with the materials evaluated in the study. The fatigue parameters based on the "most probable" curves are shown in Table 7.

A difficulty in developing these field derived fatigue relationships is that only two pavement thicknesses were used (each replicated) on the assumption that the thin sections would fail early in the wheel tracking and the thick sections substantially later. This trend occurred but the first section failed after slightly more than 80,000 wheel load applications. The longest a thick section lasted was approximately 500,000 repetitions. Thus, a range of about 400,000 repetitions was used in developing the fatigue relationships. Additionally, the fatigue relationships were influenced by the combination of initial surface cracking, full-depth design, and wheel tracking during wet weather. This combination resulted in accelerated pavement deterioration, hence, decreased fatigue life.

Considering the stated limitations, it is of interest to compare the fatigue curves for the three SEA ratios. The 30/70 and 40/60 SEA paving mixtures exhibit similar fatigue characteristics (Figure 13 and Table 7). The notable difference occurs for the 0/100 (conventional) mixture. This fatigue curve has a flatter slope which implies that the material will have a longer fatigue life at low bending strain levels and shorter life at high bending strains when compared to the 30/70 and 40/60 mixtures, however, the differences in the fatigue relationships as developed, are not considered to be significant. In addition, the actual differences in fatigue life between the conventional and SEA mixtures at high N_f levels may be minimal for some pavement designs. This is due to the generally higher stiffness of the 30/70 and 40/60 SEA mixtures which can result in correspondingly lower bending strains.

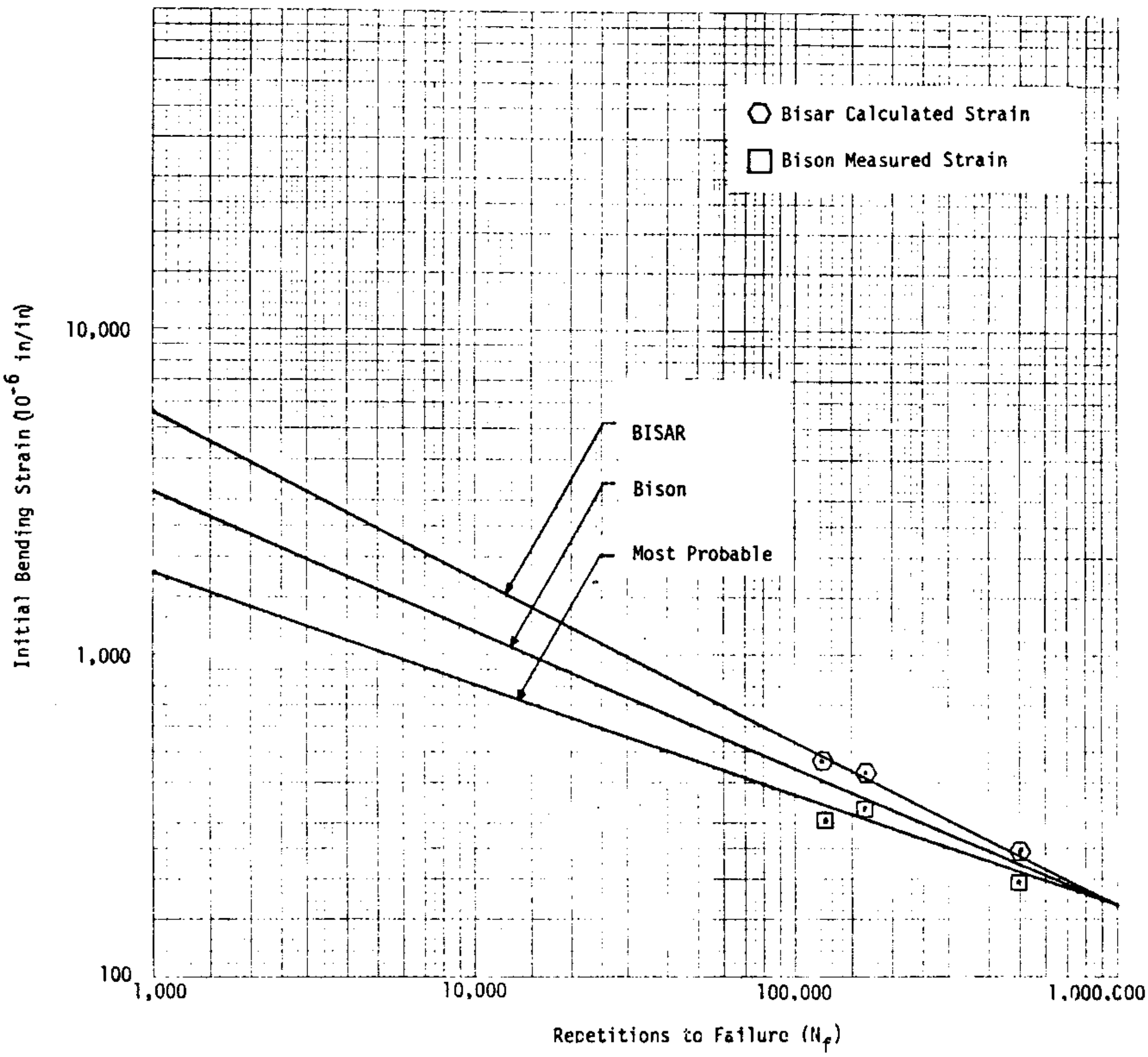


Figure 10. Test Track Derived Fatigue Relationship for 0/100 SEA Mixture (Conventional ACP)

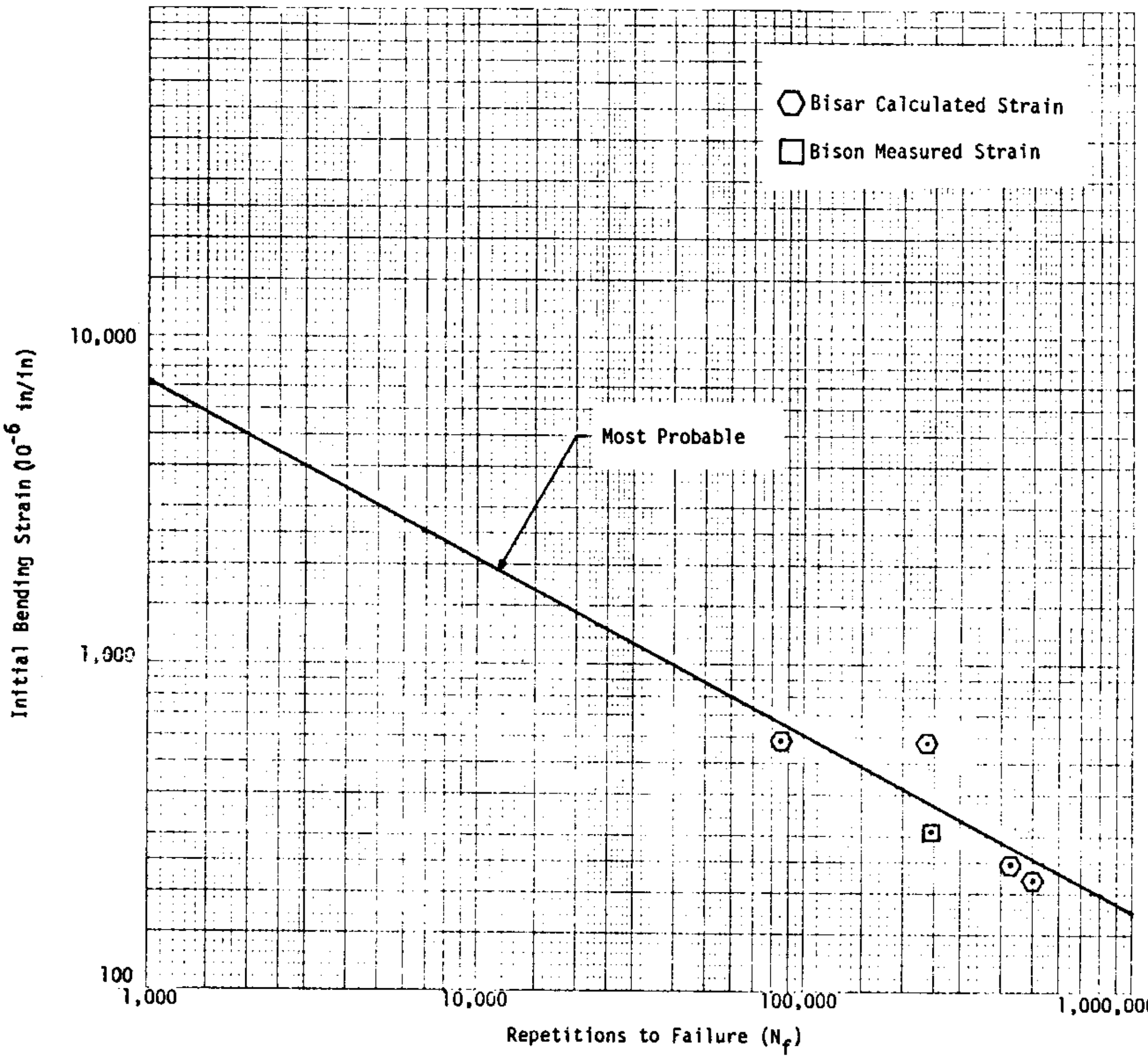


Figure 11. Test Track Derived Fatigue Relationship for 30/70 SEA Mixture

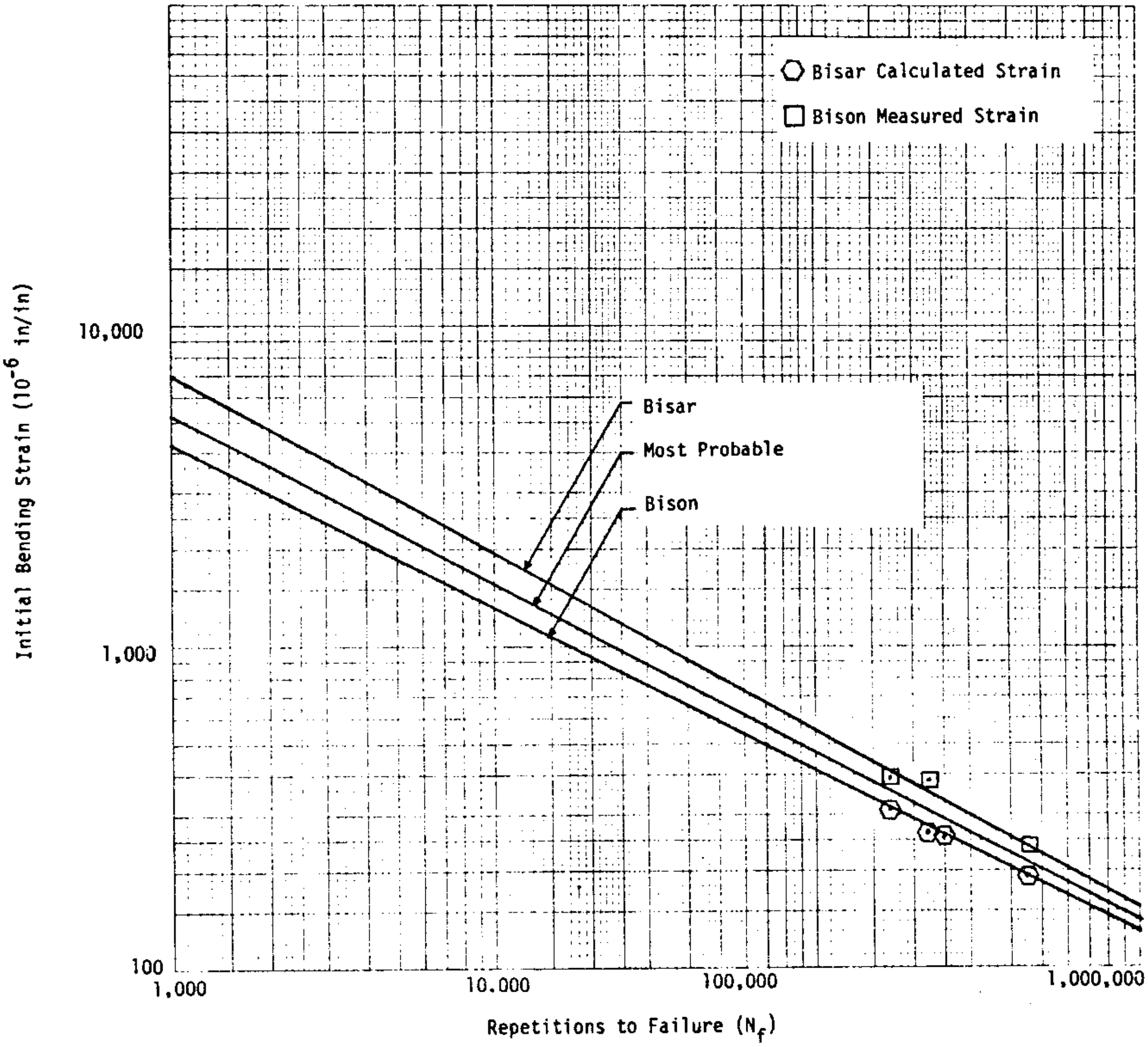


Figure 12. Test Track Derived Fatigue Relationship for 40/60 SEA Mixture

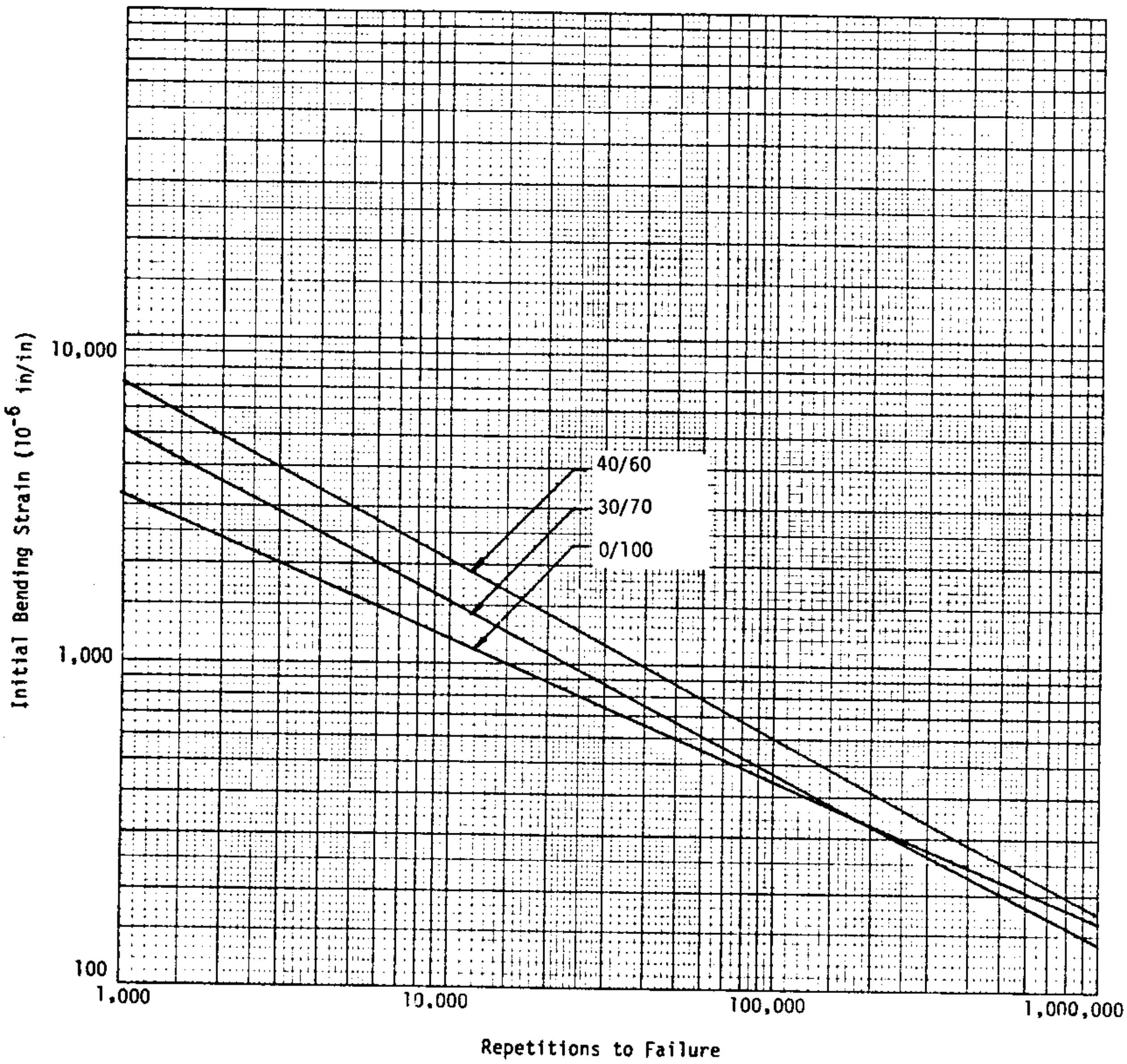


Figure 13. Summary of "Most Probable" Test Track Fatigue Relationships for 0/100, 30/70 and 40/60 SEA Mixtures.

Additional fatigue work was performed on sawed beams removed from portions of the test track which had not undergone wheel tracking. These beams were then transferred to the University of Washington Materials Laboratory for further study. The beams were trimmed to a final depth of 3.5 in (8.9 cm) by 23.75 in (60.3 cm) long prior to testing. Following trimming a strain gage was applied to the underside of each beam (Micro-measurements EA-06-20CBW-120). The instrumented beams were then placed in a linear rolling wheel laboratory test track as shown in Figure 14. This load apparatus was used to apply approximately 40 wheel loads per minute to each of the test beams. The beams were supported on a "subgrade" consisting of ground rubber and Ottawa sand. This fatigue apparatus, as configured, approximates a controlled strain test mode.

The testing of the sawed beams was conducted at a temperature of 66°F ±2°F (19°C ±1°C) with tire pressures of 38 psi (262 kPa). The beams were periodically removed and visually inspected to determine the approximate time of crack initiation (on bottom of beam) and the point of failure (crack depth equal to beam depth). The resulting fatigue parameters from this testing are shown in Table 8, the fatigue curves in Figure 15, and the source data in Table 9. A similar fatigue parameter trend appears for the three paving mixtures based on both modes of fatigue testing (field and laboratory).

Table 9 contains the initial bending strain levels and the associated number of load repetitions to initial cracking (N_i) on the bottom of each beam and total loads to failure (N_f). The determination of N_i was not an exact measurement but it is apparent that the fatigue estimates would be far more conservative if based on initial cracking alone. The ratio of N_i/N_f (as a percentage) is provided in the table for each beam tested. A relative shift can be determined by the ratio N_f/N_i. These values vary significantly but an overall average for 17 of the 20 beams tested is a shift of 20. Thus, the number of loads required to progress the crack completely through the beam after crack initiation is approximately 20 times larger than the number of loads required to start the crack.

Fatigue data from the WSU Test Track as well as other pertinent fatigue data [4, 5, 6] illustrates possible fatigue shifts (Table 10). The goal is to examine the shifts that occur for various kinds of fatigue test conditions. Van Dijk [4] used a rolling wheel apparatus to determine fatigue characteristics for three different mixtures. During this testing, the crack state at the bottom of the pavement slabs was determined. Shift ratios based on expected repetitions to failure are shown in Table 10 for three conditions:

1. Shift from initial hairline cracks to major cracks

2. Shift from major cracks to failure of the slab

3. Shift from the initial hairline cracks to failure of the slab.

The transition from hairline to major cracking for the three mixes results in a shift of 3 to 4. This can be compared to a shift of 5 obtained by comparing the WSU Test Track field fatigue relationships to one obtained from a controlled stress flexural laboratory apparatus for a similar paving mixture [6]. Although, shift ratios of a magnitude similar to those reported

Table 6. Resilient Moduli Used for BISAR Modeling (Temperature: 55°F)

Test Section	Total Thickness (in)	Surface M_R (ksi)	Base (Top Lift) M_R (ksi)	Base (Bottom Lift) M_R (ksi)	Subgrade M_R (ksi)
1	3.60	960	680	-	4
2	6.70	960	690	720	4
3	4.40	960	1130	-	4
4	6.38	960	870	1180	4
5	3.40	960	710	-	4
6	5.94	960	1170	960	4
7	4.40	960	680	-	4
8	7.00	960	690	720	4
9	3.90	960	1130	-	4
10	5.82	960	870	1180	2
11	3.50	960	710	-	2
12	6.50	960	1170	960	2

1 cm = 0.394 in

$C° = (°F - 32)\frac{5}{9}$

Table 7. Fatigue Parameters for Test Track Derived Relationships

Paving Mixture	Fatigue Parameters K_1	K_2	* Coefficient of Determination (R^2)
0/100 SEA	1.12×10^{-3}	2.36	0.79
30/70 SEA	1.39×10^{-1}	1.82	0.72
40/60 SEA	4.77×10^{-2}	1.89	0.81

*Measure of statistical correlation

Table 8. Fatigue Parameters for the University of Washington Laboratory Test Track

Paving Mixture	Fatigue Parameters K_1	K_2	Number of Beams Tested	*Coefficient of Determination (R^2)
0/100	2.49×10^{-12}	4.90	5	0.83
30/70	1.52×10^{-5}	2.65	8	0.90
40/60	7.33×10^{-6}	2.84	7	0.96

*Measure of statistical correlation

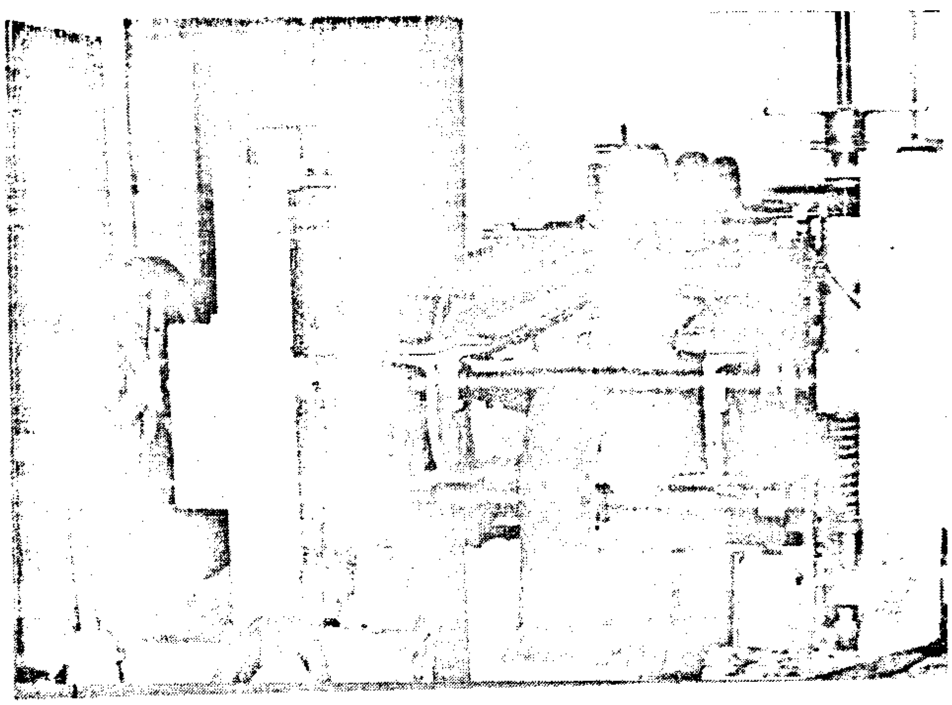


Figure 14. University of Washington Rolling Wheel Laboratory Test Track

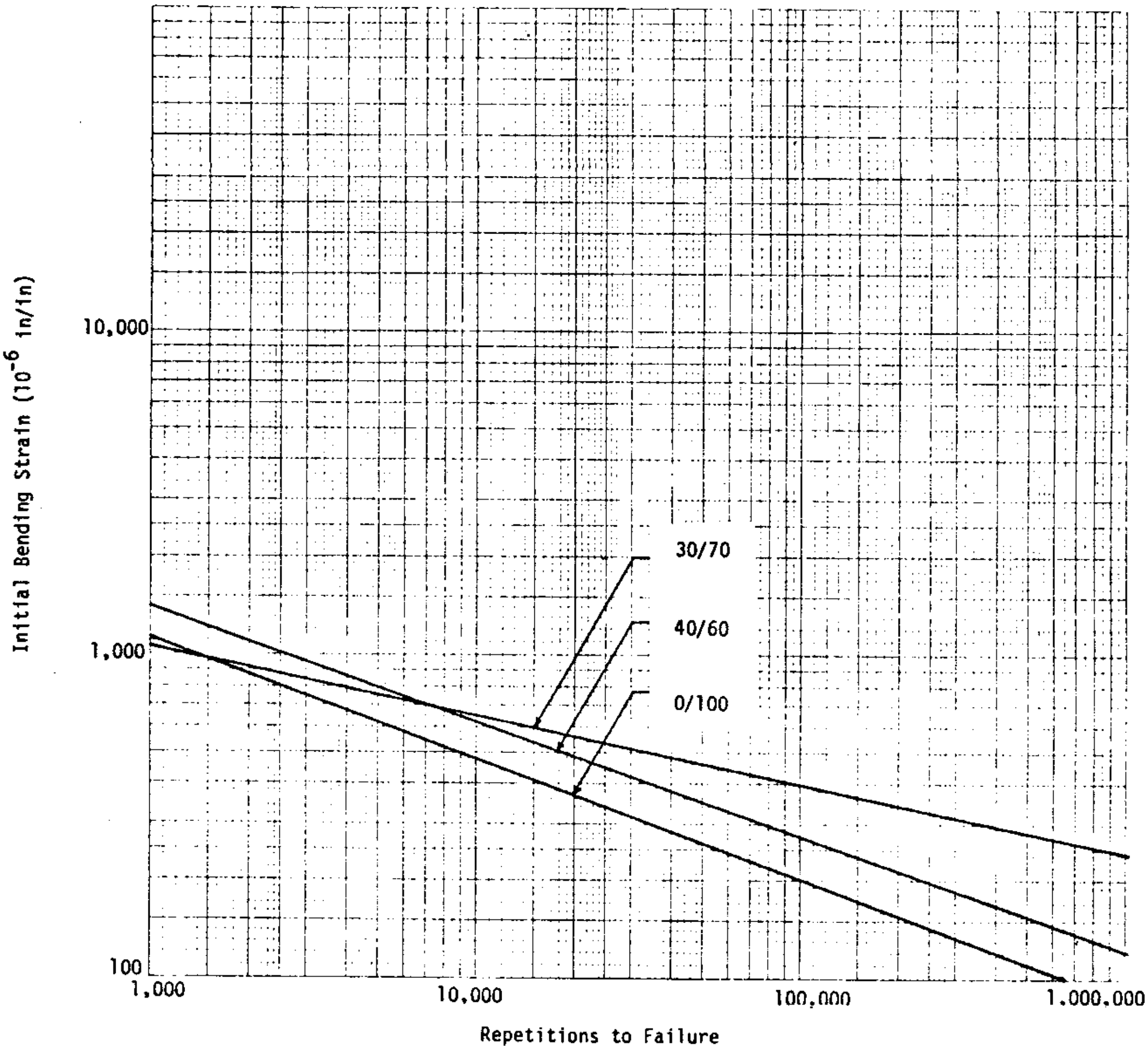


Figure 15. UW Rolling Wheel Laboratory Derived Fatique Relationship for 0/100, 30/70 and 40/60 SEA Mixtures

Table 9. Fatigue Test Results from UW Laboratory Test Track

Paving Mixture	Initial Bending Strain ($X10^{-6}$ in/in)	Number of Loads at Initiation of Cracking (N_i)	*Number of Loads at Failure (N_f)	N_i/N_f (%)	N_f/N_i
0/100	450	15,000	72,300	20.7	4.8
	550	2,200	21,700	10.1	9.9
	550	1,000	15,500	6.5	15.5
	850	10	1,085	0.9	108.5
	1200	100	1,775	5.6	17.8
30/70	300	1,300	28,000	4.6	21.5
	350	1,500	18,800	8.0	12.5
	500	1,100	8,250	13.3	7.5
	550	1,300	7,725	16.8	5.9
	700	420	1,600	26.2	3.8
	800	400	3,030	13.2	7.6
	900	400	3,500	11.4	8.8
	1300	1	720	0.1	720.0
40/60	400	500	27,700	1.8	55.4
	500	500	12,500	4.0	25.0
	550	1,700	14,500	11.7	8.5
	800	500	7,200	6.9	14.4
	1200	150	1,500	10.0	10.0
	1800	1	250	0.4	250.0
	2500	1	300	0.3	300.0

*Crack depth equal to beam depth

Table 10. Determination of Shift Ratios Based on Various Fatigue Tests

Data Source	Type of Fatigue Test	Type of Mixture	Fatigue Parameters K_1	Fatigue Parameters K_2	Loads to Failure*	Shift Ratio Case	Shift Ratio Value
1. Van Dijk [4]	Laboratory Wheel Tracking (20°C)	(a) Dutch graded ACP (AC-1)					
		(i) Hairline cracks	1.20×10^{-5}	2.75	178,400	ii ÷ i	3
		(ii) Major cracks	5.75×10^{-5}	2.71	608,000	iii ÷ ii	5
		(iii) Failure	2.29×10^{-4}	2.73	2,871,000	iii ÷ i	16
		(b) Calif. graded ACP (AC-II)					
		(i) Hairline cracks	5.89×10^{-4}	4.23	47,000	ii ÷ i	3
		(ii) Major cracks	6.92×10^{-5}	2.66	162,500	iii ÷ ii	8
		(iii) Failure	5.78×10^{-4}	2.66	1,357,600	iii ÷ i	29
		(c) U.K. Rolled Asphalt (RA)					
		(i) Hairline cracks	2.00×10^{-6}	3.04	351.500	ii ÷ i	4
		(ii) Major cracks	5.50×10^{-4}	2.53	1,255,300	iii ÷ ii	5
		(iii) Failure	4.66×10^{-3}	2.46	5,859,400	iii ÷ i	17
2. Finn, et al [5]	Field data from selected AASHO test road sections	AASHO Road Test ACP @ 500,000 psi					
		(i) ≤10% cracking	7.87×10^{-7}	3.29	1,163,000		13**
		(ii) ≥45% cracking	1.08×10^{-6}	3.29	1,596,000		17**
3. Kallas and Puzinauskas [6]	Laboratory controlled stress flexural fatigue (21°C)	Laboratory compacted materials from WSU Test Track	6.52×10^{-5}	2.50	115,300		
4. Current Study	Field data for conventional ACP-(0/100)-WSU Test Track	WSU Test Track sections (total of 4)	1.12×10^{-3}	2.36	600,900	(4) ÷ (3)	5

*Loads to failure calculated at $\varepsilon_t = 200 \times 10^{-6}$ in./in. except for 1.(b).
**Shift factor determined by Finn, et al.

by Finn [5] may be more realistic in that the experimental test sections at the WSU Test Track tended to deteriorate rapidly after initial surface cracking due to infiltration of water into the silty clay subgrade.

A final comparison of fatigue parameters is appropriate. Table 11 shows fatigue parameters developed for laboratory compacted mixtures [2] and beams which were fatigue tested in the laboratory but saw cut from field constructed pavements [3, 7]. For 0/100 mixtures, the fatigue parameters derived from the WSU Test Track compare favorably to those developed by Bergan et al, at 39°F (4°C) (comparison to test track field results). The 30/70 SEA mixture results (UW laboratory) are essentially identical to the fatigue parameters as reported by Pickett, et al, for a 26/74 SEA laboratory compacted mixture. The field derived 30/70 SEA results when compared to similar SEA mixtures tested in laboratory fatigue have a higher ability to accommodate bending strains at low N_f values. For the 40/60 SEA mixtures, the laboratory derived fatigue relationships by Bergan, et al, and sawed beams from the test track compare favorably even though the fatigue testing procedures differ.

Overall, the fatigue relationships derived from the WSU Test Track (both field and laboratory) indicate that the 0/100 (conventional) mixture has a flatter slope than the 30/70 and 40/60 SEA mixtures (desireable for high N_f), but is less able to accommodate large bending strains in the low N_f range. Additionally, the relationships for the 30/70 and 40/60 SEA mixtures are essentially the same.

Table 11. Various Fatigue Parameters Developed for Beam Specimens

Source	Paving Mixtures*	Sample Preparation	Testing Temperature (°C)	Fatigue Parameters	
				K_1	K_2
Picket, et al	26/74 SEA	Lab Compacted	20	2.94×10^{-4}	2.67
	51/49 SEA	Lab Compacted	20	1.01×10^{-8}	3.79
Bergan, et al	40/60 SEA	Field Sawed Beams	20	1.49×10^{-3}	2.57
	0/100 Conventional	Field Sawed Beams	20	1.11×10^{-2}	2.19
	40/60 SEA	Field Sawed Beams	4	9.09×10^{-8}	3.63
	0/100 Conventional	Field Sawed Beams	4	3.53×10^{-3}	2.07
Kingham and Kallas	0/100 Conventional	Field Sawed Beams	4.4	5.45×10^{-4}	4.32
	0/100 Conventional	Field Sawed Beams	15.6	6.31×10^{-11}	4.32
	0/100 Conventional	Field Sawed Beams	26.7	3.12×10^{-9}	4.14

*Percent sulfur/percent asphalt by weight

CHAPTER IV

SUMMARY AND CONCLUSIONS

Data from the twelve experimental test pavements recently constructed and tested to failure at the WSU Test Track were analyzed. The primary focus of the analysis has been to develop fatigue relationships for conventional dense graded asphalt concrete (0/100) and two SEA mixtures (30/70 and 40/60). The construction of the test pavements revealed no unusual problems with the production and placement of the SEA mixtures following a few minor plant start-up problems. The conventional and 30/70 SEA mixtures were mixed with essentially volumetrically equivalent binder contents (5.7 and 6.6 percent by weight, respectively). The 40/60 SEA mixture was mixed and placed at about 0.5 percent less than its volume equivalent when compared to the other two paving mixtures (6.6 percent by weight).

The fatigue analysis of the test pavements (field and laboratory test tracks) shows that the conventional dense graded asphalt concrete has a flatter fatigue curve when compared to the two SEA mixtures. This can be a desirable characteristic at high levels of repetitions to failure (low bending strains). The 30/70 and 40/60 SEA mixtures exhibited similar fatigue characteristics and are able to accommodate higher bending strains at low levels of repetitions to failure. The observed differences in the fatigue relationships (parameters K_1 and K_2) for both the conventional and SEA concrete mixtures are relatively small based on field data from the WSU Test Track.

To develop an overall evaluation of the SEA mixtures, the durability of these mixes are being examined. This work will be completed by mid-1982.

REFERENCES

1. Mahoney, J.P., D.C. Christensen, R.L. Terrel, J.C. Cook and R.H. Gietz, "Sulfur Extended Asphalt Pavement Evaluation in the State of Washington: Design and Construction Report," Final Draft, Washington State Department of Transportation, Agreement Y-2004, September 1981.

2. Picket, D.E., D. Saylak, R.L. Lytton, W.E. Conger, D. Newcomb, and R.A. Schapery, "Extension and Replacement of Asphalt Cement with Sulphur," Report No. FHWA-RD-78-95, Federal Highway Administration, March, 1978.

3. Bergan, A.T., A.F. Soderberg and L.G. Watson, "Fatigue Properties of Sulphur Asphalt Concrete," Proceedings of the 25th Annual Conference of Canadian Technical Asphalt Association, 1980.

4. Van Dijk, W., "Practical Fatigue Characterization of Bituminous Mixes," Proceedings, Association of Asphalt Paving Technologists, 1975, pp.38-74.

5. Finn, F., et al., "The Use of Distress Prediction Systems for the Design of Pavement Structures," Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements, 1977, pp. 3-38.

6. Kallas, B.F. and V.P. Puzinanskas, "Flexual Fatigue Tests on Asphalt Paving Mixtures," Research Report 72-5, The Asphalt Institute, College Park, Maryland, August, 1972.

7. Kingham, R.I. and B.F. Kallas, "Laboratory Fatigue and its Relationship to Pavement Performance," Research Report 72-3, The Asphalt Insitute College Park, Maryland, April, 1972.

APPENDIX A

TEMPERATURE RECORD AT THE WSU TEST TRACK

DATE	TIME	Temperature (°C)							
		Thermocouple No.							
		1	2	3	4	5	6	7	8
27 OCT	20:00		4.79	10.86	7.22		13.19	10.49	7.32
28 OCT	01:00		1.59	8.90	4.04		13.66	8.06	4.04
	03:00		0.75	7.97	3.19		13.10	7.13	3.19
	11:00		7.22	7.50	7.41		13.01	7.78	7.41
	12:00		6.94	7.50	7.41		12.73	7.88	7.41
	14:00		10.03	8.81	8.72		13.38	9.19	8.72
	16:00		5.63	8.53	7.13		12.63	8.81	7.22
	18:00		3.10	8.34	4.97		12.63	7.97	4.97
	20:00		2.63	7.88	4.04		12.63	7.41	4.04
	21:00		3.29	7.22	4.13		12.54	6.66	4.13
	23:00		3.38	6.85	4.22		12.26	6.47	4.22
29 OCT	01:00		1.88	6.85	3.47		12.26	6.38	3.57
	02:00		2.91	6.66	3.66		12.36	6.10	3.66
	04:00		3.47	6.66	4.13		12.36	6.29	4.13
	06:00		2.91	6.19	3.94		11.98	6.01	3.94
	07:00		4.88	6.29	4.79		11.98	6.10	4.69
	09:00		10.58	6.85	8.44		12.26	7.04	8.53
	11:00		16.26	7.69	13.29		12.17	9.09	13.29
	14:00		15.70	10.40	14.68		12.17	12.45	14.68
	15:00		12.08	11.05	13.94		11.89	12.82	13.84
	17:00		6.19	11.05	9.00		11.98	11.89	9.09
01 NOV	01:00		7.69	8.62	8.34		11.61	9.37	8.34
03 NOV	19:00		4.88	11.42	7.97		11.52	11.61	7.97
	20:00		4.51	11.24	7.60		11.42	11.24	7.60
	22:00		2.63	10.03	5.82		11.80	9.75	5.82
04 NOV	19:00		4.32	8.16	6.10		11.42	8.34	6.19
	21:00		4.97	7.78	5.82		11.52	7.88	5.82
	23:00		5.35	7.60	6.01		11.42	7.69	6.01
05 NOV	00:00		5.44	7.41	6.19		11.42	7.60	6.29
	02:00		5.63	7.50	6.57		11.42	7.69	6.57
	04:00		5.72	7.50	6.57		11.42	7.78	6.57
	05:00		5.63	7.41	6.38		11.24	7.60	6.38
	07:00		5.91	7.32	6.19		11.24	7.41	6.19
	09:00		9.37	7.60	8.62		11.42	8.16	8.62
	11:00		15.24	8.34	13.94		11.42	10.03	13.94
	12:00		20.15	9.37	17.09		11.52	11.89	17.09
06 NOV	02:00		6.10	8.34	7.41		11.80	8.72	7.50
	03:00		6.19	8.25	7.22		11.70	8.53	7.22
	05:00		6.01	8.53	7.32		12.08	8.72	7.32
	07:00		4.13	7.78	5.54		11.61	7.88	5.63
	11:00		16.91	8.90	14.87		11.70	10.77	14.87
	12:00		18.48	9.65	16.35		11.80	12.08	16.35
	13:00		17.65	11.24	17.47		11.80	13.75	17.47
	14:00		15.15	11.80	16.26		11.80	14.31	16.26
	17:00		7.32	11.61	10.12		11.70	12.63	10.12
	18:00		5.91	11.14	8.72		11.80	11.70	8.72
	19:00		4.69	10.58	7.32		11.61	10.86	7.32

DATE	TIME	Temperature (°C)							
		Thermocouple No.							
		1	2	3	4	5	6	7	8
08 NOV	19:00		2.91	4.41	9.09		2.72	6.29	11.14
10 NOV	01:00	10.58-	1.13	0.00	6.19-	1.31	1.22	10.30	5.35
	06:00	10.58	1.78	2.72	5.82	1.78	3.76	10.40	5.54
	08:00	10.58	2.25	3.85	5.91	2.25	4.22	10.49	5.72
	10:00	10.58	2.91	5.63	6.10	3.10	5.44	10.49	6.29
	21:00	10.40	1.12	2.25	6.01	1.31	3.47	10.21	5.91
	23:00	10.12	0.84	2.25	5.44	0.75	3.47	10.03	5.44
11 NOV	01:00	10.12	1.12	2.35	5.44	1.03	3.38	10.03	5.54
	03:00	10.21	1.59	2.35	5.44	1.41	3.47	10.03	5.44
	05:00	10.12	1.59	2.25	5.16	1.41	3.29	9.93	5.35
	07:00	10.12	2.06	3.00	5.26	1.88	3.57	9.93	5.35
	09:00	10.12	4.69	8.81	5.35	4.79	8.34	9.84	6.19
	11:00	9.75	6.57	14.68	6.85	8.62	13.57	9.93	9.09
	13:00	9.93	8.34	14.12	8.72	9.93	14.68	10.03	11.52
	21:00	9.93-	1.31-	0.65	6.47-	1.31	1.97	10.03	6.19
	23:00	10.03-	0.56-	1.03	5.44-	0.56	1.22	10.03	5.16
12 NOV	01:00	10.03-	0.28-	1.22	4.88-	0.37	1.03	10.12	4.41
	03:00	10.03-	0.09-	1.41	4.32-	0.28	0.47	10.12	3.85
	05:00	10.30	0.28-	1.31	4.22	0.18	0.37	10.40	3.66
	07:00	9.93	1.31-	0.18	3.47	1.12	0.37	9.84	3.00
	22:00	9.65-	0.28	1.78	6.38-	0.56	3.76	9.84	6.75
13 NOV	00:00	9.56-	0.75	1.03	5.72-	0.84	3.00	9.75	5.91
	02:00	9.65-	1.03	0.75	5.26-	1.22	2.72	9.75	5.44
	04:00	9.75-	1.22	0.56	4.97-	1.60	2.44	9.84	5.35
	06:00	9.65-	1.31	0.56	4.69-	1.22	2.25	9.75	4.88
	11:00	9.56	2.63	10.86	5.44	4.51	8.72	10.12	6.75
	13:00	9.47	5.35	12.26	6.94	6.66	11.61	9.84	9.00
	15:00	9.47	1.69	6.38	7.78	2.35	8.81	9.56	9.47
	18:00	9.37	0.75	3.47	7.13	0.65	5.26	9.56	7.88
	20:00	9.47	0.37	2.82	6.66	0.18	4.51	9.65	7.13
	22:00	9.47-	0.37	2.06	6.10-	0.65	3.94	9.75	6.57
14 NOV	00:00	9.37-	0.56	1.41	5.63-	0.84	3.19	9.65	5.91
	02:00	9.56-	1.41	0.94	5.35-	1.50	2.82	9.75	5.44
	04:00	9.65-	1.50	0.28	4.97-	1.50	2.35	9.75	5.16
	06:00	9.56-	3.39-	1.31	4.32-	3.49	0.94	9.47	4.41
	08:00	9.56-	2.64-	0.09	4.04-	2.92	1.12	9.56	4.04
	15:00	9.28	5.35	8.53	9.00	7.41	10.68	9.65	11.05
	17:00	9.37-	0.09	2.44	8.25	0.37	5.35	9.56	9.09
	19:00	9.37-	2.45-	0.37	6.85-	2.35	2.44	9.56	6.94
	22:00	9.28-	1.22	0.09	5.54-	1.22	1.78	9.56	5.44
15 NOV	00:00	9.56-	1.13	0.47	5.35-	1.50	2.16	10.03	5.26
	02:00	9.19-	3.86-	2.16	4.60-	4.34	0.84	9.56	4.60
	04:00	9.37-	4.71-	3.77	3.85-	5.09-	0.65	9.56	3.57
	06:00	9.37-	4.90-	4.43	3.10-	4.81-	1.60	9.47	2.63
	08:00	9.56-	1.69-	1.31	2.63-	2.07-	0.28	9.65	2.35
	10:00	9.28	4.51	8.62	2.91	6.10	6.66	9.56	4.13

DATE	TIME	Temperature (°C)							
		Thermocouple No.							
		1	2	3	4	5	6	7	8
22 NOV	05:00		0.84-	2.45	1.78-	0.94	5.72	14.77	1.41
	07:00		0.18-	0.75	1.88	0.09	5.16	14.96	1.50
	10:00		3.29	3.66	2.06	3.38	7.88	14.59	2.53
	12:00		4.41	6.75	3.38	4.41	10.21	14.31	4.41
	14:00		2.91	4.13	4.41	2.91	8.81	13.94	5.26
	17:00		1.12	1.31	4.13	1.78	5.44	13.47	4.51
	19:00		0.75	0.75	3.66	0.75	3.10	13.10	3.85
23 NOV	11:00		2.91	5.26	4.04	3.66	7.97	11.05	5.54
	14:00		4.51	6.66	4.88	5.44	10.12	10.86	6.85
	16:00		1.22	3.38	5.44	1.78	7.32	10.77	7.22
	18:00		0.00	0.47	4.79	0.09	4.04	10.49	5.54
	20:00		0.28	0.28	4.04	0.09	2.91	10.30	4.41
	23:00		0.28	1.03	3.76	0.37	3.47	10.30	4.22
24 NOV	09:00		0.09	0.65	3.00	0.09	2.16	9.56	3.10
	11:00		0.56	0.84	3.10	1.12	2.44	9.47	3.66
	13:00		0.47	2.06	3.10-	0.09	3.76	9.28	3.76
25 NOV	13:00		0.09	0.75	2.82	1.03	2.25	8.06	2.91
	15:00		0.75	0.94	3.00-	0.37	2.35	8.06	4.04
	17:00		1.41	0.65	2.72-	1.41	1.31	7.50	3.19
26 NOV	20:00		1.97	0.18	2.25-	1.79	1.03	7.22	2.25
	21:00		2.16	0.00	2.06-	1.97	0.84	6.94	1.88
27 NOV	21:00		10.31-	8.79-	0.18-	10.60-	3.96	6.38-	0.94
	23:00		5.19-	6.99-	0.84-	5.38-	4.05	6.57-	1.88
28 NOV	02:00		6.04-	7.18-	1.13-	6.13-	4.15	6.19-	2.64
	04:00		6.32-	7.65-	0.84-	6.23-	4.43	6.19-	3.01
	06:00		6.23-	7.84-	0.84-	6.61-	4.62	6.29-	3.39
	11:00		3.49-	3.01-	0.28-	2.54	1.41	5.91-	0.84
	13:00		2.54	1.69	0.65-	1.41	3.19	6.01	0.84
	15:00		3.39-	1.69	0.75-	2.07	0.75	5.63	2.72
	17:00		5.19-	5.28	0.37-	5.19-	1.79	5.54	1.31
	19:00		6.61-	6.89-	0.28-	6.61-	3.39	5.44	0.75
	21:00		9.74-	8.13-	0.56-	9.84-	4.24	5.44-	0.75
	23:00		5.76-	7.37-	0.75-	6.04-	4.43	5.54-	2.45
29 NOV	01:00		6.99-	7.94-	0.84-	7.08-	4.62	5.54-	3.11
	03:00		8.22-	8.60-	1.13-	8.32-	4.90	5.35-	3.77
	05:00		7.75-	8.41-	1.22-	7.94-	5.09	5.16-	4.34
	07:00		6.70-	7.84-	1.31-	6.61-	4.71	5.26-	4.53
	10:00		4.81-	1.97-	0.94-	3.86	0.18	5.16-	2.92
	12:00		3.01	1.69	0.47-	1.97	3.19	5.44	0.65
	14:00		3.01	0.65	0.94-	0.84	1.97	5.16	1.41
	16:00		6.13-	4.90	0.56-	6.13-	1.22	4.88	1.59

DATE	TIME	Temperature (°C)							
		Thermocouple No.							
		1	2	3	4	5	6	7	8
30 NOV	00:00		2.64-	2.26-	0.09-	2.82-	0.75	4.88-	0.47
	02:00		2.35-	1.79	0.09-	2.54-	0.56	4.88-	0.18
	05:00		2.07-	1.50	0.18-	2.26-	0.37	4.88	0.09
	07:00		2.07-	1.31	0.28-	2.07-	0.37	4.97	0.28
	14:00		0.75	1.03	1.12-	0.47	1.78	4.88	2.82
	16:00		1.22-	0.09	1.03-	1.31	1.12	4.97	2.63
	17:00		1.69-	0.94	0.75-	1.69	0.56	5.07	2.16
	19:00		1.97-	1.31	0.65-	2.07	0.18	5.26	1.78
	21:00		1.79-	1.03	0.94-	1.88	0.09	5.54	1.59
	23:00		1.88-	1.41	0.28-	2.16-	0.18	5.26	1.03
01 DEC	01:00		1.41-	1.13	0.47-	1.50	0.00	5.35	1.22
	12:00		0.84	2.91	0.75	0.94	2.06	5.63	0.94
	14:00		1.12	2.44	1.12	1.03	2.16	5.82	2.91
	16:00		1.50	1.69	1.12	1.41	1.97	5.91	3.00
	18:00		1.50	1.03	0.75	1.59	1.59	5.82	2.91
	19:00		2.91	1.03	0.84	3.19	1.69	6.19	2.91
05 DEC	08:00		3.00	1.41	3.10	2.82	1.03	0.00	3.94
	11:00		5.26	5.63	3.94	5.07	4.22	0.00	5.44
	19:00		2.82	2.44	4.60	3.00	4.32	0.00	5.72
	20:00		1.41	1.59	4.22	1.69	3.47	6.57	5.16
	21:00		1.12	1.12	4.22	1.22	3.47	6.75	5.16
10 DEC	19:00		2.54-	4.15	3.10-	2.35	0.65	7.13	2.91
11 DEC	16:00		0.84-	0.75	1.41-	0.94	0.37	4.97	2.44
	18:00		0.28-	0.47	1.41-	0.28	0.37	5.07	2.25
	21:00		0.28-	0.09	1.69	0.28	0.65		2.35
	23:00		0.94	0.47	1.88	1.03	1.03		2.63
14 DEC	09:00		5.44	3.94	2.44	6.10	3.38		3.85
	12:00		7.69	7.78	4.04	7.88	4.69		5.07
	14:00		6.94	7.22	4.60	7.41	4.69		5.44

APPENDIX B

WSU SUMMARY OF DAILY TRACK OPERATORS JOURNAL

Section 1

Date	Revolutions	Description of Events
10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	Pavement okay, no visible cracking
11-06-79	43,225	Half of section developing alligator cracks; longitudinal crack (3 ft) along outside edge of wheel path
11-09-79	50,639	3 ft long, 1/2" longitudinal shear failure on outside edge of wheel path; continued development of alligator cracking within wheel path of beginning half of the section
11-11-79	57,698	Continued expansion of longitudinal crack; noticeable shear separation outside edge of wheel path; permanent deformation beginning
11-12-79	62,052	Cold patched deepest deflections
11-14-79	72,140	Pavement outside wheel path heaving, 2 1/2" vertical separation
11/17/79	81,475	Water ponding in deflected areas; subgrade pumping; entire length of section failed
11-18-79	83,068	Section dug out; hot asphalt placed

Section 2

10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No visible cracking
11-06-79	43,225	No visible cracking
11-29-79	108,090	No apparent cracking
12-02-79	120,567	No apparent cracking
12-14-79	129,323	Transition 2-3 forming transverse cracks (18" length)
12-18-79	133,698	No change
01-02-80	138,659	No evidence of cracking
01-23-80	152,000	No evidence of cracking

Section 3

Date	Revolutions	Description of Events
10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	8 transverse cracks within wheel path; 2 ft lengths
11-06-79	43,225	10 transverse cracks across complete wheel path; permanent deformation noticeable
11-09-79	50,639	No noticeable change
11-11-79	57,698	Noticeable deflection; longitudinal crack development at middle of section and on outside edge of wheel path; alligator cracking beginning to develop
11-14-79	68,517	Transverse crack the width of the wheel path covering entire first half of section
11-15-79	77,713	Water ponding in permanent deformation; mud visible in cracks; considerable increase in alligator cracking
11-18-79	83,068	Section dug up; hot asphalt placed

Section 4

10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No visible cracks
11-06-79	43,225	No visible cracks
11-12-79	60,968	Longitudinal cracks beginning to form
11-23-79	87,447	3 ft longitudinal crack on inner half of wheel path; only crack evident
11-24-79	91,324	Gauge lost cover
11-29-79	108,090	No change; transition 4-5 forming transverse cracks at patch joint; some settlement occurring
11-30-79	111,481	Longitudinal crack expanded to 5 ft length
12-14-79	129,323	No change
12-18-79	133,698	No change
01-02-80	138,659	Transverse cracks beginning to form from longitudinal crack

Section 4 (continued)

Date	Revolutions	Description of Events
01-21-80	145,311	At outside of track middle of section, 4 transverse cracks 2 ft in length; no change in longitudinal crack
1-23-80	152,000	7 ft longitudinal crack; 6 transverse cracks, about 2 ft wide, center of section

Section 5

10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No visible cracks
11-06-79	43,225	No visible cracks
11-12-79	60,968	A few small transverse cracks beginning to form (5" to 8" in length)
11-15-79	77,713	A few small transverse cracks beginning to form (5" to 8" in length)
11-18-79	83,068	Alligator cracking and permanent deformation at beginning end of section; transverse cracks the width of the wheel path across remaining center of the section; water ponding in depressions Section dug up, replaced with asphalt
12-07-79	121,732	Section dug up again and portland cement concrete placed

Section 6

10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No cracks
11-06-79	43,225	No cracks
11-29-79	108,090	No visible evidence of cracking
12-02-79	120,567	No visible evidence of cracking
12-06-79	129,323	Cracking progressing from 6-7 line into section 6 (transverse and longitudinal cracking) approximately 3 ft into section 6
12-18-79	133,698	No change; 5-6 transition patched with portland cement concrete

Section 6 (continued)

Date	Revolutions	Description of Events
01-02-80	138,543	Section 6 showing no evidence of cracking
01-14-80	143,302	No change
01-16-80	144,096	No change
01-22-80	148,785	No change
01-23-80	152,000	No evidence of cracking in section 6, except around transition zones

Section 7

Date	Revolutions	Description of Events
10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	7 transverse cracks within wheel path, 2½ ft lengths
11-06-79	43,225	Subgrade squeezed out at center of section, 3 ft X width of wheel path; covered with alligator cracking; longitudinal cracks along inside and outside edge of wheelpath; noticeable permanent deformation
11-09-79	50,639	Shear failure developing along outside edge of wheel path
11-11-79	55,215	7 and 8 transition zone 2" depression
11-11-79	57,698	Alligator cracking expanding throughout section; increasing permanent deflection; noticeable heaving of outside edge of wheel path
11-12-79	60,968	Entire section covered by alligator cracking; permanent deflection full length of section
11-12-79	62,052	Cold patched
11-17-79	81,475	Entire section failed; outside of wheel path heaving
11-18-79	83.068	Section dug up; hot asphalt patch placed
12-07-79	121,732	Portland cement concrete placed because of patch break-up

Section 8

Date	Revolutions	Description of Events
10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No crack development
11-06-79	43,225	Transition 7 and 8, transverse cracking developing
11-12-79	62,052	No change
11-29-79	108,090	Longitudinal crack (2 ft length) formed center section
12-01-79	119,043	No change
12-14-79	129,323	Longitudinal crack expanding at center of section; no evidence of any transverse cracks; longitudinal crack progressing inward from both transition zones
12-18-79	133,698	Center longitudinal crack 5 ft long, longitudinal from section 7, 6 ft long
12-22-79	137,565	Section 9 collapse progressing 3 ft into section 8
01-02-80	138,659	Longitudinal crack from Section 7 expanded 8 ft into section 8
01-14-80	143,302	No change
01-23-80	152,000	No change

Section 9

10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No cracks
11-06-79	43,225	Fatigue cracking at 9 and 10 transition zone
11-10-79	51,953	8" transverse crack; slight deflection with wheel pass
11-10-79	52,438	Transverse cracks spreading from 9 and 10 transition zone
11-11-79	58,324	No development of longitudinal cracks as of yet
11-12-79	60,968	Alligator cracks beginning to form at 9 and 10 transition zone
11-14-79	69,920	Same

Section 9 (continued)

Date	Revolutions	Description of Events
11-18-79	83,068	Transverse cracks throughout entire section; noticeable permanent deformation at center of section; subgrade pumping. Section dug up; hot asphalt placed

Section 10

Date	Revolutions	Description of Events
10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No cracks
11-06-79	43,225	Fatigue cracking at 9 and 10 transition zone
11-12-79	60,968	Evidence of small transverse crack
11-14-79	72,140	Transverse cracking continuing to form within the section
11-18-79	83,068	Transverse cracking throughout entire section; noticeable permanent deflection; hot asphalt placed at 9 and 10 transition zone; zealous paving crew replaced almost half of the section with asphalt
11-22-79	85,806	Extreme alligator cracking, plus longitudinal cracking inside and outside edges of wheel path; mud working up from subgrade; permanent deflection on remaining unpaved part of section
11-26-79	95,750	Deep depression, continued break-up
12-07-79	121,732	Portland cement concrete placed over entire section

Section 11

Date	Revolutions	Description of Events
10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	2 ft x 4 ft fatigue failure; alligator cracking developing
11-05-79	38,562	Alligator cracking developed throughout entire section; pumping of subgrade; longitudinal cracking (14 ft) along outside edge of wheel path; noticeable deformation
11-06-79	43,225	Outside edge heaving; 3 ft x ½" deep shear failure outside edge, continued development of alligator cracking
11-09-79	50,639	1" to ½" vertical pavement separation along entire outside edge of the wheelpath; extreme alligator cracking developing over entire section area

Section 11 (continued)

Date	Revolutions	Description of Events
11-12-79	62,052	Continued pavement separation on edge of outside wheel path, extreme permanent deformation for entire length of section Cold patch applied to reduce wheel bounce
11-14-79	72,140	3½" separation heave on outside of wheel path; cold patch applied
11-18-79	83,068	Section dug up; asphalt hot mix placed

Section 12

10-25-79	5,875	Round the clock track operation begun
11-02-79	28,152	No cracking
11-06-79	43,225	No cracking
11-09-79	50,639	11 and 12 transition zone break-up
11-14-79	72,140	Longitudinal crack from section 11 expanding through transition zone of 11 and 12; center of section 12 still intact
11-18-79	83,068	Center section still okay
11-29-79	108,090	14" longitudinal crack at center of section
11-30-79	111,481	3 transverse cracks (1 ft length), center of section; longitudinal crack 2 ft long
12-01-79	110,043	5 (1 ft) transverse cracks; longitudinal crack 30" in length
12-14-79	129,323	8 transverse cracks now extend across wheel path; longitudinal crack 33" long
12-15-79	131,620	Alligator cracking developing; noticeable subgrade expulsion
12-22-79	137,565	2 ft x 3 ft alligator cracking around area by sensor
01-02-80	138,543	Transverse cracks developing throughout entire section within wheel path
01-14-80	143,302	No increase or change
01-16-80	144,096	No increase or change

Section 12 (continued)

Date	Revolutions	Description of Events
01-23-80	152,000	3 ft by width of wheel path around center of section covered with alligator cracks; rest of section okay, only slightly visible evidence of transverse cracking

Testing terminated February, 1980. All sections failed or cracking.