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# **A STUDY OF FLEXURAL FATIGUE BEHAVIOR OF ASPHALT-RUBBER MIXES**

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16. Abstract <p>The objective of this study is to evaluate the fatigue behavior of crumb-rubber modified asphalt. The research involved flexural fatigue testing of beams made with hot-mix asphalt rubber using the wet process where the crumb rubber reacted with the asphalt at high temperature. Two types of asphalt-rubber were studied: Asphalt Rubber Surface (ARS) and Asphalt Rubber Base (ARB). The ARS was a gap-graded aggregate mix with 1/2 in. maximum size and 7% design asphalt-rubber content using CRM-III (minus #10 mesh) rubber. The ARB had a denser gradation with a 3/4 in. maximum aggregate size and 7% design asphalt-rubber content also using CRM-III rubber. A conventional asphalt concrete mix (BM-1B) was used as a control and contained 5% AC-10 with no rubber and 1/2 in. maximum aggregate size.</p> <p>The beams were prepared by placing the asphalt-rubber in molds 3"x4"x16" in size and compacting with a California kneading compactor. Flexural fatigue tests were then performed under constant stress type loading using a three point mode of loading. The ARS beams were tested at 41 and 68°F and the ARB and control beams were tested at 68°F. The applied fatigue loads were fractions of the ultimate load with a haversine loading of 0.1 sec. with no rest period. The deflection at the center of the beam after 200 cycles of load was measured and converted into initial strain using common elastic beam analysis method. The flexural stiffness of each mix was calculated. The samples were loaded repeatedly until failure and the number of cycles noted.</p> <p>Testing showed that stiffness had little effect of the number of cycles to failure. For dense-graded mixes (ARB and BM-1B) stiffness was not affected by air voids. For open-graded mixture (ARS) the stiffness decreased sharply with an increase in air voids. At 68°F the number of repetitions to failure decreased as the air voids increased. Tensile strains at the bottom of asphalt concrete layer and associated fatigue lives for three in service test sections on I-135 were predicted by three different equations; the Asphalt Institute, SHRP, and this study. All equations showed higher fatigue life for the ARB layer than for the BM-1B layer. The ARB sections appeared to have much higher fatigue lives than the BM-1B mixtures at all strain levels. The ARS mixture did not appear to be suitable as a structural layer.</p>					
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# **A STUDY OF FLEXURAL FATIGUE BEHAVIOR OF ASPHALT-RUBBER MIXES**

Final Report

Prepared for

**Kansas Department of Transportation**

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## EXECUTIVE SUMMARY

Pavements must be designed for the repeated loadings caused by traffic if they are to give satisfactory service over a reasonable period of time. The usual manifestation of the distresses resulting from lack of resistance of an asphalt pavements to repeated loadings is fatigue (or "alligator") cracking. The objective of this study is to study the fatigue behavior of crumb-rubber modified asphalt concrete.

The research involved flexural fatigue testing of beams made with hot-mix asphalt rubber using the "wet" process, i.e. where the crumb rubber is reacted with the asphalt at higher temperature. A conventional asphalt mix was also studied as the "control" mix which had 0% rubber content, and optimum binder content as determined in the Marshall mix design. These mixes were used on recently-constructed pavement projects on I-135 near McPherson, Kan. Two types of asphalt-rubber mixes were studied: Asphalt Rubber Surface (ARS) and Asphalt Rubber Base (ARB). The ARS was a "gap-graded" aggregate mix with a ½-in maximum size. The design asphalt-rubber content was 7.0% based on the Marshall method of mix design. The crumb rubber used was CRM-III (minus #10 mesh) rubber. The ARB had a denser gradation with a maximum aggregate size of ¾ inch and had a design asphalt-rubber content of 7.0% with the same rubber content. The control mixture was a KDOT designation BM-1B mixture. The mixture was a 1/2 inch nominal maximum size mixture with 5% optimum AC-10 asphalt content, designed according to the Marshall method of mix design.

The beams were prepared by placing the asphalt-rubber hot mix in rectangular molds of 3" x 4"x 16" size and compacted by a California kneading compactor. The compaction was done in two layers, and the foot-pressure of the kneading compactor was successively increased to 100 psi, 200 psi, and 300 psi for each of the approximately 40 tamps per layer. After cooling, the beams were demolded.

Flexural fatigue tests on the asphalt beams were performed under constant stress type of controlled loading. The beams were tested in a three-point mode of loading. For ARS, tests were conducted at 41° F and 68° F and for ARB and BM-1B mixtures at 68° F. The fatigue loads applied were fractions of the ultimate load (carried in static mode) with a haversine loading of 0.1 sec duration with no rest period. The deflection at the center of the beam after 200 cycles of load repetition was measured and converted into initial strain using common elastic beam analysis method. The flexural stiffnesses of the mixes were also calculated. The samples were loaded repeatedly to failure (or, full-depth cracking), and the number of cycles needed to cause failure was noted. In addition to the fatigue tests, density and void analysis were performed for all samples.

The results showed that the flexural stiffness of the ARS mixtures at 42° F varied from 70 ksi to 133 ksi with a mean value of 102 ksi. The average air void was 10.3 %. The

average stiffness value of the ARS mixtures at 68° F was 60 ksi with a coefficient of variation of 27% and average air void of 7.2%. The ARB mixtures had an average stiffness of 109 ksi at 68° F with a coefficient of variation of 27.5% and air void of 4.6%. The control, BM-1B mixtures showed an average stiffness of 74 ksi with 4.2% average air voids.

The correlation analysis among the number of cycles to fatigue failures, stiffness and air voids showed that the stiffness had little effect on the number of cycles to failure which is well expected in a constant stress-type testing. For dense-graded mixtures (ARB and BM-1B) stiffness was not affected by air voids, but for open-graded mixture (ARS), it was highly affected by the air void. The stiffness sharply decreased with increase in air voids. For ARS, the number of load repetitions to failure was highly correlated with the air voids of the sample. At 68° F, the number of repetitions to failure decreased as the air voids increased.

Tensile strains at the bottom of asphalt concrete layer and associated fatigue lives for three in-service test sections on I-135 were predicted by three different equations; the Asphalt Institute, SHRP and this study. All equations showed higher fatigue life for the ARB layer than the BM-1B layer although the BM-1B layer was 25 mm thicker than the ARB layer. The results obtained by the KSU and Asphalt Institute equations were close, but the SHRP equations tended to give very high fatigue lives for each mixture. The ARB sections appeared to have much higher fatigue lives than the BM-1B (control) mixtures at all strain levels. The difference was very prominent at higher strain levels for the ARB sections. However, the opposite is true for the control or conventional mix section.

A comparison of the results of this study with those from the FHWA ALF study for SHRP shows that the fatigue relationships obtained in this study are very reasonable. The asphalt-rubber base mixture (ARB) performance is the best. However, the ARS mixture did not appear to be suitable as a structural layer -its fatigue life is marginally improved at lower strain level as compared to the other mixtures. However, the fatigue lives of the ARS layer at the same strain levels at lower temperature indicate that this mix might be very suitable for low-temperature thermal fatigue resistance. Further studies are recommended in this area.

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## CHAPTER 1

### INTRODUCTION

#### Introduction

Each year approximately 285 million tires are added to stockpiles, landfills or illegal dumps across the United States (1). The EPA estimates that the present size of the scrap tire problem is 2 to 3 billion tires. Introduction of scrap rubber into asphalt concrete pavement has the potential for solution of this waste problem. It has been estimated that if only 10% of all asphalt pavement laid each year in the United States contained 3% rubber, all the scrap tires produced for that year in this country would be consumed (2). The potential benefits a cost-effective product would bring has kept interest in asphalt-rubber high throughout the world. The use of scrap tire rubber as an additive for asphalt concrete has been developing for over 30 years. Recently, it has been recognized as a viable choice.

The use of rubber as an additive in asphalt has been discussed and researched for the past 30 years. Although the use of asphalt-rubber is attractive from the view-point of environmental preservation, it is not widely used because its performance and cost effectiveness have not been conclusively proved. The asphalt-rubber production can be broken down into the "wet" process and the "dry" process.

The wet process uses the rubber as an additive to the asphalt binder. In this process, anywhere from 10% to 30% rubber, by weight, can be introduced into the binder at a high temperature, and the rubber is allowed to react with the binder. The reaction time is usually recommended by the rubber supplier. The resulting asphalt-rubber binder is typically used in hot-mix hot-laid asphalt concrete but can also be used in stress absorbing

membranes (SAM) or stress absorbing membrane interlayers (SAMI) where spray-type applications are common.

The "dry" process uses rubber as an aggregate. Usually 2% to 3% rubber is added, as a solid, with coarse and fine aggregates to a pure asphalt binder. The most popular mix design for this product was patented under the trade name "PlusRide". A generic system, called the TAK system, had also been developed and used on a few construction projects (2).

### **Problem Statement**

The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) mandated the use of recycled rubber in asphalt pavements as a percentage of total tons of asphalt to be laid in federally aided projects up to 20 percent in 1997, starting with 5 percent for the year 1994 (repealed in 1995). The impact of this ISTEA legislation on the paving policy of federally aided KDOT projects was thought to be very significant. Although rubber modified asphalt concrete has successfully been used by some Western states, experimental uses in Kansas on KDOT highway system had produced mixed results in the past. (3). However, KDOT was building a number of pavements using asphalt-rubber starting in early nineties. More research was deemed necessary in Kansas to use this material cost-effectively and to reap probable long-term benefits.

### **Objectives**

The objective of this study was to study the fatigue behavior of crumb-rubber modified ("wet" process) asphalt concrete. The study would provide KDOT with data about the engineering properties of Asphalt Rubber Surface (ARS) and Asphalt Rubber Base (ARB)

mixes as well as conventional mixes. The study was expected to lead to a better understanding of flexural fatigue lives of crumb-rubber modified asphalt mixes, and the results should be helpful in the structural design of asphalt-rubber pavements..

### **Organization of the Report**

This report is divided into six chapters. Chapter 1 is the introduction to the problem. Chapter 2 describes the background and significance of the work done. Chapter 3 is the literature review on the laboratory fatigue tests. Chapter 4 discusses the research accomplished, followed by Chapter 5 which presents the results and discussions. Finally, Chapter 6 includes the conclusions and recommendations based on this study.

## CHAPTER 2

### BACKGROUND AND SIGNIFICANCE OF WORK

#### **Fatigue Testing of Asphalt Concrete**

Pavements must be designed for the repeated loadings caused by traffic if they are to give satisfactory service over a reasonable period of time. F.N. Hveem of the California Division of Highways was one of the first to investigate the effects of repeated loadings on asphalt pavements (4).

Hveem established three major factors related to the failure of bituminous pavements: (i) flexural strength, (ii) the weight of the mix on the subgrade, and (iii) the flexibility to withstand repeated bending. Experience and empirical design procedures such as those developed by Marshall and Hveem have enabled engineers to design mixtures against the most common premature failure mechanisms such as rutting and bleeding, but, because of its complex nature, fatigue failure is difficult to design and analyze.

When investigating pavement flexibility, Hveem developed a fatigue testing device capable of testing small beams cut from asphaltic pavements. Other tests were developed in the early stages of fatigue testing by Hennes and Chen (5), Nijboer (6), Van der Poel (7), and Monismith (8). Hennes and Chen tested beam specimens in flexure with a device in which the specimens were supported on a steel leaf spring. Nijboer and Van der Poel developed a repeated loading device that tested cylindrical bars of asphaltic concrete in a rotational cantilever mode. This test method was further developed by Pell (9). Monismith developed a repeated flexure testing apparatus with a spring base intended to

simulate the base-subgrade combination in the pavement structure.

As fatigue testing has progressed, engineers have become more aware of the complexities entailed and many approaches have been adopted for analyzing the fatigue life of pavements. Monismith and several other researchers have developed and refined test methods using beam specimens (10, 11, 12, 13). Jimenez (14) has studied the effects of flexure loadings on circular plate specimens. Several tests have been performed using various odd shaped specimens such as trapezoidal ones (15, 16). Maupin and Freeman (17) recommended the use of a simplified fatigue test based on the indirect tensile mode of loading of asphalt concrete specimens. In the Strategic Highway Research Program (SHRP), an accelerated performance-related test method for asphalt mixture fatigue was studied in detail (18).

## **IMPROVEMENTS TO THE FATIGUE TEST PROCEDURE AND EQUIPMENT IN SHRP RESEARCH**

In the SHRP research, two major improvements were made to the flexural beam fatigue test procedure and equipment: the size of test specimen was increased, and a new fatigue beam module was designed and built that could be used as a stand-alone test equipment or could be used as a module in the Universal Testing Machine (UTM) developed by SHRP Project A-003A for the permanent deformation test program. Specific goals for improving the equipment were to increase the ease, the simplicity, and the reliability of the fatigue test.

### **Specimen Size**

The size of the test beam was increased from a 1.5 x 1.5 in. cross-section used in pilot test

program to a rectangular cross-section with a 2.5 in. width and 2.0 in. height. The increase to a specimen width of 2.5 in. was the maximum achievable given the space restrictions of the fatigue module in the UTM. Similarly, the beam length was also restricted to 15 in.; however, the beam span (length between the reaction points) was increased from the original 12 to 14 in. in order to minimize shear deformation in the beam.<sup>1</sup> The selection of a maximum beam height of 2.0 in. resulted in approximately a 5 percent shear deformation (18).

### **Test Equipment**

Specific changes in the test equipment included the following:

- Design of the new test equipment to simplify and reduce the set-up time. This change was achieved by automating the specimen clamping procedure through the use of torque motors, which reduced the set-up time for each test from the approximately 30 to 45 minutes of the pilot test program to less than 5 minutes.
- Improvements in the linear and torsional bearings to minimize any extraneous stress, such as torsion, in the beam specimen and to maintain zero moment at the beam ends.
- Design of the various components to conform to the larger beam specimen and accommodation of the module within the UTM.
- Automation of temperature and test control, data acquisition, and data reduction.

---

<sup>1</sup>The ratio of shear to bending deformation in a beam specimen is proportional to the square of the height (h) to beam span (L) ratio. For shear deformations to be neglected,  $(h/L)^2 < 1$ .

The new fatigue test equipment, with its hydraulic pressure system, has a better response to and more precise control of the stress or strain induced in the specimen than its predecessor, which used an electropneumatic test system. Sinusoidal loads applied at up to 25 Hz frequency, with or without rest periods, can easily be achieved at temperatures ranging between 14° and 104° F. Once the specimen is mounted in the loading frame, the test itself, including temperature control, test control, data acquisition, and data reduction, is completely run by the computer. The equipment developed by University of California at Berkely for SHRP A-003A uses the automated testing system software for test control and data acquisition. A data analysis software package FATIGUE was developed to facilitate fatigue data reduction for the A-003A project.

The improvements in the test equipment and procedure significantly improved the repeatability of the test in relation to the results from the pilot test program and reduced the overall testing time by a factor of approximately 6. Significant improvements in fatigue data repeatability using the new test equipment and procedure are indicated by a coefficient of variation of 40.2 percent for fatigue life versus approximately 90 percent for the pilot test program using the old equipment reported earlier in the SHRP program. This reduction is most likely due to improvements in control of the induced strain as well as to the use of larger beam specimens compacted by rolling-wheel compaction. The use of rolling-wheel compaction virtually eliminated fracturing of the aggregate, which was observed in the specimens compacted with kneading compaction in the pilot test program. The specifications for the fatigue testing equipment are available from SHRP.

## Specimen Testing

Beam specimens ready for testing were stored at the required temperature for at least 2 hours. All specimens in this test program were tested at 68°F, except for the temperature equivalency study, in which specimens were tested at four temperatures: 41°, 50°, 68°, and 77°F. Specimens were tested at the required strain (deformation) level under the controlled-deformation mode of loading. All tests were conducted at 10 Hz frequency, corresponding to a total loading time under sinusoidal load of 0.1 seconds, with no rest periods. The loading applied imparted tension only at the extreme fiber. Initial peak-to-peak load amplitude was noted and the test terminated when the observed load amplitude was less than half the initial value. Sinusoidally varying load and deformation magnitudes and patterns were recorded and automatically saved on the computer hard drive at predefined cycles spaced at logarithmic intervals.

## Analysis of Results

Test data were analyzed using the FATIGUE computer program to compute the stress, strain, stiffness, phase angle, and dissipated energy per cycle as functions of the number of load cycles, and the cumulative dissipated energy to a given load cycle. Fatigue life was defined as the number of cycles corresponding to a 50 percent reduction in initial stiffness; initial stiffness was measured at the 50th load cycle. Maximum stress, strain, and stiffness were computed by using the following relationships:

$$\text{Stress } (\sigma) = 3aP/(wh^2)\dots\dots\dots(2.1)$$

$$\text{Strain } (\epsilon) = 12 h \delta/(3L^2-4a^2)\dots\dots\dots(2.2)$$

$$\text{Stiffness } (S) = \sigma/\epsilon\dots\dots\dots(2.3)$$

where:

$\sigma$	=	peak-to-peak stress, psi,
$\epsilon$	=	peak-to-peak strain, in./in.,
$P$	=	applied peak-to-peak load, lbf,
$S$	=	stiffness, psi,
$L$	=	beam span, in.,
$w$	=	width of beam, in.,
$h$	=	height of beam, in.,
$\delta$	=	beam deflection at neutral axis, in., and
$a$	=	$L/3$ .

Several working hypotheses were supported in the SHRP study. For example, one hypothesis stated that crack initiation in a given mix is related to stress or strain level as follows:

$$N_f = a(1/\epsilon)^b \dots\dots\dots(2.4)$$

or  $N_f = c(1/\sigma)^d \dots\dots\dots(2.5)$

where:

$N_f$	=	number of load application to crack initiation,
$\epsilon, \sigma$	=	tensile strain and tensile stress, respectively, and
$a, b, c, d$	=	experimentally determined coefficients dependent on test temperature.

These relationships were consistently confirmed for the ranges of stresses and strains to which the laboratory specimens were subjected. Replacing strain or stress with the energy dissipated during an initial loading cycle,  $w_o$ , yielded an equally reliable and accurate expression as follows:

$$N_f = e(1/w_o)^f \dots\dots\dots(2.6)$$

where:  $e, f$  = experimentally determined coefficients dependent of test temperatures.

Early literature advanced the notion that a unique relationship might possibly exist

between the number of cycles to failure and the cumulative energy dissipated to failure. If so, laboratory testing could be abbreviated, surrogates to testing appeared more promising, and compound loading could be handled more directly. Because of these advantages, considerable effort was made to investigate possible relationships between cycles to failure and cumulative dissipated energy. These efforts confirmed that, when strain is the only test variable, cycles to failure for a given mix are related to cumulative dissipated energy as follows:

$$W_N = A(N_f)^z \dots\dots\dots(2.7)$$

where:  $N_f$  = number of cycles to failure,  
 $W_N$  = cumulative dissipated energy to failure, and  
 $A, z$  = experimentally determined coefficients.

## **FLEXURAL FATIGUE TESTS ON ASPHALT-RUBBER MIXTURES**

In 1993, Kansas State University, in cooperation with KDOT, began studying crumb rubber (minus #4 size) from recycled auto tires for possible uses in hot-mixes or crumb-rubber modified mixes (CRM). This research focussed on the development of an optimal design of crumb rubber-modified asphalt concrete mix using the "wet" process. The study involved determining the indirect tensile strength, Marshall stability, and fracture properties of asphalt-rubber mixes. However, little information was available about the flexural fatigue of asphalt-rubber mixes. This was a problem especially when KDOT was experiencing cracking with the asphalt-rubber pavements. According to an unpublished study conducted by the University of Arizona, fatigue resistance of asphalt mix was found to be impeded by rubber inclusion (19). The advantage of third-point loading over the center-point loading

is the existence of a constant bending moment over the middle third of the specimen, so any weak spot due to nonuniform material properties will show up in the test results. In this study, the third-point loading for beam specimens was proposed to be used for dynamic fatigue testing of asphalt-rubber mixes using "wet" process.

## CHAPTER 3

### LITERATURE REVIEW OF LABORATORY FATIGUE TESTS

This literature review focused on fatigue test methods and equipment, the data acquired in these tests, and the analytical methods used to evaluate the test results. The discussion presented is directed primarily toward experimental laboratory fatigue testing.

#### **Methods of Testing**

A general discussion of the testing modes used, the load variables, and definitions of the types of failure found in fatigue testing is presented herein.

#### ***Testing Modes***

Laboratory fatigue testing methods predominately have used two modes of loading for bituminous specimens. These modes, controlled stress and controlled strain, are designed to hold either the stress or strain at a desired value while an unconstrained variable is monitored.

#### **Controlled Stress**

The controlled stress mode of testing requires that a load of constant value be applied to the specimen throughout the testing process as illustrated in Figure 1. When this testing mode is used, the deflection of the specimen is monitored to determine the strain corresponding to the applied load. The controlled stress test mode is used to test the bituminous materials which provide the primary structural support of the roadway, i.e., materials placed in thicknesses greater than 6 in.

#### **Controlled Strain**

The controlled strain mode of testing is performed by maintaining the strain at a desired

level and monitoring the corresponding stress. In this mode, a predetermined value of deflection, or strain, is placed on the specimen, and the load required to produce this deflection is recorded throughout the test. Graphic illustrations of strain vs. cycles to failure and stress vs. cycles to failure are given in Figure 2.

The controlled strain test is used to test bituminous materials used as thin surface layers, the reason being that the surface layer of a bituminous roadway gives little if any structural support and deflects an amount controlled by the subgrade, base material, and bituminous base.

### ***Load Variables***

Many types of loadings can be used in a laboratory fatigue test. The primary variables are the load history, the rate of load application, and the pattern of applying the load.

### ***Load History***

A specimen may be subjected to two types of load history - simple and compound. In simple loading, whether controlled stress or controlled strain, the load condition remains unchanged throughout the fatigue test. In compound loading there are changes in the load condition during the test, with a change being defined as a change in the amount of stress or strain applied to the specimen or a change in the environment, such as an increase or decrease in temperature.

Compound loadings can be preprogrammed to simulate the loadings a pavement receives from traffic; however, the process is quite involved, so simple loadings are more widely used.

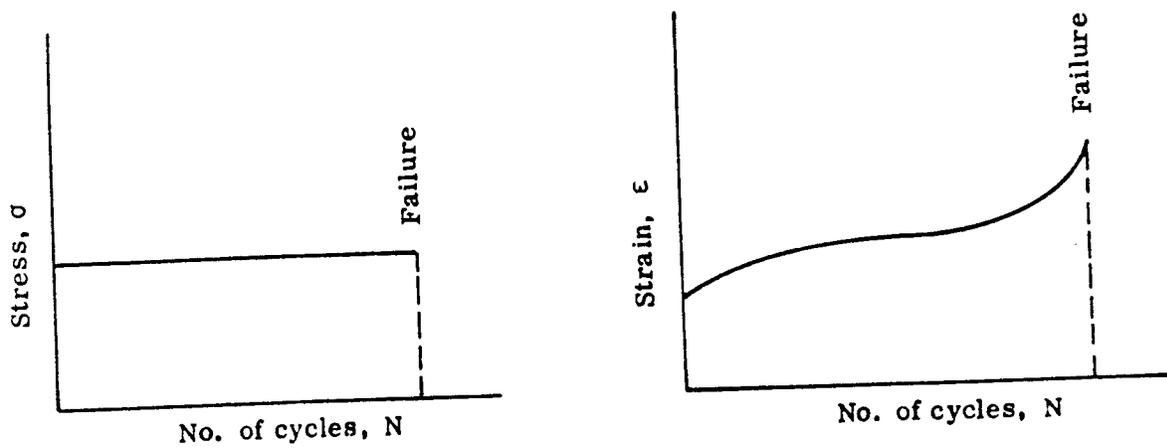


FIGURE 1 Controlled Stress Fatigue Test

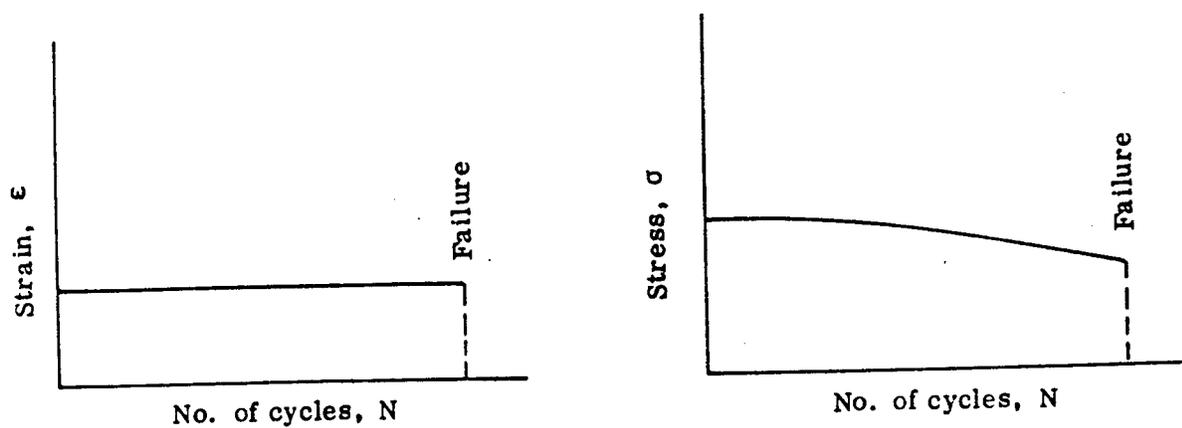


FIGURE 2 Controlled Strain Fatigue Test

### ***Load Rate***

The rate of loading is the number of load applications made over a specified period of time. It has been proven that the fatigue life varies with the rate of loading. Tests by Deacon and Monismith (10) indicated that over loading rates ranging from 30 to 100 repetitions per minute, there was a significant decrease in fatigue life as the loading rate increased. In tests performed by Taylor, it was found that loading rates of less than 200 repetitions per minute caused a greater variation in specimen service life than did higher loading rates (20).

### ***Patterns of Applying Loads***

The load patterns commonly used are block, sinusoidal, and haversine. The block pattern for a simple loading is shown in Figure 3. As was previously discussed, for a simple load rate the level of stress or strain is kept constant throughout the test. When applying a compound loading, as shown in Figure 4, the levels of stress or strain are varied. Compound loading tests are done predominately with the block pattern; however, haversine and sinusoidal patterns may also be used (17).

There are two ways in which a compound loading can be applied - sequentially or randomly. Sequential loading is performed by applying a fixed number of loadings under one load condition, then another fixed number under a different condition. This pattern, which is illustrated in Figure 4, is continued until the specimen fails. In random loading, each load applied is selected randomly so that the probability of any load being selected is equal to that of any other load, regardless of the preceding order of applied load conditions.

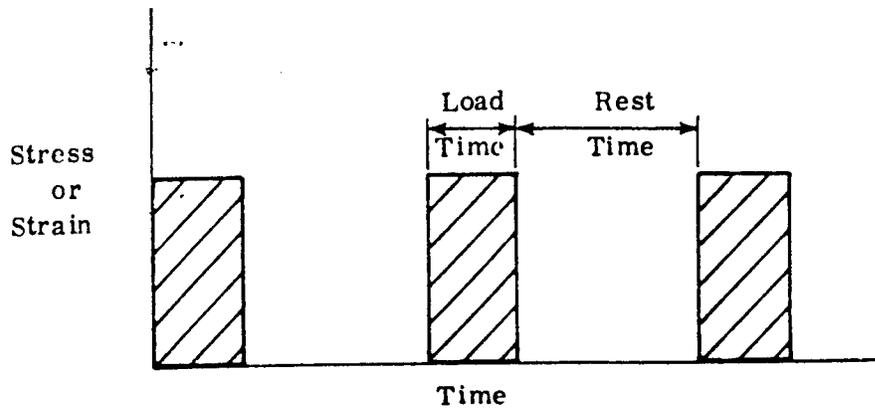


FIGURE 3 Block Pattern for Simple Loading (after 17)

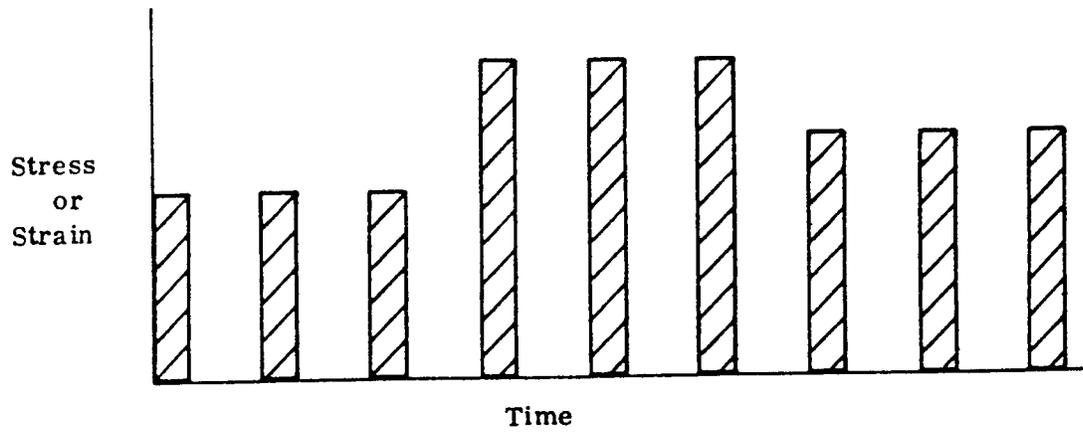


FIGURE 4 Block Pattern for Compound Loading (after 17)

The haversine pattern is used mostly for simple loading rather than compound loading. It constitutes the compressive half of the sine curve, in which the simply supported beam is loaded and then enough tension is applied to force it back to the neutral axis. This pattern is preferred over the sinusoidal pattern because it more closely resembles the loadings of roadway pavements. The surface layer of a roadway undergoes both tensile and compressive forces during a wheel loading; however, the compressive forces far outweigh the tensile forces (17).

### **Definition of Failure**

Failure of a specimen is generally defined as the point at which it no longer has the ability to satisfactorily withstand a desired load (10). For fatigue tests, the failure condition varies depending on the mode of testing used.

In the controlled stress mode of testing, fatigue life is defined as the number of loadings required for the specimen to completely fracture. In the controlled strain mode of testing the dynamic load applied to the specimen is recorded after the first 200 to 300 load applications, and the fatigue life is reached when the dynamic load reduces to a predetermined percentage of the initial dynamic load. This percentage usually varies between 50% and 75%. It has been reported by Epps and Monismith that 25% and 50% reductions in stiffness correspond to small and extensive crack propagations, respectively (21). Another method used to determine failure involves gluing foil strips to the tensile sides of the specimen, 12.5 mm from each bottom edge (22). The strips are wired in parallel so that both must be broken for failure to be reached. This method of determining failure is used primarily in constant stress testing.

## ANALYSIS METHODS

### Linear Fatigue Life Relationships

The methods used to analyze the data are the same regardless of the size of the specimen used. The basic equations for extreme fiber stress, stiffness modulus, and extreme fiber strain are listed below (12). The equations apply to a beam of uniform cross section which is simply supported at the ends and loaded by two symmetrical, concentrated loads applied near the center.

$$\sigma = \frac{3aP}{bd^2} \dots\dots\dots(3.1)$$

$$E_s = \frac{Pa(3\ell^2 - 4a^2)}{48Id} \dots\dots\dots(3.2)$$

$$e = \frac{12td}{(3\ell^2 - 4a^2)} \dots\dots\dots(3.3)$$

where

$\sigma$	=	extreme fiber stress (kPa)
$a$	=	$\frac{1}{2}$ (reaction span length - distance between load clamps) (mm)
$P$	=	dynamic load applied to deflect beam (N)
$b$	=	specimen width (mm)
$d$	=	specimen depth (mm)
$E_s$	=	flexural stiffness modulus based on deflection (kPa)
$\ell$	=	reaction span length (mm)
$I$	=	specimen moment of inertia (mm <sup>4</sup> )
$t$	=	dynamic deflection of beam center (mm)
$e$	=	extreme fiber strain of mix in region of equal moment calculated from deflection of beam center (mm/mm)

The stress,  $\sigma$ , and fatigue life,  $N_f$ , can be correlated using a least squares regression analysis that results in a linear log-log plot of  $\sigma$  versus  $N_f$  (12). This relationship is shown in the form:

$$N_f = K_1 (1/\sigma)^n \dots\dots\dots(3.4)$$

where

- $N_f$  = number of load applications to failure
- $K_1$  = constant depending on the mix
- $\sigma$  = extreme fiber bending stress, kPa
- $n$  = constant (slope of regression line)

With the above equation, the fatigue life for a given bending stress can be estimated.

A similar relationship can be established for strain,  $\epsilon$ , versus fatigue life,  $N_f$  (12).

This relationship is also obtained from a least squares regression analysis, and is shown

as

$$N_f = K_2 (1/\epsilon)^{n_2} \dots\dots\dots(3.5)$$

where

- $N_f$  = number of load applications to failure
- $K_2$  = constant depending on the mix
- $\epsilon$  = initial bending strain based on center point deflection of specimen
- $n_2$  = constant (slope of regression line)

## CHAPTER 4

### RESEARCH ACCOMPLISHED

#### Research Approach

The research involved fatigue testing of hot-mix asphalt rubber using the "wet" process as covered by the KDOT special provision 90P-3346-Rev. A conventional asphalt mix was also studied as the "control" mix design with no rubber, and optimum binder content as determined in the Marshall mix design. These mixes were all used on recently-constructed pavement projects on I-135 near McPherson, Kan. Two types of asphalt-rubber mixes were used: Asphalt Rubber Surface (ARS) and Asphalt Rubber Base (ARB).

#### ***Asphalt Rubber Surface (ARS)***

The ARS had a "gap-graded" aggregate gradation. The aggregate blend consisted of 30% Martin-Marietta rocks (CS-2) from Dickinson County, 60% CS-1A (Kanopolis rock) from Ellsworth County and 10% Sunflower sand (SSG-1) from Rice County. Table 1 shows the gradation of individual aggregates and the blend. The coarse aggregate was a ½-in maximum size aggregate. The mix design was based on the Marshall method and the design asphalt-rubber content was 7.0%. However, in actual construction, the binder content varied from 7.0 to 7.5%. The highest Marshall stability obtained during design was 1342 lbs. The amount of rubber was 13% by weight of the asphalt. The asphalt cement used was an AC-10 produced by Coastal Derby of El Dorado, Kan. The crumb rubber used was CRM-III (minus #10 mesh) rubber.

#### ***Asphalt Rubber Base (ARB)***

The ARB had a denser gradation with a maximum aggregate size of 3/4 inch and

TABLE 1 GRADATIONS OF INDIVIDUAL AND COMBINED AGGREGATES FOR ASPHALT RUBBER SURFACE MIX (ARS) (Asphalt Content = 7.5%)

Sieve Size (mm/ $\mu$ m)	Percent Aggregate Retained			
	CS2 (30%)	CS1A (60%)	SSG1 (10%)	Combined Cumulative (100%)
19	0	0	0	0
12.7	0	0	0	0
9.5	4	20	2	12.4
4.75	38	88	15	65.7
2.36	57	98	37	79.6
1.18	73	98	70	87.7
600	78	98	88	91.0
300	83	98	95	93.2
150	84	98	98	93.8
75	86	98.6	98.5	94.8

consisting of 20% CS-1 (Martin-Marietta rocks), 30% CS-1B (Kanopolis rock), 35% CS-2 (Martin-Marietta screening) and 15% sand (SSG-1) from Reno County. Table 2 shows the gradation of individual aggregates and the blend. The Marshall method of mix design showed a design asphalt-rubber content of 7.0% with 1653 lbs stability. The amount of rubber was 13% by weight of the asphalt. The asphalt cement used was an AC-10 produced by Coastal Derby of El Dorado, Kan. The crumb rubber used was CRM-III (minus #10 mesh) rubber.

### ***Control Mixture (BM-1B)***

The control mixture studied was a KDOT designation BM-1B mixture. The mixture is a 1/2 inch nominal maximum size mixture. The combined gradation consisted of 1/2" Bedding from Fogle Quarry, 30% Martin-Marietta Screening and 25% Kansas river sand. Table 3 lists the gradation and Figure 5 shows the combined gradation. The asphalt content according to the Marshall mix design was 5%, and the binder used was an AC-10.

The experimental program consisted of testing the flexural fatigue characteristics of the asphalt-rubber concrete beams. Three level of stresses were selected during tests so that the specimens will fail within a range from 1,000 to 10,000 repetitions. A static test on a companion specimen determined the maximum flexural capacity of the mix to be used, and was used to determine the applied stress magnitudes. On the average, **three** specimens for the mixes at **three** different stress levels were tested to establish the fatigue relationship for a given temperature. Tests at **two** different temperatures were done for ARS to establish the effect of stiffness or temperature on the fatigue life. This resulted in  $3 \times 3 \times 2 = 18 + 2$  (companion for static ultimate load testing) = 20 specimens for the ARS

TABLE 2 GRADATIONS OF INDIVIDUAL AND COMBINED AGGREGATES FOR ASPHALT RUBBER BASE MIX (ARB) (*Asphalt Content = 7.0%*)

Sieve Size (mm)	Percent Aggregate Retained				
	CS1 (20%)	CS1B (30%)	CS2 (35%)	SSG1 (15%)	Combined Cumulative (100%)
19	7	0	0	0	1.4
12.7	58	47	0	1	25.9
9.50	92	85	3	2	45.3
4.75	97	96	35	12	62.3
2.36	98	97	59	40	75.4
1.18	98	97	72	69	89.3
0.600	98	97	78	85	88.8
0.300	98	98	83	96	92.5
0.150	98	98	85	98	93.5
0.075	98	98	88	99	94.7

TABLE 3 GRADATIONS OF INDIVIDUAL AND COMBINED AGGREGATES FOR CONTROL MIX (BM-1B) (Asphalt Content = 5%)

Sieve Size	Percent Aggregate Retained				
	½" Bedding Fogle Quarry (45%)	Shilling Screening (30%)	Shilling Sand (25%)	Combined Cumula- tive (100%)	KDOT Spec.
½ in	0	0	0.3	0	0-10
3/8 in	37.8	3.8	0.7	18.3	12-26
No. 4	99.7	36.8	5.2	57.2	39-56
No. 8	99.8	56.2	19.3	66.6	60-76
No. 16	99.8	67.6	41.8	75.6	72-87
No. 30	99.8	73.0	65.8	83.3	79-92
No. 50	99.8	81.4	91.1	92.1	84-95
No. 100	99.8	84.3	98.2	94.8	88-98
No. 200	99.8	85.3	98.3	95.0	92-98

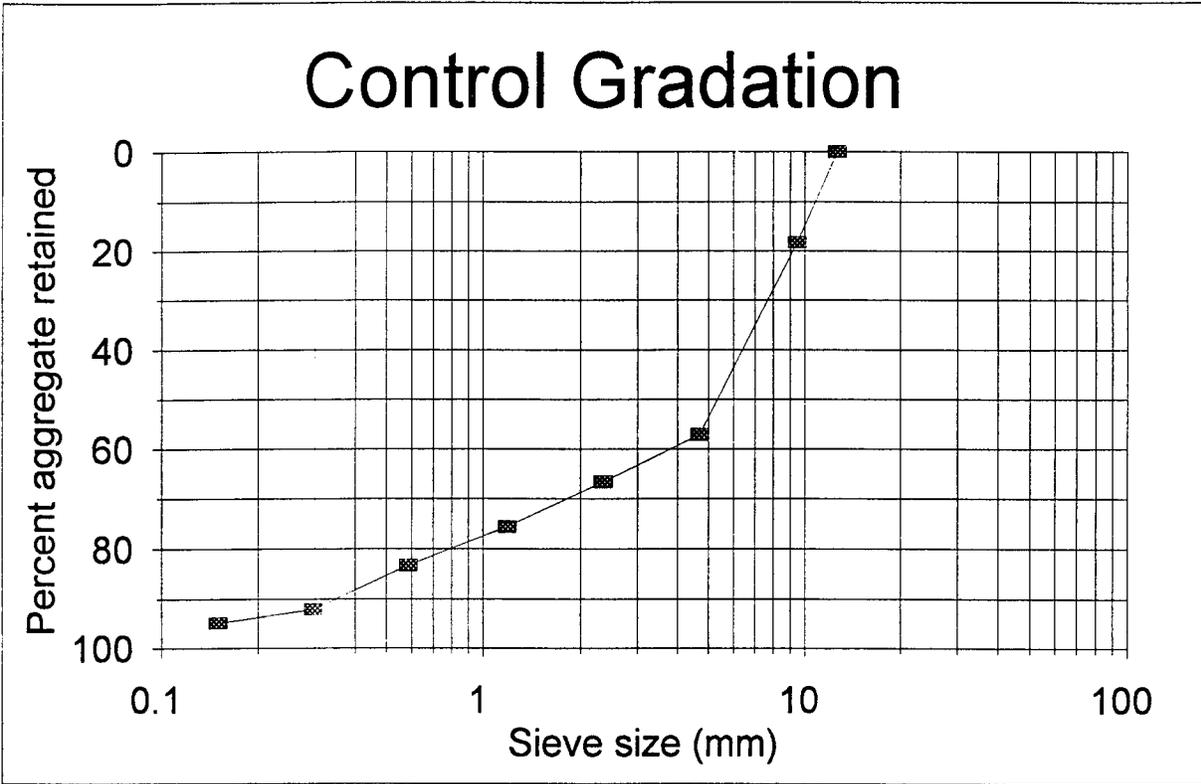


FIGURE 5 Combined Gradation of Control Aggregates (BM-1B mix)

mix and  $3 \times 3 \times 1 = 9 + 1$  (companion for static ultimate load testing) = 10 specimens for each of ARB and BM-1B. The test matrix is shown in Table 4. The actual number of specimens tested in fatigue was also shown in Table 4 in parentheses. The number varies slightly because of unavoidable problems, e.g., catastrophic failure of the specimens due to localized defects. In total, the number of beams tested was 30. In addition to these, density and void analysis were performed for all samples.

### **Sample Preparation**

For asphalt mix beam fabrication, the asphalt-rubber concrete mix was placed in a rectangular mold of 3" x 4" x 16" size and compacted by a California kneading compactor (manufactured by Cox & Sons) at the Materials Research Center of KDOT in Topeka, Kan. The compaction was done in two layers. The foot-pressure of the kneading compactor was successively increased to 100 psi, 200 psi, and 300 psi for each of the approximately 40 tamps per layer. After the mold was removed from the kneading machine it was placed under a static load for five minutes. The mold was then placed in a refrigerator for 20 minutes to cool. After cooling, the beam was extracted from the mold with a hydraulic jack.

### **Control Sample Preparation**

An asphalt concrete sample with no rubber was designated as the control sample. The control sample was a conventional KDOT BM-1B type mix. A ½-in. nominal max. size aggregate, sand and screening were used with an AC-10 asphalt. The optimum asphalt content of this mix in the Marshall mix design was found to be 5.0%.

### **Testing of Samples**

Flexural fatigue tests on asphalt beams were performed in this experiment under constant

TABLE 4 TEST MATRIX FOR ASPHALT RUBBER MIX FLEXURAL FATIGUE TESTS

Mixture Type	Rubber Content (%)	Binder Content (%)	Number of samples to be tested at	
			41° F	68° F
Asphalt-Rubber Base (ARB)	13	7	9 (8)	9 (7)
Asphalt-Rubber Surface (ARS)	13	7.5	-	9 (8)
Control (KDOT BM-1B)	0	5	-	9 (7)

stress type of controlled loading. The beams were tested in a three-point mode of loading as shown in Figure 6. The test temperatures were 41° F and 68° F for ARS and 68° F for ARB and BM-1B. The ultimate load carried in a three-point loading mode was determined earlier in a static universal test machine. The fatigue loads applied were fractions of this ultimate load with a haversine loading of 0.1 sec duration with no rest period. The deflection at the center of the beam at the 200th cycle of load repetition was measured with a strain gage at the bottom fiber of the beam. The hack-saw blade strain gage used is shown in Figure 7. A full-bridge set up was used to connect the strain gage in the electrical circuit and a digital strain gage indicator was used for read out. Figure 8 illustrates the full-bridge set up used. The deflection reading was found from the calibration chart of the electrical strain gage with a micrometer. After the strain reading was taken at the 200th cycle, the strain measurement set up was dismantled and the samples were loaded repeatedly to failure (or full-depth cracking). The number of cycles needed to cause failure was noted.

In addition to these, an environmental chamber was fabricated for low temperature testing and the schematic of this chamber is shown in Figure 9. The repeated flexure apparatus was enclosed in this controlled-temperature environmental chamber for low-temperature testing as illustrated in Figure 10.

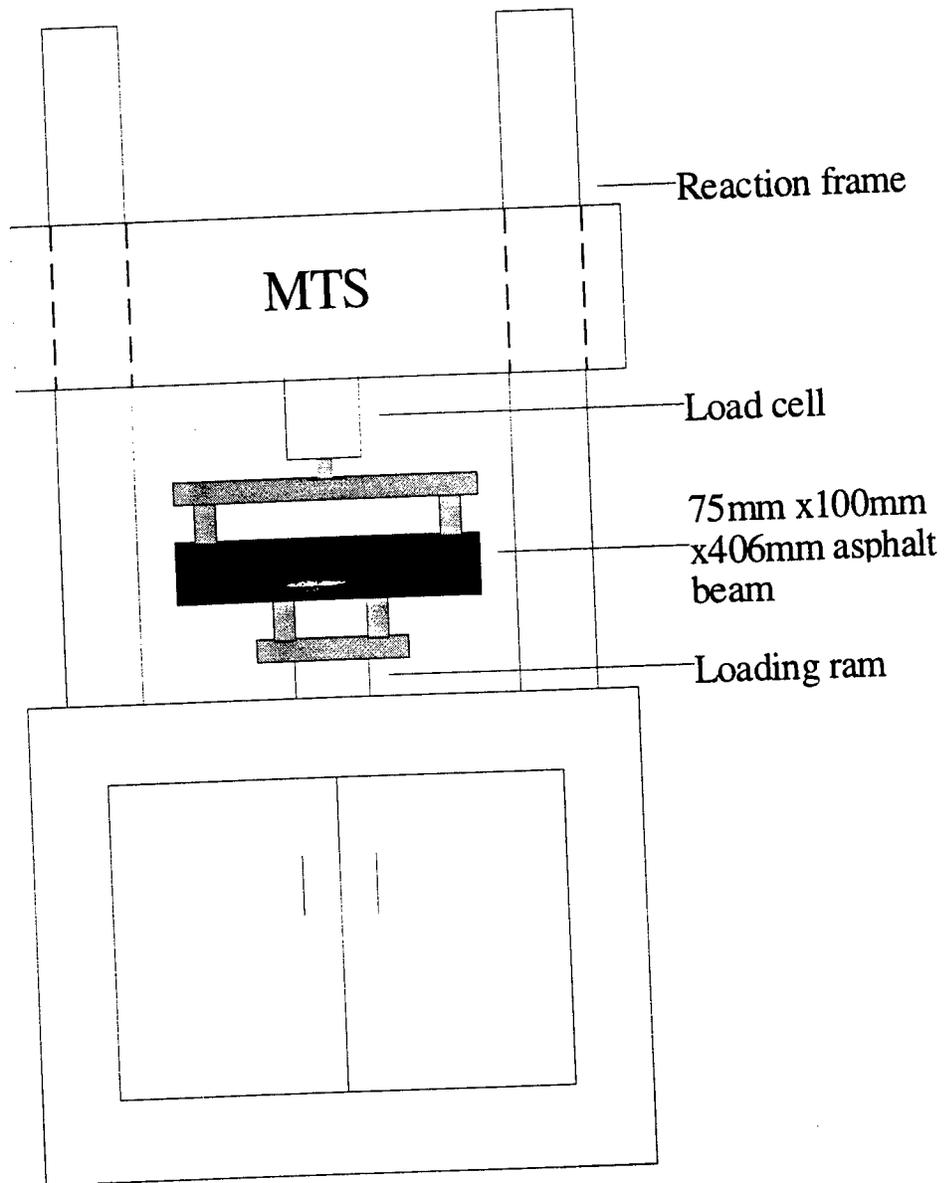


FIGURE 6 Test Set Up for Flexural Fatigue Testing of Asphalt Beams

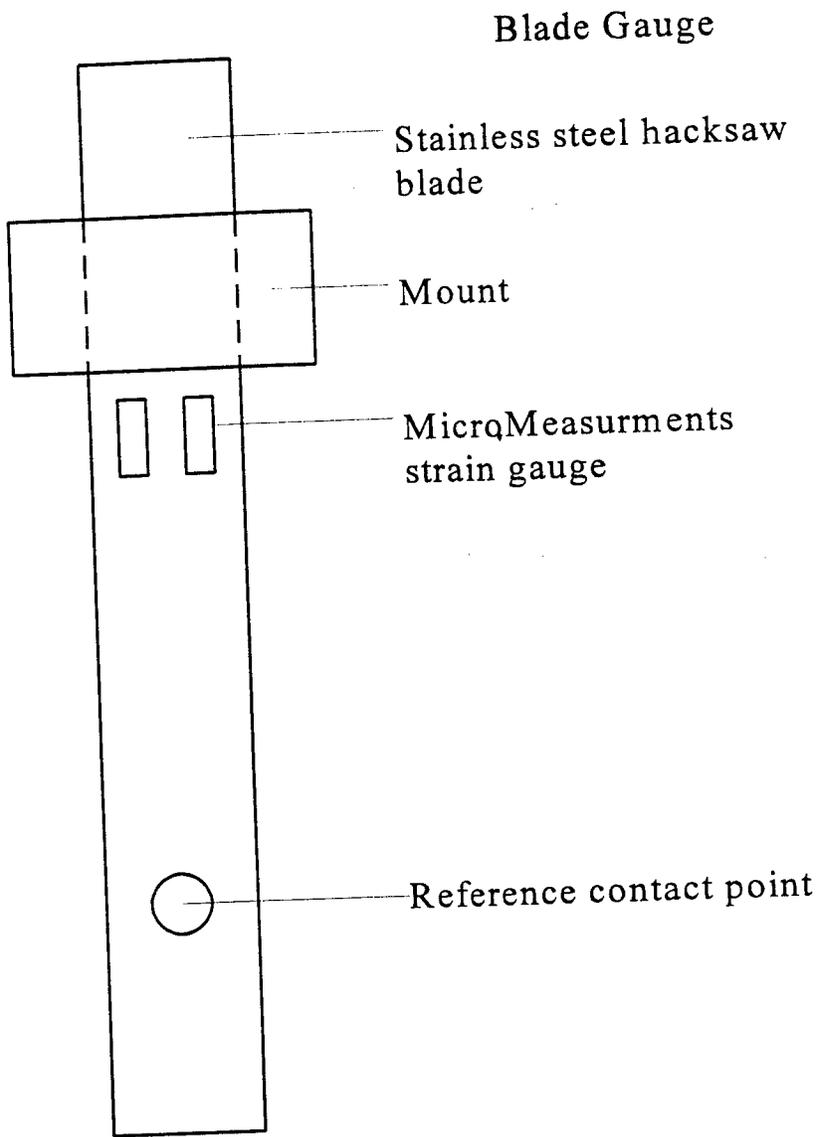


FIGURE 7 Hack-Saw Blade Gauge Details

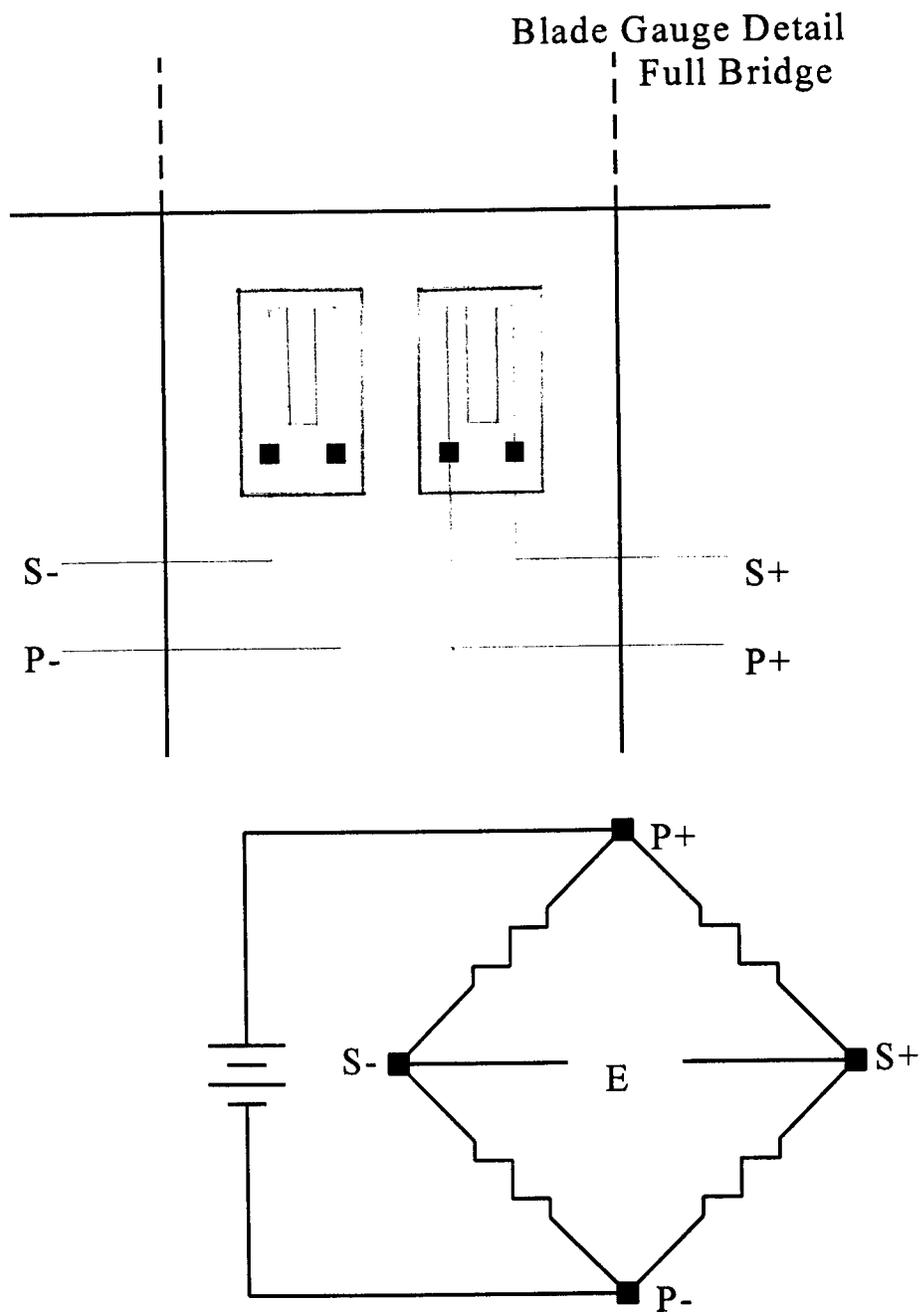


FIGURE 8 Full-Bridge Circuit Details

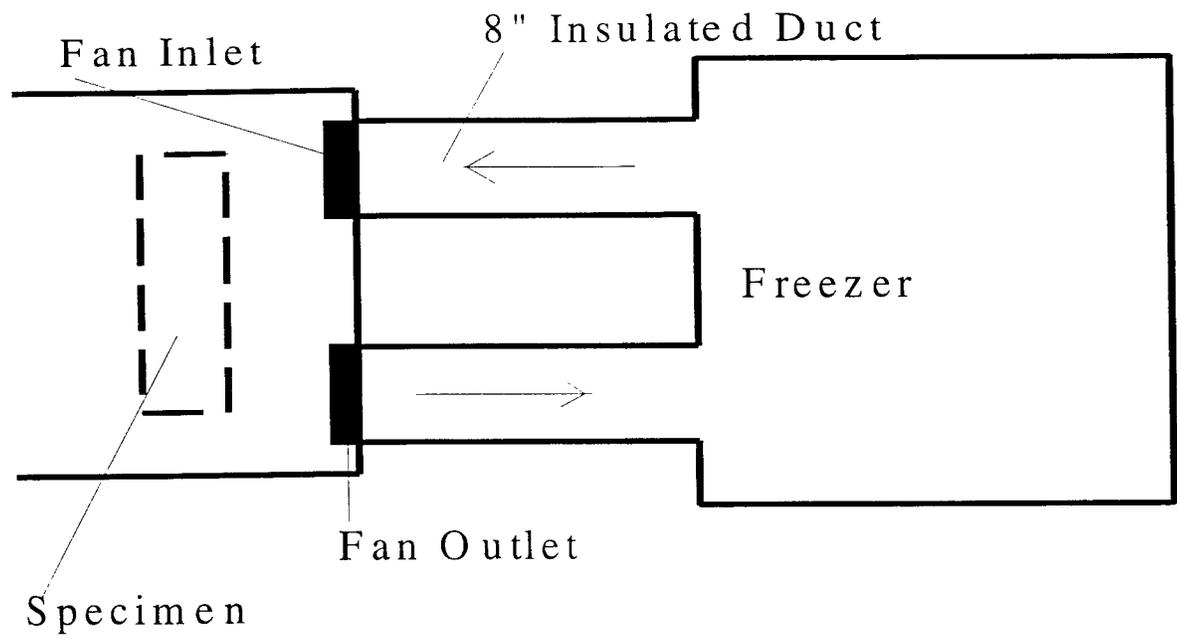


FIGURE 9 Environmental Chamber Schematic

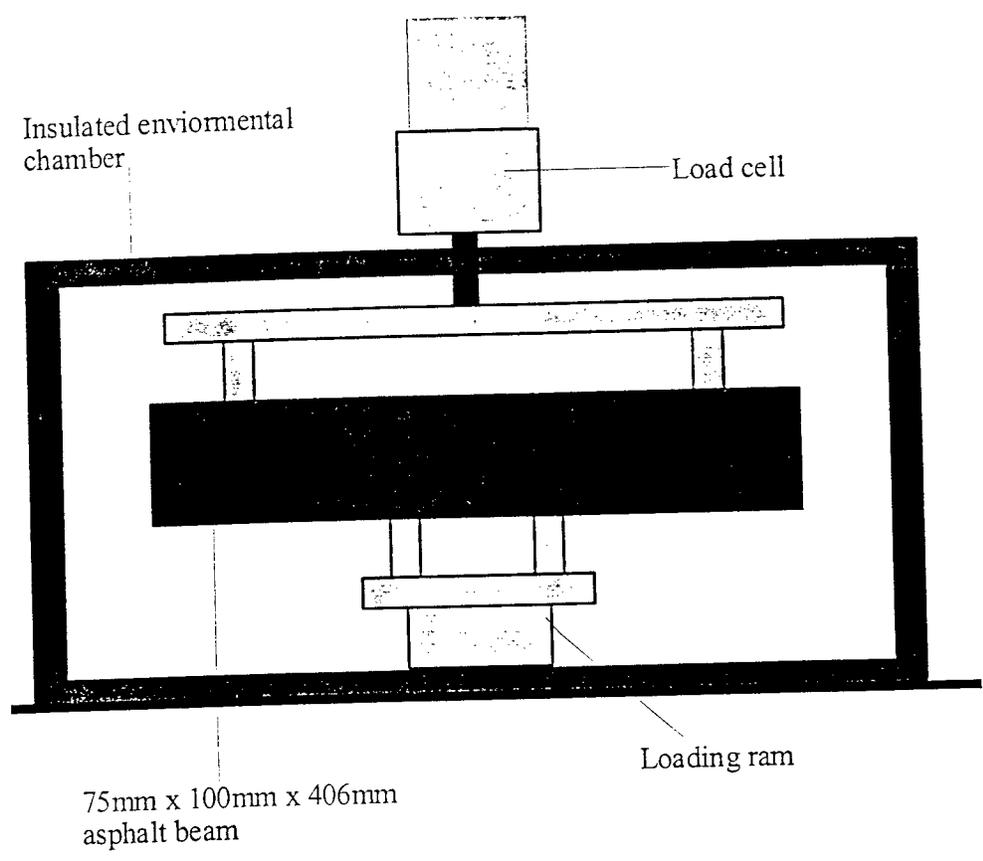


FIGURE 10 Flexural Fatigue Test Set Up Enclosed in Environmental Chamber

## CHAPTER 5

### RESULTS AND DISCUSSIONS

#### Data Analysis

In the constant stress test, the stress remains constant but the strain increases with the number of repetitions. The constant stress type of loading is applicable to thicker pavements, wherein the hot mix asphalt layer is more than 6 in. thick and is the main load-carrying component (e.g., ARB). The constant strain type of loading is applicable to thin pavements with HMA less than 2 in. thick because the strain in the asphalt layer is governed by the underlying layers and is not affected by the decrease in stiffness of the asphalt mix. For intermediate thicknesses, a combination of constant stress and constant strain exists (23). The stiffness modulus and the initial strain of each test were determined at the 200th repetition by using Eqs. 1 and 2, respectively (23).

$$E_s = \frac{Pa(3L^2 - 4a^2)}{4bh^3\Delta} \dots\dots\dots(5.1)$$

$$\epsilon_t = \frac{\sigma}{E_s} = \frac{12h\Delta}{3L^2 - 4a^2} \dots\dots\dots(5.2)$$

where,

- |                |   |
|----------------|---|
| $E_s =$        | flexural stiffness modulus                          |
| $\epsilon_t =$ | initial tensile strain                              |
| $P =$          | total dynamic load                                  |
| $h =$          | specimen height                                     |
| $b =$          | specimen width                                      |
| $L =$          | beam span length                                    |
| $a =$          | distance between support and the first applied load |
| $\Delta =$     | beam center deflection                              |

Tables 5, 6, 7 and 8 show the fatigue test results for ARS at 42° F, 68° F, ARB at 68° F and BM-1B at 68° F, respectively. The tables also show the air voids of the beams used in testing. The stiffness of the ARS mixtures at 42° F varied from 70 ksi to 133 ksi with a mean value of 102 ksi. The coefficient of variation was 21%. The air voids of these beams were also higher. The average air void was 10.3 %. The stiffness values of the ARS mixtures at 68° F were very low. The average value was 60 ksi with a coefficient of variation of 27%. The average air void of the mixtures was 7.2%.

The ARB mixtures had an average stiffness of 109 ksi with a coefficient of variation of 27.5% at 68° F. The average air void of the ARB samples was 4.6% with a coefficient of variation of 59%. The control, BM-1B mixtures had an average stiffness of 74 ksi with a coefficient of variation of 24%. The average air void for these dense-graded samples was 4.2% with a coefficient of variation of 31%.

The correlation analysis among the number of cycles to fatigue failures, stiffness and air voids showed that the stiffness had little effect on the number of cycles to failure which is well expected in a constant stress-type testing. For dense-graded mixtures (ARB and BM-1B) stiffness was not affected by air voids, but for open-graded mixture (ARS) it was highly affected by the air void. The stiffness sharply decreased with increase in air voids. For ARS, the number of load repetitions to failure was highly correlated to air voids of the sample. At 68° F, the number of repetitions to failure decreased as the air voids increased. This trend was observed by the SHRP researchers for the dense graded

TABLE 5 ASPHALT RUBBER SURFACE MIX AT 41° F

Sample ID	$N_f$ (repetitions)	$\epsilon_f$ (micro-strain)	$E_s$ (ksi)	% Air Voids
ARS - 4	1,563	2045	113	5.7
ARS - 6	975	2008	121	8.3
ARS - 9	4,746	1686	84	13.5
ARS - 10	1,727	2354	70	10.6
ARS - 11	8,367	1252	89	13.9
ARS - 12	2,956	1471	115	10.4
ARS - 13	2,434	1638	133	9.1
ARS - 15	4307	1244	91	10.7
Mean			102	10.3
Std. Dev.			21.6	2.7
Coeff. of Var. (%)			21	26
Sample Size			8	8

TABLE 6 ASPHALT RUBBER SURFACE MIX AT 68-70° F

Sample ID	$N_f$ (repetitions)	$\epsilon_t$ (micro-strain)	$E_s$ (ksi)	% Air Voids
ARS - 16	1,920	826	40	10.3
ARS - 18	3,333	848	40	7.0
ARS - 19	1,805	791	56	8.5
ARS - 22	1,826	564	61	8.6
ARS - 23	3,714	477	76	4.4
ARS - 24	2,832	629	82	5.3
ARS - 25	2,947	823	63	6.1

TABLE 7 ASPHALT RUBBER BASE MIX AT 68-70° F

Sample ID	$N_f$ (repetitions)	$\epsilon_t$ (micro-strain)	$E_s$ (ksi)	% Air Voids
ARB - 1	3,550	936	89	3.5
ARB - 4	5,100	603	162	7.2
ARB - 7	3,384	750	68	7.0
ARB - 9	1,377	773	125	3.3
ARB - 10	1,533	784	120	2.0
ARB - 11	3,093	748	126	2.5
ARB - 12	1,188	1285	90	8.8
ARB - 13	743	1295	90	2.2

TABLE 8 CONTROL (BM-1B) MIX AT 68-70° F

Sample ID	$N_f$ (repetitions)	$\epsilon_t$ (micro-strain)	$E_s$ (ksi)	% Air Voids
CON - 2	979	1,067.00	60	2.8
CON - 3	578	1,467.00	64	6.5
CON - 4	3,596	645.00	50	3.6
CON - 5	426	1,395.00	78	4.9
CON - 6	485	1,325.00	83	4.0
CON - 7	1,155	721.00	77	4.5
CON - 8	2,037	523.00	103	2.8

mixtures (18). However, for ARS, the relationship between the number of repetitions to failure and air voids is reverse at lower temperature (42° F). This indicates that the ARS mixture may be more resistant to the fatigue due to low-temperature thermal cycles.

### Fatigue Equations

The initial strains measured were plotted versus the number of load repetitions to failure on log scales. The equation of the line was expressed by

$$N_f = f_1 (\epsilon_t)^{-f_2} \dots\dots\dots(5.3)$$

in which  $N_f$  is the number of repetitions to failure,  $f_1$  is a fatigue constant that is the value of  $N_f$  when  $\epsilon_t=1$ , and  $f_2$  is the inverse slope of the straight line. The following relationships were obtained for different mixtures:

ARS:

$$N_f = 6.292 \cdot \epsilon_t^{-3.8302} \quad (\text{at } 42^\circ \text{ F}) \quad (R^2 = 0.77) \dots\dots\dots(5.4)$$

$$N_f = 0.01046 \cdot \epsilon_t^{-1.7119} \quad (\text{at } 68^\circ \text{ F}) \quad (R^2 = 0.61) \dots\dots\dots(5.5)$$

ARB:

$$N_f = 0.0001 \cdot \epsilon_t^{-2.3788} \quad (\text{at } 68^\circ \text{ F}) \quad (R^2 = 0.87) \dots\dots\dots(5.6)$$

BM-1B:

$$N_f = 0.000446 \cdot \epsilon_t^{-2.1012} \quad (\text{at } 68^\circ \text{ F}) \quad (R^2 = 0.85) \dots\dots\dots(5.7)$$

Figures 11, 12, 13 and 14 show these fatigue relationships for ARS at 42° F, 68° F, ARB at 68° F and BM-1B at 68° F, respectively.

### Prediction of Fatigue Life

For prediction of fatigue lives of ARB and BM-1B mixtures, three different existing pavement sections on I-135 were chosen. Two of these sections are test sections

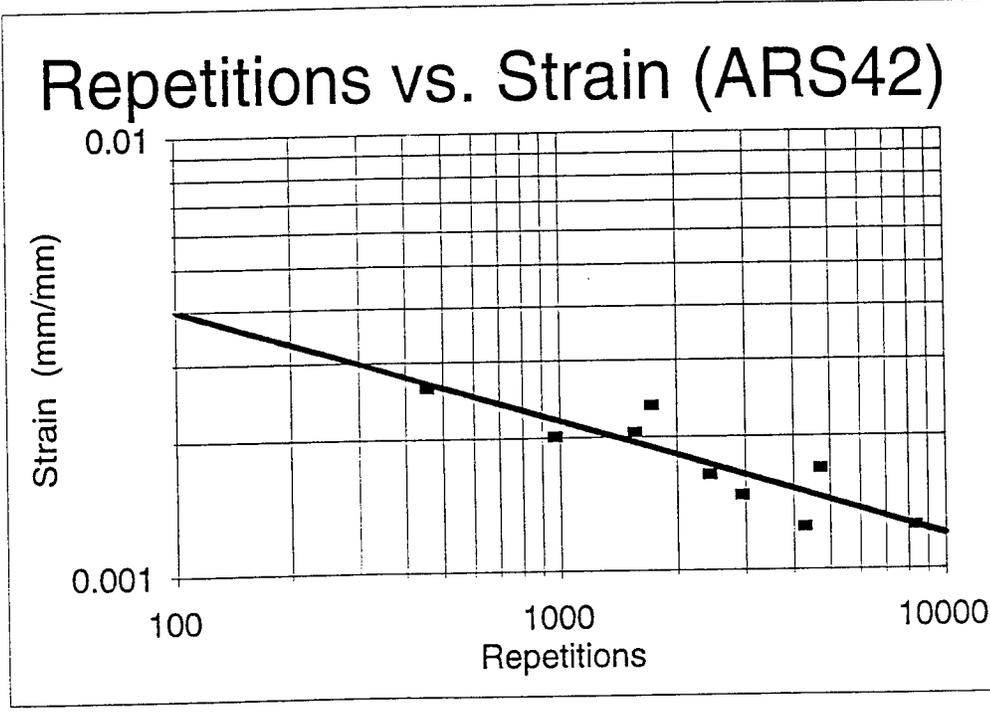


FIGURE 11 Fatigue Relationship for ARS at 42° F

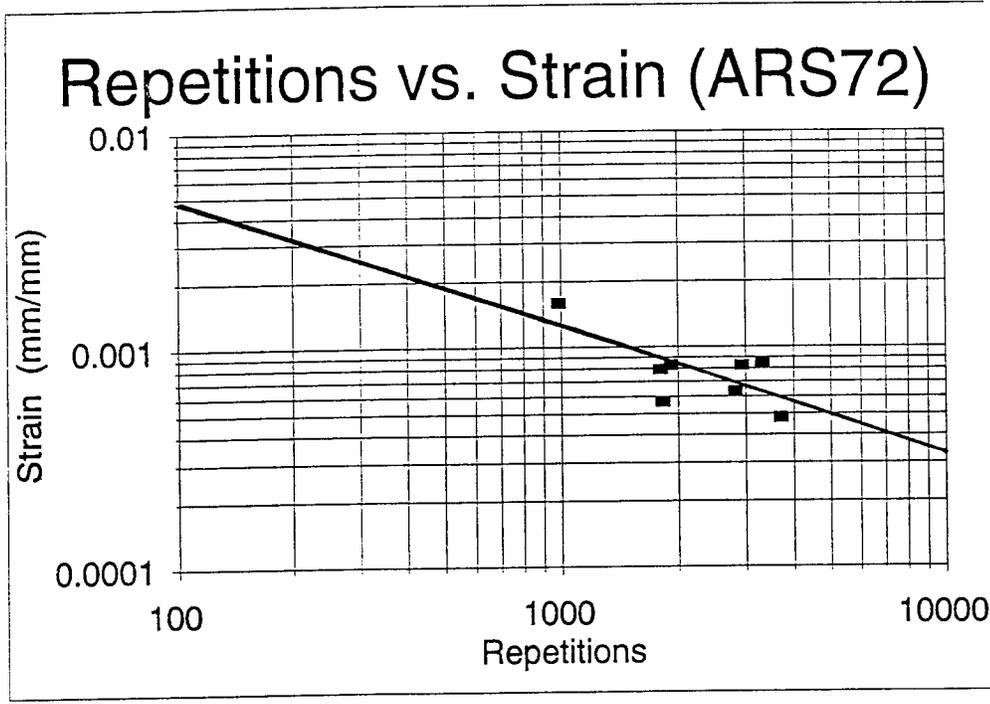


FIGURE 12 Fatigue Relationship for ARS at 68° F

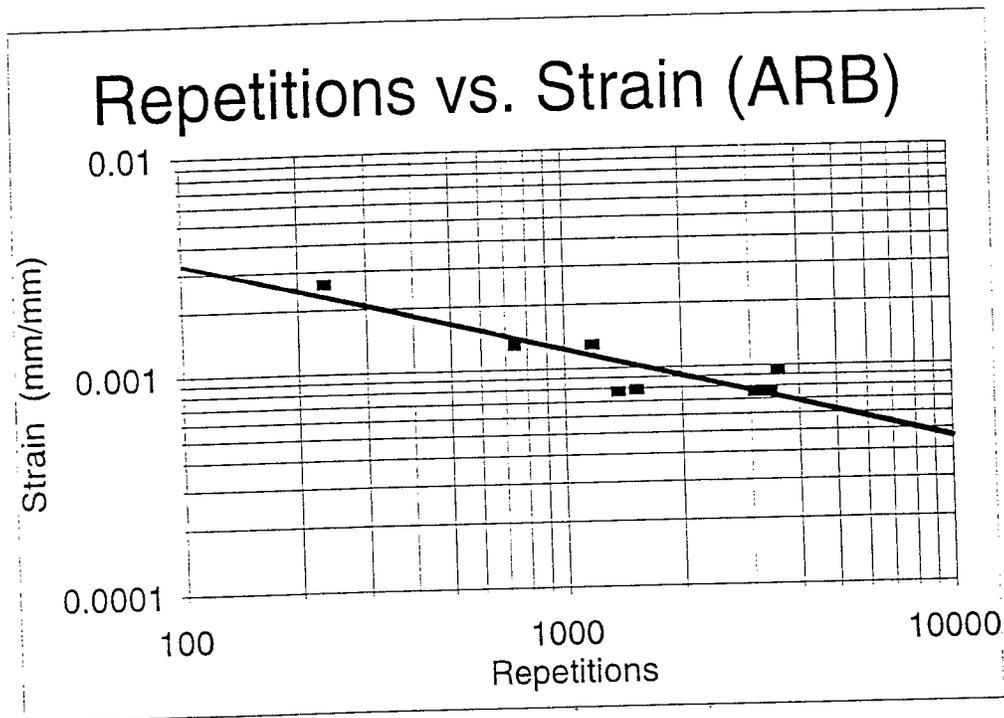


FIGURE 13 Fatigue Relationship for ARB at 68° F

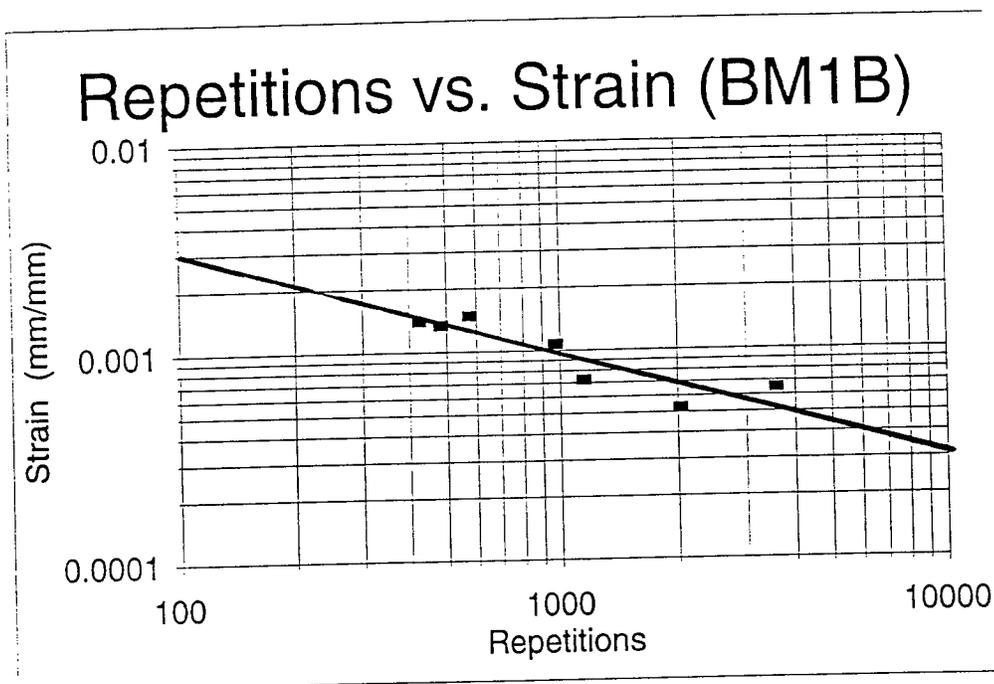


Figure 14 Fatigue Relationship for BM-1B at 68° F

incorporating ARB mixtures as asphaltic base. Table 9 shows the cross-sections of the test sections. The layer moduli for different layers were backcalculated from the Falling Weight Deflectometer test results. Details of the backcalculation have been reported by Habib and Hossain (24).

On each section with ARB, the tensile strain at the bottom of the ARB layer was computed corresponding to wheel loads of 9, 18 and 22.5 kip with 100 psi tire pressure. On the control section, the tensile strain was computed at the bottom of the conventional asphalt base layer. These strain values were substituted in to three different sets of equations for predicting fatigue lives: (i) SHRP A-003A Laboratory Testing Method, (ii) The Asphalt Institute Fatigue Equations and (iii) Equations developed in this study. Table 10 shows the fatigue equations and associated shift factor used in this study. A shift factor of 100 was chosen for the KSU equations as per suggestion by Brown (25) due to no rest period used in this study.

Table 11 shows the computed strains and associated fatigue lives predicted by each equation. Figures 15, 16 and 17 show the predicted fatigue lives in a graphical form for all test sections. On section 1, all equations show higher fatigue life for the ARB layer than the BM-1B layer on Section 3 although the BM-1B layer was 1 inch thicker than the ARB layer. Overall, the thickness of the control section is slightly higher than Section 1. The results obtained by the KSU and Asphalt Institute equations are close, but the SHRP equations tend to give very high fatigue lives for each mixture. The fatigue life of the ARB mixtures on section 2 is considerable higher than Section 1, clearly because the ARB layer on Section 1 is about 1.5 in. thinner. The total asphalt thickness on Section 2 is approx.

TABLE 9 LAYER TYPES AND THICKNESSES OF DIFFERENT TEST SECTIONS

Route	Test Section No.	Layer					
		Surface		Base		Subbase	
		Material Type	Thickness (in)	Material Type	Thickness (in)	Material Type	Thickness (in)
	1	ARS	1.5	ARB	7	Rubblized JRC	9
	2	ARS	1	ARB	8.5	Rubblized JRC	9
	Control	Conventional Asphalt Surface	1	Conventional Asphalt Base	8	Rubblized JRC	9

TABLE 10 COMPARISON AMONG DIFFERENT FATIGUE MODELS AND SHIFT FACTORS

DESIGN METHOD	SHIFT FACTOR
<b>SHRP A-003A LABORATORY TESTING METHOD</b>	
Top lift (air voids= 6.8%): $N_f = 4.06 \times 10^{-8} \times e_t^{-3.348}$	13
Bottom lift (air voids= 3.7%): $N_f = 8.36 \times 10^{-8} \times e_t^{-3.420}$	
<b>ASPHALT INSTITUTE</b>	
$N_f = 0.00432 C e_t^{-3.291}  E^* ^{-0.854}$ $C = 10^M$ $M = 4.84 \left( \frac{V_b}{V_a + V_b} - 0.69 \right)$	18.4
<b>KSU STUDY</b>	
ARB: $N_f = 0.0001 \cdot e^{-2.3788}$ (at 68 F) ( $R^2 = 0.87$ )  Dense Graded (BM-1B): $N_f = 0.000446 \cdot e^{-2.1012}$ (at 68 F) ( $R^2 = 0.85$ )	100*

\* Due to no rest period, as per suggestion by Brown.

Notes:-  $N_f$  = Fatigue life,  $e_t$  = Initial strain,  $E^*$  = Dynamic ( $\approx$  Elastic) modulus (psi),  
 $C$  = Fatigue life multiplying factor,  $V_b$  = Volume of binder,  $V_a$  = Volume of air voids.

TABLE 11 SUMMARY OF ASPHALT PAVEMENT STRAINS AND FATIGUE LIVES.

Section	Load (kip)	Tensile Strain at the bottom of the asphalt base layer (micro-strain)	Fatigue Life (Repetitions, Millions)		
			Asphalt Institute	SHRP A-003A	KSU Study
1 (ARB)	9	74.75	94.13	140.7	65.44
	18	138.7	12.3	16.99	15.04
	22.5	167.1	6.67	8.99	9.66
2 (ARB)	9	34.8	1429	1917	402.5
	18	63.69	243.3	195.8	95.8
	22.5	76.2	108.7	131.8	62.52
3 Control (BM-1B)	9	54.06	22.77	42.63	41.25
	18	101.4	2.874	49.6	11.0
	22.5	122.9	1.526	25.7	7.345

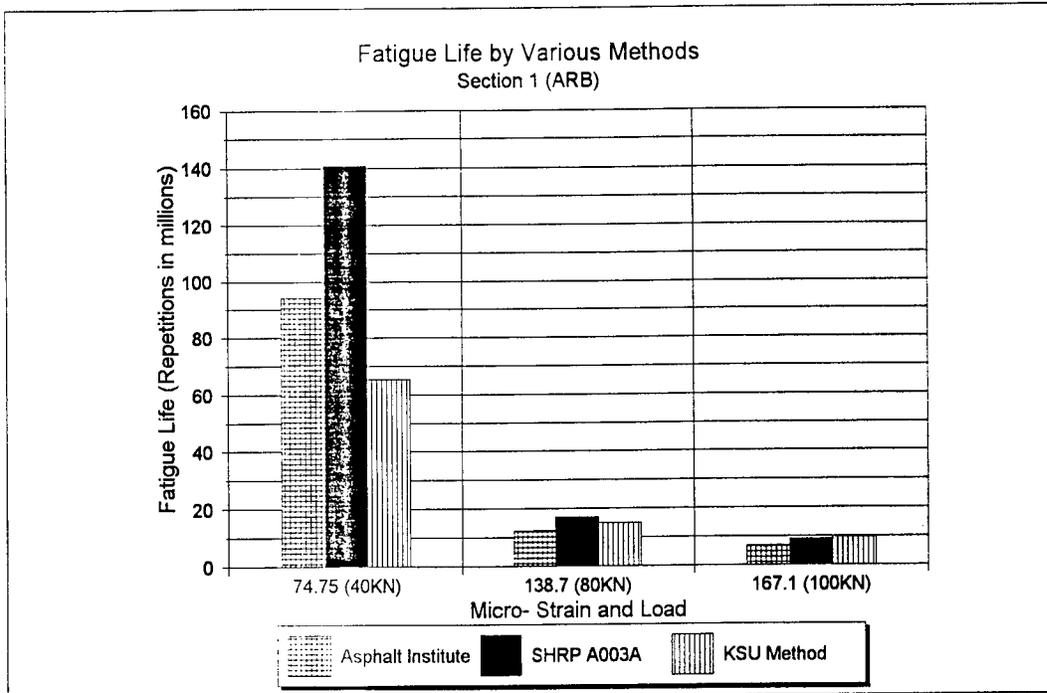


FIGURE 15 Fatigue Life of Section 1

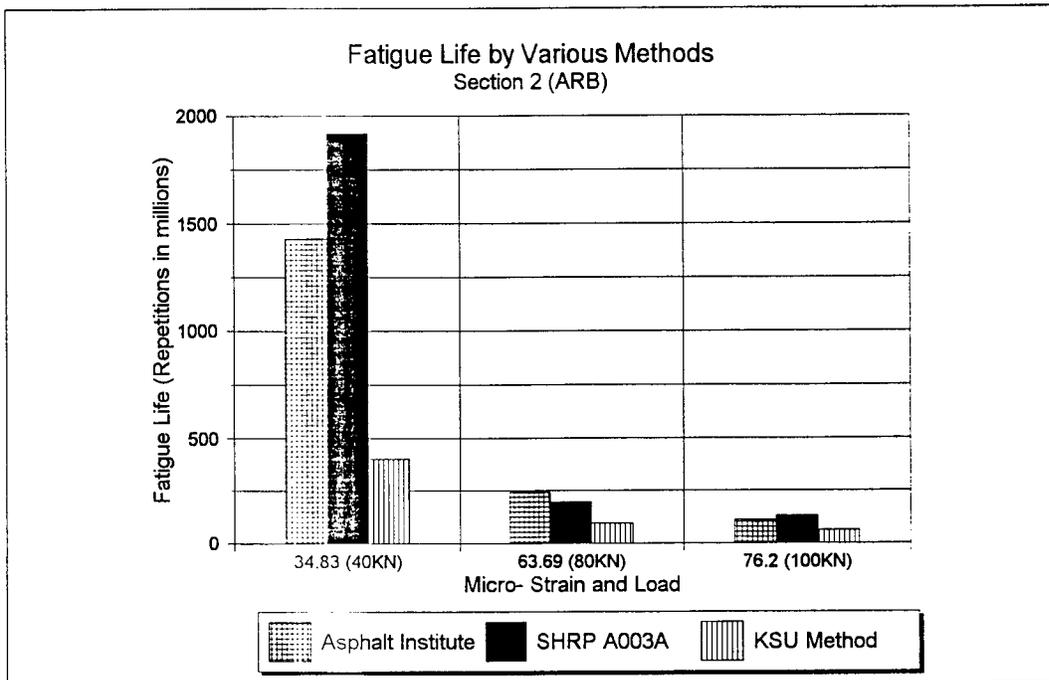


FIGURE 16 Fatigue Life of Section 2

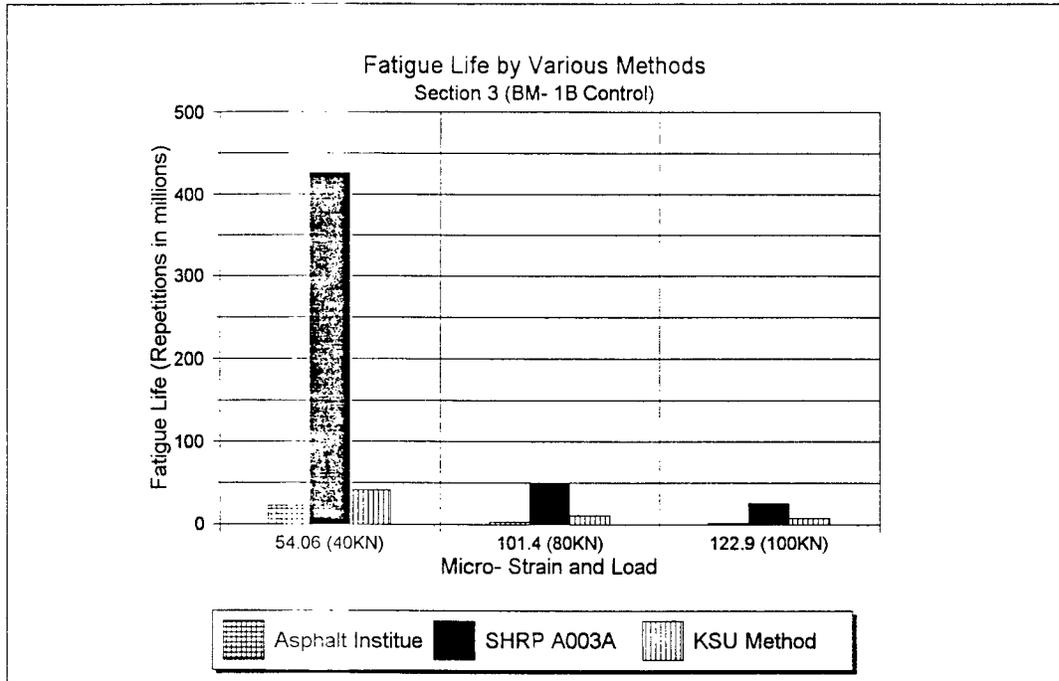


FIGURE 17 Fatigue Life of Control Section

1 in. higher than Section 1. The ARB sections appear to have much higher fatigue lives than the BM-1B (control) mixtures at all strain levels. The difference is very prominent at higher strain levels for the ARB sections. However, the opposite is true for the control or conventional mix section. The design number of 18-Kip Equivalent Single Axle Loads (ESALS) for these sections was 3,319,164 for a 10-year period, which is very close to the Asphalt Institute (AI) prediction for the conventional or control pavement. At the same strain level, if the same shift factor as the AI equation (18.4) is used, the KSU equation would result in 2.2024 million repetitions which is 23% lower than the AI prediction.

#### **COMPARISON OF ASPHALT-RUBBER MIXTURE LIVES USING ALF DATA**

The objective of the SHRP FHWA-ALF pavement study was to evaluate the fatigue performance of a thin asphalt section when subjected to dual- versus single-tire loading (18). The fatigue equations developed in this study were compared with the fatigue results during the SHRP study on the beams for a pavement section at the FHWA Accelerated Loading Facility (ALF) in McLean, VA. The pavement sections consists of 3.5 inch asphalt layer (stiffness = 700,000 psi) over a 12 in. base layer (stiffness = 15,000 psi). Preliminary results reported by SHRP indicated a fatigue life to surface crack initiation of approximately 55,000 and 110,000 repetitions for the single- and dual-tire configurations, respectively. Although the mixtures tested in this study are different from the FHWA ALF study, and all KSU mixtures except ARS are not intended for thinner pavements, it is clear from the results in Table 12 that the fatigue relationships obtained by KSU are very reasonable. The asphalt-rubber base mixture (ARB) performance is the best. However, the ARS mixture did not appear to be suitable as a structural layer -its fatigue life is

TABLE 12 ESTIMATED FATIGUE LIFE COMPARISON FOR THE FHWA-ALF STUDY

Tire Type*	Subgrade E (psi)	Tensile strain under AC layer**	Fatigue Life (Univ. of Calif.)	Fatigue Life (KSU)	ARS Fatigue Life (ARS)	BM-1B Fatigue Life (KSU)	Low Temp. ARS Fatigue Life (KSU)
Single	5,000	551	40,000	64,000	40,000	31000	1,910,000
Single	10,000	526	47,000	72,000	43,000	35,000	2,280,000
Dual	5,000	467	72,000	95,000	53,000	45,000	3,600,000
Dual	10,000	443	87,000	108,000	58,000	50,000	4,400,000

\* 12,000 lb wheel load, 140 psi tire pressure

\*\* micro-strains

Note: For comparison, a section with a 6-inch AC layer (modulus= 435,000 psi) and a 6- inch aggregate base (modulus = 25,000 psi) over a subgrade of 10,000 psi stiffness shows tensile strain of 225 micro-strains under a 9,000 lb dual wheel load with 100 psi tire pressure.

marginally improved at lower strain level as compared to the other mixtures. However, the results for lower temperature for the ARS mixtures indicates that this mix might be very suitable for low-temperature thermal fatigue resistance. Further studies are needed in this area.

## CHAPTER 6

### CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the following conclusions can be drawn:

(1) The flexural stiffness of the ARS mixtures at 42° F varied from 70 ksi to 133 ksi with a mean value of 102 ksi. The average air void was 10.3 %. The stiffness values of the ARS mixtures at 68° F were very low. The average value was 60 ksi with a coefficient of variation of 27%. The average air void of the mixtures was 7.2%. The ARB mixtures had an average stiffness of 109 ksi with a coefficient of variation of 27.5% at 68° F. The average air void of the ARB samples was 4.6% with a coefficient of variation of 59%. The control, BM-1B mixtures had an average stiffness of 74 ksi. The average air void for these dense-graded samples was 4.2% with a coefficient of variation of 31%.

(2) The correlation analysis among the number of cycles to fatigue failures, stiffness and air voids showed that the stiffness had little effect on the number of cycles to failure which is well expected in a constant stress-type testing. For dense-graded mixtures (ARB and BM-1B) stiffness was not affected by air voids, but for open-graded mixture (ARS) it was highly affected by the air void. The stiffness sharply decreased with increase in air voids. For ARS, the number of load repetitions to failure was highly correlated to air voids of the sample. At 68° F, the number of repetitions to failure decreased as the air voids increased.

(3) Tensile strains at the bottom of asphalt concrete layer and associated fatigue lives were predicted by three different equations, the Asphalt Institute, SHRP and this study, for three in-service test sections on I-135. All equations show higher fatigue life for the ARB layer than the BM-1B layer although the BM-1B layer, in one instance, was 1 in. thicker

than the ARB layer. The results obtained by the KSU and Asphalt Institute equations are close, but the SHRP equations tend to give very high fatigue lives for each mixture. The ARB sections appear to have much higher fatigue lives than the BM-1B (control) mixtures at all strain levels. The difference is very prominent at higher strain levels for the ARB sections. However, the opposite is true for the control or conventional mix section.

(4) A comparison of the results in this study with those from the FHWA ALF study for SHRP shows that the fatigue relationships obtained in this study are very reasonable. The asphalt-rubber base mixture (ARB) performance is the best. However, the ARS mixture did not appear to be suitable as a structural layer - its fatigue life is marginally improved at lower strain level as compared to the other mixtures. However, the fatigue lives of the ARS layer at the same strain levels at lower temperature indicates that this mix might be very suitable for low-temperature thermal fatigue resistance. Further studies are needed in this area.

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