

IMPACT OF VARIATION IN MATERIAL
PROPERTIES ON ASPHALT PAVEMENT LIFE
EVALUATION OF CASTLE ROCK-CEDAR CREEK
PROJECT

HP & R Study: 0815157

Interim Report

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<p>16. Abstract</p> <p>Construction and short-term pavement performance problems were noted in the Pacific Northwest and throughout the United States during the past five years. Several reasons have been suggested to explain this sudden change in pavement performance, such as recent variabilities in asphalt properties and new developments in paving technology. Using the data and construction materials issued from a recent project built in 1979, Oregon State Highway Department and Oregon State University conducted a laboratory study to determine the relationship between asphalt concrete pavement performance and mix level of compaction, asphalt content, and mix gradation. Conventional tests and improved dynamic tests were run on laboratory compacted samples to determine mix stiffness, fatigue life and permanent deformation characteristics. Based on fatigue and permanent deformation test results, preliminary pay adjustment factors were developed by comparing performance of mix specimens prepared at the design optimum with the performance of mix out of specifications. It was found that performance is primarily affected by the mix level of compaction. Fatigue data corroborated the design optimum asphalt content (6%), and showed a strong interaction between the asphalt content and the amount of fines. Mix susceptibility to permanent deformation decreased when increasing the amount of fines and decreasing the asphalt content. A summary table giving the most critical pay adjustment factors between the fatigue and the permanent deformation criteria is developed in the conclusions and recommendations chapter.</p>			
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This report is the third of a series of reports concerned with the impact of variations in material properties of asphalt pavement life. The data developed in this report will be combined with that developed for two other projects (North Oakland-Sutherlin and Warren-Scappose). All projects will be analyzed together to formulate recommendations for pay adjustment factors. These recommendations will appear in the final report. Assistance provided by Glen Boyle and staff, Oregon Department of Transportation, in the testing associated with Chapter 3 and that provided by Jose R. Montalvo and Michael Wynkoop, students of Oregon State University, in testing associated with Chapter 4 is acknowledged. The project was conducted in cooperation with the U.S. Department of Transportation Federal Highway Administration.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the Oregon Department of Transportation or the Federal Highway Administration.

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1.0 INTRODUCTION

Problem Definition

Several changes have occurred in recent years in highway materials and in asphalt paving technology. New asphalt sources have been brought on line, introducing changes in asphalt properties. New equipment has also been developed, affecting mixing (dryer drum mixers, more efficient dust collector systems), storage (mix storage silos) and compaction (vibratory compactors). In the same period, economic constraints have resulted in increasing use of lower quality aggregate. As a result, there has been an increase in construction or short-term performance problems throughout the Pacific Northwest (1). The impact of such changes on the mix properties is, however, difficult to evaluate. Table 1 summarizes the main changes observed and their expected influence on the mix behavior.

One recent project, located on the Three Rivers Highway, between Hebo and Valley Junction, referred to as the Castle Rock-Cedar Creek project, was built in 1979. Progressive pavement raveling and potholing were noticed during the months following construction of this project. Evaluation of the reduction in pavement life resulting from changes in the design specifications (e.g., aggregate quality, gradation, density, asphalt content) requires a study of the mix dynamic properties under controlled conditions. A rational approach is needed to assess the effects of these mix variables on pavement life.

Purpose

The purpose of this report is to obtain a better understanding of the causes of the pavement problems noticed in the past years, and to develop relationships between pavement performance and the different mix variables. Such information will be useful in developing pay-adjustment factors for projects not complying fully with specifications.

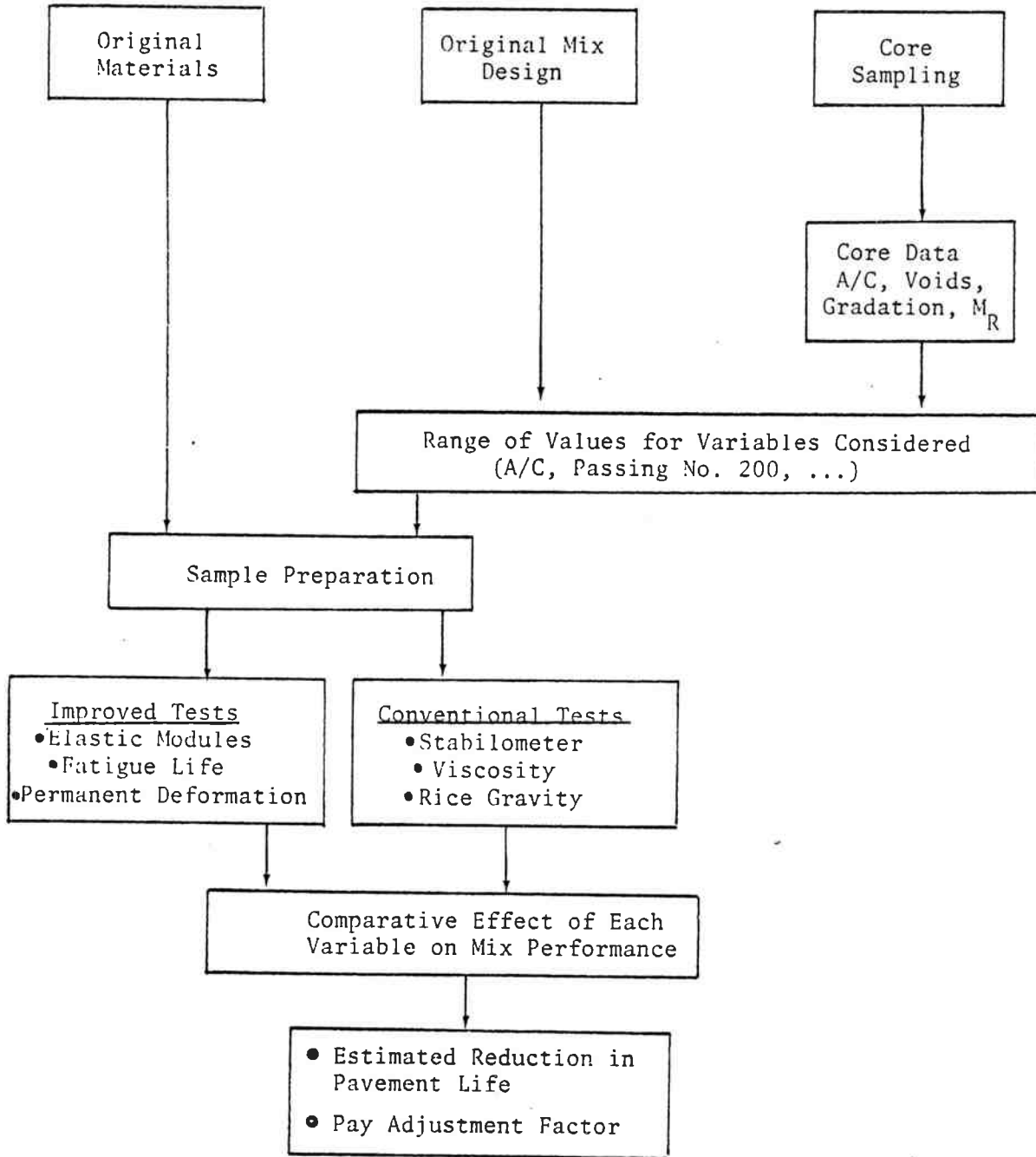
Table 2 illustrates a flow chart of the approach followed for the study of the Castle Rock-Cedar Creek project. Three mix variables were considered in the study:

- (1) Asphalt content
- (2) Percent Passing No. 200 sieve (.074 mm).
- (3) Mix density.

Table 1. Recent Changes in Asphalt Paving Technology Affecting Pavement Behavior

ITEM	CHANGES OBSERVED	EXPECTED IMPACT ON PAVEMENT
ASPHALT	Wide difference between asphalt temperature-viscosity curves from various suppliers. Increased temperature - susceptibility	Compaction difficulty Slow setting mixes Reduced resistance to thermal and fatigue cracking
	Reduced compatibility between asphalt and aggregate	Increased ravelling Reduced resistance to damage from water and freeze-thaw effects
AGGREGATE	Reduced aggregate quality	Increased ravelling Reduced resistance to damage from water and freeze-thaw effects
	Single stockpile Elimination of Plant Screens	Reduced uniformity of gradation Segregation
EQUIPMENT	Use of collector dust	Reduced uniformity of gradation Flashing
	High Mix production rate	Reduced uniformity of gradation and asphalt content
	Lower mixing and laydown temperatures	Reduced uniformity of asphalt viscosity. Increased moisture. Reduced asphalt-aggregate adhesion
	Use of vibratory compactors	Breakage of aggregates Low compaction from improper use
	Drum mixers	Incomplete coating of aggregate
	Mix storage silos and Belly dump hauling equipment	Mix segregation from improper use

Table 2. Flow Chart of Study.



The range of values selected for each of the above variables was determined from project sampling and from cores taken in the spring of 1980 (See Appendix A). These are as follows:

- (1) Asphalt content: 5% - 6% - 7%
- (2) Percent Passing No. 200: 2% - 6% - 10%
- (3) Mix level of compaction: 100% - 97% - 92% - 90%

Following the standard ODOT procedure, 4 inches (10 cm) in diameter by 2.5 inches (6 cm) high samples were fabricated for each set of conditions, using the same materials (asphalt and aggregate) as used during construction of the Castle Rock-Cedar Creek project.

The main types of pavement failure considered during the test program include fatigue cracking and rutting. All samples are tested in the diametral mode for elastic modulus, fatigue life and permanent deformation. To obtain complete characterization of the mixture, conventional tests were also run (stabilometer, void content, index of retained strength).

To identify the potential for stripping and raveling, elastic modulus, fatigue life and permanent deformation tests are performed both before and after vacuum saturation of the samples, followed by a freeze-thaw cycle.

Scope of Report

After a description of the Castle Rock-Cedar Creek project (Chapter 2), the test results will be presented in Chapter 3 (ODOT research) and in Chapter 4 (OSU research). Tests performed by Oregon Department of Transportation include conventional tests. All dynamic tests were performed at Oregon State University. Analysis of data include the development of fatigue life and permanent deformation criteria for the as compacted samples and the conditioned samples. Finally, pay adjustment factors are determined in Chapter 5 using the fatigue and permanent deformation models developed in Chapter 4.

2.0 PROJECT DESCRIPTION

Location

The Castle Rock-Cedar Creek project is a section of the Hebo-Valley Junction Highway, located in Tillamook and Yamhill counties (Figure 1). Precise location of the project is shown on Figure 2. The project overall length is 11.7 miles (18.7 km).

Cross-Section

Reconstruction of this section of the Hebo-Valley Junction highway included an asphalt concrete base course and an asphalt concrete wearing surface, on top of the existing bituminous surface. Both layers were built using an ODOT class B mix. The average for the as constructed thickness is 2.0" (5.1 cm) for the base and 1.7" (4.3 cm) for the wearing surface.

Mix Design

A summary of the original mix design is presented in Table 3. This mix design was used for both the base and the top layers. The aggregate gradation was also the same for both layers, and correspond to a type B mix (Table 4). The recommended asphalt content was 6.1 percent for the wearing surface and 6.7 percent for the base course. The asphalt grade recommended was an AR 4000, from Chevron. The recommended mix temperature at time of placement was 270°F (132°C).

Project Data

Pavement raveling, potholing, variation in mix gradation and asphalt content were noticed during construction of the Castle Rock-Cedar Creek project in 1979.

Inspection of the mix showed that the coarse aggregate were 40 to 95 percent coated. Aggregates were dirty and contained soft materials (AASHTO T-112), and the asphalt was not uniformly mixed with the aggregates.

Table 5 summarizes the field test results run during pavement construction. The variables considered are the mix bulk specific gravity, asphalt content and percent passing No. 200 and No. 10. Compared to the core data and the specified job mix tolerances (Table 6), it appears from the average field

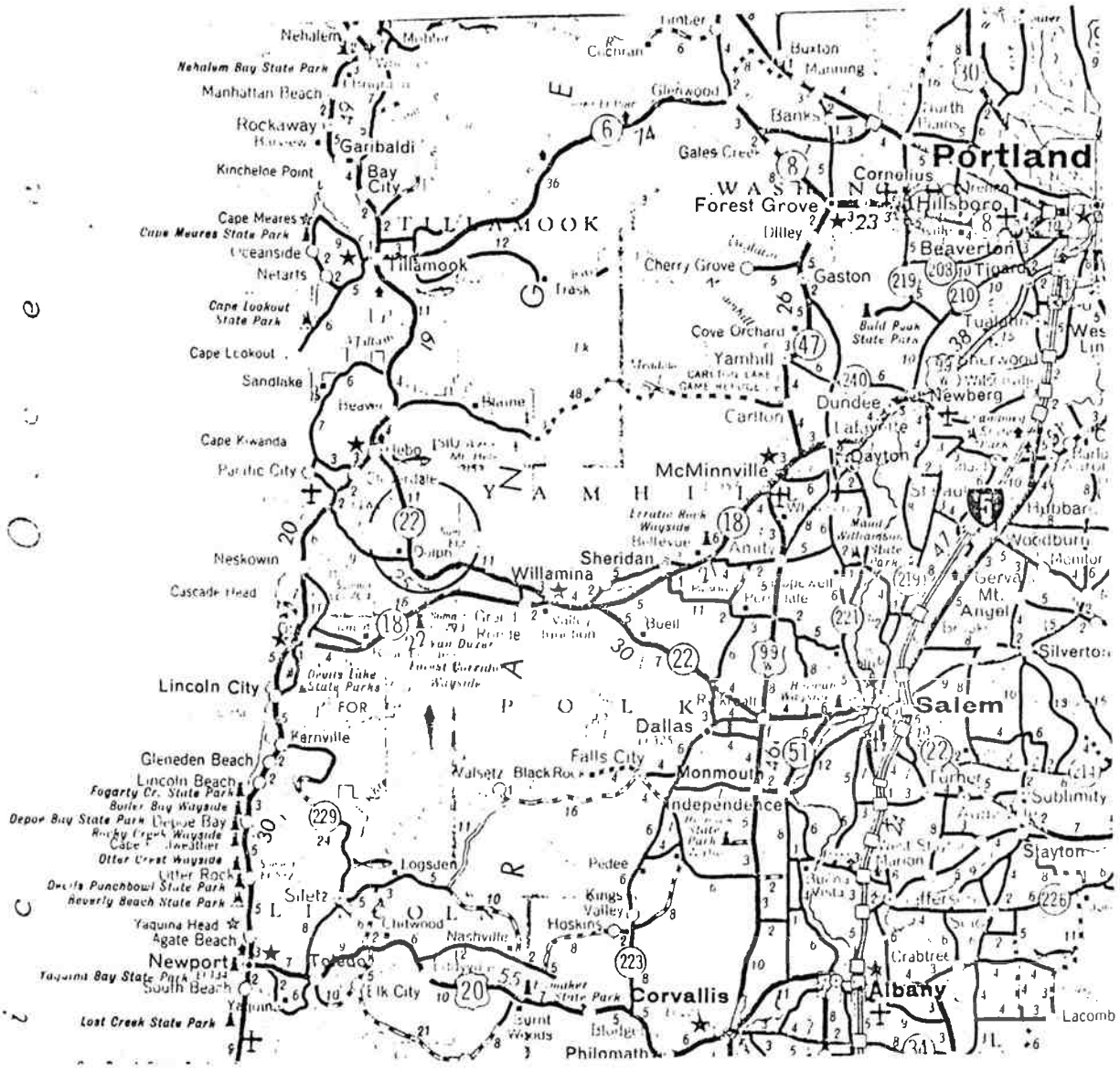


Figure 1. Map of Northwestern Oregon Project Location

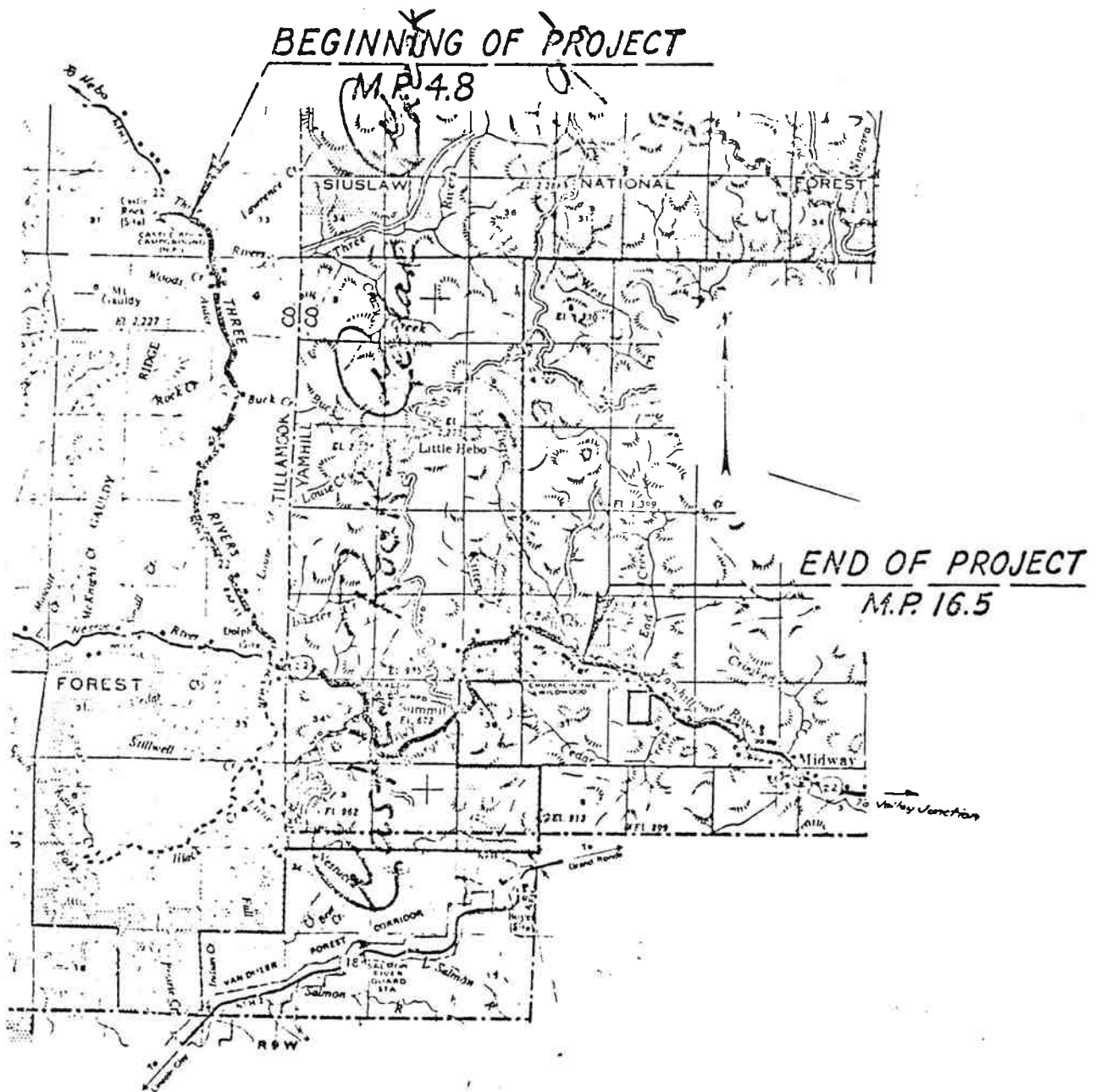


Figure 2. Castle Rock - Cedar Creek
Detail of Project Location

Table 3. Original Mix Design Test Results (ODOT)
Hebo Valley Junction Project

	5.0	5.5	6.0	6.5	7.0
Asphalt Content - AR 4000					
Asphalt Film Thickness	Suff.	Suff.	Suff. Thick.	Thick	V. Thick
Stability Value, 1st Compaction	41	41	37	37	39
Bulk Spe. Gravity, 1st Compaction	2.22	2.24	2.26	2.28	2.29
Percent Voids, 1st Compaction	11.2	9.7	8.1	6.6	5.4
Stability Value, 2nd Compaction	49	51	51	51	50
Bulk Spe. Gravity, 2nd Compaction	2.31	2.33	2.35	2.37	2.38
Percent Voids, 2nd Compaction	7.6	6.0	4.5	2.9	1.7
Rice Gravity	2.50	2.48	2.46	2.44	2.42
Index of Retained Strength AASHTO-T-165	56	-	79	-	87

Table 4. Mix Design: Aggregate Gradation, Class B

SIEVE SIZE	COMBINED AGGREGATE AASHTO-T-27	WASHED SIEVE AASHTO-T-11	JOB MIX TOLERANCE	SPECIFICATION
1"	100	100	100	100
3/4"	99	99	95 - 100	95 - 100
1/2"	90	90	81 - 93	-
1/4"	63	65	57 - 69	52 - 72
# 10	26	28	22 - 30	21 - 41
# 40	10	11	8 - 16	8 - 24
#200	3.6	4.6	3 - 7	3 - 7

Table 5. Summary of Construction Reports - 1979
Base and Top Lift Bituminous Mix Class "B"

IN PLACE MIX DATA	TOP LIFT		BASE LIFT	
	Average Value	Max. and Min. Values	Average Value	Max. and Min. Values
Mix Bulk Specific Gravity	2.15 + .03 (10 tests)	2.11 - 2.19	2.21 + .02 (5 tests)	2.17 - 2.23
Asphalt Content	6.04 + .28 (27 tests)	5.4 - 6.5	6.56 + .51 (30 tests)	5.1 - 7.2
Percent Passing No. 200	5.54 + .47 (28 tests)	4.4 - 6.3	5.75 + .42 (30 tests)	4.7 - 6.4
Percent Passing No. 10	27.23 + 3.48 (28 tests)	20.6 - 35.8	27.87 + 2.93 (30 tests)	22 - 34

Table 6. Comparison Between Construction Information,
Core Data and Mix Specification

	TOP LIFT				BASE LIFT				
	Daily Plant Test Results	Core Data	Job Mix Tolerance	Daily Plant Test Results	Core Data	Job Mix Tolerance	Daily Plant Test Results	Core Data	Job Mix Tolerance
Mix Bulk Specific Gravity	2.15	2.12	-	2.21	2.14	-			
Asphalt Content	6.04	6.0	5.6 - 6.6	6.56	7.0	6.2 - 7.2			
Percent Passing No. 200	5.54	6.2	3 - 7	5.75	6.6	3 - 7			
Percent Passing No. 10	27.23	27	22 - 30	27.87	29	22 - 30			

data that the asphalt content and the amount passing No. 10 sieve were high, but the amount passing No. 200 was reasonably within specifications.

Table 5 also indicates that the mix variables were ranging within a very wide band, indicating quality control problems during mixing (asphalt content, gradation) and during compaction (mix bulk specific gravity). This is corroborated by the ODOT inspector's report which noted that the contractor's quality control was nonexistent, production erratic and workmanship sloppy.

Consequently, the pavement quality was largely reduced. ODOT field tests for production control of the mix indicated that the pavement raveling and pot-holing are the result of inadequate asphalt coating of aggregate, excess variation in mix gradation and asphalt content and excess soft material contained in the aggregate.

3.0 TEST RESULTS - ODOT

The Oregon State Highway Division testing program included the conventional tests such as standard mix design for each mix variable, gradation, asphalt content, void percent compaction content and resilient modulus of pavement samples from five locations and recovered asphalt properties. This chapter presents the results of their work.

Mix Design Data

The results of the mix design tests are presented in Table 7. For each set of variables, standard samples were tested to determine mix characteristics. The percent voids of all samples prepared for this project were determined using the Rice gravities indicated on Table 7. Modulus and bulk specific gravities shown on this table were used as reference values during sample preparation at Oregon State University.

Core Data

Five core sampling sites were selected on the Castle Rock-Cedar Creek project. For each site, asphalt concrete cores were sampled across each panel at two foot intervals starting from the road centerline (See Appendix A for details). Table 8 summarize the results of the tests run on a total of 25 core samples. The mix density was low in both lifts which resulted in unusually high voids. The gradation limits shown for each aggregate size are minimum and maximum values. Shown on Figures 3 and 4 are the aggregate gradation for the surfacing and the base mixes, along with the job mix tolerances. Both mix gradations are out of specification below the No. 10 sieve size, with an excess amount of fines for both the top and the base layers. In both cases, the specified amount of passing No. 10 sieve has been respected. Above the No. 10 sieve size, the wearing surface gradation shows wide variability, with a tendency toward a fine gradation. Less variability can be noticed in the coarse part of the base gradation, which is within the specified gradation range. The excess amount of fines and the relatively finer gradation of the surface course can be partially explained by the presence of some soft materials in the mix aggregate.

Study of the cores also showed insufficient asphalt coating of the aggregate. From the inspection of the cores, it appears that the coarse aggregate is 40 to 95 percent coated. Tests run on the asphalt recovered from the mix

Table 7. Summary of OSHD Mix Designs for Variables Evaluated: Castle Rock - Cedar Creek

MIX TYPE	2% PASSING NO. 200			6% PASSING NO. 200			10% PASSING NO. 200			92% COMPACTION			88% COMPACTION		
	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0
Asphalt Content	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0
Rice Grav. T 209	2.46	2.41	2.37	2.47	2.43	2.39	2.46	2.42	2.38	2.43	2.39	2.36	2.44	2.40	2.38
1st Bulk Spe. Grav.	2.17	2.19	2.21	2.23	2.27	2.29	2.24	2.28	2.30	2.08	2.10	2.12	2.05	2.07	2.08
Voids, %	11.8	9.1	6.8	9.7	6.6	4.2	8.9	5.8	3.4	14.4	12.1	10.2	16.0	13.8	12.6
2nd Bulk Spe. Grav.	2.23	2.27	2.31	2.32	2.35	2.37	2.30	2.35	2.37	-	-	-	-	-	-
Voids, %	9.3	5.8	2.5	6.1	3.3	0.8	6.5	2.9	0.4	-	-	-	-	-	-
Modulus x 10 ³ psi	353	305	310	381	420	355	757	479	401	236	191	189	173	132	131
Stability 1st	37	39	34	32	34	31	40	32	26	25	25	24	24	20	22
Stability 2nd	49	49	47	44	51	34	55	45	28	-	-	-	-	-	-
Dry	248	237	237	318	302	276	308	327	329	170	178	202	185	186	172
Wet	127	143	170	160	196	231	157	224	257	111	154	170	124	168	161
Index, %	51	60	72	50	65	84	51	69	78	65	87	84	67	90	94
P 200 Batched	-	1.6	-	-	4.8	-	-	8.0	-	-	-	-	-	-	-
P 200 Extracted	-	2.9	-	-	5.8	-	-	8.2	-	-	-	-	-	-	-
Asphalt Extracted	-	5.4	-	-	5.3	-	-	5.5	-	-	-	-	-	-	-

Table 8. Core Data - Average Values and Standard Deviations

		CORE DATA		JOB MIX TOLERANCE (Class "B" Mix)	
		TOP LAYER	BASE LAYER	TOP LAYER	BASE LAYER
Thickness		1.7" ± .3	2.0" ± .5	-	-
Bulk S.G.		2.12 ± .04	2.14 ± .05	-	-
% Voids In Place		13.4 ± 2.5	11.5 ± 2.1	-	-
Modulus x 10 ³ psi		197 ± 46	214 ± 37	-	-
GRADATION RANGES, % PASSING	3/4	96 - 100	98 - 100	95 - 100	
	1/2	69 - 95	84 - 96	81 - 96	
	3/8	50 - 86	66 - 87		
	1/4	31 - 68	51 - 74	57 - 69	
	10	14 - 33	22 - 38	22 - 30	
	40	7 - 16	11 - 17	8 - 16	
	200	3.5 - 7.6	5.2 - 7.6	3 - 7	
% A.C.		6.0 ± .7	7.0 ± .5	5.6-6.6	6.2-7.2
RECOVERED ASPHALT PROPERTIES AASHTO-T-170	Penetration At 70°F(21°C) (cm/100)	55 ± 8	58 ± 5	---	
	Kinematic Viscosity At 275°F(135°C) (cs.)	392 ± 69	396 ± 21	---	
	Absolute Viscosity At 140°F(60°C) (Poise)	2379 ± 669	2090 ± 247	---	

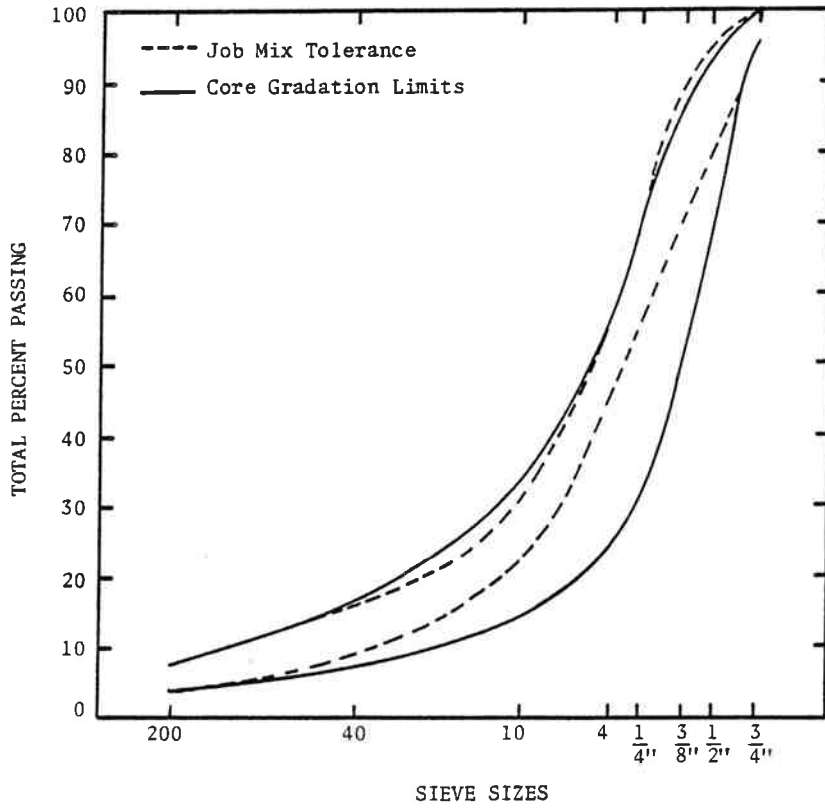


Figure 3. Core Gradation, Top Layer

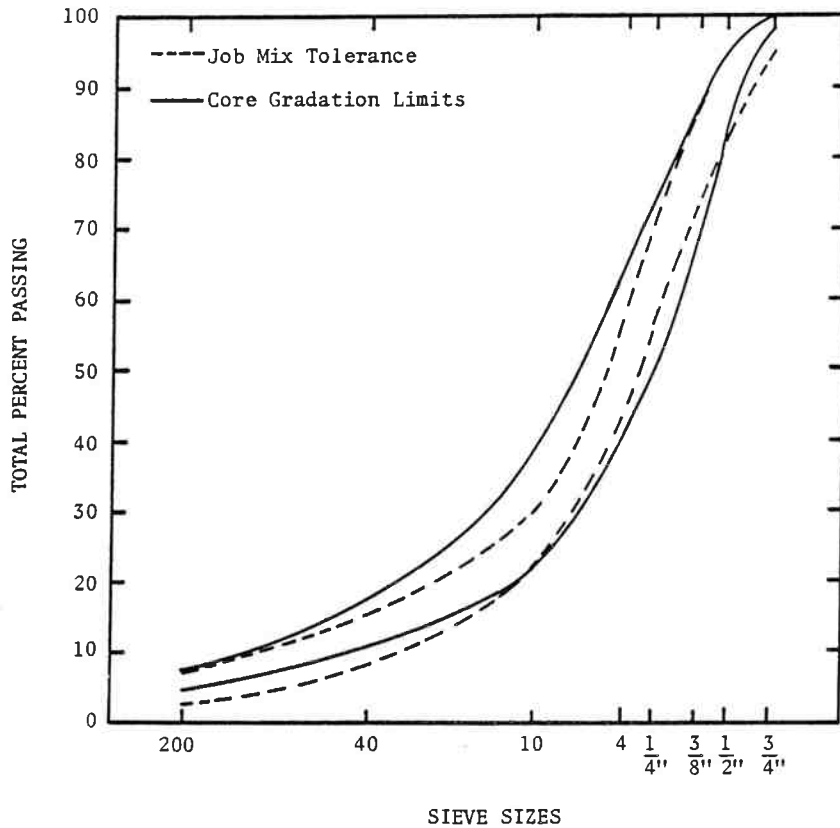


Figure 4. Core Gradation, Base Layer

indicate a softer consistency than expected for an AR4000 grade, which indicated a low mixing temperature, less than 300°F (149°C) to 325°F (163°C). The average asphalt content is 6.0 percent for the surfacing course and 7.0 percent for the base course, which is relatively close to the design values: 6.1 percent for the surfacing course and 6.7 percent for the base course. However, as indicated by the standard deviation, the variation in mix asphalt content exceeds the job mix tolerance.

In summary, analysis of the core samples brought the following information:

1. Excess variability in aggregate gradation and asphalt content;
2. Excess amount of fines (excess soft material in aggregate);
3. Inadequate asphalt coating of aggregate, and
4. Low recovered asphalt consistency (probably related to a low mixing temperature);
5. Low mix density (or high voids).

These data were used to establish the laboratory program described in the next chapter.

4.0 TEST RESULTS - OSU

The purpose of the tests performed at Oregon State University was to determine the fatigue life and permanent deformation characteristics of the asphalt mix. All tests were performed over the selected range of variables on standard laboratory samples using the repeated load indirect tensile test. The samples were prepared according to the Oregon State Highway Division standard procedure (2). The materials used are the same as used for the mix design reported in Section 3.0.

Test Program

A minimum of 16 samples were prepared for each condition. Eight samples are tested as compacted, and eight samples are tested after conditioning.* Table 9 gives the flow chart for the test program followed. The principal variables studied included:

- (1) Mix level of compaction: 100% - 97% - 92% - 90%
- (2) Percent passing No. 200 sieve: 2% - 6% - 10%
- (3) Percent asphalt content: 5% - 6% - 7%

Each of the above variables was studied relative to a standard mix, consisting of 6% passing No. 200 sieve and 6% asphalt content. When studying the influence of the mix density, the standard mix was compacted at 97%, while a 92% compaction standard mix was selected to study the influence of the amount of fines, asphalt content and aggregate quality. Detail of the combination of variables used in this analysis are shown in Table 10.

*The sample conditioning procedure followed was based on the moisture damage test defined by Lottman (3). The following are the main steps:

1. Determine the resilient modulus of the as-compacted samples, after overnight cure. Mark along which samples axis the modulus was measured.
2. Vacuum saturate the samples for two hours.
3. Place the saturated samples in a freezer at -18°C for 15 hours.
4. Place the frozen, saturated specimen in a warm water bath for 24 hours.
5. Place the specimen in a water bath at room temperature for three hours.
6. Run the mechanical property tests, along the same sample axis as the as-compacted modulus was measured (Step 1).

Table 9 . Test Program - OSU

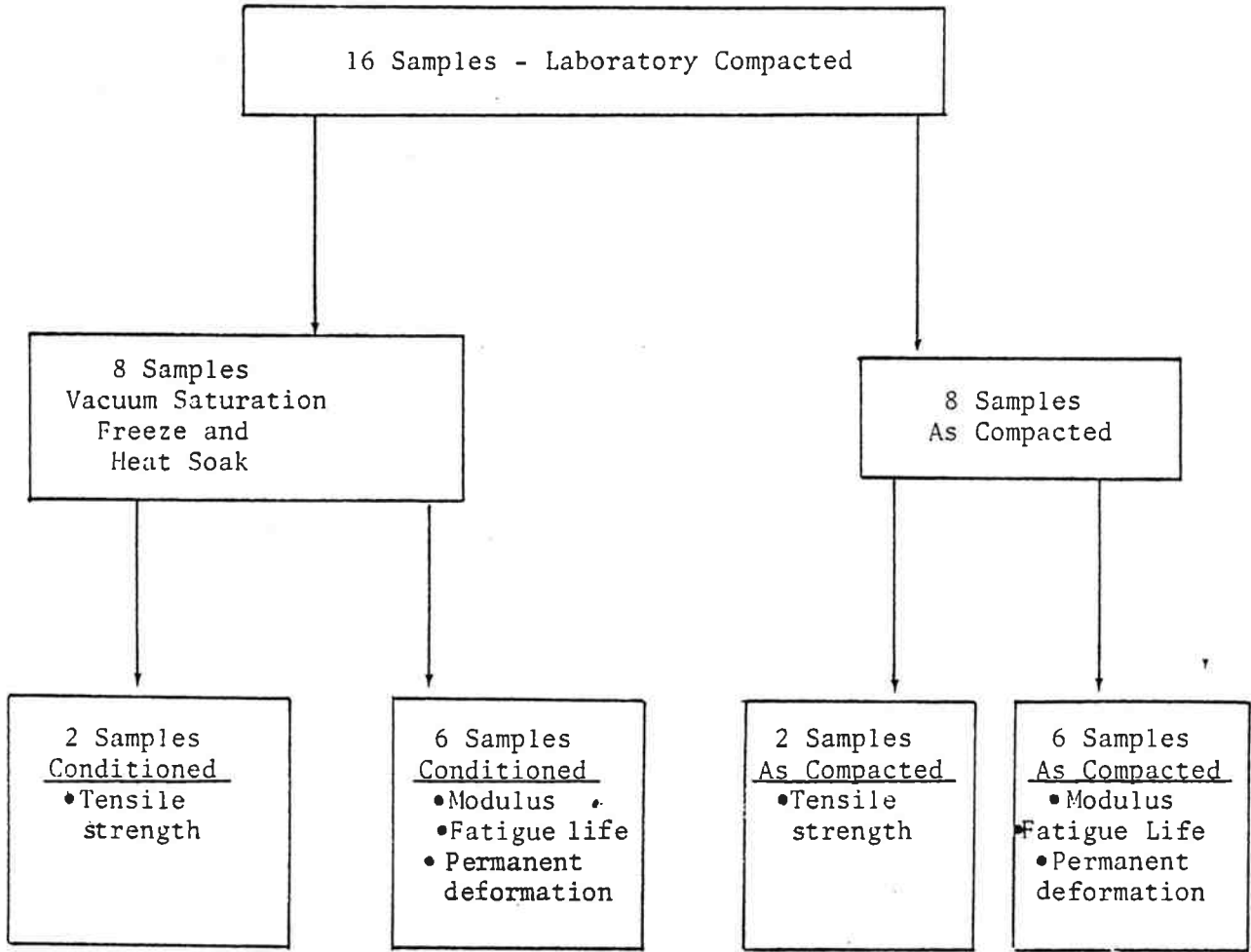


Table 10. Range of Mix Variables Considered in This Study
 (Crossed Boxes)
 North Oakland - Sutherland Project

Level of Compaction	2% Passing No. 200			6% Passing No. 200			10% Passing No. 200		
	Asphalt Content			Asphalt Content			Asphalt Content		
	5	6	7	5	6	7	5	6	7
2nd Compaction					X				
1st Compaction					X				
95 Blows at 100 psi 500 psi Leveling Load	X			X			X		
30 Blows at 100 psi 300 psi Leveling Load									X

Test Equipment

Figure 5 shows the testing equipment used to determine the resilient modulus, fatigue life and permanent deformation characteristics of the specimens. Testing conditions were kept constant, and are summarized as follows:

- (1) A static load of 10 lbs was applied to hold the sample in place.
- (2) The dynamic load duration was fixed at 0.1 seconds and the load frequency at 60 cycles per minute.
- (3) Test temperature was defined as the average sample temperature during testing (normally $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$).
- (4) Load platens are 1/2" (1.3 cm) wide.

Test Procedure and Calculations

All tests were run for mix tensile strain ranging between 50 and 150 microstrain. The parameters recorded during the dynamic diametral test are the maximum load applied, the sample horizontal elastic deformation and the sample vertical permanent deformation (Figure 6).

Dynamic diametral tests were run using the following procedure:

- (1) Place the sample in the dynamic diametral test apparatus.
- (2) Apply approximately 100 load applications until the permanent deformation recorded is negligible compared to the sample elastic response.
- (3) Adjust the dynamic load to achieve the desired initial mix tensile strain.
- (4) Maintain the control set at the load level required and start the fatigue life tests (also monitor permanent deformation).
- (5) Record the number of repetitions to failure.

The maximum load applied and the horizontal elastic tensile deformation were recorded to determine the modulus using the following equation (4):

$$M_R = \frac{P}{\Delta H \times h} \left[.2692 + .9974\nu \right] \quad (1)$$

where

M_R = Resilient modulus, psi

ΔH = Horizontal elastic tensile deformation, inches

P = Dynamic load, pounds

h = Sample thickness, inches

ν = Poisson's ratio

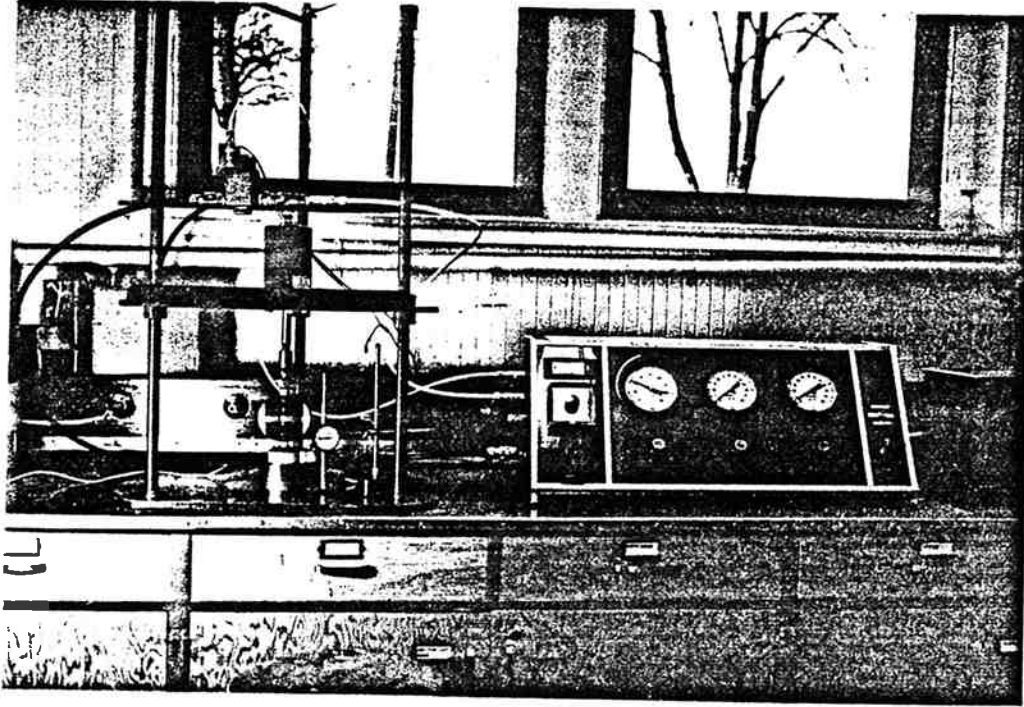


Figure 5. Diametral Test Apparatus

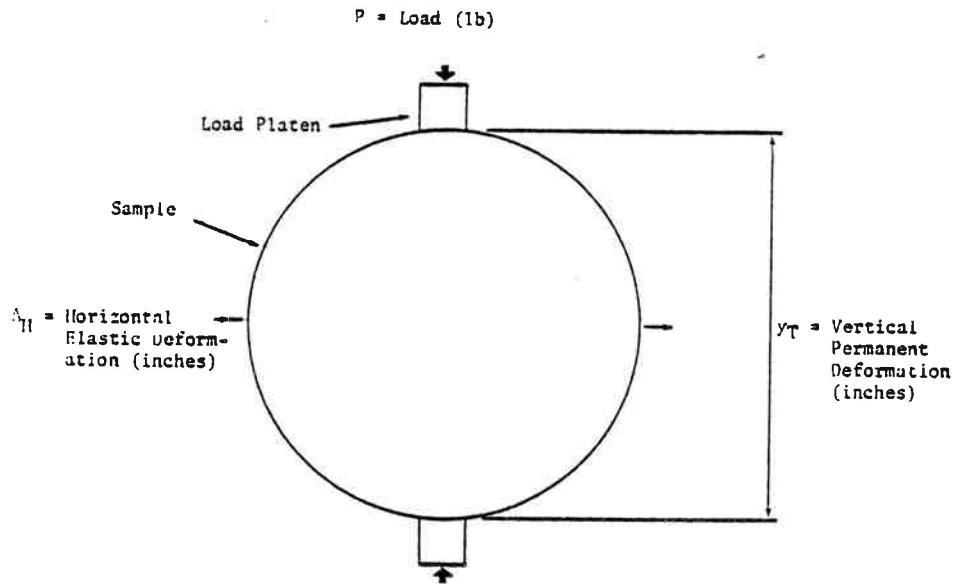


Figure 6. Diametral Test - Variables Recorded

Poisson's ratio was assumed constant and equal to .35, which simplifies equation (1) to:

$$M_R = \frac{P \times .6183}{\Delta H \times h} \quad (2)$$

Fatigue life is characterized by the number of load applications required to cause failure of the sample. Attempts to relate the number of load applications to the sample state of stress and strain showed that the best correlation exists between the tensile strain and the number of load applications, according to the following model (5,6,7,8):

$$N_f = K \left(\frac{1}{\epsilon_t} \right)^m \quad (3)$$

where:

N_f = Number of load repetitions to failure

K, m = Regression constants

ϵ_t = Horizontal elastic tensile strain

The fatigue life of a specific mix is therefore defined by the constants K and m . For each set of mix variables, six samples were tested at different values of the initial tensile strain. The number of load repetitions to failure was then measured and recorded. The constants K and m are determined using linear regression by the method of least squares. The tensile strain ϵ_t is calculated from the following equation (3):

$$\epsilon_t = \Delta H \left[\frac{.03896 + .1185\nu}{.0673 + .2494\nu} \right] \quad (4)$$

where

ϵ_t = Horizontal elastic tensile strain

ΔH = Horizontal elastic tensile deformation, inches

ν = Poisson's ratio

Assuming the Poisson's ratio is constant and equal to .35, equation (4) becomes:

$$\epsilon_t = \Delta H \times .5203 \quad (5)$$

The number of load repetitions to fatigue failure was defined as the number of repetitions required to get a vertical crack approximately 1/4" (.64 cm) wide in the samples. To stop the test at the specified level of

sample deformation, a thin aluminum strip was attached to the sides of the samples, along a plan perpendicular to the plane formed by the load platen (see Figure 7). The aluminum strip is connected to a normally closed relay, which controls the dynamic load system. As the sample deforms, the aluminum strip is stressed. When the sample deformation exceeds a certain level, the aluminum strip breaks and opens the relay, which shuts off the test. Proper calibration of the length of the aluminum strip will cause the test to stop for a specific sample crack width (Figure 8).

The vertical permanent strain is also recorded during the fatigue test as a function of the number of load repetitions. The permanent deformation strain is given by (3):

$$\epsilon_C = \mu_t \left[\frac{-.03896v - .1185}{.0156v - .8954} \right] \quad (6)$$

where

ϵ_C = Vertical permanent compressive strain

μ_t = Vertical permanent compressive deformation, inches

v = Poisson's ratio

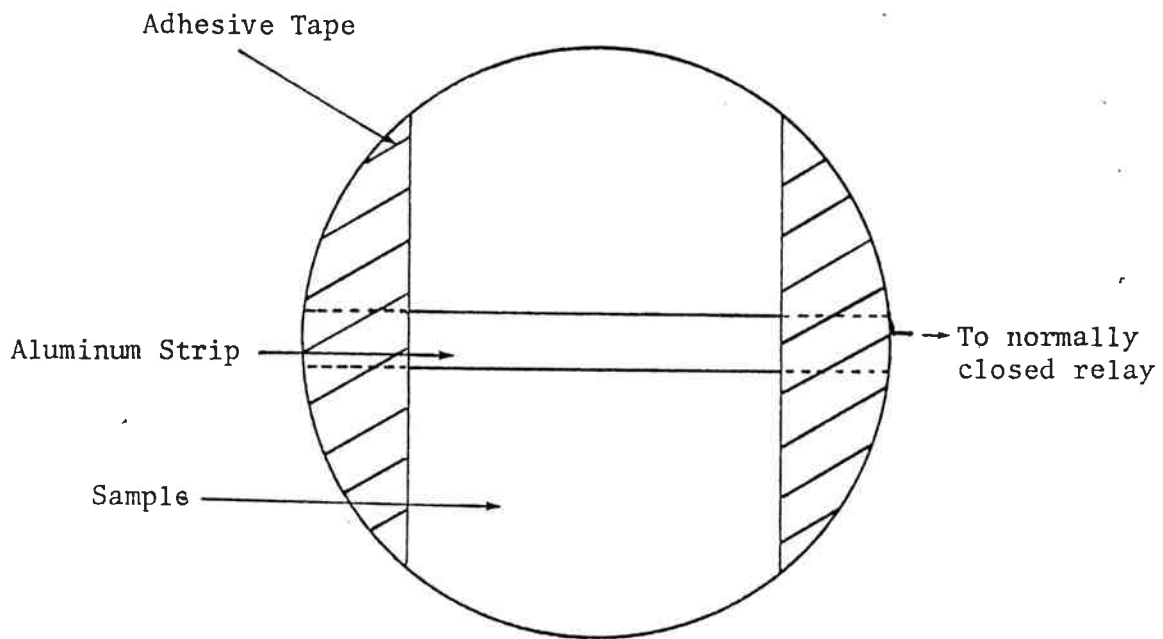
If the Poisson's ratio is assumed constant and equal to .35, equation (6) becomes:

$$\epsilon_C = \mu_t \times .1485 \quad (7)$$

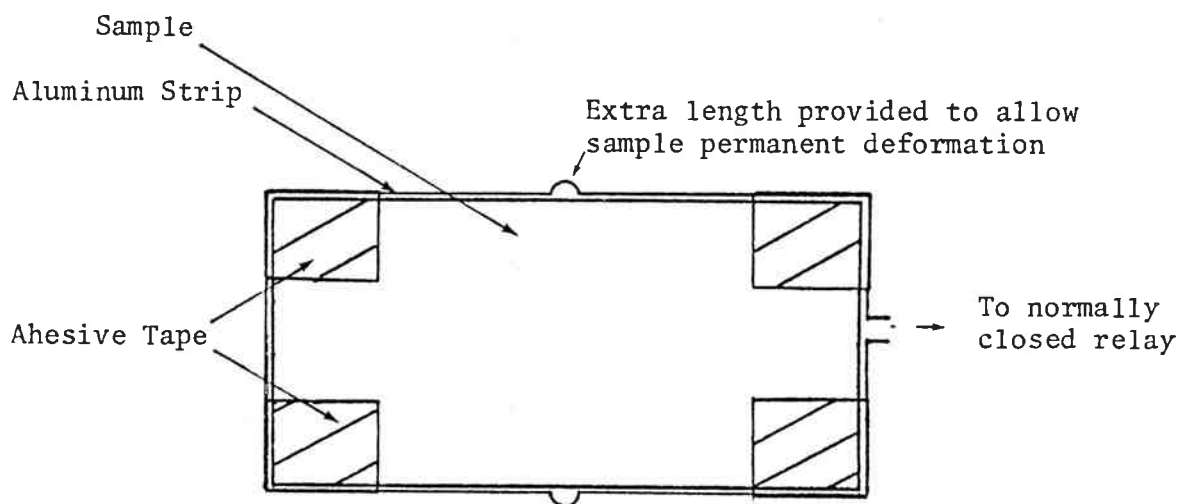
Resilient modulus, fatigue and permanent deformation models and tensile strength values have been determined for each set of variables considered in this study. The significance of these results and their correlation with other mix properties are developed later in this chapter.

Resilient Modulus Data

The resilient modulus of the as compacted samples are presented in Table 11, along with the mix Bulk Specific Gravity and percent voids. The influence of the Bulk Specific Gravity on the resilient modulus obviously predominates the other factors considered in this study. Plotted on Figure 9, the relationship between the as compacted mix resilient modulus and the Bulk Specific Gravity appears linear and affected by the asphalt and fines content only when both the asphalt and fines exceed the design optimum (example: 7% asphalt - 10% fines). Excess fines and asphalt results in a decrease in



(a) Side view



(b) Top view

Figure 7. Schematic View of the Automatic Shut-Off Device for Fatigue Testing

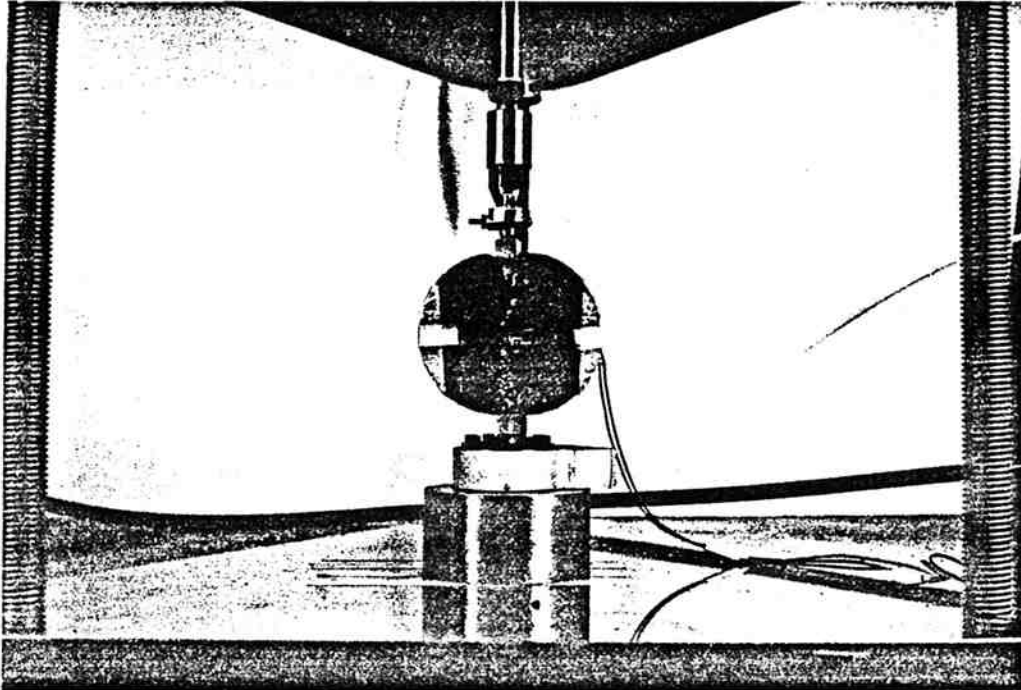


Figure 8. Sample at End of Fatigue Test

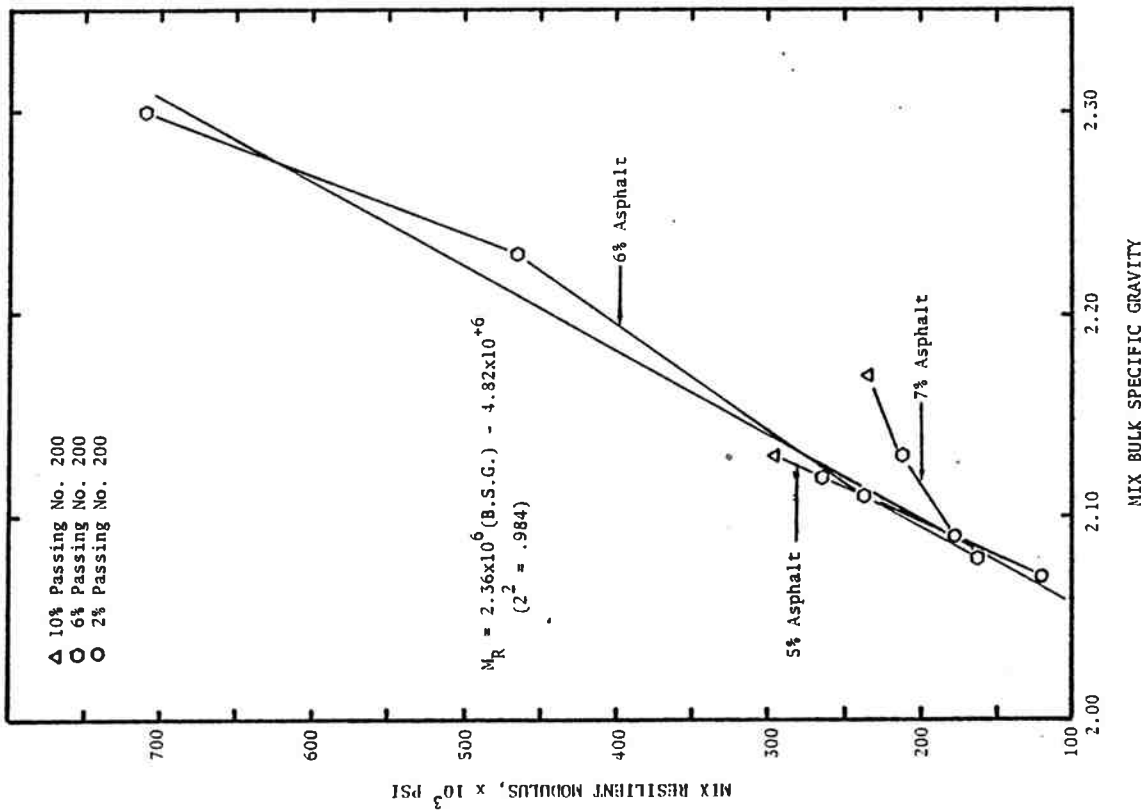


Figure 9. Influence of Bulk Specific Gravity on Resilient Modulus, As Compacted Samples.

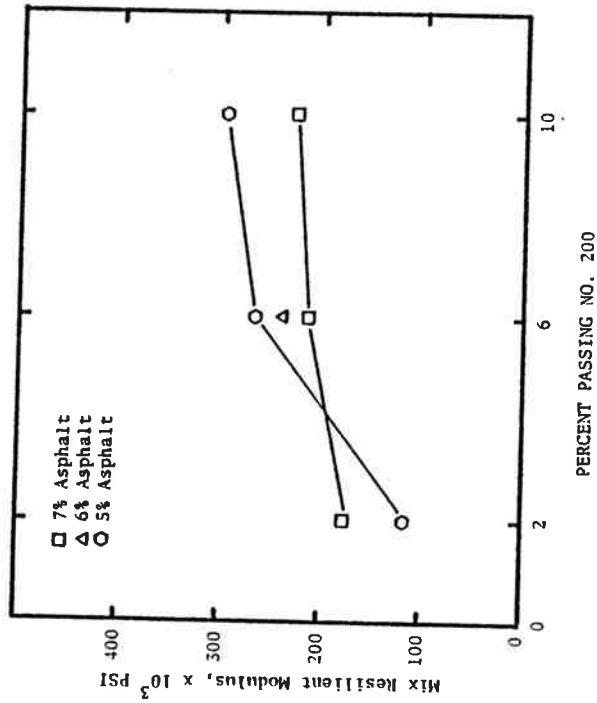


Figure 10. Influence of Amount of Fines on Resilient Modulus - As Compacted Samples.

the mix resilient modulus. Linear regression analysis of the relationship between resilient modulus and Bulk Specific Gravity gave a coefficient of correlation equal to .984, when the two points corresponding to the 7 percent asphalt, 6 and 10 percent fines samples are not included in the calculation. The influence of the amount of fines and asphalt content at a constant level of compaction is illustrated on Figure 10, which shows that mixes composed of 5% asphalt have higher modulus than mixes with 6 or 7% asphalt. However, decreasing the asphalt and fines content causes a substantial decrease in the mix stiffness. Similar trends can be observed with the conditioned samples. Moduli values of conditioned samples are presented in Table 11b together with their percentage of retained stiffness (compared with the mix modulus measured before sample conditioning). These data indicate wide variations in the percentage of retained stiffness, with no clear correlation with the amount of asphalt and fines or with the mix Bulk Specific Gravity. The relationship between conditioned modulus and the mix Bulk Specific Gravity (Figure 11) presents slightly more scatter than for the as-compacted modulus, but shows predominant effect of the Bulk Specific Gravity over the other factors, at least within the range of asphalt and amount of fines considered in this study. Linear regression analysis gave a coefficient of correlation equal to .885, all points being included. The samples prepared with 7 percent asphalt content have been slightly affected by the conditioning process, but the samples prepared with 5 percent asphalt content show a significant loss in stiffness after conditioning. Increasing the asphalt content therefore improves the mix resistance to water. A peak value of the mix modulus at 6 percent passing the No. 200 sieve for the 5 percent asphalt content mix seems to indicate that 6 percent fines is optimum when using 5 percent asphalt content. (see Fig. 12)

In summary, the mix modulus is primarily affected by the mix Bulk Specific Gravity. For a constant amount of passing the No. 200 and after conditioning, the mix modulus increases when the asphalt content increases. A peak modulus value appeared at 5 percent asphalt content for 6 percent passing the No. 200 sieve.

Fatigue Data

The fatigue life of asphalt mixes is a function of initial tensile strain and follows the equation:

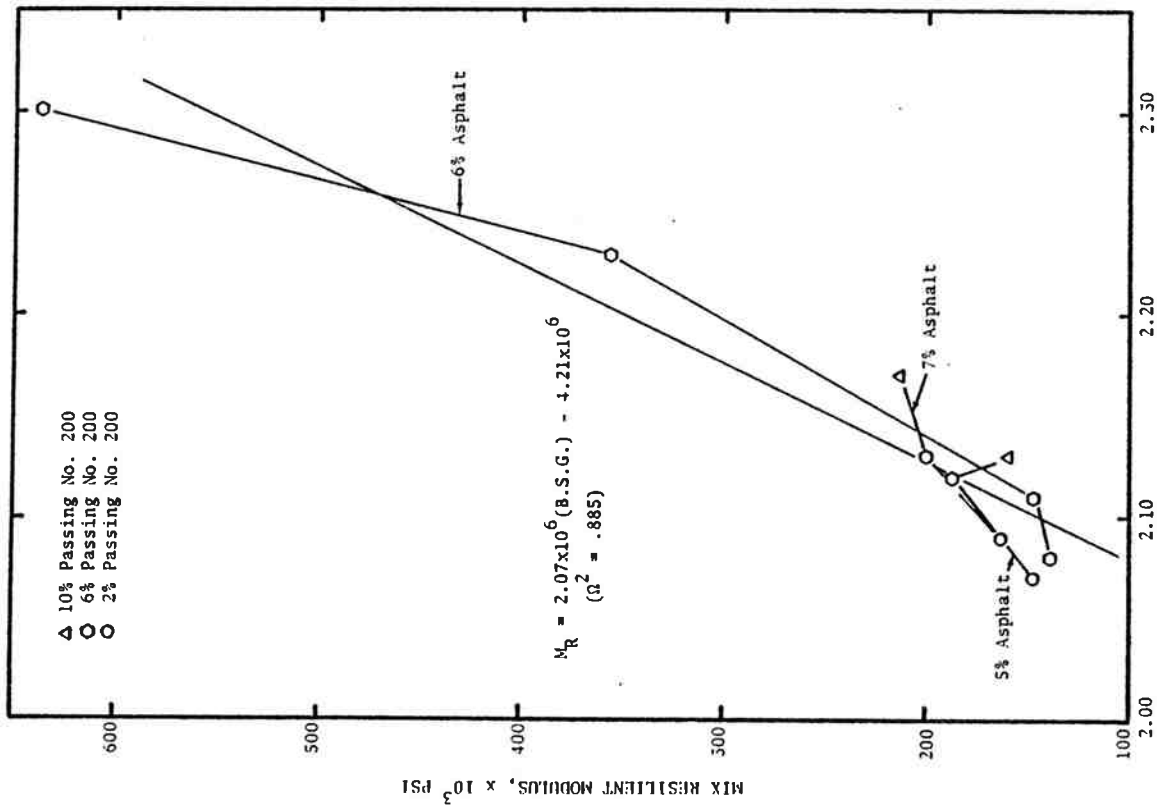


Figure 11. Influence of Bulk Specific Gravity on Resilient Modulus, Conditioned Samples.

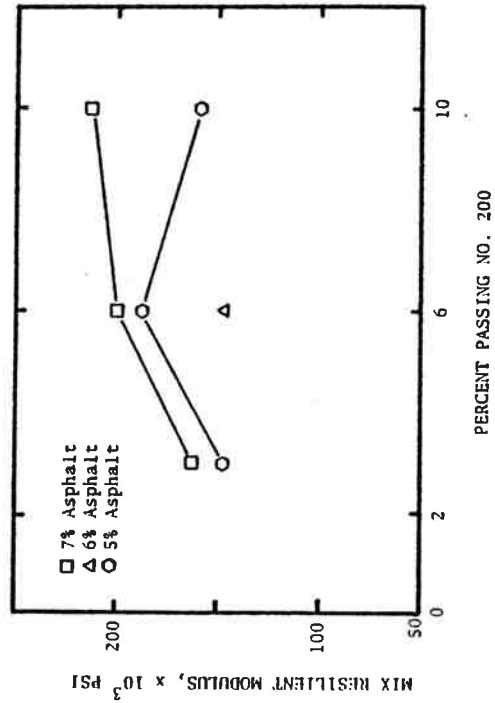


Figure 12. Influence of Amount of Fines on Resilient Modulus - Conditioned Samples.

Table 11a. Resilient Modulus Data, As Compacted Samples

- Resilient Modulus, psi
- Percent Voids
- Bulk Specific Gravity

LEVEL OF COMPACTION	2% PASSING No. 200			6% PASSING No. 200			10% PASSING No. 200		
	ASPHALT CONTENT			ASPHALT CONTENT			ASPHALT CONTENT		
	5	6	7	5	6	7	5	6	7
100%					710,000 5.3 2.30				
97%					466,000 8.2 2.23				
92%	117,000 15.9 2.07		176,000 11.8 2.09	265,000 14.2 2.12	238,000 13.2 2.11	212,000 10.9 2.13	297,000 13.4 2.13		227,000 8.8 2.17
90%					163,000 14.4 2.08				

Table 11b. Resilient Modulus Data, Conditioned Samples

- Resilient Modulus
- % Retained Stiffness $\left(\frac{\text{Conditioned Modulus}}{\text{As Compacted Modulus}} \times 100 \right)$

LEVEL OF COMPACTION	2% PASSING No. 200			6% PASSING No. 200			10% PASSING No. 200		
	ASPHALT CONTENT			ASPHALT CONTENT			ASPHALT CONTENT		
	5	6	7	5	6	7	5	6	7
100%					638,000 89.9%				
97%					357,000 76.6%				
92%	148,000 126%		163,000 92.6%	188,000 70.9%	147,000 61.8%	200,000 94.3%	159,000 53.5%		213,000 93.8%
90%					139,000 85.9%				

$$N_f = K(\epsilon_t)^m \quad (8)$$

where

N_f = Number of load repetitions to failure

ϵ_t = Initial tensile strain

K, m = Regression constants

Both K and m are affected by the mix variables. For each set of mix conditions, six samples were tested at the following initial tensile strains: 50, 65, 85, 100, 125 and 150 microstrain. The coefficients K and m were then determined by linear regression analysis. Table 12a shows the as-compacted K and m values found for different percentages of asphalt, amount of fines and level of compaction.

From this data, the relationship between $-m$ and $\log K$ was plotted in Figure 13. The relationship m versus $\ln K$ follows the equation:

$$m = A_1 \ln(K) + A_0 \quad (9)$$

Linear regression run on the as-compacted data gave:

$$A_1 = .124$$

$$A_0 = -.875$$

$$\text{Coefficient of correlation: } r^2 = .982$$

It can be deduced from this relationship between m and $\ln(K)$ that fatigue curves, expressed in Number of Load Repetitions versus Mix Tensile strain, should intercept at a common point, called focus point (11, 12, 13). The coordinates of this focus point (ϵ_0, N_0) can be deduced from equation (8) and (9):

$$m = A_0 + A_1 \ln(K) \quad (10)$$

$$N_F = K(\epsilon)^m \Leftrightarrow \ln(N_F) = \ln(K) + m \ln(\epsilon) \quad (11)$$

(11) is also true at the focus point

$$\begin{aligned} \ln(N_0) &= \ln(K) + m \ln(\epsilon_0) \\ \Rightarrow m &= \frac{\ln(N_0)}{\ln(\epsilon_0)} - \frac{1}{\ln(\epsilon_0)} \times \ln(K) \end{aligned} \quad (12)$$

Comparison between equation (10) and equation (12) gives:

$$A_0 = \frac{\ln(N_0)}{\ln(\epsilon_0)} \quad \text{and} \quad A_1 = \frac{-1}{\ln(\epsilon_0)}$$

Coordinates of the as-compacted samples focus point gave:

$$\epsilon_0 = 316 \times 10^{-6}$$

$$N_0 = 1.15 \times 10^3$$

Knowing the coordinates of the focus point, linear regression analysis were rerun for each set of samples, and fitted through the focus point. Table 13a gives the new K and m values (noted k' and m').

The same approach was followed for the conditioned test results. Table 12b gives the K and m values computed from the test results. The relationship found between K and m is:

$$m = .116 \ln(K) - 1.01 \quad (13)$$

The coordinates of the focus point for the conditioned samples are $\epsilon_0 = 184 \times 10^{-6}$ microstrain and $N_0 = 5.97 \times 10^3$ load repetitions. The corrected K' and m' for the conditioned samples are given in Table 13b.

The effect of asphalt content, passing No. 200 and level of compaction on fatigue life can be estimated directly by plotting for each set of conditions, mix tensile strain versus the number of repetitions to failure. The fatigue curves for 6% asphalt content and 6% passing the No. 200 sieve are presented in Figure 14a for the as-compacted samples and Figure 14b for the conditioned samples. As-compacted and conditioned results show a substantial decrease in fatigue life when the mix density drops from 97% to 92%. The influence of asphalt content is illustrated in Figure 15. The optimum asphalt content (6%) is noticeable with the conditioned samples. The as-compacted samples show a continuous increase in fatigue life when the asphalt content is increased.

The influence of the percent passing No. 200 on the mix fatigue life was studied at 5 percent asphalt content (Figure 16) and 7 percent asphalt content (Figure 17). At both asphalt contents the mix fatigue life decreases when the amount of fines is reduced to 2 percent. The optimum amount of fines is more apparent when using 5 percent asphalt in the mix, Figure 16a and 16b showing a longer fatigue life for the mix with 6 percent passing the No. 200 sieve.

The mix fatigue life is, therefore, primarily affected by the mix density. Optimum asphalt content (6%) and optimum percent passing No. 200 (6%) are both apparent in the test results of the conditioned samples.

Table 12a. Fatigue Data, As Compacted Samples

$$(N_F = k(\epsilon_T)^m)^*$$

LEVEL OF COMPACTION	2% PASSING No. 200			6% PASSING No. 200			10% PASSING No. 200		
	ASPHALT CONTENT			ASPHALT CONTENT			ASPHALT CONTENT		
	5	6	7	5	6	7	5	6	7
100%					$k=1.15 \times 10^{-7}$ $m=-2.95$ $\log k=-6.94$				
97%					$k=1.76 \times 10^{-8}$ $m=-3.10$ $\log k=-7.75$				
92%	$k=2.13 \times 10^{-2}$ $m=-1.30$ $\log k=-1.67$		$k=6.28 \times 10^{-6}$ $m=-2.34$ $\log k=-5.48$	$k=7.98 \times 10^{-4}$ $m=-1.77$ $\log k=-3.10$	$k=4.99 \times 10^{-4}$ $m=-1.83$ $\log k=-3.30$	$k=1.95 \times 10^{-4}$ $m=-2.03$ $\log k=-3.71$	$k=3.65 \times 10^{-7}$ $m=-2.58$ $\log k=-6.44$		$k=3.75 \times 10^{-5}$ $m=-2.21$ $\log k=-4.43$
90%					$k=3.28 \times 10^{-5}$ $m=-2.08$ $\log k=-4.48$				

* N_F : Number of Load Repetitions to Failure

ϵ_T : Mix Elastic Tensile Strain

k,m: Regression Constants

Table 12b. Fatigue Data, Conditioned Samples

$$(N_F = k(\epsilon_T)^m)^*$$

LEVEL OF COMPACTION	2% PASSING No. 200			6% PASSING No. 200			10% PASSING No. 200		
	ASPHALT CONTENT			ASPHALT CONTENT			ASPHALT CONTENT		
	5	6	7	5	6	7	5	6	7
100%					$k=6.67 \times 10^{-10}$ $m=-3.51$				
97%					$k=8.92 \times 10^{-5}$ $m=-2.22$				
92%	$k=1.28 \times 10^{-1}$ $m=-1.21$		$k=7.52$ $m=-.821$	$k=4.36 \times 10^{-6}$ $m=-2.38$	$k=1.86 \times 10^{-2}$ $m=-1.46$	$k=3.00 \times 10^{-4}$ $m=-1.95$	$k=1.43 \times 10^{-3}$ $m=-1.76$		$k=4.99 \times 10^{-7}$ $m=-2.67$
90%					$k=2.88 \times 10^{-5}$ $m=-2.18$				

* N_F : Number of Load Repetitions to Failure

ϵ_T : Mix Elastic Tensile Strain

k,m: Regression Constants

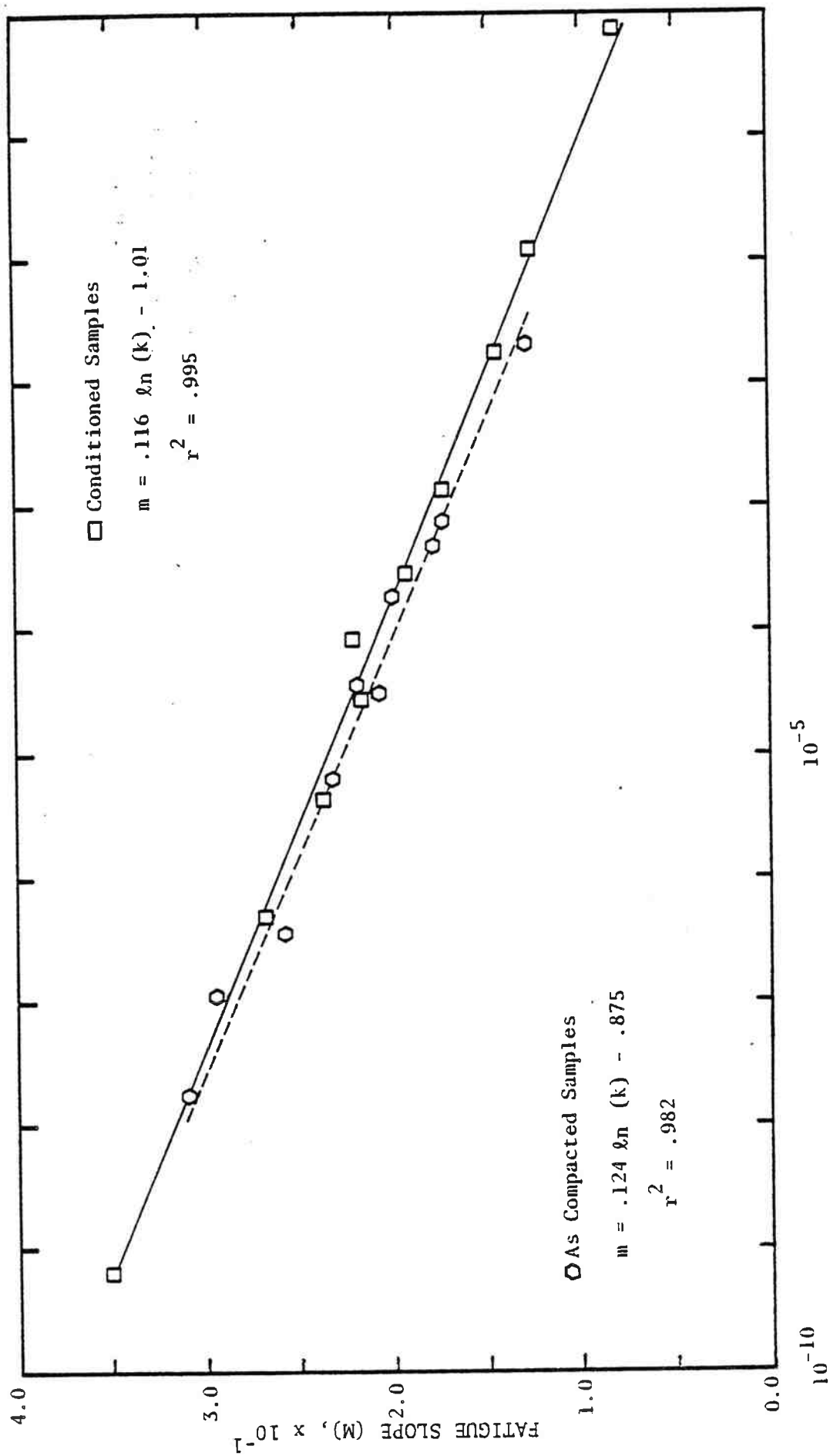


Figure 13. Relationship Between k and m.

Table 13a. Corrected Fatigue Data, As Compacted Samples

$$(N_f = k'(\epsilon_T)^{m'})^*$$

LEVEL OF COMPACTION	2% PASSING No. 200			6% PASSING No. 200			10% PASSING No. 200		
	ASPHALT CONTENT			ASPHALT CONTENT			ASPHALT CONTENT		
	5	6	7	5	6	7	5	6	7
100%					$k'=1.06 \times 10^{-9}$ $m'=-3.44$				
97%					$k'=8.59 \times 10^{-9}$ $m'=-3.18$				
92%	$k'=4.77 \times 10^{-1}$ $m'=-.966$		$k'=2.61 \times 10^{-5}$ $m'=-2.18$	$k'=3.98 \times 10^{-4}$ $m'=-1.85$	$k'=1.98 \times 10^{-4}$ $m'=-1.93$	$k'=1.79 \times 10^{-6}$ $m'=-2.52$	$k'=5.24 \times 10^{-4}$ $m'=-1.81$		$k'=6.00 \times 10^{-7}$ $m'=-2.65$
90%					$k'=2.04 \times 10^{-3}$ $m'=-1.64$				

* N_f : Number of Load Repetitions to Failure

ϵ_T : Mix Elastic Tensile Strain

k', m' : Regression Constants, with $m' = .124 I_n(k') = .875$

Table 13b. Corrected Fatigue Data, Conditioned Samples

$$(N_f = k'(\epsilon_T)^{m'})^*$$

LEVEL OF COMPACTION	2% PASSING No. 200			6% PASSING No. 200			10% PASSING No. 200		
	ASPHALT CONTENT			ASPHALT CONTENT			ASPHALT CONTENT		
	5	6	7	5	6	7	5	6	7
100%					$k'=9.72 \times 10^{-12}$ $m'=-3.96$				
97%					$k'=3.94 \times 10^{-10}$ $m'=-3.53$				
92%	$k'=8.57$ $m'=-.761$		$k'=1.73 \times 10^{-1}$ $m'=-1.22$	$k'=1.58 \times 10^{-3}$ $m'=-1.76$	$k'=5.38 \times 10^{-5}$ $m'=-2.15$	$k'=6.37 \times 10^{-4}$ $m'=-1.87$	$k'=3.89 \times 10^{-3}$ $m'=-1.66$		$k'=6.46 \times 10^{-6}$ $m'=-2.40$
90%					$k'=3.47 \times 10^{-3}$ $m'=-1.67$				

* N_f : Number of Load Repetitions to Failure

ϵ_T : Mix Elastic Tensile Strain

k', m' : Regression Constants, with $m' = .116 I_n(k') = 1.01$

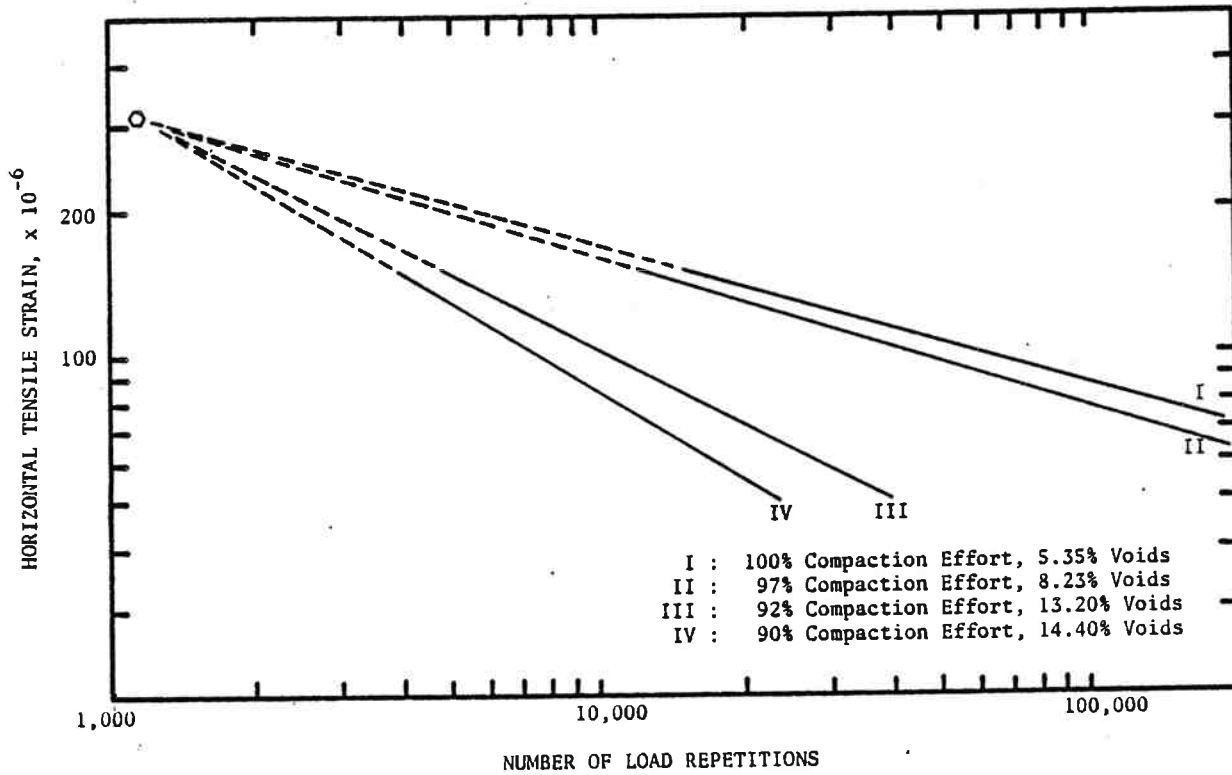


Figure 14a. Influence of Mix Density on Fatigue Life, As Compacted Samples.
6% Passing No. 200 - 25% Passing No. 10 - 6% Asphalt

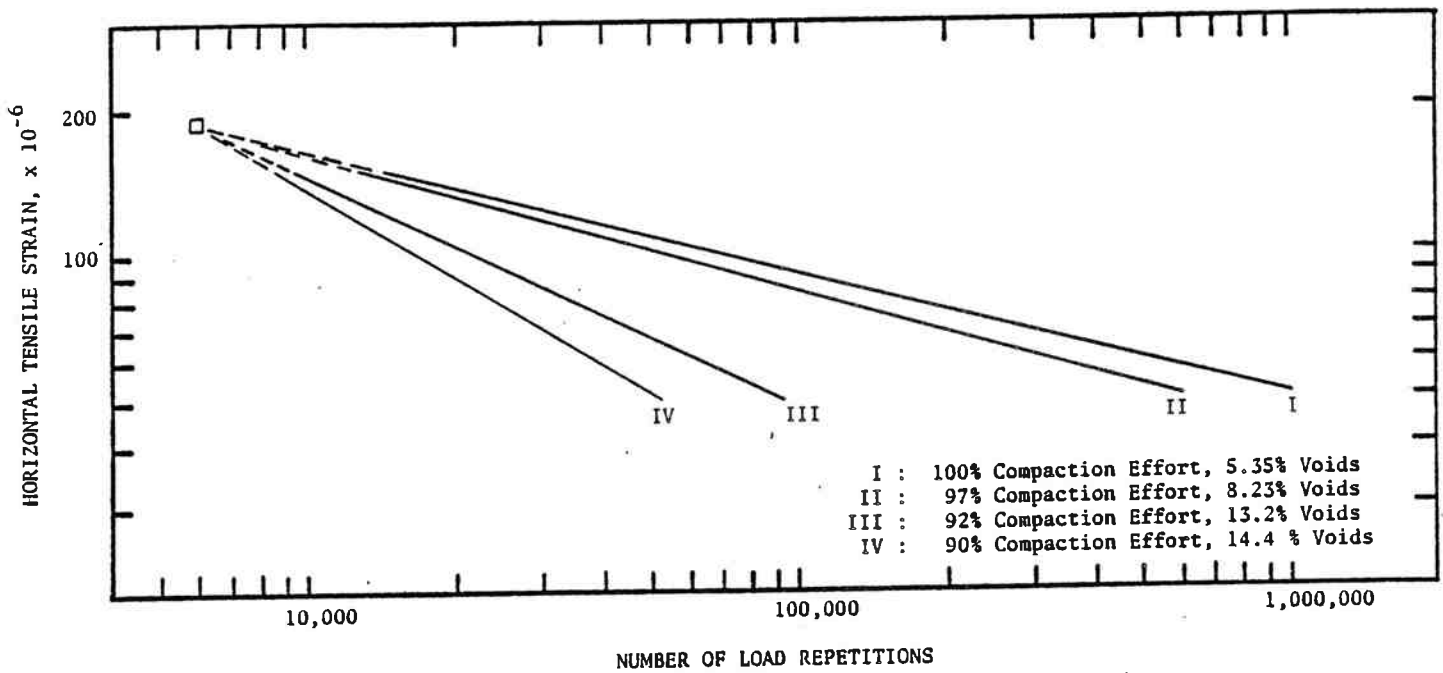


Figure 14b. Influence of Mix Density on Fatigue Life, Conditioned Samples.
6% Passing No. 200 - 25% Passing No. 10 - 6% Asphalt

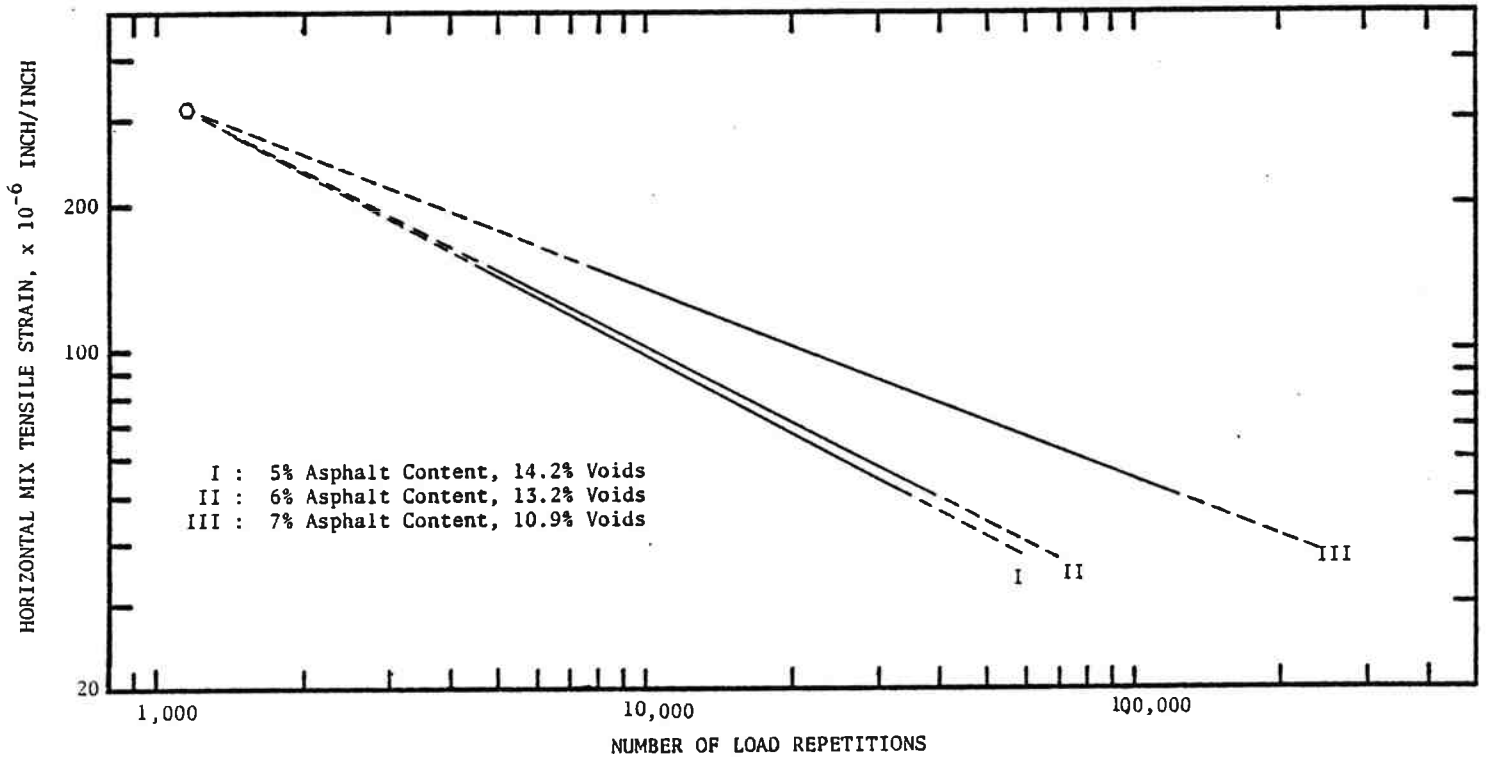


Figure 15a. Influence of Asphalt Content on Fatigue Life, As Compacted Samples
6% Passing No. 200 - 25% Passing No. 10 - 92% Compaction

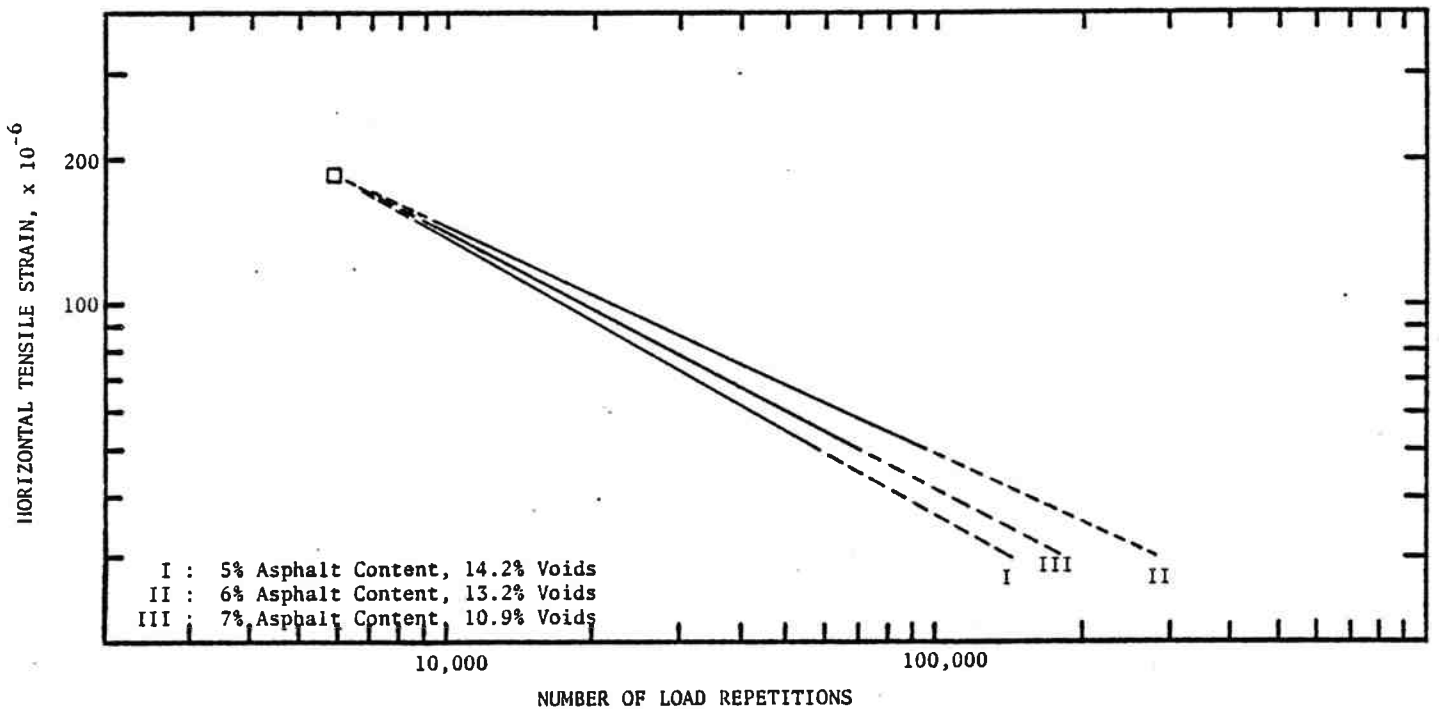


Figure 15b. Influence of Asphalt Content on Fatigue Life, Conditioned Samples
6% Passing No. 200 - 25% Passing No. 10 - 92% Compaction

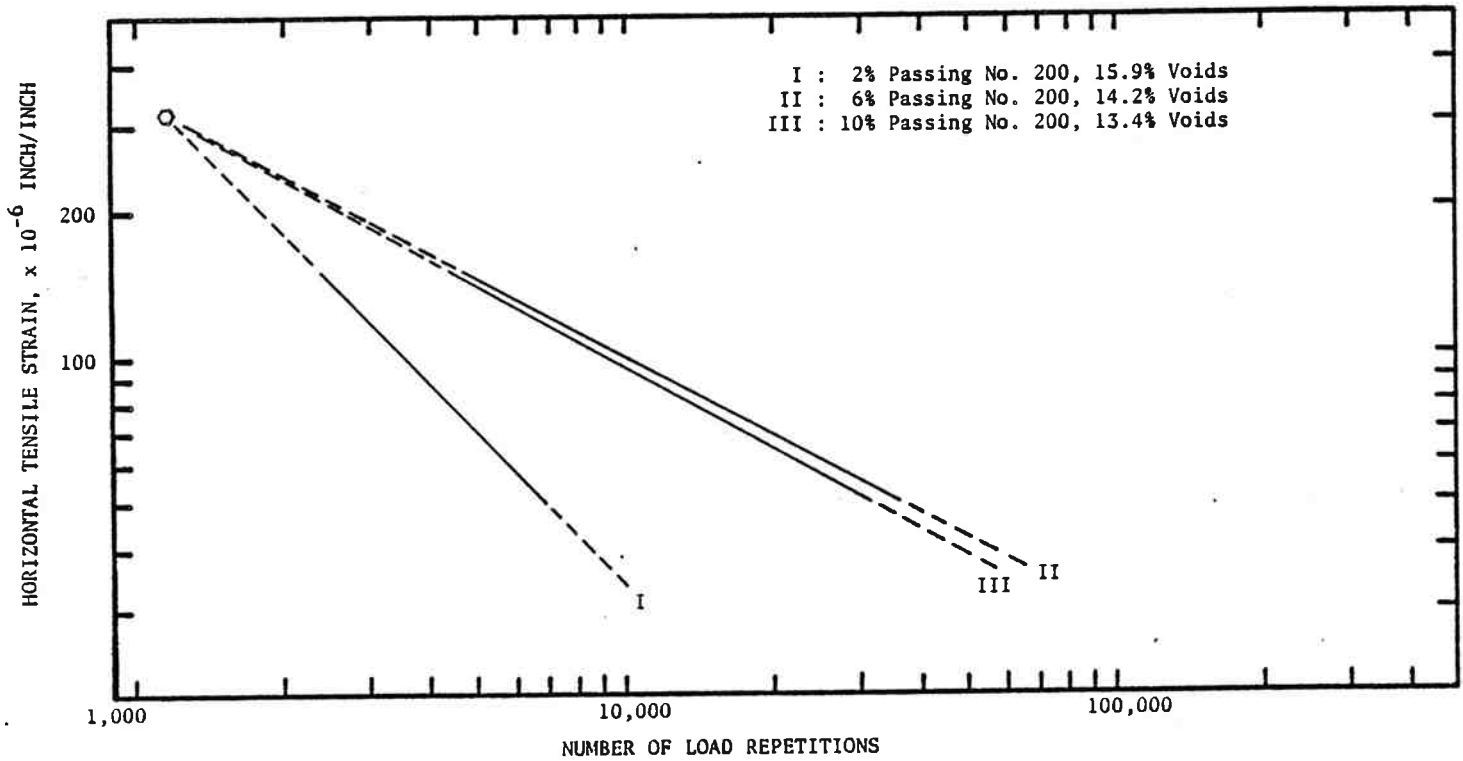


Figure 16a. Influence of Passing No. 200 on Fatigue Life, As Compacted Samples
5% Asphalt Content - 92% Compaction

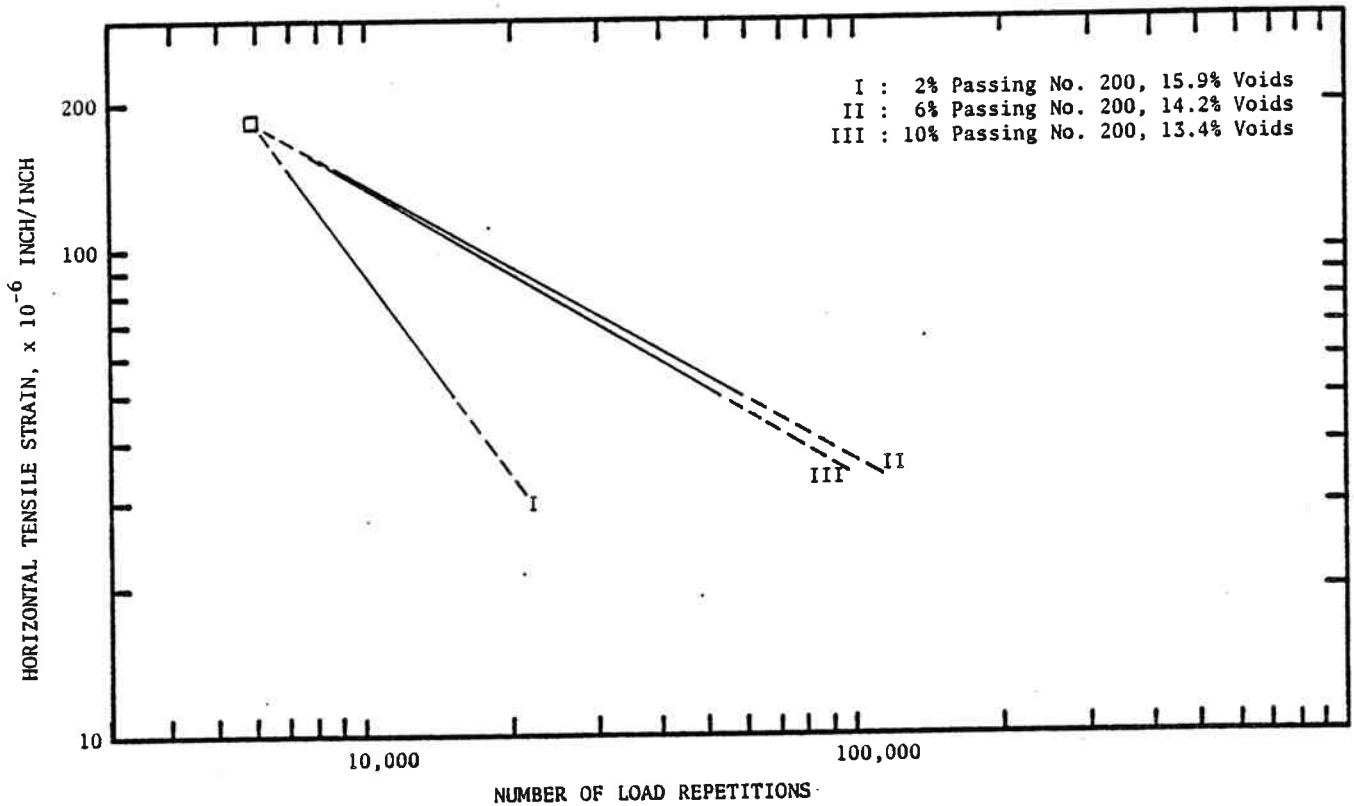


Figure 16b. Influence of Passing No. 200 on Fatigue Life, Conditioned Samples.
5% Asphalt - 92% Compaction