EFFECT OF MOISTURE ON ASPHALT PAVEMENT LIFE

Interim Report

HP & R Study: 083:5157

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16. Abstract

Considerable research has been carried out on the effect of water on asphalt mixtures, and test methods to investigate the effect of water have been developed. However, most of this work has been related to stripping and the effect of additives, where external water enters or affects the pavement following construction. There is little published research directly concerned with the problems of mixing moisture in hot mixed asphalt concrete and long-term durability related to mixing moisture.

This report presents the results of a study to investigate the effects of mixing moisture on mechanical properties of asphalt mixtures. The potential benefits of lime and Pavebond Special were also investigated. The repeated load diametral test device was used to measure the resilient modulus, fatigue, and permanent deformation characteristics of laboratory specimens prepared with and without moisture (0, 1, and 3%) and with and without lime (0, 1%) and Pavebond Special (0, 0.5%). Mixtures were prepared which were representative of two projects for which considerable field data were available. One project utilized marginal aggregate and the other good quality aggregate. To evaluate the long-term durability of mixtures, they were tested before and after conditioning using the Lottman approach.

The test results showed that inferior performance occurred for mixtures with 3% moisture, but was most pronounced in mixtures with high void contents. However, the mixtures with marginal aggregate showed improved performance at 1% moisture content, associated with their lower void contents, which may be due to absorbed moisture preventing asphalt absorption and the higher asphalt content of these mixtures. The addition of lime resulted in distinct improvement of performance for moist samples from the project which had good quality aggregate, but high air void contents. However, neither additive showed substantial benefit for moist mixtures from the project with marginal aggregate and low air void contents.

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THE EFFECT OF MOISTURE ON THE PERFORMANCE OF ASPHALT MIXTURES

1.0 INTRODUCTION

1.1 Problem Statement

Considerable research has been done on the effect of water on asphalt mixtures, and test methods to investigate the effect of water have been developed. However, most of this work has been related to stripping and the effect of additives (1,2,3,4,5), where external water enters or affects the pavement following construction. There is little published research directly concerned with the problems of mixing moisture in hot mixed asphalt concrete and long-term durability related to mixing moisture.

The increased presence of mixing moisture in asphaltic concrete mixtures due to the changes of materials and equipment is well known and has been the subject of considerable discussion recently (43,44). In the conference held during the Highway Research Board Annual Meeting in January 1974, there were many questions and considerable discussion about the residual moisture (6). Among them:

- Are the moisture controls set at too low a level?
- Is percent moisture a good measure of moisture effect?
- Is the basic problem moisture or workability?
- In the present situation, can we continue to say the drier the better?
- If not, how high can we go and what should we control?

In order to obtain the answers concerned with the problems of mixing moisture, to limit the moisture content of fresh mixtures, and to select adequate additives based on rational research findings, the study of the effect of moisture and additives on the mechanical properties of asphalt mixtures is necessary. For this study two mixtures were prepared which were representative of two projects of about five years of age, for which considerable field data were available.

1.2 Purpose

The purpose of this study is to obtain a better understanding of the causes of the pavement problems associated with moisture, to develop relationships between pavement performance and the mixing moisture contents, considering possible use of additives, and to develop mix design procedures which consider the moisture content and aggregate quality of asphalt mixtures. Such information will be useful in providing for limiting the moisture content of fresh mixtures and for selection of additives that may reduce the subsequent damage to mixtures containing moisture as a result of mixing with damp aggregates.

The specific objectives of this study are:

1) To evaluate the effect of moisture on mechanical properties of asphalt mixtures, such as resilient modulus, fatigue life, and permanent deformation.
2) To evaluate the effect of additives for reducing the damage from moisture.
3) To provide guidelines to minimize the effects of moisture on pavement performance.

1.3 Research Approach

The research includes tests on laboratory-prepared specimens from two projects, North Oakland-Sutherlin and Warren-Scappoose. Following the standard Oregon Department of Transportation (ODOT) procedure (7), specimens 4 inches (10 cm) in diameter by 2.5 inches (6.5 cm) high were fabricated. All specimens were tested in the diametral mode (30) for resilient modulus, fatigue life, and permanent deformation to evaluate the effects of moisture and additives and to obtain the characteristics of the mixtures. Both as-compacted and conditioned specimens were tested because the Lottman conditioning procedure used (8) is a very good indicator of long-term durability.

A general literature review concerned with the effect of moisture on workability, the effect of asphalt cement, aggregate and additives, and test methods to investigate the moisture effect is presented in Chapter 2. The projects evaluated, mix variables considered, test program, and specimen preparation are described in Chapter 3. In Chapter 4, the test results for mix design, cores, and mechanical properties of asphalt mixtures are presented. The effect of moisture and additives on the performance of asphalt mixtures is discussed in Chapter 5. Chapter 6 presents conclusions and recommendations derived from this study. Finally, Appendices present summary data for original mix designs and core properties.

2.0 LITERATURE REVIEW

2.1 Introduction

This chapter presents the results of a search of literature related to the following aspects of the effects of moisture on asphalt mixtures:

1) Residual moisture,
2) Asphalt cement,
3) Aggregate,
4) Additives,
5) Test methods.

2.2 Effect of Residual Moisture

There are two important areas of asphalt mixture operations concerning mixing moisture: workability and durability (9). Workability is needed to achieve initial mixture properties during the paving operations that will affect the final product of the mix, such as achieving adequate mixing, finishing, and compaction. The initial voids and other physical properties are established at this level.

Sometimes aggregate mixes are incompletely dried in the plant, due in part to the changes of materials and equipment as shown in Table 2.1. When the aggregate is incompletely dried at the time it is mixed with asphalt, water in the pores of aggregate will continue to be vaporized until equilibrium is reached. Evolution of steam may continue although the temperature may have dropped substantially. As reviewed later in this chapter, asphalt absorption increases with decreasing asphalt viscosity and with contact time between the asphalt and the aggregate at elevated temperatures. As indicated by Schmidt et al. (10), however, moisture either as a liquid or steam occupy-

Table 2.1. Recent Changes in Asphalt Paving Technology Affecting Pavement Behavior (After Walter et al. (28,29)).

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 raveling Reduced resistance to damage from water and freeze-thaw effects
Aggregate	Reduced aggregate quality	Increased raveling 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 Flushing
	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

ing the aggregate pores might prevent asphalt absorption even though the viscosity of asphalt is low at elevated temperatures.

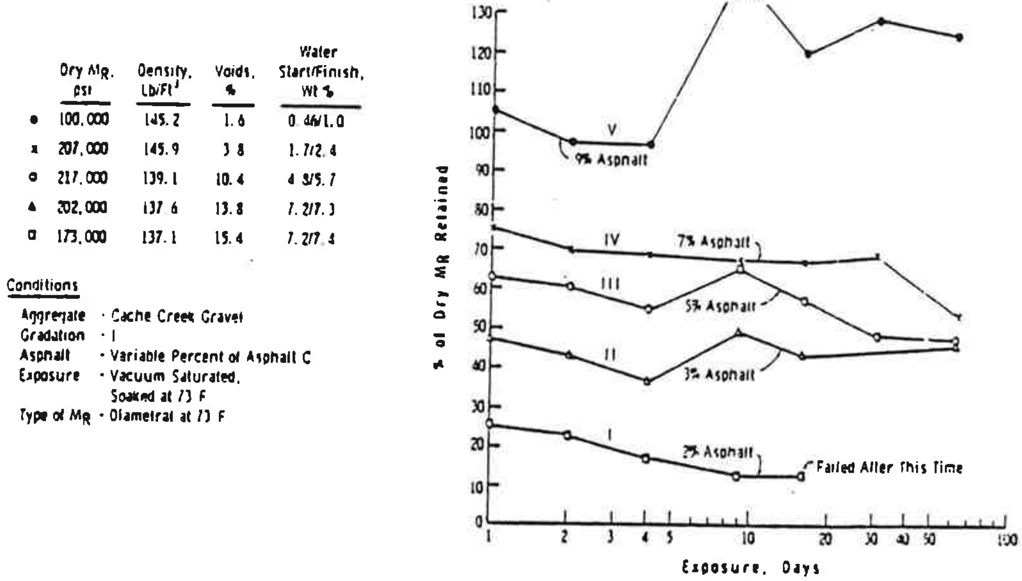
Schmidt (11) points out that moisture may lower the asphalt absorption, and in effect increase the volume of asphalt in the voids. The moisture occupying void space is expected to lubricate the mix, which in turn would affect the stability of the mix during compaction. Schmidt indicates that if such secondary volumes are too high, adequate compaction would suffer. In summary, adequate amounts of moisture in a mix may help compaction because of its greater lubricating ability. However, too much moisture in a mix can contribute to the overfilling of the voids and prevent good coating of the aggregate by asphalt cement, making the mix unstable.

The major detrimental effects of mixing moisture are: changes in the initial compaction, a reduced stability (and consequent effects on other mechanical properties) and possibly a problem of durability with freeze-thaw damage.

2.3 Effect of Asphalt Cement

2.3.1 Asphalt Content

Schmidt and Graf (12) show that increasing the asphalt content of asphalt-treated mixes reduces the effect of water on the resilient modulus. Plots of modulus (M_R) vs. exposure time are shown in Figures 2.1 and 2.2. For the dense-graded mix containing 5% asphalt, about 80% of the dry modulus is retained after 30 days of moisture exposure in a 73°F (22.8°C) water bath following vacuum saturation as shown in Figure 2.2. However, the mix containing 3% asphalt obtains only 50% of the dry modulus after the same period of exposure. This effect is mainly due to the thicker asphalt films that clog the aggregate-asphalt interface and to the reduction in air voids which decreases the penetration of water into the mixtures (19).

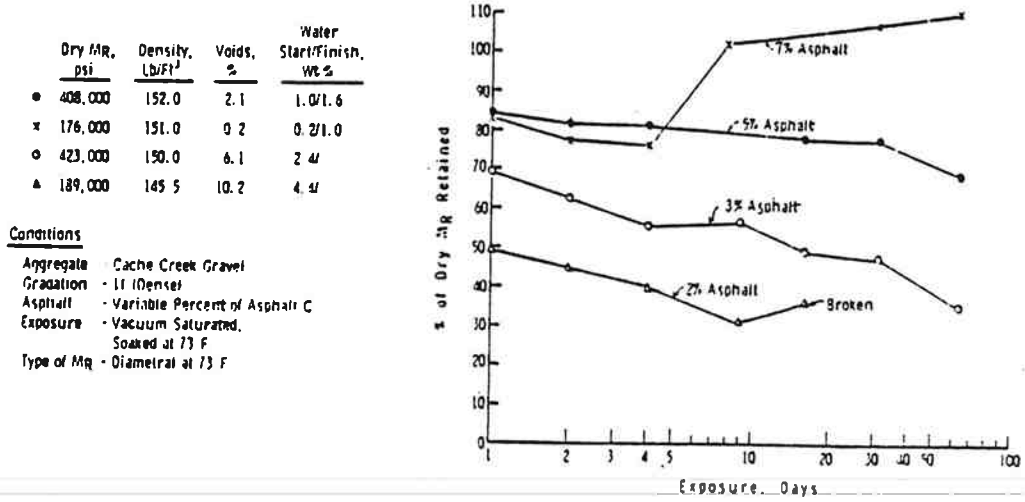


	Dry M_R, psi	Density, Lb/Ft^3	Voids, %	Water Start/Finish, Wt %
●	100,000	145.2	1.6	0.46/1.0
x	207,000	145.9	3.8	1.7/2.4
○	217,000	139.1	10.4	4.5/5.7
▲	202,000	137.6	13.8	7.2/7.3
□	173,000	137.1	15.4	7.2/7.4

Conditions

Aggregate - Cache Creek Gravel
Gradation - I
Asphalt - Variable Percent of Asphalt C
Exposure - Vacuum Saturated, Soaked at 73 F
Type of M_R - Diametral at 73 F

Figure 2.1 - Effect of Asphalt Content on the M_R Drop of High Void Mixes (after Schmidt and Graf (<u>12</u>))



	Dry M_R, psi	Density, Lb/Ft^3	Voids, %	Water Start/Finish, Wt %
●	408,000	152.0	2.1	1.0/1.6
x	176,000	151.0	0.2	0.2/1.0
○	423,000	150.0	6.1	2.4/
▲	189,000	145.5	10.2	4.4/

Conditions

Aggregate - Cache Creek Gravel
Gradation - II (Dense)
Asphalt - Variable Percent of Asphalt C
Exposure - Vacuum Saturated, Soaked at 73 F
Type of M_R - Diametral at 73 F

Figure 2.2 - Effect of Asphalt Content on the M_R Drop of Dense-Graded Mixes (after Schmidt and Graf (<u>12</u>))

2.3.2 Asphalt Consistency

In general, adhesion at the aggregate-bitumen interface is influenced by the viscosity of the binder (2). Higher viscosity can reduce the coatability and wetting of the asphalt in the coating phase. However, when good initial coating and wetting are achieved, the resistance to stripping is increased with the increasing viscosity of binder (14).

Heukelom and Klomp (13) show that the stiffness (resilient modulus, M_R) of asphalt concrete is proportional to the stiffness of the asphalt binder. The results of experiments performed by Schmidt and Graf (12) are consistent with this principle. Figure 2.3 shows that the harder the asphalt used, the higher the stiffness. The mixes used differ only by the grade of asphalt used.

2.4 Effect of Aggregate

2.4.1 Specifications

Specifications to restrict the retained moisture in aggregates in order to eliminate stripping are necessary to ensure durability of mixtures. Two types of specifications used are (1) limiting moisture content in aggregates and (2) eliminating the use of highly absorptive aggregates (9). According to Sonderegger (15), 48 state highway departments and the District of Columbia specifications were surveyed by R.R. Biege of the Kansas Highway Commission in relation to residual moisture requirements in asphaltic concrete aggregates at the time of mixing or immediately after mixing. A summary of the results of this survey is shown in Figure 2.4. Figure 2.4 shows that 40 out of 49 departments had some form of specified moisture control at the time of the survey. Of these 40, 22 have a numerical moisture limit in the form of a percentage, and the remaining 18 simply state that the aggregate shall be dry

	Density, Lb/Ft³	Voids, %	Water Start/Finish, Wt %
●	141.2	9.1	4.2/4.7
x	141.9	8.6	3.6/4.7
○	141.9	8.6	4.2/5.2
▲	143.0	7.9	3.1/2.5
□	142.9	8.0	4.0/4.9

Conditions

Aggregate	- Cache Creek Gravel
Gradation	- I
Asphalt	- 5% of Asphalts A, B, C, D, or E
Exposure	- Vacuum Saturated Soaked at 73 F
Type of M_R	- Diametral at 73 F

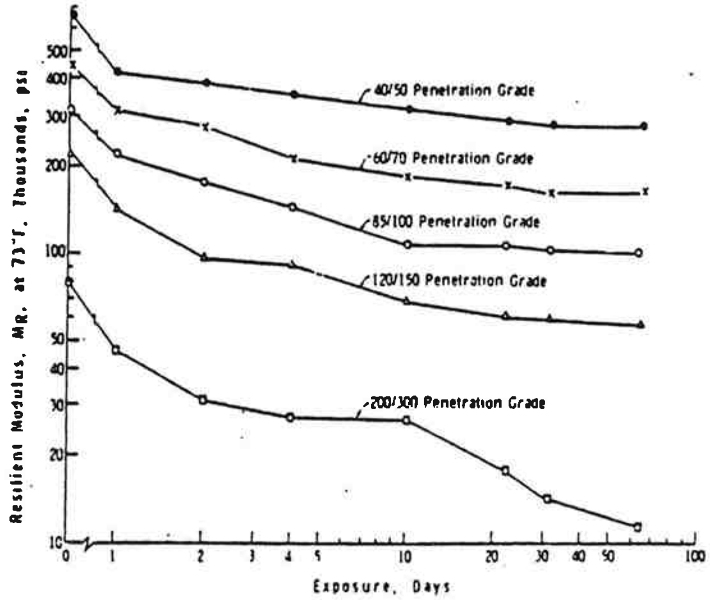


Figure 2.3 - Effect of Grade of Asphalt on the M_R Drop (after Schmidt and Graf (12))

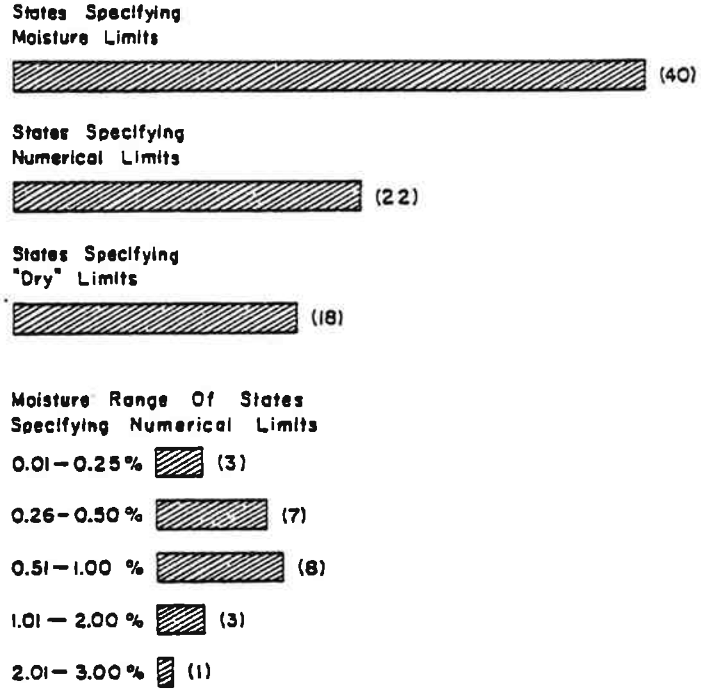


Figure 2.4 - States Specifying Residual Moisture Limits (after Sonderegger (15))

or free of moisture. Figure 2.4 also shows the distribution by ranges of the various specified moisture percentages. This varies from 0.05% to 3.0% under some conditions, with most of the limits being in the range of 0.26% to 1.0%. Currently, ODOT specifies that the moisture content of the mixture at the time of placement shall not exceed 0.7% (20), which is about the median of the values specified.

According to the survey performed by Moore et al. (16) in 1979, 21 agencies of 46 state agencies and the District of Columbia evaluate the mix moisture content as part of their specifications, confirming Biege's survey. Therefore, during the last 20 years, there appears to have been no significant change in moisture control specifications.

2.4.2 Gradation

Sonderegger (15) evaluates the effect of mixing moisture in relation to mix properties, such as slumping, cracking, and flushing of fines and asphalt, by linear measurements and visual comparisons. Sonderegger indicates that one of the prime factors causing sensitivity to residual moisture is the gradation of aggregate. From this research Sonderegger makes typical grading curves for sensitive and nonsensitive mixtures as shown in Figure 2.5 and indicates that the difference in residual moisture sensitivity between a skip grading and a smooth grading is the filter effect of the uniform gradation. For a smooth gradation, flushing of fines to the surface is retarded by the filtering effect of the intermediate-sized aggregate. If the mixture is skip graded, especially between the No.4 and No. 40 sizes, the steam pressure of mixing moisture tends to extrude the sand asphalt mortar to the surface between the larger aggregate particles causing slick spots and nonuniform surface texture.

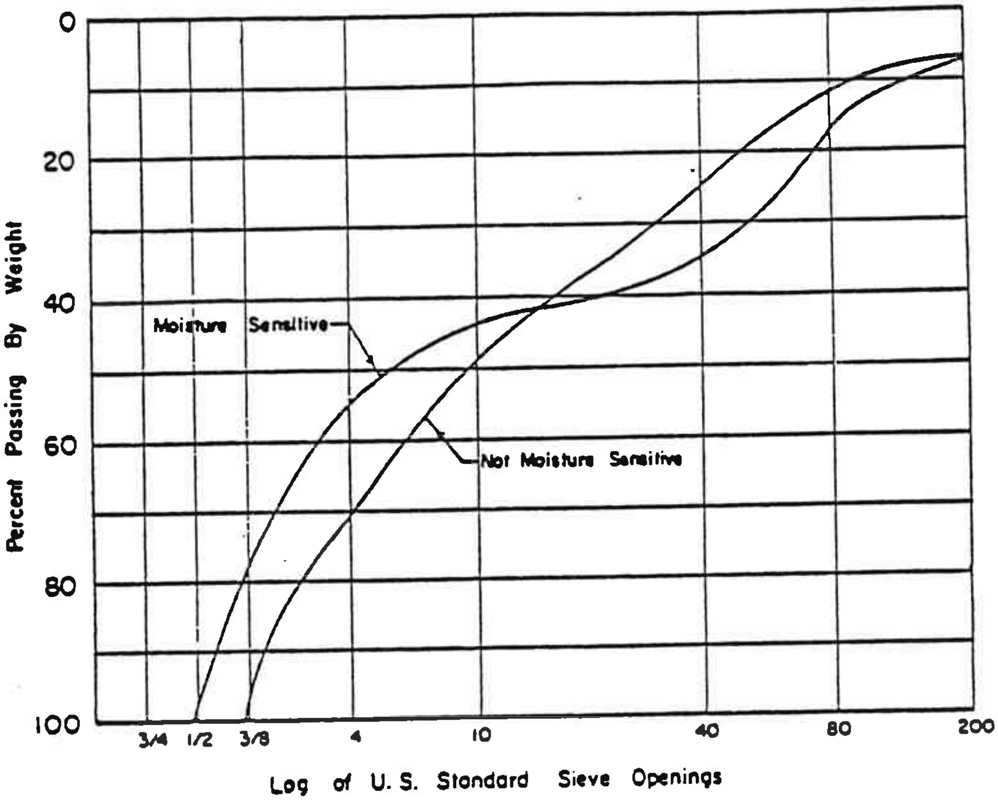


Figure 2.5 - Typical Moisture Sensitive and Nonsensitive Gradations (after Sonderegger (15))

2.4.3 Water and Asphalt Absorption of Aggregate

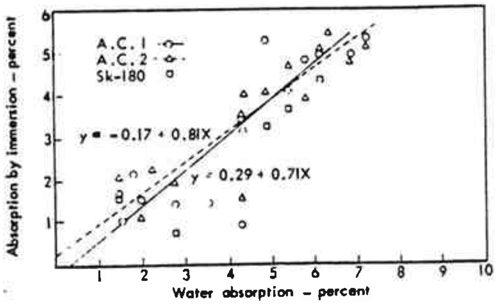
Since the penetration of a liquid into aggregate pores (absorption) is basically a capillary phenomenon, the degree of absorption is affected by not only the pore size but also the surface tension and contact angle of the liquid (18). Therefore, the differences of absorption for different liquids are to be expected. For asphalt cement, the asphalt absorption increases with contact time between the asphalt and the aggregate at elevated temperatures. Also, the asphalt absorption increases as the viscosity of asphalt decreases.

Even though the water absorption of an aggregate is not a 100% reliable test for predicting asphalt absorption, several efforts have been made to correlate water absorption of aggregate to asphalt absorption and to use the former as an index for the latter (17) since the water absorption is simple to run. The relationships between water and asphalt absorptions of the aggregates obtained by Lee (18) using three different test methods are plotted in Figure 2.6. Lee concludes that aggregates having high water absorption were more likely to absorb asphalt than low water absorption.

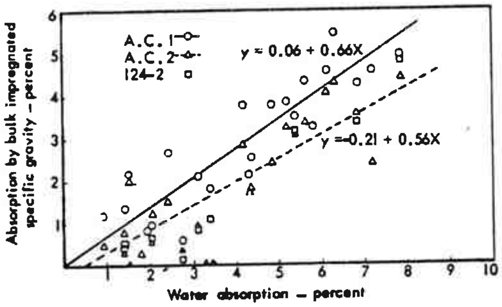
2.5 Antistrip Additives

2.5.1 Lime

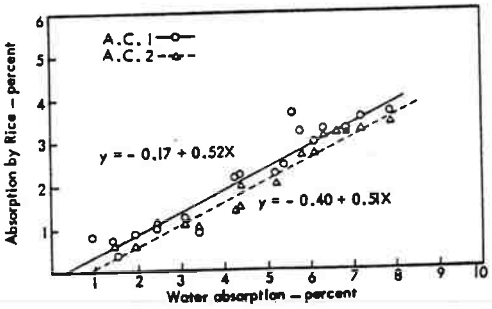
Lime is usually considered to function by means of a reaction in which the hydrogen, sodium, potassium, and other cations on the aggregate surfaces are replaced by calcium from the lime (12). The calcium-rich surface formed is shown to react with long chain organic acids to form water-resistant surfaces (12). Plancher et al. (22) indicate that the effect of hydrated lime in improving the stripping resistance of asphalt mixtures, is in part, a result of its interaction with certain asphaltic acids, which are readily adsorbed to the aggregate surface. Scott (21) indicates that one of the



a) Immersion Method



b) BISG Method



c) Rice Method

Figure 2.6 - Water Absorption vs. Asphalt Absorption (after Lee (18))

functions of hydrated lime is not just to put calcium ions on the surface of the aggregate, but also to remove oxygen-containing asphalt components and to reduce the concentration in which they are adsorbed on the mineral surface. Plancher et al. (22) suggest that the hydrated lime absorbs carboxylic acids in the asphalt, which results in a more water-resistant asphalt aggregate bond.

Ishai and Craus (2) show that the superior adhesion potential of the hydrated lime filler mixture with optimum asphalt content is intensified at 140°F (60°C) water immersion. Under this higher temperature, specimens gained strength during the entire immersion period. The reason for this behavior is that the physico-chemical process in the hydrated lime mastic-aggregate interface, in the presence of water, is accelerated and intensified under the higher temperature immersion. Also, Ishai and Craus emphasize that the contribution of the hydrated lime to adhesion is valid only in the presence of water. In dry conditions, no physico-chemical modification in the interface should be expected. The adhesion mechanism in the interface between hydrated lime as a filler and siliceous aggregate is described very well by Ishai and Craus (2).

Chehovits and Anderson (24) suggest that hydrated lime is more effective as an antistripping additive if it is added as a slurry rather than as a filler, and allowed to cure for several days. The test results obtained by Kennedy et al. (45) using the Texas Freeze-Thaw Pedestal Test and indirect tensile tests indicate that the improvement is greater for lime slurry treatment than for treatment with dry lime. The benefit of slurry lime may come from a friable and crystalline lime-mortar bond between aggregate particles that is synergistic with the binding action of the asphalts and not to a reaction on the aggregate surface (12).

2.5.2 Commercial Additives

There are many commercial additives available claiming to enhance the properties of asphalt mixtures. Pavebond Special, used in this study, is an example of an antistrip agent and is just one of a series of products available from the Carstab Company (41). Pavebond Special is recommended for acidic aggregates. Other Pavebond additives are also available for acidic or basic aggregates, and, clearly, selection of the appropriate additive and dosage requires care and experience. The description and properties of additives used currently by ODOT are documented well by Takallou (23).

The results of tests performed at Oregon State University shows that preblending Pavebond Special additive to asphalt is more effective than adding it during mixing (28). One series of tests consisted of adding asphalt and Pavebond Special to the aggregate without preblending, while another consisted of thoroughly blending Pavebond Special with asphalt before mixing. A comparison between the results of the two methods show that preblending obtained a higher resilient modulus for both as-compacted and conditioned specimens, and higher retained modulus than the addition during mixing, as presented in Table 2.2. This result indicates the importance of proper distribution of Pavebond Special in an asphalt before mixing.

2.6 Test Methods

Current practical tests used to evaluate the effects of water on adhesion in aggregate bitumen systems can be divided into three major groups (2):

a) Visual inspection of coating conditions of the coated aggregate after a period of water immersion,

b) Measurements of the interfacial forces at the aggregate-bitumen-water intersurface, and

Table 2.2. Effect of Adding Method for Pavebond Special on Resilient Modulus (After Walter et al. (28)).

Type of Mix	Resilient Modulus (M_R), x10^3 psi		Retained**
	As-Compacted	Conditioned	Modulus Ratio
Standard*	389	214	.55
Standard with Pavebond Special Added During Mixing	412	292	.71
Standard With Pavebond Special Added to Asphalt	464	443	.95

* 6% Passing No. 200, 25% Passing No. 10, 6% Asphalt, 96% Compaction

$$** \quad \text{Retained Modulus Ratio} = \frac{M_R \text{ of Conditioned}}{M_R \text{ of As-Compacted}}$$

c) Measurements of the strength of the bituminous mixture properties before and after water exposure.

Recently, the third group, including indirect tension test and resilient modulus test, is receiving increased attention, and these are discussed below.

2.6.1 Indirect Tension Test

The indirect tension test for predicting moisture susceptibility, as developed by Lottman (8, 25), determines the tensile strength and instantaneous tensile stiffness, called an "E-modulus", of cylindrical specimens by use of an unconfined compression test equipment at a specified loading rate and temperature. The data for calculation of tensile E-modulus are obtained during the indirect tension test by measuring tensile (horizontal) displacements of a specimen, and recording corresponding loads at 5, 10, or 15 sec intervals up to the maximum load. These data are used in diametral elastic equations (12) to calculate E-modulus values. The moduli calculated by the E-modulus device may be lower than resilient moduli reviewed in the next section because of the higher strain measurements used in the E-modulus device. The resulting data are normalized by expressing it in the form of a tensile strength ratio (TSR) and an E-modulus ratio (E-mod R), where the tensile strength and E-modulus of dry specimens are used as reference bases. Lottman recommends a separation point of 0.7 for tensile strength ratio or E-modulus ratio, as determined for the specimens subjected to vacuum saturation plus thermal cycling, or the accelerated conditioning (vacuum-saturated, freeze, thaw, and soak) to distinguish between moisture susceptible mixtures and moisture resistant mixtures.

More recently, Lottman included the fatigue life ratio at 100,000 load cycles as well as tensile strength ratio and resilient modulus ratio as a laboratory test method for predicting moisture-induced damage to asphalt concrete (5,35). Lottman's method has been criticized for being too severe with regard to moisture conditioning; however, this appears to be a procedural matter rather than a problem inherent in the test method (26). Moisture conditioning could be modified to simulate more accurately the climatic conditions that prevail locally (27). No special equipment is needed for the proposed test method because most of the needed equipment is available in the majority of highway materials laboratories.

2.6.2 Resilient Modulus Test

The resilient modulus test, used by Schmidt and Graf (12) to evaluate the effect of water on asphalt mixtures, uses a 0.1 sec duration pulsing load applied across one diameter of a cylindrical specimen made in accordance with ASTM D1561-65, using the Hveem kneading compactor. During application of the pulsing load across one diameter of the specimen, the resultant elastic deformation across the perpendicular, or opposite, diameter is measured. The resilient modulus (M_R) is calculated from the loading and deformation values, the specimen thickness, and an assumed value of Poisson's ratio. The resilient modulus is a property that is directly related to the load carrying ability of a flexible pavement; therefore, the resilient modulus test offers a great potential for correlating moisture damage observed in the laboratory with field performance (26). One factor that may limit use of the resilient modulus test is the cost and availability of the necessary testing equipment. However, diametral devices are of lower cost than repeated load triaxial devices and have proved to be reliable. Such equipment has been used by several researchers for both asphalt mixtures and soils (28,29,30,49), and has recently been standardized by ASTM D 4123-82 for use with asphalt mixtures.

3.0 EXPERIMENT DESIGN

3.1 Projects Evaluated

3.1.1 North Oakland-Sutherlin Project

3.1.1.1 Location. The North Oakland-Sutherlin project is a section of Interstate 5 located approximately 12 miles (19 km) north of Roseburg (Figure 3.1). The overall project length is 3.21 miles (5.14 km).

3.1.1.2 Cross Section. The pavement cross section is illustrated in Figure 3.2. The original pavement constructed in 1959 was composed of a 3.5 inch (9 cm) asphalt concrete layer over a 15.5 inch (39 cm) stone base layer. The new section of the pavement was built in 1978 and 1979. The 1978 lift was Class B asphalt concrete base built with a borderline aggregate which caused pavement distress (e.g., raveling) soon after construction. Patching of the first lift of base course was required prior to construction of the second 2 inch (5 cm) lift of asphalt concrete in 1979. A 1 inch (2.5 cm) Class E open-graded friction course was placed as the wearing surface.

3.1.1.3 Mix Design. A summary of the original mix design for the 1978 asphalt concrete base lift is presented in Appendix A. This mix is that used for the project and is different than that used in this research study due to the availability of materials five years after construction. To achieve an index of retained strength (AASHTO T-165) greater than 70%, 6.9% of an AR 8000 asphalt cement treated with 0.85% Pavebond Special was recommended. The need for the antistrip agent was related to the low quality of the aggregate. The aggregate soundness test (AASHTO T-104) indicated a percentage loss between 6.6 and 24.1 for the 0.75 inch-0.25 inch (19.1 mm-6.4 mm) fraction and between 17.7 and 45.2 for the 0.25 inch (6.4 mm) minus fraction. Aggregates used in

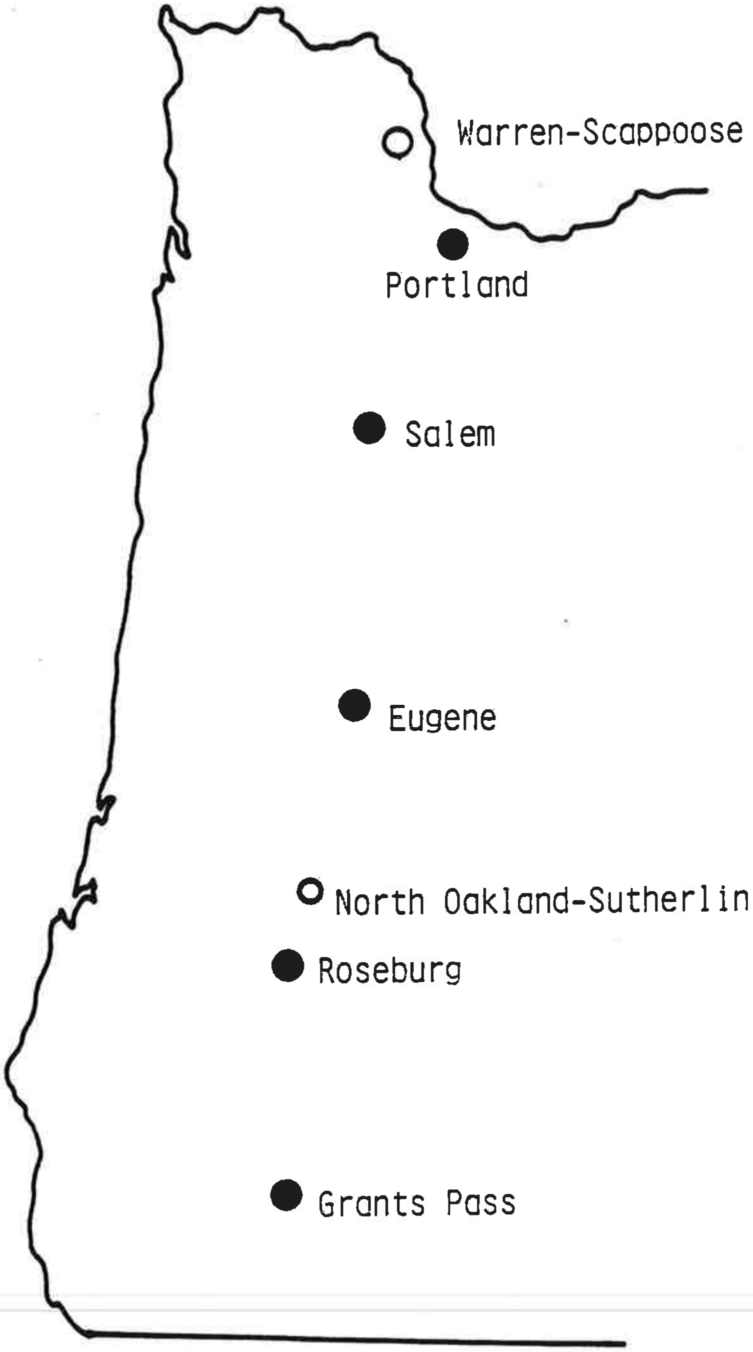
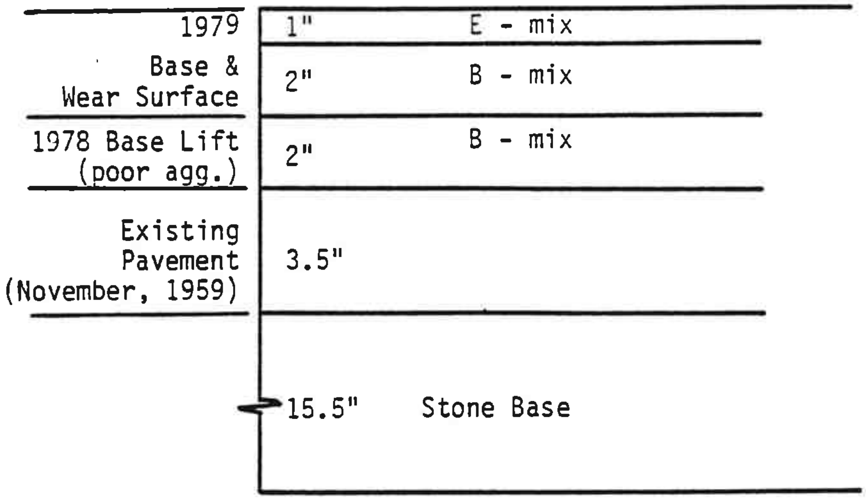
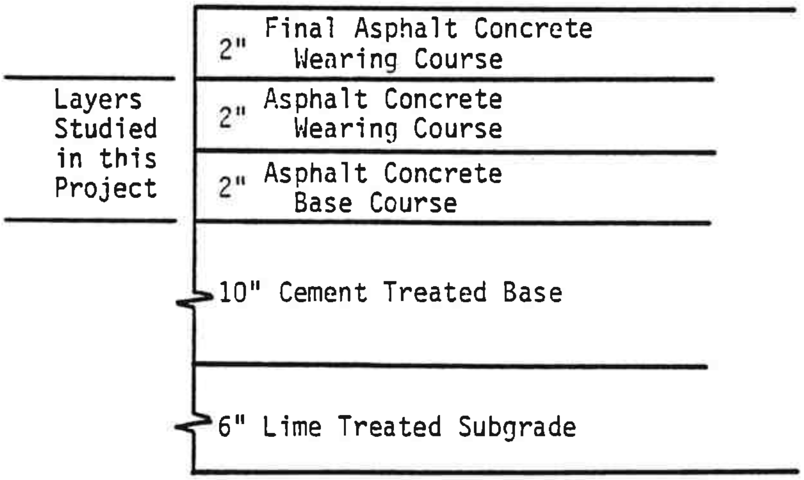


Figure 3.1 - Map of Project Locations



a) North Oakland - Sutherlin



b) Warren - Scappoose Project

Figure 3.2 - Pavement Cross Sections

this project were from the Oak Creek Quarry, located in the western foothills of the Cascade Range. Rock from this quarry is a submarine basalt containing seams of sulfate compounds of calcium, sodium, and magnesium. The aggregate gradation used for the base layer corresponds to a Class B mix. Details of the mix formula, gradation, tolerance, and specification broad band are shown in Table 3.1. A Class E open-graded mix was used for the wearing surface.

3.1.2 Warren-Scappoose Project

3.1.2.1 Location. The Warren-Scappoose project is a section of the Columbia River Highway, located in Columbia County (Figure 3.1). The overall project length is 5.05 miles (8.13 km).

3.1.2.2 Cross Section. This section of the Columbia River Highway includes an asphalt concrete base course and an asphalt concrete wearing surface, on top of a lime-treated subgrade and a cement-treated base. The base course was constructed in 1979 and the wearing surface in 1980. Both asphalt concrete layers were built using Class B mixes. A typical cross section of the pavement is shown in Figure 3.2.

3.1.2.3 Mix Design. A summary of the original mix design is presented in Appendix A. Again, this original mix design is different than the mix design for the study of moisture effect described in Chapter 4. This mix design was used for both the base and top layers. The aggregate gradation was also the same for both layers, and corresponded to a Class B mix. The recommended asphalt content was 5.1% for the wearing surface and 5.7% for the base course. The asphalt grade recommended was AR 4000. The recommended mix temperature at time of placement was 270°F (132°C).

Table 3.1. Mix Design: Aggregate Gradation, Class B.

Sieve Size	Mix Tolerances North Oakland-Sutherlin	Mix Tolerances Warren-Scappoose	Specification
3/4"	95-100	92-100	95-100
1/2"	80-92	82-94	-
1/4"	54-66	54-66	52-72
#10	21-29	26-34	21-41
#40	8-16	8-16	8-24
#200	3.0-7.0	2.6-6.6	2-7

3.2 Variables Considered

The variables considered in this study are:

1) Percent of moisture: 0, 1, and 3;
2) Percent of antistrip agent and type: 0, 1 percent lime, and 0.5 percent Pavebond Special; and
3) Conditioning: as-compacted and conditioned.

Each of the above variables was studied relative to a standard mix, consisting of the recommended aggregate gradation and mix asphalt content for this study. All specimens were prepared to a target density of 96% of theoretical maximum. The range and combination of mix variables considered in this study are presented in Table 3.2. Specimen preparation and conditioning procedures are explained below.

3.3 Test Program and Specimen Preparation

3.3.1 Test Program

A flow chart of the test program followed in this study is given in Figure 3.3. A minimum of 12 specimens were prepared for each one of the conditions presented in Table 3.2. Six specimens were tested as compacted, and six tested after conditioning. All 12 specimens were tested for resilient modulus, fatigue, and permanent deformation. All tests were run for mix tensile strain ranging between 50 and 200 microstrain.

A specific method of asphalt concrete moist specimen preparation has not been developed. Sonderegger used the pressure heating method in order to prepare wet aggregate for the research of the residual moisture effect with the assumption that all, or nearly all, residual moisture in a mixture was originally contained in the coarse aggregate fraction (15). The Oregon State Highway Materials Section used a trial and error procedure. In general, the

Table 3.2. Range of Mix Variables Considered in This Study.

Conditioning:	As Compacted			Conditioned		
Anti-Strip Agent:	None	1% Lime	0.5% Pavebond	None	1% Lime	0.5% Pavebond
Moisture:						
Standard (none)	X	X	X	X	X	X
1% Moisture	X			X		
3% Moisture	X	X	X	X	X	X

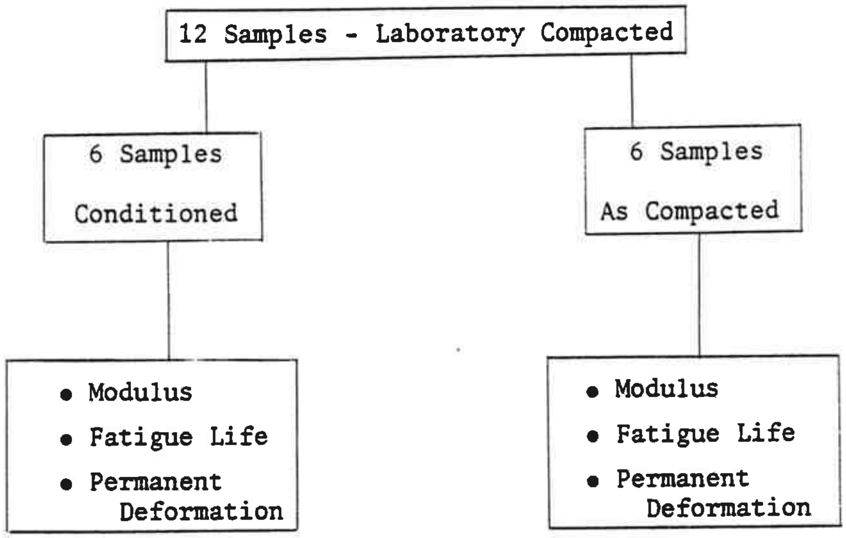


Figure 3.3 - Flow Chart - Test Program

aggregate is soaked in water overnight and then is dried to an initial water content that produces, after moisture loss during mixing and compacting, a specimen at the end desired moisture content. This moist specimen procedure preparation is presented in the next section.

The specimen conditioning procedure was based on the moisture damage test defined by Lottman (8). In summary, 1) vacuum (26 inches (66 cm) Hg) saturate the specimens for two hours, 2) place the saturated specimens in a freezer at 0°F (-18°C) for 15 hours, 3) place the frozen, saturated specimen in a warm water bath (140°F (60°C)) for 24 hours, 4) place the specimen in a water bath at room temperature for three hours, 5) dry the specimen at room temperature for two hours, and 6) run the diametral test.

3.3.2 Specimen Preparation

The desired moisture contents for the asphalt concrete used in this study were from 0% moisture to a value of 3%, which has been demonstrated to be detrimental to asphalt concrete pavement. Hence, asphalt concrete specimens were prepared at 0, 1, and 3% moisture content. In addition, an antistrip agent was included in the preparation of some specimens. The antistrip agents used were lime (1%) and Pavebond Special (0.5%). The range and combination of mix variables studied are presented in Table 3.2. The asphalt concrete moist specimen preparation procedure was based on trial and error tests performed by the Oregon State Highway Materials Section. The following are the main steps:

1) Prepare sample aggregate (1100 gr),
2) Obtain the dry weight,
3) Soak aggregate in water overnight,
4) Heat the wet aggregate until the desired initial moisture content is obtained,

5) Add the asphalt cement required,

6) Mix and compact the sample following AASHTO T-247 procedure.

The hydrated lime is added to the aggregate portion of the mix as a weight percentage of the aggregate, while Pavebond Special is added as a weight percentage of the asphalt concrete.

3.4 Test Methods

The resilient modulus, fatigue, and permanent deformation tests were performed using the repeated load diametral test apparatus (ASTM D 4123-82). The test procedures employed are essentially the same as used in previous studies (28,29). In summary:

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

The parameters recorded during the repeated load diametral test are the maximum load applied, the horizontal elastic deformation, the vertical permanent deformation, with number of repetitions, and the number of repetitions to failure as indicated in Figure 3.4. During the tests, the dynamic load duration was fixed at 0.1 sec and the load frequency at 60 cycles per minute. A static load of 10 pounds (4.5 kg) was applied to hold the specimen in place. The tests were carried out at 72.5 ± 2.7°F (22.5 ± 1.5°C) and at 67.6 ± 2.7°F

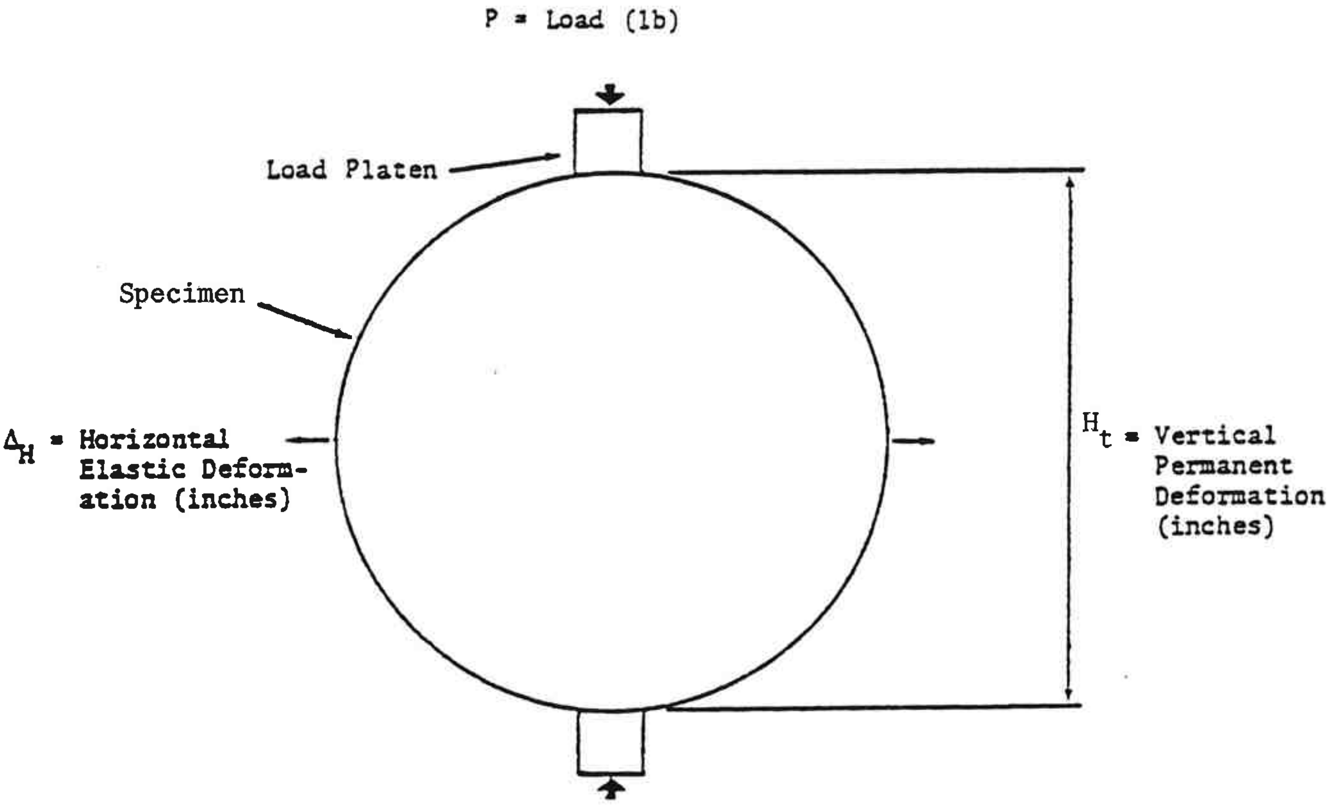


Figure 3.4 - Diametral Test - Variables Recorded

(19.8 ± 1.5°C) for the Warren-Scappoose and the North Oakland-Sutherlin projects, respectively.

3.4.1 Resilient Modulus

The maximum load applied and the horizontal elastic tensile deformation were recorded to determine the resilient modulus using the following equations (30):

$$M_R = \frac{P}{\Delta Hxt} (.2692 + .9974\nu) \tag{3.1}$$

where:

M_R = Resilient modulus, psi;

ΔH = Horizontal elastic tensile deformation, inches;

P = Dynamic load, lbs;

t = Specimen thickness, inches; and

ν = Poisson's ratio.

Poisson's ratio was assumed constant and equal to .35, which simplifies Eq. (3.1) to:

$$M_R = \frac{0.6183P}{\Delta Hxt} \tag{3.2}$$

3.4.2 Fatigue Life

Fatigue has been defined (48) as "the phenomenon of fracture under repeated or fluctuating stress having a maximum value generally less than the tensile strength of the material." However, the failure, or the end point of a fatigue test, in the laboratory has been defined by investigators in many ways. It may be the point corresponding to complete fracture of the test specimen, the point at which a crack is first observed or a certain width of crack in the specimen is detected (28,29), or the point at which the stiffness or some other property of the specimen has been reduced by a specific amount from its initial value (37).

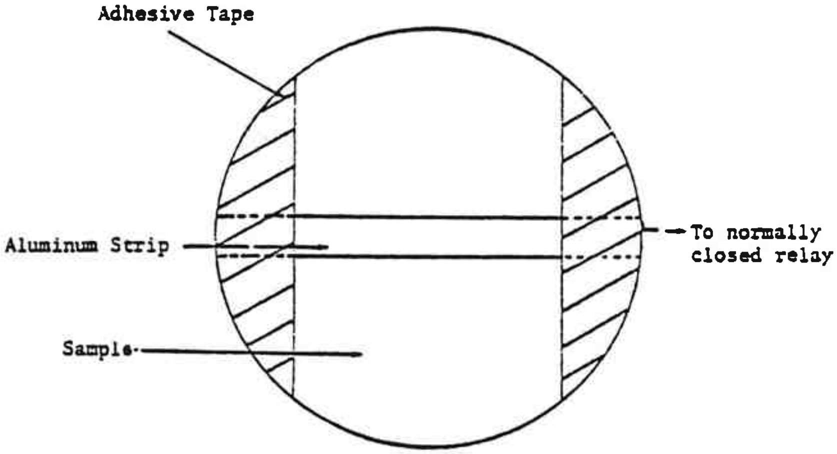
For this study, the number of load repetitions to fatigue failure was defined as the number of repetitions required to get a vertical crack approximately 0.25 inch (.64 cm) wide in the specimens. To stop the test at the specified level of specimen deformation, a thin aluminum strip was attached to the sides of the specimens, along a plane perpendicular to the plane formed by the load platen (Figure 3.5). The aluminum strip is connected to a normally closed relay, which controls the dynamic load system. As the specimen deforms, the aluminum strip is stressed. When the specimen 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 specimen crack width.

In fatigue testing of asphalt mixtures, the logarithm of the life expressed in number of repetitions to failure is a linear function of the logarithm of the initial strain or stress (31,32,33,34,46,47):

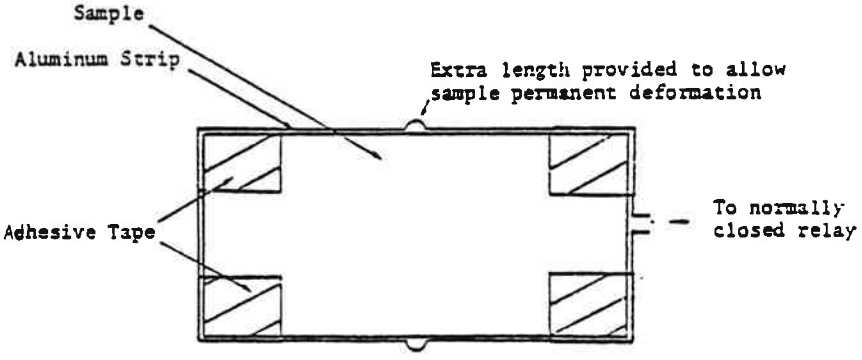
$$N_f = K \left(\frac{1}{\varepsilon_t}\right)^m \tag{3.3}$$

$$N_f = C \left(\frac{1}{\sigma_t}\right)^n \tag{3.4}$$

where:



a. Side view



b. Top view

Figure 3.5 - Schematic View of the Automatic Shut-Off Device for Fatigue Testing

N_f = Number of load repetitions to failure;

K,m,C,n = Regression constants;

ε_t = Initial horizontal elastic tensile strain; and

σ_t = Tensile stress, psi.

The initial horizontal elastic tensile strain, ε_t, is calculated from the following equation:

$$\varepsilon_t = \Delta H \left[\frac{.03896 + .1185\nu}{.0673 + .2494\nu}\right] \tag{3.5}$$

where:

ε_t = Initial horizontal elastic tensile strain;

ΔH = Horizontal elastic tensile deformation, inches; and

ν = Poisson's ratio.

Assuming again the Poisson's ratio is constant and equal to .35, Eq. (3.5) becomes:

$$\varepsilon_t = \Delta H \times .5203 \tag{3.6}$$

3.4.3 Permanent Deformation

The vertical permanent strain was also recorded during the fatigue test as a function of the number of load repetitions. The permanent deformation strain is given by (30):

$$\varepsilon_c = H_t \left[\frac{-.03896\nu - .1185}{.0156\nu - .8954}\right] \tag{3.7}$$

where:

ε_c = Vertical permanent compressive strain;

H_t = Vertical permanent compressive deformation, inches; and

ν = Poisson's ratio.

If the Poisson's ratio is assumed constant and equal to .35 again, Eq. (3.7) becomes:

$$\varepsilon_c = H_t \times .1485 \tag{3.8}$$

4.0 TEST RESULTS

4.1 Mix Design

The conventional standard mix designs (AASHTO T-246) carried out at the Oregon State Highway Division Materials Section for this study are presented in this section. Due to the availability of materials five years after construction, the mix designs for the study of moisture effect presented in this section are different from the original mix designs for two projects described in Chapter 3. For each set of variables considered in this study, standard specimens were tested to determine mix characteristics. Mix design properties for both projects (Warren-Scappoose and North Oakland-Sutherlin) were determined and are presented in the following subsections.

4.1.1 Warren-Scappoose

Mix design properties for this project are presented in Table 4.1a. The recommended asphalt content was 5.0% for the wearing course. The asphalt grade recommended was an AR 4000, from Shell. The recommended mix temperature at time of placement was 270°F (132°C). A type B aggregate mix gradation was recommended for this project as shown in Table 4.2.

4.1.2 North Oakland-Sutherlin

Mix design properties for this project are presented in Table 4.1b. The recommended asphalt content was 6.2% and asphalt grade was an AR 4000 from Chevron. The recommended mix temperature at time of placement was 270°F (132°C). Again, a type B aggregate mix gradation was recommended for this project.

4.2 Core Data

4.2.1 North Oakland-Sutherlin

Two core sampling sites were selected on the North Oakland-Sutherlin project. For each site, layer thicknesses were recorded and core samples of

Table 4.1. Summary of Testing for Mix Design Properties
a. Warren-Scappoose

Mix Type	No Moisture			No Moisture 1% Lime			No Moisture 0.5% Pavebond		
Asphalt Content, %	4.5	5.5	6.5	4.0	5.0	6.0	4.5	5.5	6.5
Max. Sp. Gr. (T-209)	2.506	2.467	2.457	2.519	2.492	2.460	2.506	2.476	2.457
1st Bulk Sp. Gr.	2.35	2.39	2.41	2.35	2.39	2.42	2.34	2.38	2.42
Voids, %	6.2	3.1	1.9	6.7	4.1	1.6	6.6	3.9	1.5
Stability @ 1st Comp.	37	35	24	38	35	25	40	36	34
2nd Bulk Sp. Gr.	2.41	2.45	2.46	2.41	2.45	2.46	2.42	2.44	2.45
Voids, %	3.8	0.7	0.0	4.3	1.7	0.0	3.4	1.5	0.3
Stability @ 2nd Comp.	40	41	17	43	42	17	47	42	19
Index Ret. Str. (T-165), %	83	95	100+	70	91	100+	87	98	100+
As-Compacted Modulus, x10^3 psi	762	617	602	1082	1016	849	738	736	567
Conditioned Modulus, x10^3 psi	481	387	383	537	547	521	494	510	496
Retained Modulus Ratio	.631	.627	.636	.496	.538	.614	.669	.693	.875

Table 4.1. Summary of Testing for Mix Design Properties
a. Warren-Scappoose (continued)

Mix Type	1% Moisture*			3% Moisture*			3% Moisture* 1% Lime			3% Moisture* 0.5% Pavebond		
Asphalt Content, %	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0
Max. Sp. Gr. (T-209)	2.532	2.507	2.484	2.543	2.505	2.480	2.533	2.493	2.479	2.573	2.508	2.493
1st Bulk Sp. Gr.	2.34	2.38	2.40	2.33	2.37	2.40	2.35	2.39	2.41	2.31	2.35	2.37
Voids, %	7.6	5.1	3.4	8.4	5.4	3.2	7.2	4.1	2.8	10.2	6.3	4.9
Stability @ 1st Comp.	36	38	30	38	37	34	42	37	15	35	34	25
2nd Bulk Sp. Gr.	2.40	2.44	2.46	2.41	2.45	2.47	2.40	2.44	2.45	2.39	2.43	2.44
Voids, %	5.2	2.7	0.9	5.2	2.2	0.4	5.2	2.1	1.1	7.1	3.1	2.1
Stability @ 2nd Comp.	44	47	32	46	46	29	49	38	25	38	44	42
Index Ret. Str. (T-165), %	73	92	100+	43	46	64	95	100+	100+	80	100+	100+
As-Compacted Modulus, x10^3 psi	828	721	510	359	311	281	663	512	262	286	325	299
Conditioned Modulus, x10^3 psi	286	301	326	39	40	41	372	353	298	86	108	144
Retained Modulus Ratio	.345	.417	.639	.109	.129	.146	.561	.689	1.137	.301	.332	.482

* ±0.5%

Table 4.1. Summary of Testing for Mix Design Properties
b. North Oakland-Sutherlin

Mix Type	No Moisture			No Moisture 1% Lime			No Moisture 0.5% Pavebond		
Asphalt Content, %	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0
Max. Sp. Gr. (T-209)	2.532	2.495	2.479	2.529	2.493	2.470	2.541	2.512	2.485
1st Bulk Sp. Gr.	2.32	2.36	2.40	2.35	2.38	2.40	2.33	2.36	2.38
Voids, %	8.4	5.4	3.2	7.1	4.5	2.8	8.3	6.1	4.2
Stability @ 1st Comp.	36	39	30	41	40	35	42	44	42
2nd Bulk Sp. Gr.	2.38	2.42	2.45	2.41	2.45	2.47	2.41	2.45	2.48
Voids, %	6.0	3.0	1.2	4.7	1.7	0.0	5.2	2.5	0.2
Stability @ 2nd Comp.	46	50	12	49	50	35	47	45	20
Index Ret. Str. (T-165), %	16	24	59	12	28	57	52	62	88
As-Compacted Modulus, x10^3 psi	362	327	275	588	574	402	567	550	438
Conditioned Modulus, x10^3 psi	21	68	276	36	262	300	188	400	418
Retained Modulus Ratio	.058	.208	1.004	.061	.456	.746	.332	.727	.954

Table 4.1. Summary of Testing for Mix Design Properties
b. North Oakland-Sutherlin (continued)

Mix Type	1% Moisture*			3% Moisture*			3% Moisture* 1% Lime			3% Moisture* 0.5% Pavebond		
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
Max. Sp. Gr. (T-209)	2.548	2.505	2.464	2.530	2.501	2.477	2.522	2.482	2.461	2.532	2.490	2.472
1st Bulk Sp. Gr.	2.40	2.42	2.41	2.43	2.47	2.43	2.41	2.44	2.42	2.42	2.46	2.43
Voids, %	5.8	3.4	2.2	4.0	1.2	1.9	4.4	1.7	1.7	4.4	1.2	1.7
Stability @ 1st Comp.	47	37	44	36	9	2	50	34	13	39	13	1
2nd Bulk Sp. Gr.	2.45	2.47	2.46	2.48	2.50	2.47	2.45	2.48	2.47	2.46	2.49	2.47
Voids, %	3.8	1.4	0.2	2.0	0.0	0.0	2.9	0.1	0.0	2.8	0.0	0.0
Stability @ 2nd Comp.	58	40	12	67	4	3	47	15	4	50	7	3
Index Ret. Str. (T-165), %	12	18	57	58	77	74	70	84	104	76	82	119
As-Compacted Modulus, x10^3 psi	739	589	456	492	350	174	356	376	194	298	241	190
Conditioned Modulus, x10^3 psi	108	119	139	115	235	175	321	370	213	208	218	175
Retained Modulus Ratio	.146	.202	.305	.234	.671	1.006	.902	.984	1.098	.688	.905	.921

* ±0.5%

Table 4.2. Mix Design for Laboratory Prepared Specimens: Aggregate Gradation, Class B

Sieve Size	Recommended Aggregate Gradation, %
1"	100
3/4"	98
1/2"	87
3/8"	79
1/4"	65
10	33
40	14
200	5.0

the top and the two base lifts were collected. Five cores were taken at 2-foot intervals across the permanent panel at each sampling site. The core data are summarized in Appendix B. The core data of the 1978 base layer (bottom lift) considered in this study show very high average air voids of 15.6% and low modulus of 232 ksi compared to the test results of the laboratory specimens presented in the following section. The moduli values of the wearing surface and 1979 base layer (top lift) could be used for a multilayer elastic analysis of the pavement structure, although this is outside the scope of this study.

4.2.2. Warren-Scappoose

At two locations, 5 asphalt concrete cores were sampled across the panel. The core data are summarized in Appendix B. The core data of the Warren-Scappoose project are more detailed than those of the North Oakland-Sutherlin project. The core data show that the water content ranged from 0.64 to 1.0% for both layers and poor adhesion or stripping was observed. Poor adhesion or stripping might have resulted due in part to the water content being below 1%.

4.3 Modulus

Six specimens were tested as-compacted and 6 specimens were tested both before and after conditioning for each project. The test results including specific gravity (Sp. Gr.), air voids, and maximum specific gravity (AASHO T-209) of laboratory fabricated specimens, and water intrusion during the Lottman's conditioning procedure are summarized in Table 4.3. Moduli values of as-compacted and conditioned specimens from the Warren-Scappoose and North Oakland-Sutherlin projects are presented in Table 4.4 and Figures 4.1 through 4.3. In order to determine the conditioning effect (the moisture susceptibility of specimen) the retained modulus ratio, which is the ratio of retained

Table 4.3 Specific Gravity and Air Voids of Laboratory Specimens

a. Warren-Scappoose

	Max. Sp. Gr.	Sp. Gr.	Air Voids (%)	Water* Intrusion (%)
0% Moisture	2.487	2.284	8.16	N.A.[1]
1% Lime	2.492	2.309	7.34	1.76
0.5% Pavebond Special	2.496	2.293	8.13	1.78
1% Moisture	2.507	2.314	7.69	1.81
3% Moisture	2.505	2.287	8.70	2.07
3% Moisture/ 1% Lime	2.493	2.315	7.14	1.19
3% Moisture/ 0.5% Pavebond Special	2.508	2.256	10.05	1.82

N.A.[1]: Non Available

b. North Oakland-Sutherlin

	Max. Sp. Gr.	Sp. Gr.	Air Voids (%)	Water* Intrusion (%)
0% Moisture	2.493	2.285	8.34	1.60
1% Lime	2.485	2.305	7.24	0.74
0.5% Pavebond Special	2.503	2.335	6.71	0.47
1% Moisture	2.501	2.358	5.72	0.42
3% Moisture	2.494	2.415	3.17	0.20
3% Moisture/ 1% Lime	2.478	2.388	3.63	0.47
3% Moisture/ 0.5% Pavebond Special	2.486	2.430	2.25	0.17

* Water intrusion, % =

$$\frac{\text{Wt. after vacuum saturation - wt. before vacuum saturation}}{\text{Wt. before vacuum saturation}} \times 100$$

Table 4.4. Modulus Data (x10^3 psi)

a. Warren-Scappoose (AR 4000, 5% Asphalt Cement)

	As-Compacted*		After Conditioning	Retained Ratio (After Cond./Before Cond.)
	As-Compacted	Before Conditioning		
0% Moisture	525.6	430.4	388.7	.903
1% Lime	562.6	566.5	529.5	.935
0.5% Pavebond Special	613.3	537.4	489.7	.911
1% Moisture	340.3	337.6	293.6	.870
3% Moisture	207.6	256.4	109.4	.427
3% Moisture/ 1% Lime	267.8	308.3	423.5	1.423
3% Moisture/ 0.5% Pavebond Special	180.6	231.7	190.1	.765

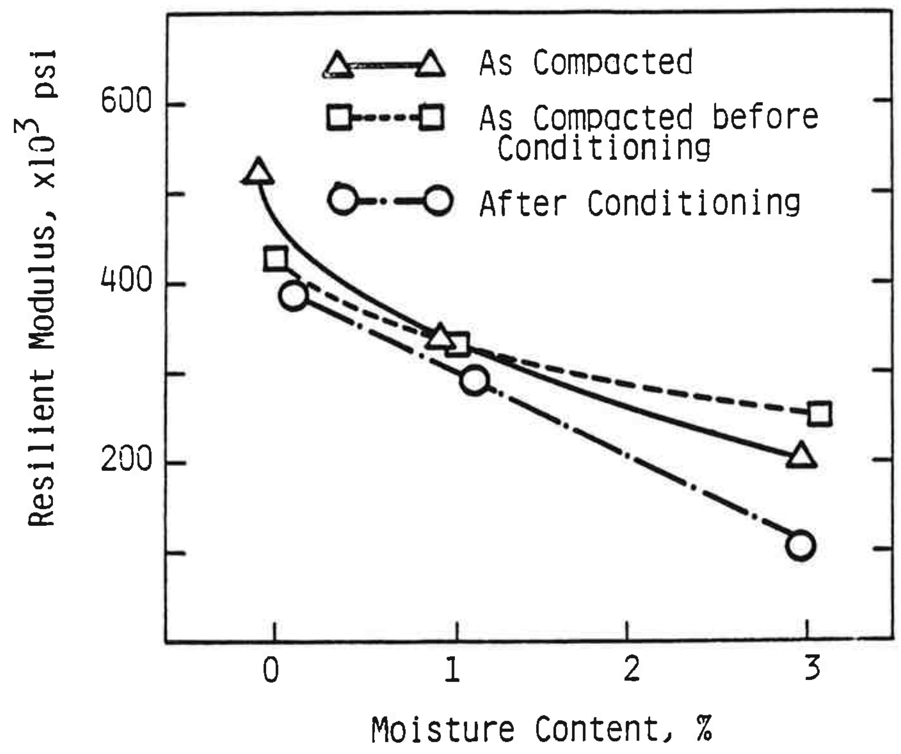
* The period between as compacted and before conditioning is about 7 weeks.

Table 4.4. Modulus Data (x10^3 psi) (Continued)

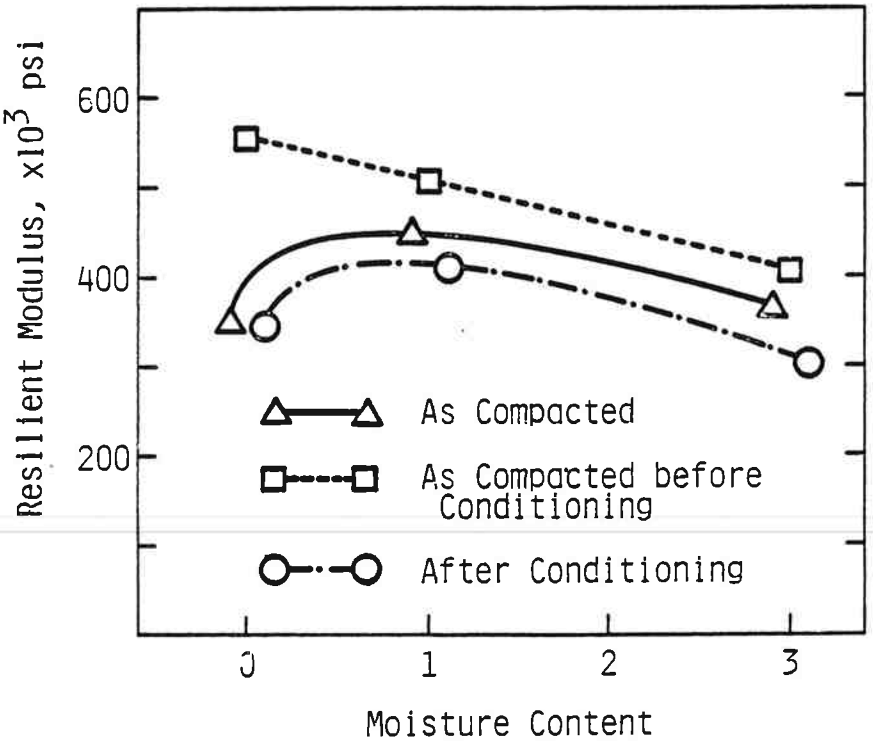
b. North Oakland-Sutherlin (AR4000, 6.2% Asphalt Cement)

	As-Compacted*		After	Retained Ratio
	As-Compacted	Before Conditioning	Conditioning	(After Cond./Before Cond.)
0% Moisture	350.8	557.8	347.6	.623
1% Lime	435.3	642.2	450.1	.701
0.5% Pavebond Special	430.9	542.9	428.1	.789
1% Moisture	448.4	509.5	411.9	.808
3% Moisture	366.6	406.0	301.3	.742
3% Moisture/ 1% Lime	343.0	347.0	266.5	.768
3% Moisture/ 0.5% Pavebond Special	367.0	281.3	263.3	.936

* The period between as-compacted and before conditioning is about 7 weeks.

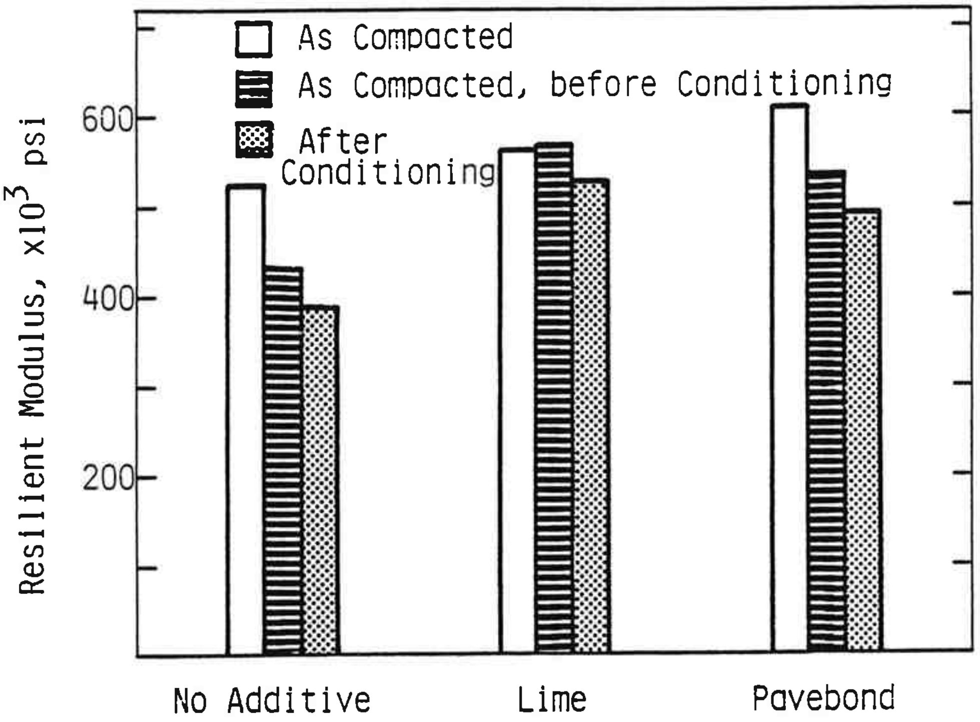


a. Warren-Scappoose

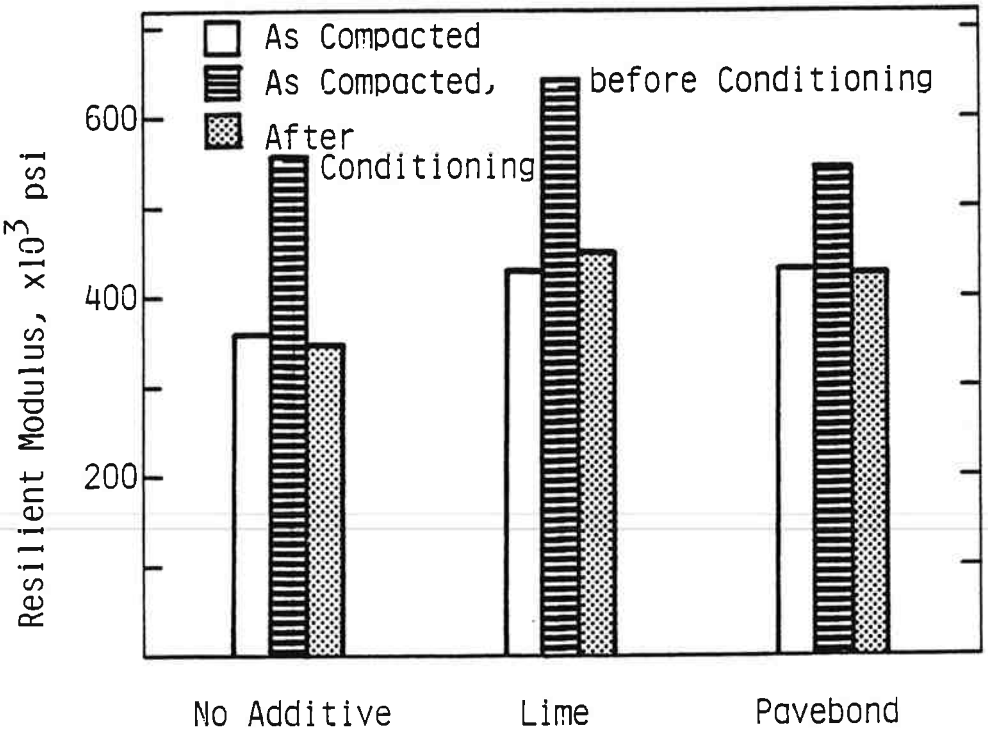


b. North Oakland-Sutherlin

Figure 4.1 - Effect of Moisture on Resilient Modulus

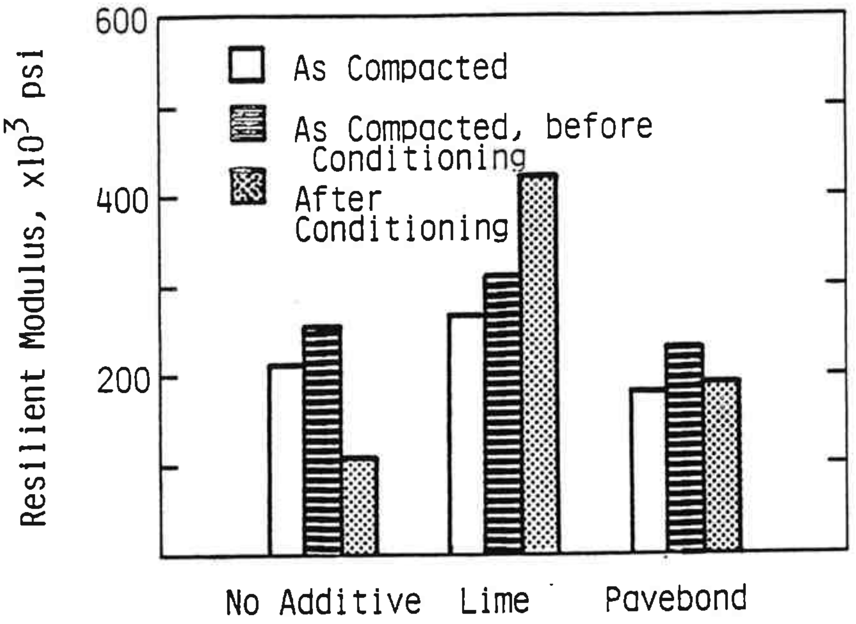


a. Warren-Scappoose

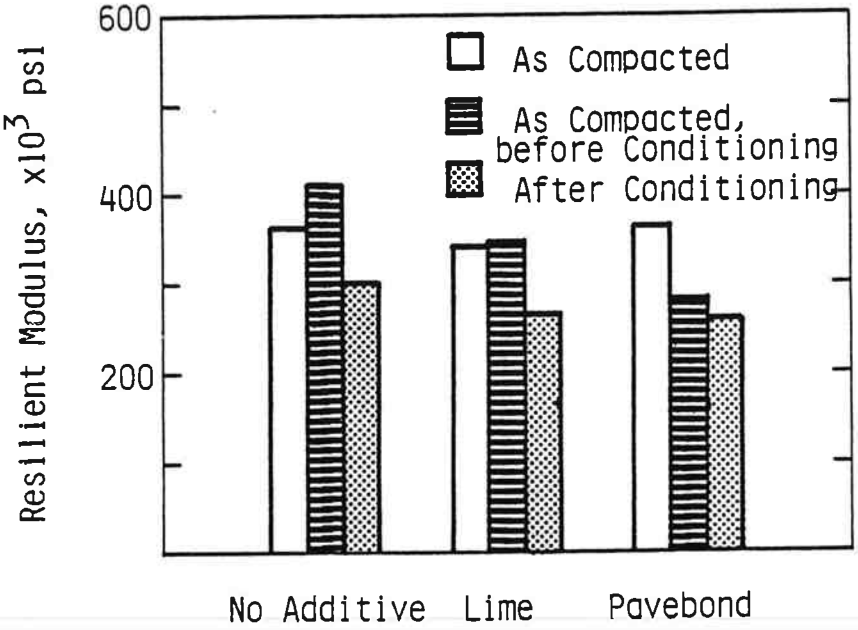


b. North Oakland-Sutherlin

Figure 4.2 - Effect of Additives without Moisture on Resilient Modulus



a. Warren-Scappoose



b. North Oakland-Sutherlin

Figure 4.3 - Effect of Additives with Moisture on Resilient Modulus

stiffness after conditioning to the stiffness before conditioning, is also presented in Table 4.4. Because there was a difference of about 7 weeks between tests with as-compacted specimens and the conditioning test, two moduli values of as-compacted specimens per each variable set are shown in Table 4.4 and in Figures 4.1 through 4.3.

Moduli values greater than 500 ksi were obtained for as-compacted specimens with no moisture from the Warren-Scappoose project, and the retained ratios were greater than 0.9. With moisture, moduli values of as-compacted specimens were in the range 180 to 340 ksi, and retained ratios were from 0.4 to 1.4 depending on the moisture content and kind of additives. For the North Oakland-Sutherlin project, moduli values of as-compacted specimens with no moisture were in the range 350 to 640 ksi, and retained ratios ranged from 0.62 to 0.79. With moisture, moduli values of as-compacted specimens were from 280 to 510 ksi, and retained ratios ranged from 0.74 to 0.94.

4.4 Fatigue Life

After resilient modulus was measured, the fatigue test was run at fixed initial tensile strains between 50 and 200 microstrains. The fatigue life of asphalt mixtures is a function of initial tensile strain and may be expressed by Eq. (3.3). The constants K and m were determined by linear regression analysis following completion of a test. Table 4.5 summarizes the K and m values for both Warren-Scappoose and North Oakland-Sutherlin projects along with the coefficient of determination, r^2. Figures 4.4 through 4.9 illustrate the effects of various varibles on fatigue life.

Table 4.5. Fatigue Data ($N_f = k(\frac{1}{\varepsilon_t})^m$)

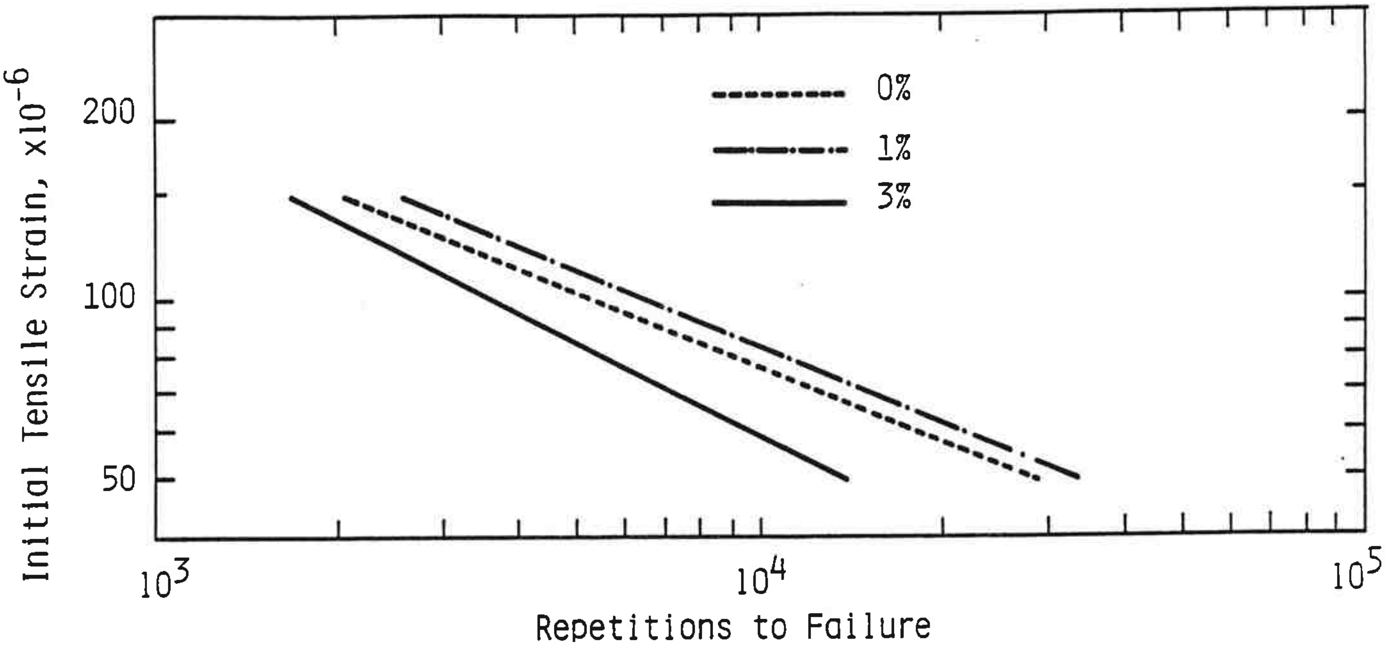
a. Warren-Scappoose

	As-Compacted			Conditioned		
	K	m	r^2	K	m	r^2
0% Moisture	1.492×10^{-6}	2.387	.995	5.636×10^{-4}	1.790	.925
1% Lime	3.101×10^{-9}	3.080	.972	7.133×10^{-9}	3.010	.978
0.5% Pavebond Special	1.268×10^{-8}	2.903	.978	3.845×10^{-6}	2.303	.959
1% Moisture	2.729×10^{-6}	2.344	.912	1.270×10^{-7}	2.718	.929
3% Moisture	6.821×10^{-5}	1.932	.953	4.908×10^{-9}	3.044	.919
3% Moisture/1% Lime	4.989×10^{-8}	2.921	.968	5.412×10^{-6}	2.321	.911
3% Moisture/0.5% Pavebond Special	9.186×10^{-5}	1.922	.975	1.004×10^{-2}	1.474	.941

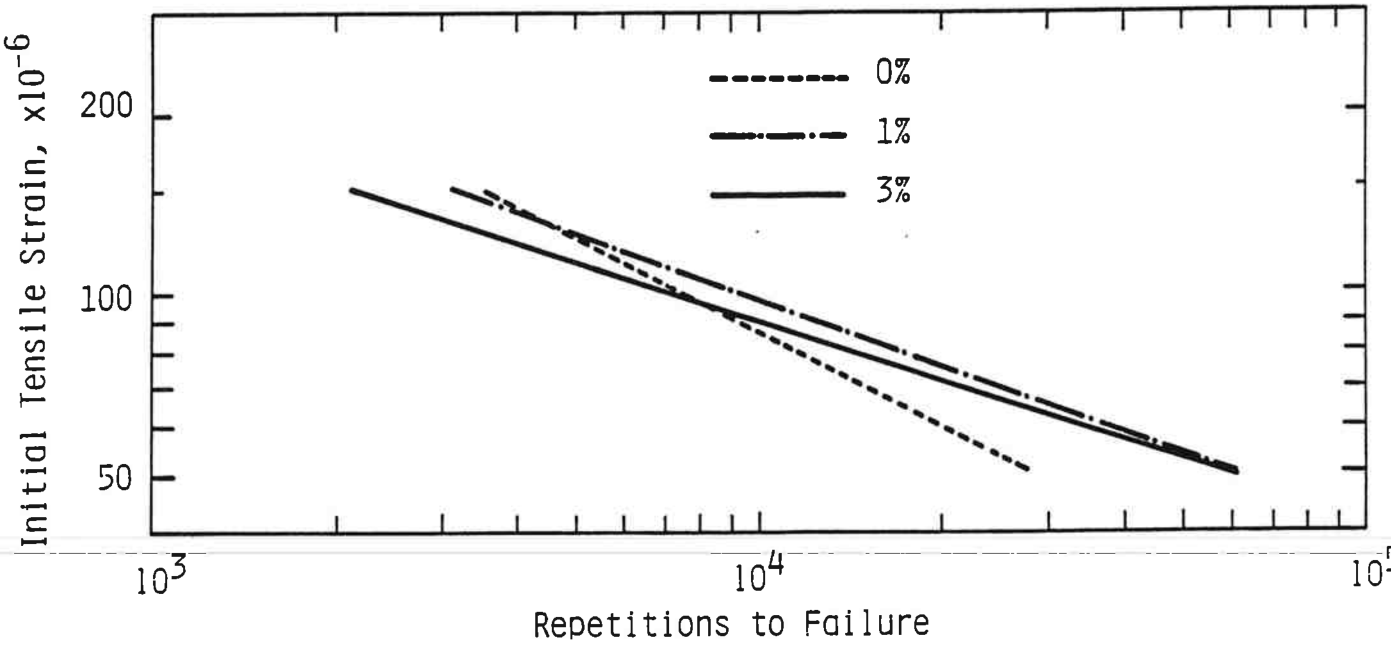
Table 4.5. Fatigue Data ($N_f = k(\frac{1}{\varepsilon_t})^m$)

b. North Oakland-Sutherlin

	As-Compacted			Conditioned		
	K	m	r^2	K	m	r^2
0% Moisture	$2.451x10^{-7}$	2.658	.999	$1.637x10^{-16}$	5.083	.976
1% Lime	$6.541x10^{-9}$	3.109	.941	$1.295x10^{-8}$	3.023	.905
0.5% Pavebond Special	$2.498x10^{-11}$	3.724	.968	$4.797x10^{-20}$	6.055	.960
1% Moisture	$6.717x10^{-11}$	3.621	.944	$4.617x10^{-14}$	4.464	.826
3% Moisture	$3.604x10^{-18}$	5.599	.861	$3.102x10^{-14}$	4.712	.927
3% Moisture/1% Lime	$1.716x10^{-18}$	5.675	.944	$2.982x10^{-4}$	2.075	.880
3% Moisture/0.5% Pavebond Special	$4.210x10^{-17}$	5.307	.973	$1.735x10^{-14}$	4.797	.917

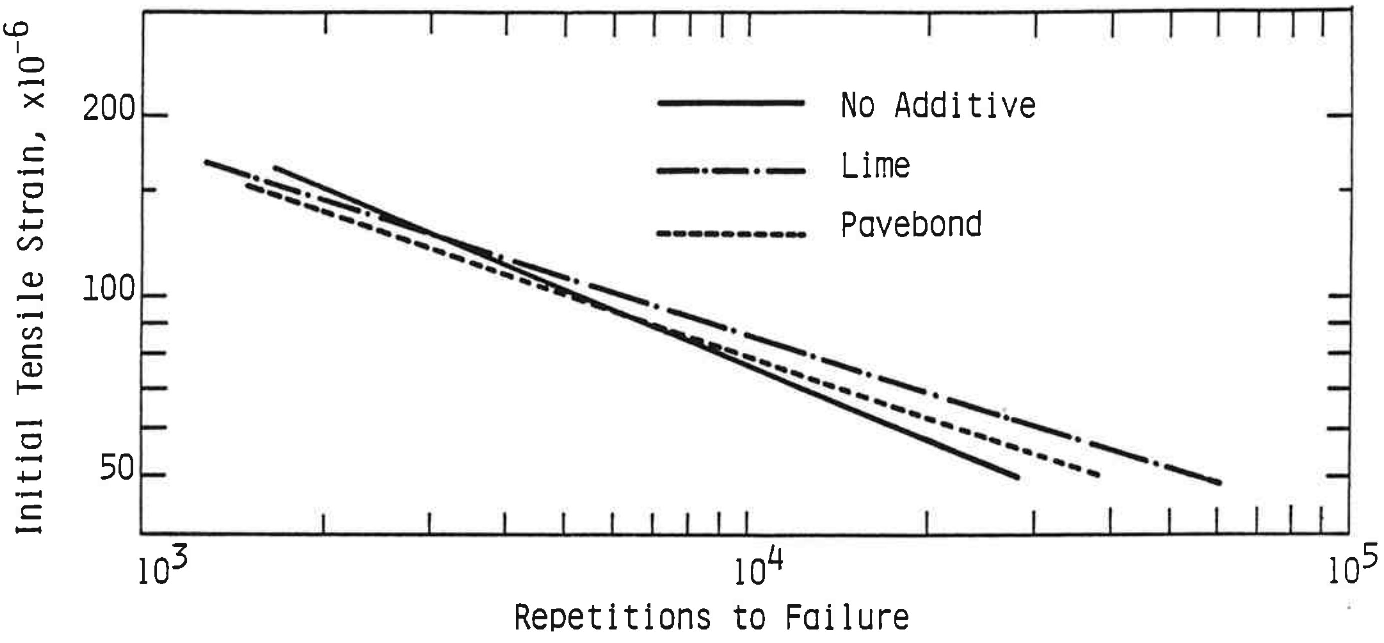


a. As Compacted

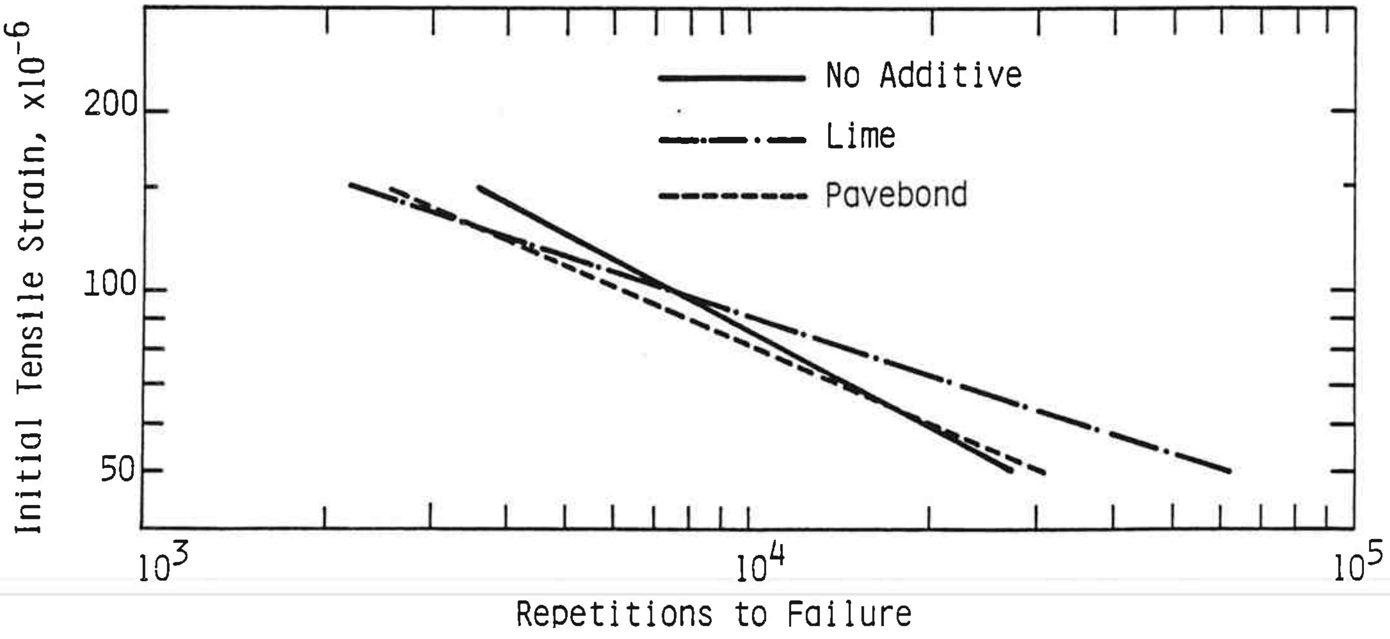


b. Conditioned

Figure 4.4 - Effect of Moisture on Fatigue Life of Warren-Scappose Project

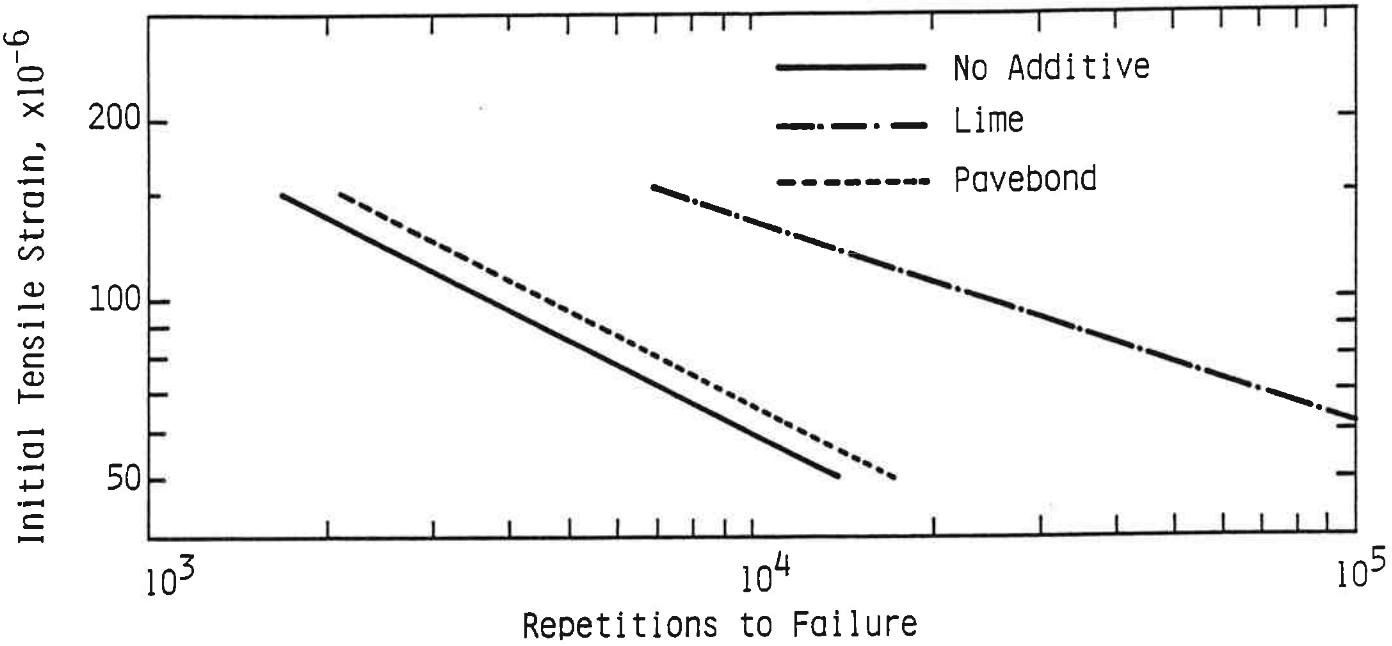


a. As Compacted

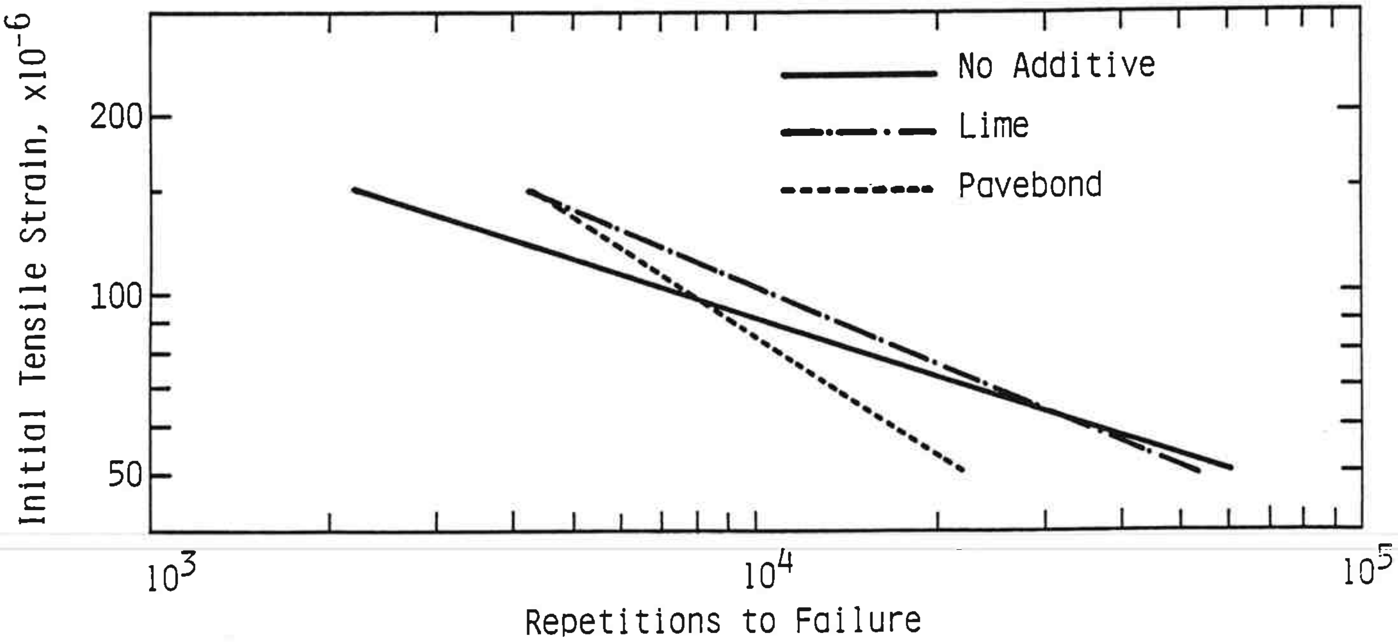


b. Conditioned

Figure 4.5- Effect of Additives without Moisture on Fatigue Life of Warren-Scappose Project

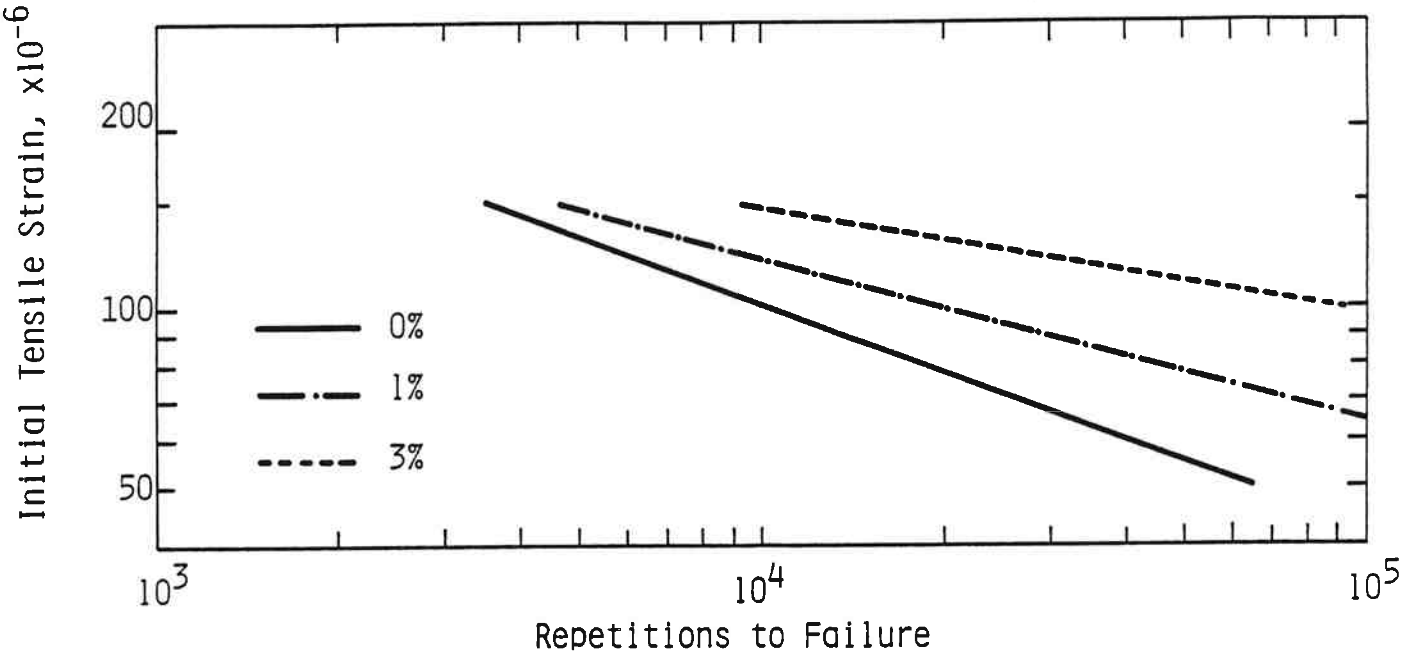


a. As Compacted

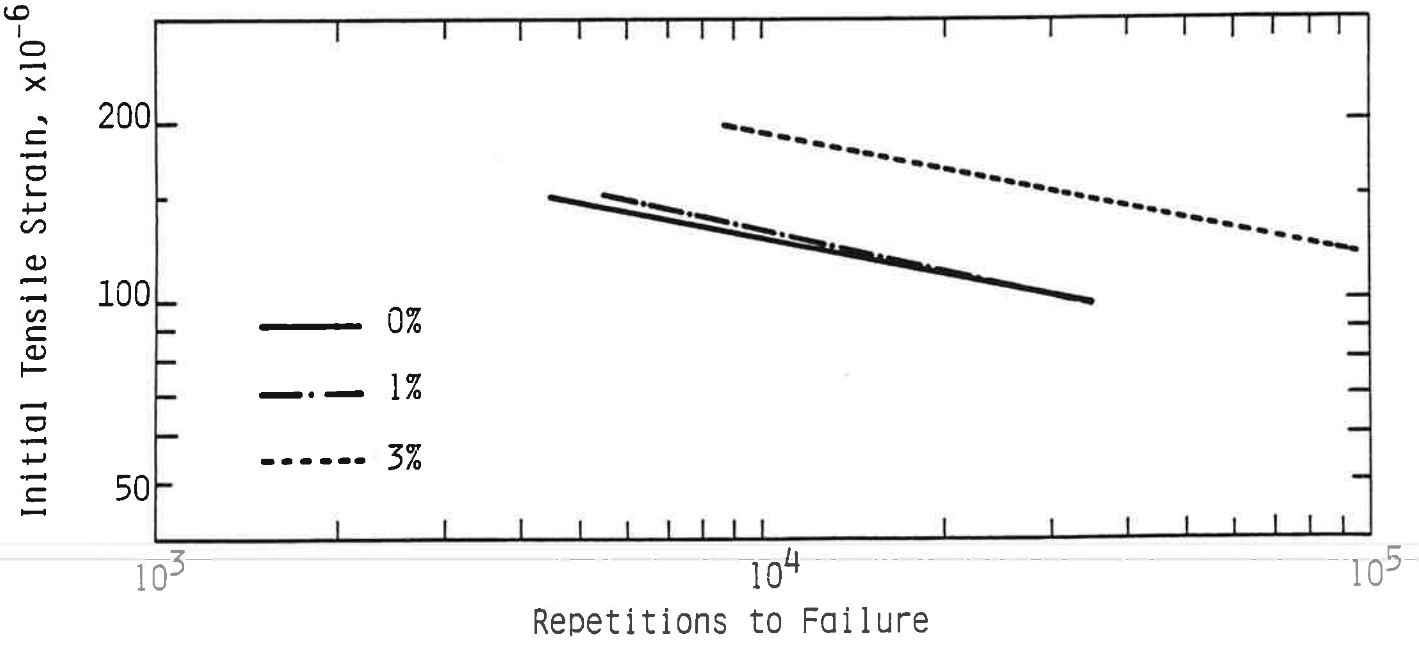


b. Conditioned

Figure 4.6 - Effect of Additives with Moisture on Fatigue Life of Warren-Scappoose Project

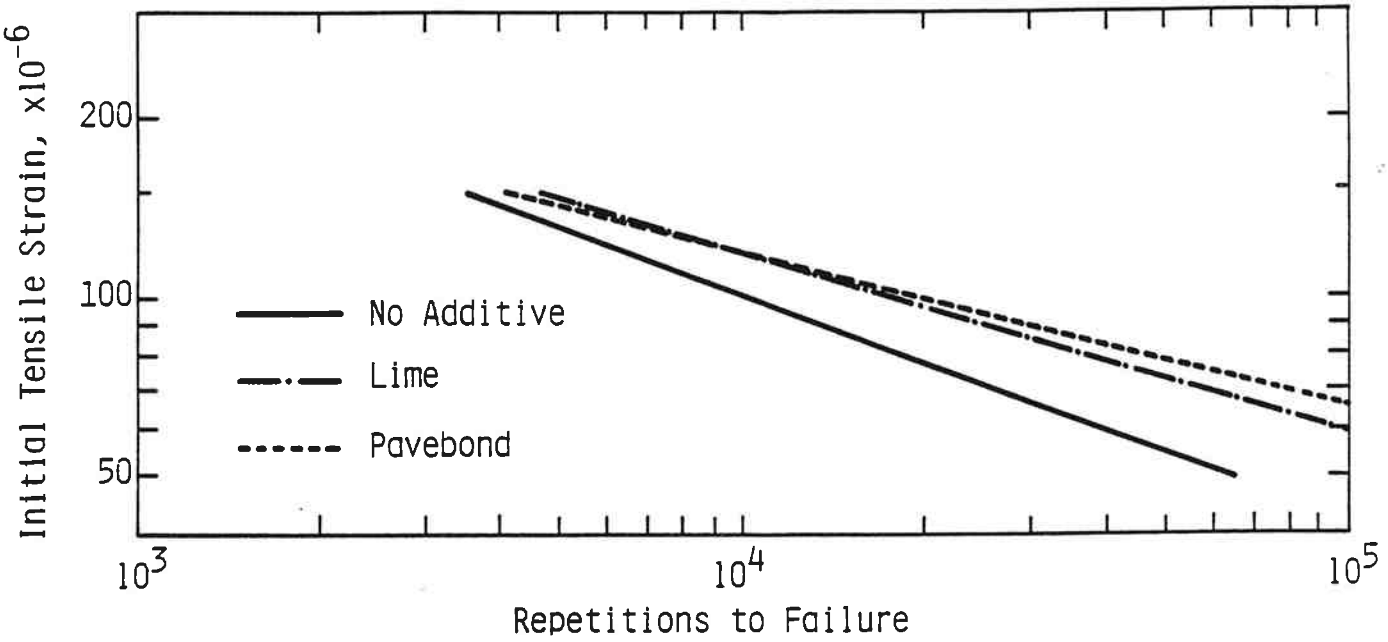


a. As Compacted

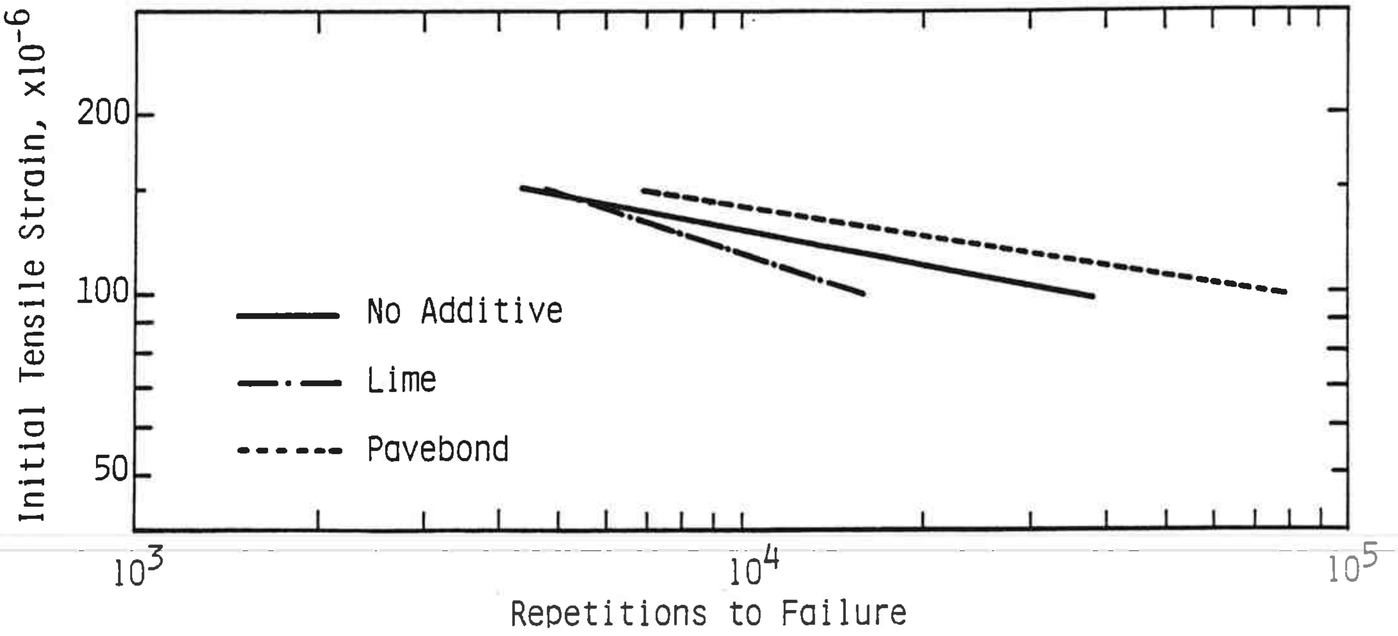


b. Conditioned

Figure 4.7 - Effect of Moisture on Fatigue Life of North Oakland-Sutherlin Project

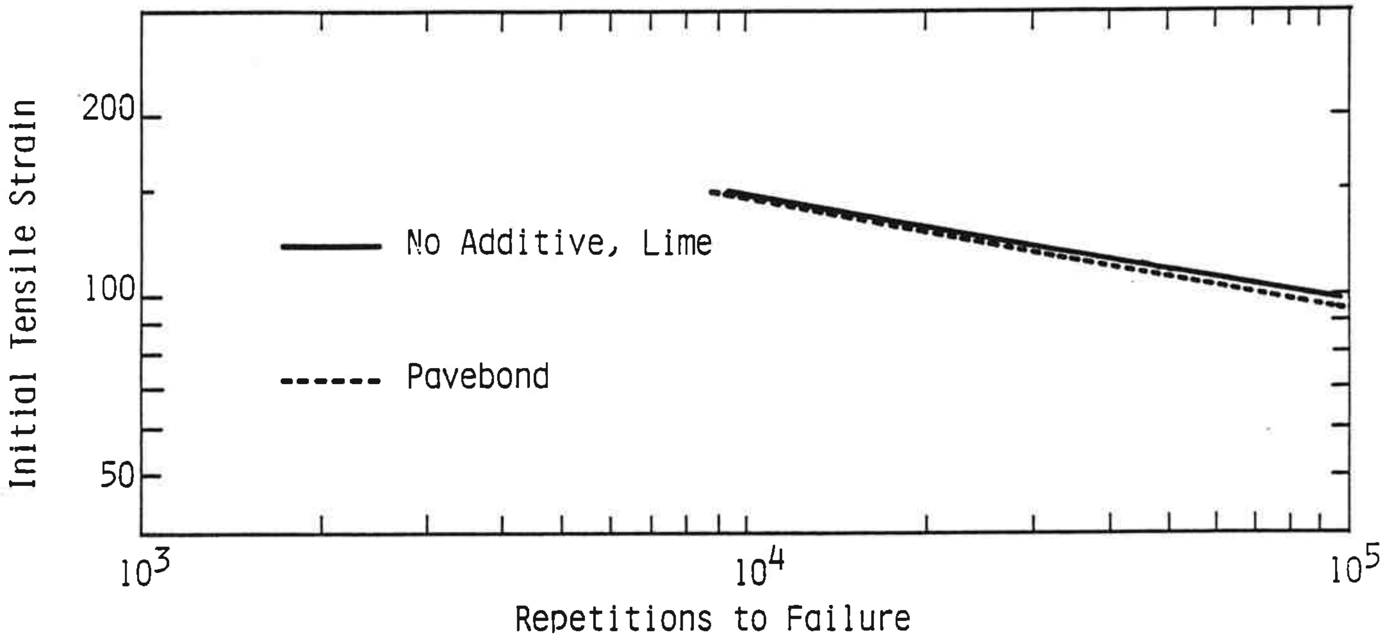


a. As Compacted

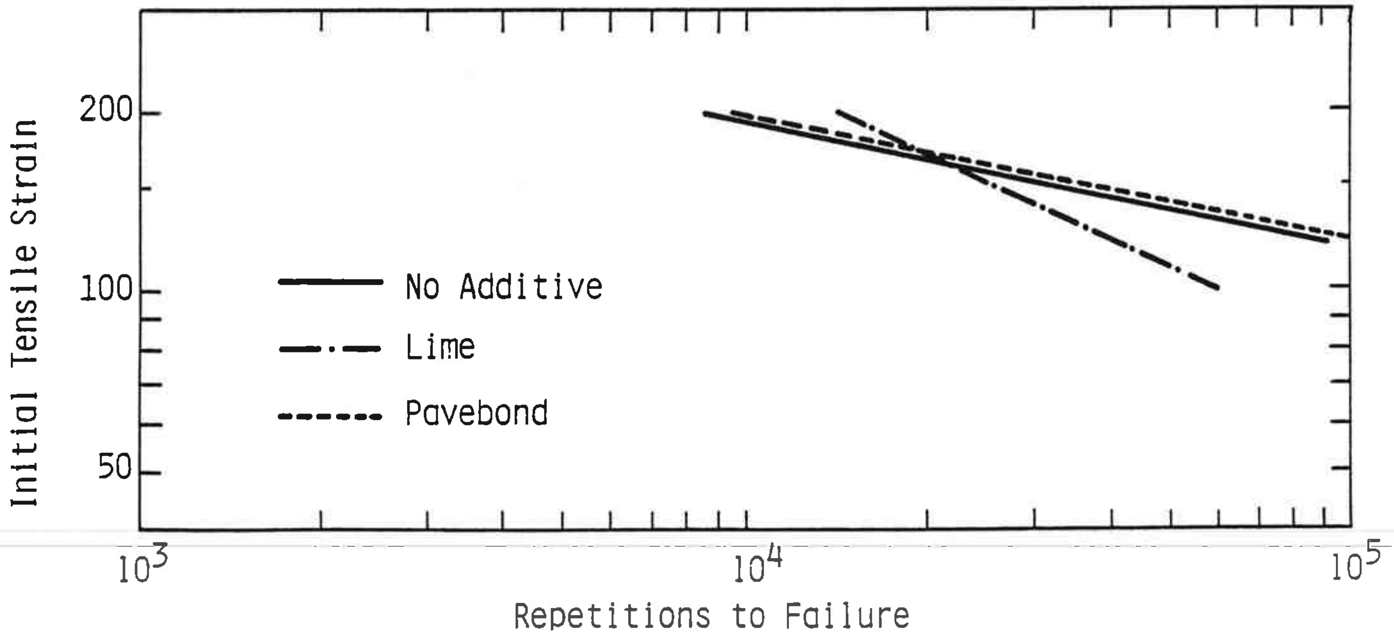


b. Conditioned

Figure 4.8 - Effect of Additives without Moisture on Fatigue Life of North Oakland Sutherlin Project



a. As Compacted



b. Conditioned

Figure 4.9 - Effect of Additives with Moisture on Fatigue Life of North Oakland-Sutherlin Project

4.5 Permanent Deformation

Vertical compressive permanent deformation was measured during the fatigue test using a dial gauge. The vertical permanent strain was calculated from the vertical permanent deformation according to Eq. (3.6). For each test, the relationship between vertical permanent strain and number of load repetitions appears to be linear on log-log scale. It is possible to express the vertical permanent deformation as a function of repetitions:

$$\varepsilon_c = I(N)^s \tag{4.1}$$

where:

ε_c = Compressive permanent vertical strain,

I,s = Regression constants, and

N = Number of load repetitions.

Constants I and s, computed from the test results, are presented in Table 4.6. Nonconsistent values (early readings and readings close to failure) were not included in the linear regression. Figures 4.10 through 4.15 illustrate the effects of various variables on permanent deformation at ε_t of 100 microstrain for the Warren-Scappoose project and ε_t of 150 microstrain for the North Oakland-Sutherlin project.

Table 4.6. Permanent Deformation Data ($\varepsilon_c = I(N)^s$)

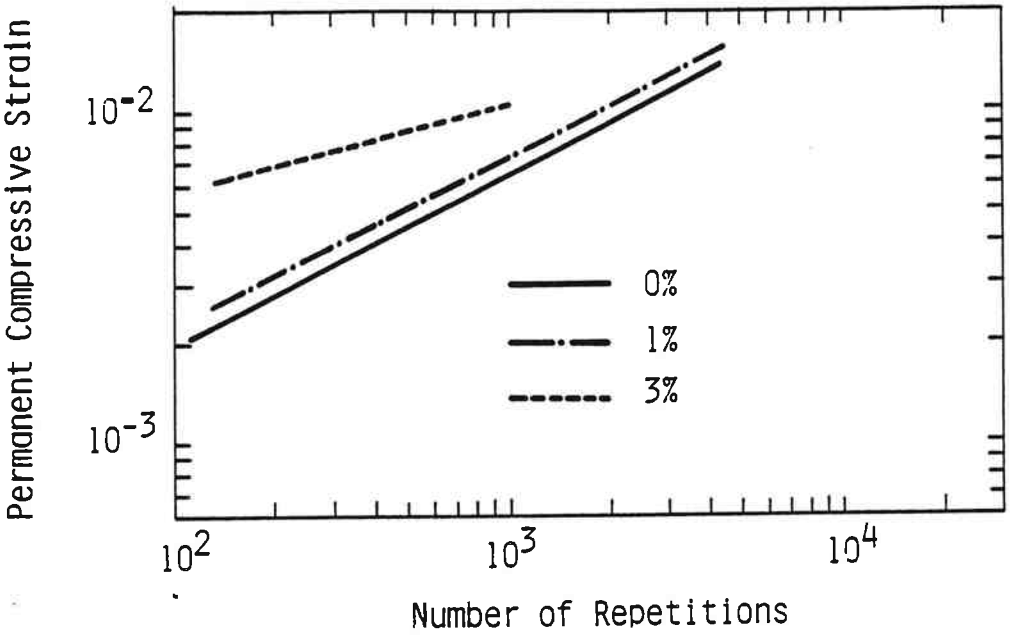
a. Warren-Scappoose

	As-Compacted			Conditioned		
	Tensile Strain Level ($x10^{-6}$)	I ($x10^{-4}$)	S	Tensile Strain Level ($x10^{-6}$)	I ($x10^{-4}$)	S
1	50	3.22	.338	50	3.25	.356
	100	1.92	.509	100	2.12	.452
	150	5.04	.485	150	0.75	.650
2	50	4.09	.309	50	5.51	.254
	100	3.27	.409	100	1.23	.555
	150	5.05	.516	150	.30	.916
3	50	3.87	.329	50	1.53	.433
	100	0.43	.701	100	9.56	.341
	150	2.38	.591	150	8.91	.419
4	50	3.24	.365	50	4.37	.281
	100	2.33	.498	100	3.72	.406
	150	3.98	.533	150	19.50	.275
5	50	21.11	.213	50	3.30	.327
	100	20.30	.236	100	0.88	.584
	150	1.93	.632	150	1.58	.582
6	50	6.68	.248	50	4.09	.313
	100	6.61	.341	100	0.29	.719
	150	2.45	.487	150	4.29	.493
7	50	3.76	.329	50	0.82	.464
	100	1.84	.527	100	6.90	.324
	150	0.65	.794	150	4.42	.469

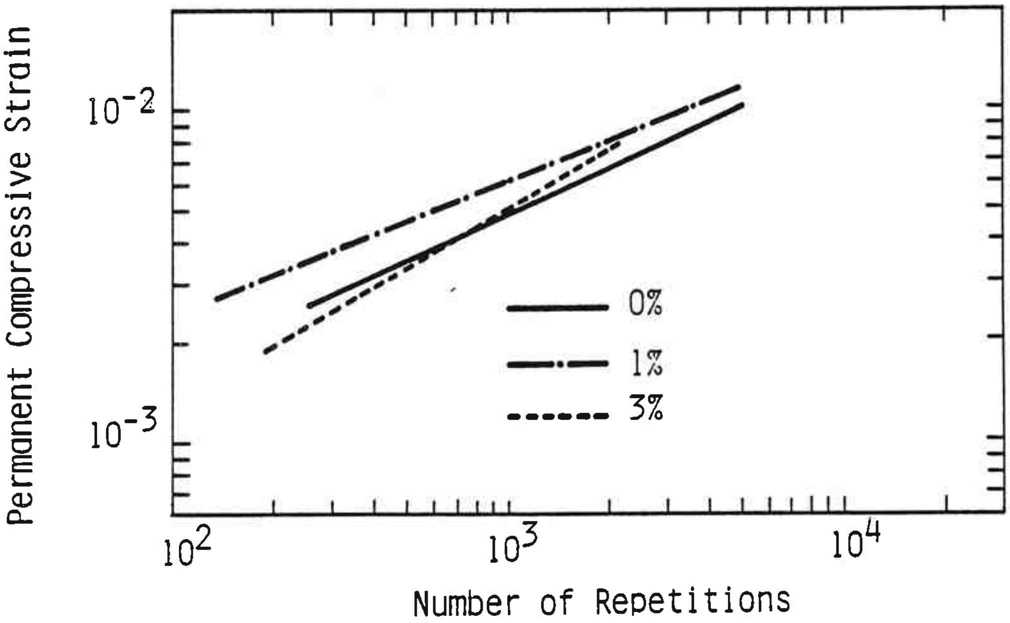
Table 4.6. Permanent Deformation Data ($\varepsilon_c = I(N)^s$) (Continued)

b. North Oakland-Sutherlin

	As-Compacted			Conditioned		
	Tensile Strain Level ($\times 10^{-6}$)	I ($\times 10^{-4}$)	S	Tensile Strain Level ($\times 10^{-6}$)	I ($\times 10^{-4}$)	S
1	50	0.821	.510	100	6.61	.381
	100	7.59	.359	125	3.16	.503
	150	6.49	.424	150	4.48	.521
2	50	0.99	.474	100	5.40	.434
	100	2.96	.382	125	8.20	.452
	150	4.75	.355	150	8.25	.380
3	50	2.14	.330	100	2.75	.485
	100	3.98	.326	125	10.69	.314
	150	5.64	.410	150	5.81	.463
4	50	2.01	.368	100	7.94	.355
	100	3.77	.388	125	7.24	.417
	150	3.77	.463	150	6.82	.393
5	50	13.44	.196	125	6.13	.389
	100	5.14	.401	150	6.32	.418
	125	2.27	.502	200	8.18	.376
	150	5.17	.456			
6	100	6.89	.320	100	3.04	.382
	125	5.84	.330	150	3.98	.396
	150	8.08	.307	200	7.64	.359
7	100	12.64	.262	100	3.87	.400
	125	4.16	.429	125	5.00	.373
	150	4.57	.474	150	3.64	.465
				200	3.57	.545

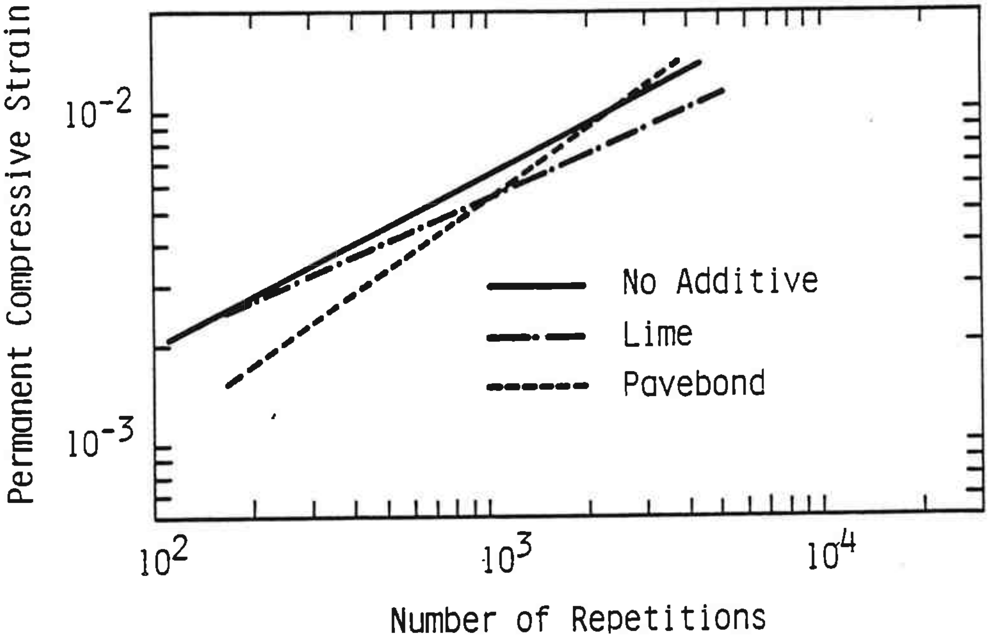


a. As Compacted

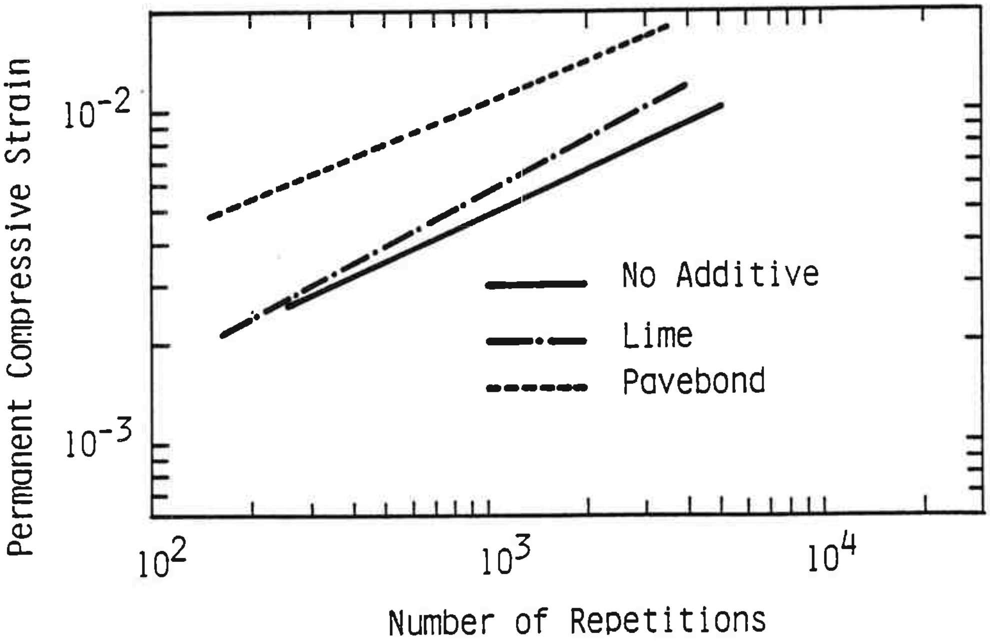


b. Conditioned

Figure 4.10 - Effect of Moisture on Permanent Deformation of Warren-Scappoose Project at ε_t of 100 Microstrain

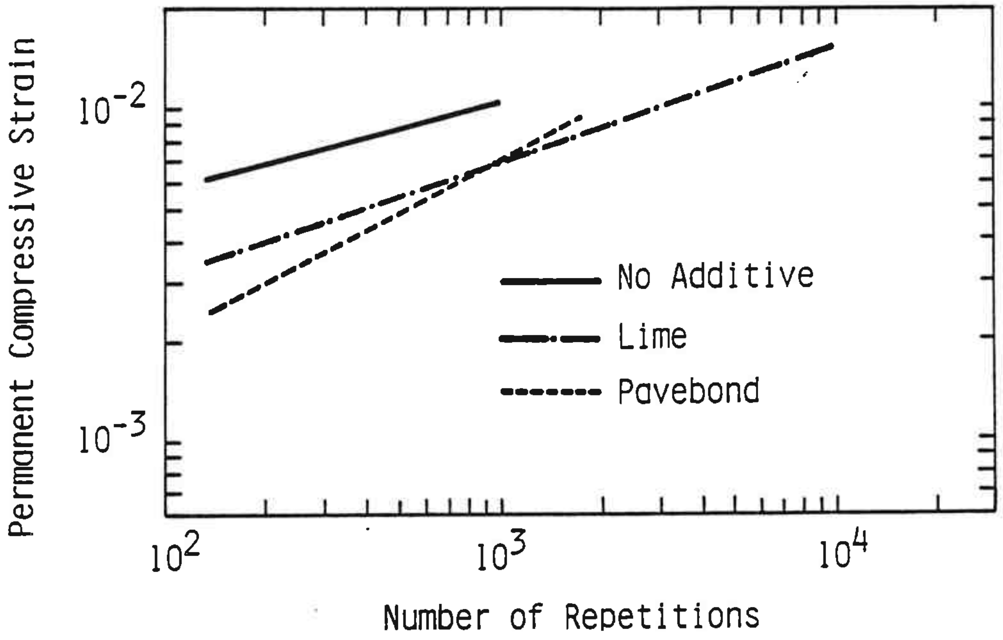


a. As Compacted

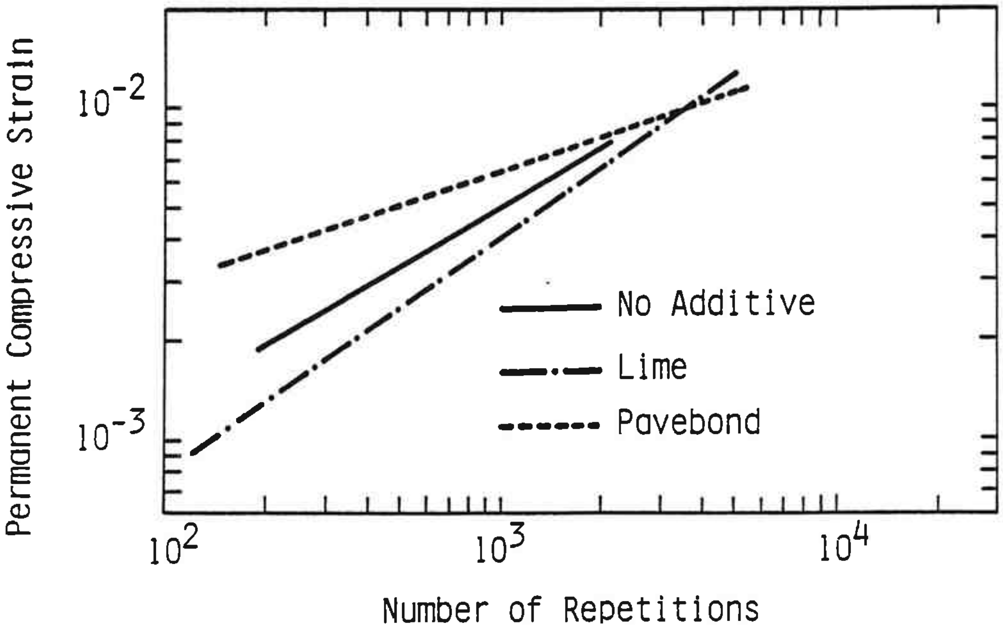


b. Conditioned

Figure 4.11 - Effect of Additives without Moisture on Permanent Deformation of Warren-Scappoose Project at ε_t of 100 Microstrain

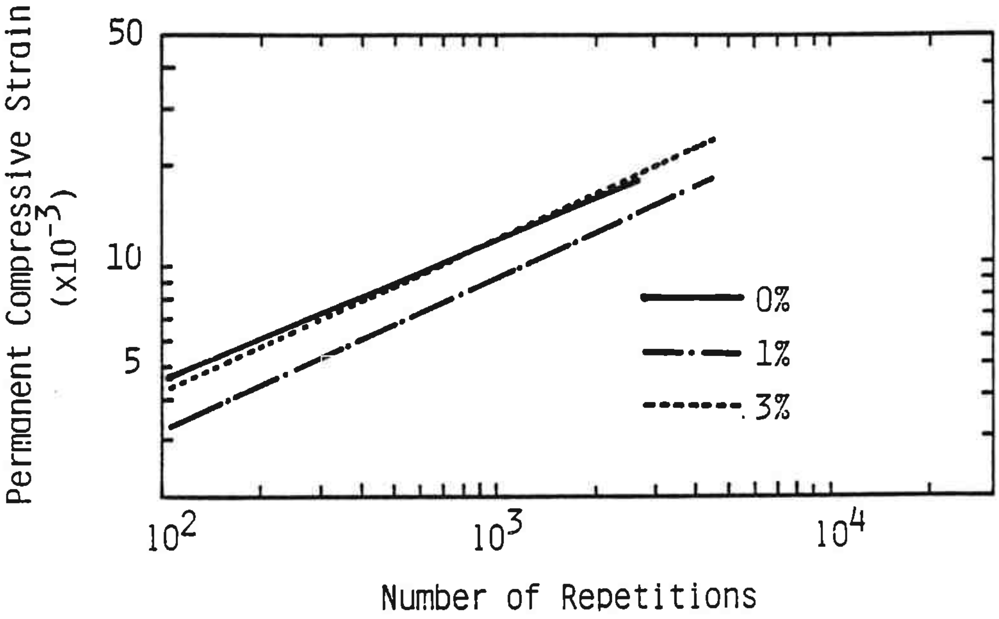


a. As Compacted

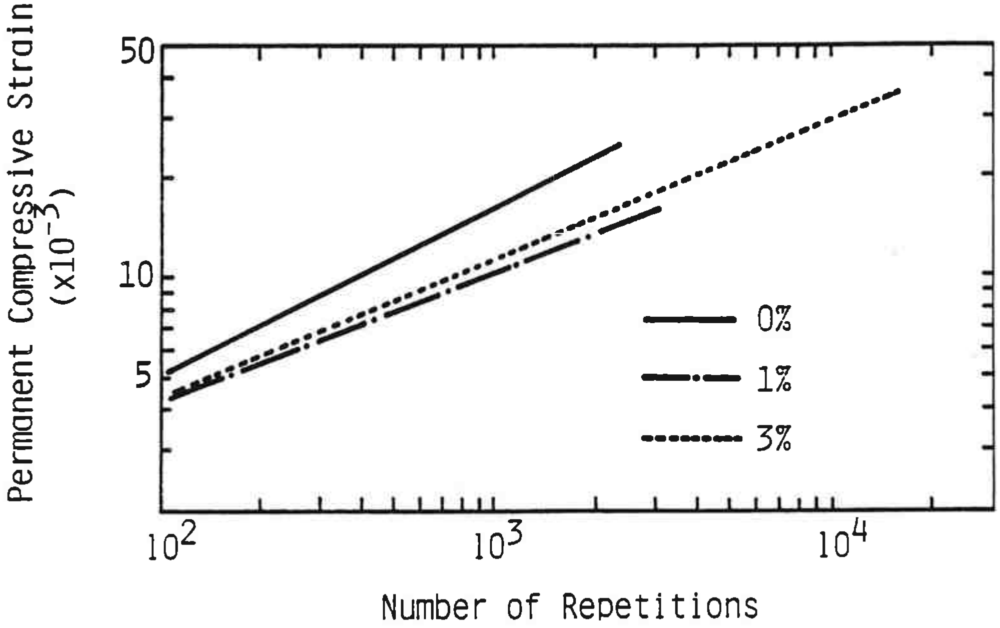


b. Conditioned

Figure 4.12- Effect of Additives with Moisture on Permanent Deformation of Warren-Scappoose Project at ε_t of 100 Microstrain

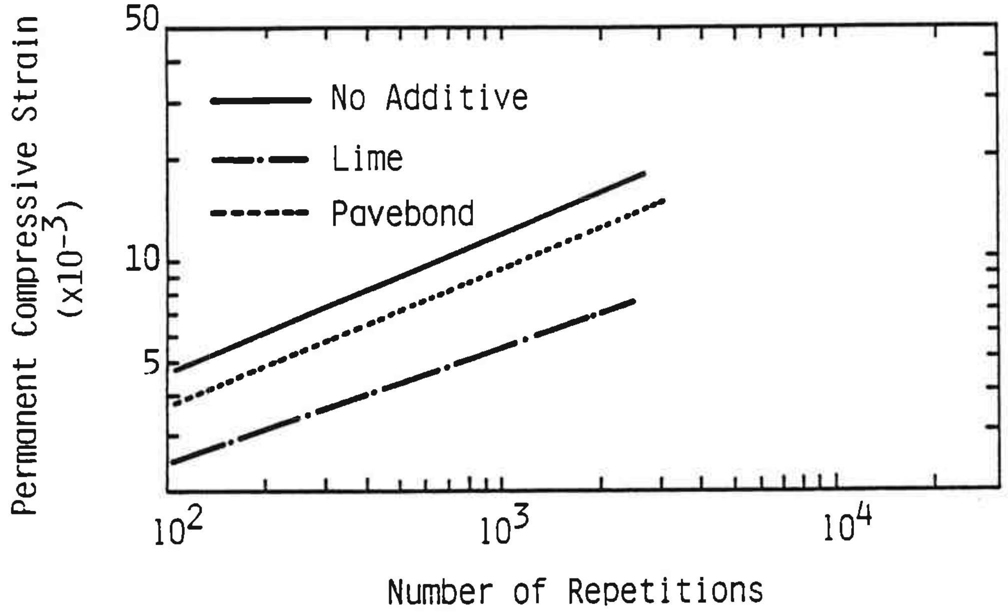


a. As Compacted

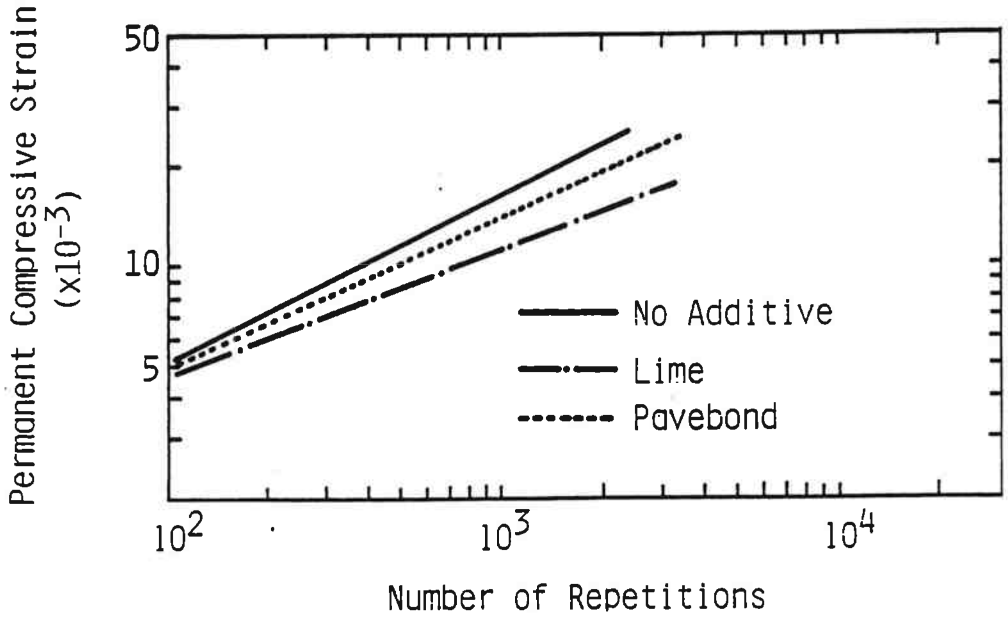


b. Conditioned

Figure 4.13 - Effect of Moisture on Permanent Deformation of North Oakland-Sutherlin Project at ε_t of 150 Microstrain

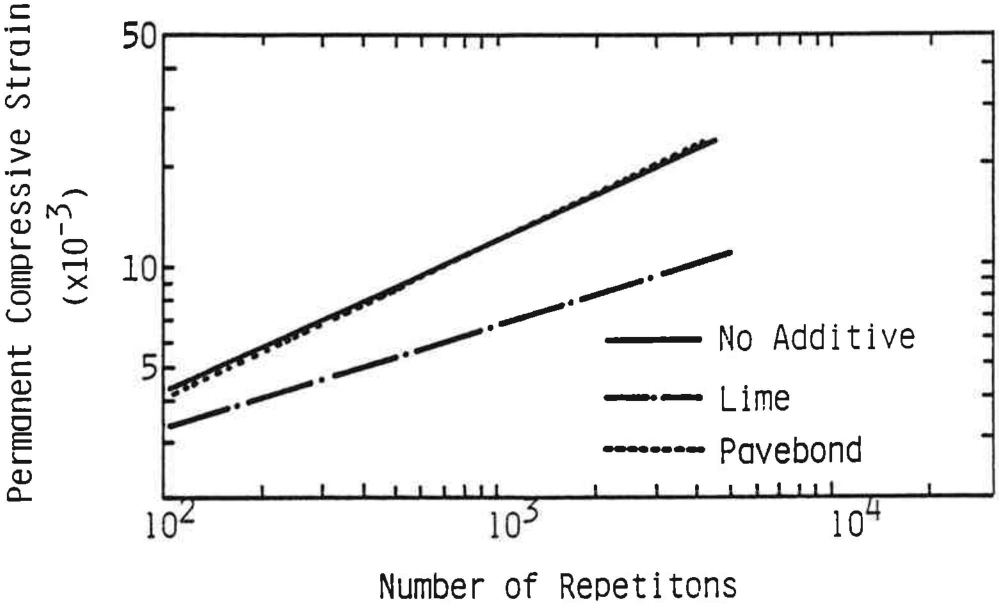


a. As Compacted

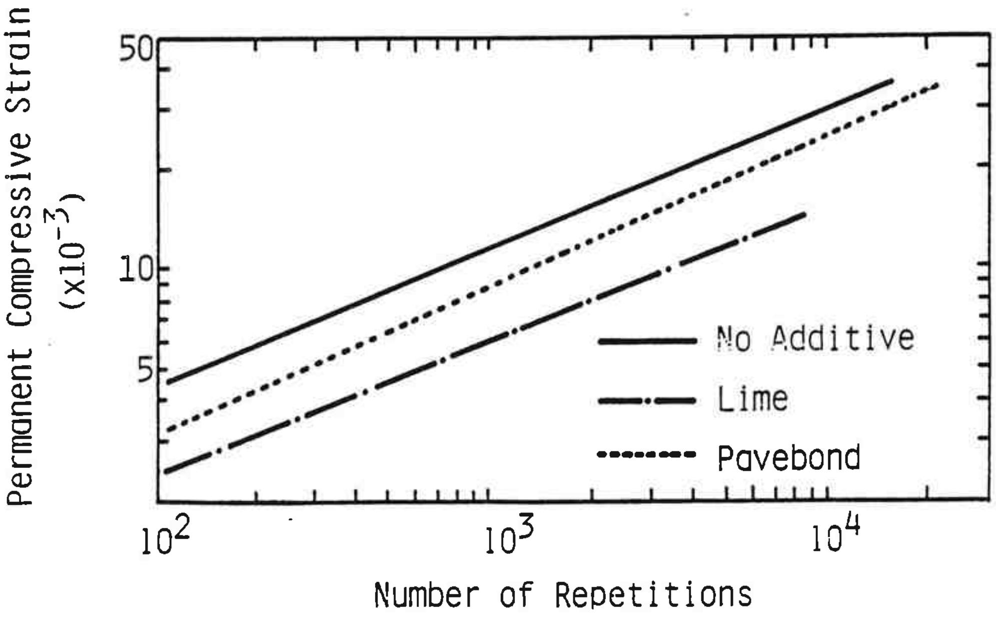


b. Conditioned

Figure 4.14 - Effect of Additives without Moisture on Permanent Deformation of North Oakland-Sutherlin Project at ε_t of 150 Microstrain



a. As Compacted



b. Conditioned

Figure 4.15 - Effect of Additives with Moisture on Permanent Deformation of North Oakland-Sutherlin Project at ε_t of 150 Microstrain

5.0 DISCUSSION OF RESULTS

The results are discussed below in three major parts: first, the results of the mix design; second, the effects of moisture on mixtures with no additives; and finally, the effects of additives on mixtures with and without moisture. It should be noted that the moisture content refers to the amount incorporated during mixing, whereas "conditioning" refers to a test procedure (8) to evaluate durability of mixtures. In evaluating the results, the effect of moisture in "as-compacted" specimens (those involving no conditioning) is of much less significance than in "conditioned" specimens. The effect of conditioning is assessed by comparing properties measured with "as compacted" and "conditioned specimens" such as a retained modulus ratio.

5.1 Mix Design

For the Warren-Scappoose project, the specimen mixed with 3% moisture obtained the lowest index of retained strength, as presented in Table 4.1. The moduli values of both as-compacted and conditioned specimens decrease as the moisture content increases. For moist mixtures, specimens mixed with additives obtain much higher index of retained strength than those without additives. It should be noted that the retained modulus ratio of whole mix design increases with increasing of the asphalt content.

Without additives, mixtures with 3% moisture show the highest index of retained strength for the North Oakland-Sutherlin project. With and without moisture specimens mixed with Pavebond Special obtained the highest index of retained strength. As with the Warren-Scappoose project, moist mixtures with additives show much higher index of retained strength than those without additives. It is noted, again, that the retained modulus ratio for the North

Oakland-Sutherlin project increases as the asphalt content increases. In general, the moduli values of conditioned specimens increase as the asphalt content increases, while those of as-compacted specimens decrease with increasing asphalt content.

For the Warren-Scappoose project, the index of retained strength of each mix variable is greater than the retained modulus ratio. This trend is shown again for the mixtures without moisture of the North Oakland-Sutherlin project, while with moisture the trend is irregular or the retained modulus ratio is greater than the index of retained strength, particularly with additives. The result of the comparison between two parameters for measuring the moisture susceptibility of mixtures, which are the index of retained strength and retained modulus ratio obtained after different treatment, recommends that the retained modulus ratio from Lottman's conditioning procedure is preferred to the index of retained strength for determining the moisture susceptibility of mixtures and for selecting adequate additives.

From the results of mix design, it is recommended that optimum asphalt content for each project should be determined on the basis of the properties of conditioned specimens as well as those of as-compacted specimens.

5.2 Effect of Moisture for Mixtures Without Additives

5.2.1 Resilient Modulus Results

The effect of moisture on modulus for both projects is shown in Figure 4.1. For the Warren-Scappoose project, it is quite apparent from the test results that modulus and retained modulus ratio decrease with increasing moisture content as discussed in the previous section. The average modulus of as-compacted specimens with 3% moisture content is 208 ksi, which is 40% of the average modulus of as-compacted speceimens with no moisture. Also, it is noted that the retained modulus ratio of mixtures with 3% moisture content is only 0.43 as indicated in Table 4.4.

The North Oakland-Sutherlin project exhibits different behavior than the Warren-Scappoose project. Not only the average modulus of the as-compacted and conditioned specimens but also retained modulus ratio increases as the moisture content increases up to 1% and then decreases with increasing moisture. This behavior is due in part to decreasing air voids from 8.34% for specimens without moisture to 5.72% for specimens with 1% moisture as shown in Table 4.3. Above 1% moisture, the benefits from low air voids, including high modulus value and retained modulus ratio, may be offset by the moisture damage due to high water content.

For the North Oakland-Sutherlin project which used low-quality aggregate, the average retained modulus ratio of specimens with no moisture is lower than that for the Warren-Scappoose project which used good-quality aggregate. Similar results were obtained in the previous study (28,29). However, with 3% moisture content, the retained modulus ratio for the North Oakland-Sutherlin project is almost double that for the Warren-Scappoose project. This trend is attributed to different asphalt cement contents, 5% for the Warren-Scappoose project and 6.2% for the North Oakland-Sutherlin project as well as a big difference of air voids indicated in Table 4.3.

The above results may be explained by considering the effects of asphalt quantity as indicated by Schmidt and Graf (12) in Figure 2.3 and aggregate quality on mixture resilient modulus. High stiffness (resilient modulus) is achieved by a high aggregate density, with pronounced interparticle friction and interlock. Aggregate density increases to a maximum (dependent on gradation) as the fluids content in a mixture increases until a maximum is reached, after which further additions of fluids, either moisture or asphalt cement, causes a reduction in density, like the interaction between soil and water. Maximum aggregate density may not correspond to maximum stiffness since asphalt contributes to mixture stiffness adversely once an aggregate density is reached that will mobilize interparticle friction and aggregate interlock. Addition of further asphalt will reduce aggregate interlock and interparticle friction. The presence of moisture at the time of mixing will contribute to additional fluids in the mixture and will therefore reduce the compactive effort necessary to achieve maximum aggregate density, as explained by Schmidt et al. (10) (see Chapter 2). For absorptive aggregates, free moisture in the aggregate leaves more asphalt available for coating the aggregate. However, the bond between an asphalt cement and aggregate will usually be adversely affected by moisture, the severity depending on the aggregate and asphalt chemistry. This bond may not be very influential on mixture stiffness once the mixture becomes dry and stays dry (12); however, the durability of the mixture may be significantly affected by wet-dry cycles or freeze-thaw cycles such as in the conditioning procedure used in this study (8).

The phenomena outlined above are all exhibited by the two projects in this study. For the specimens from the Warren-Scappoose project, the modulus decreases with increased fluids content due to loss of interparticle friction and interlock, since there was no increase in density of the mixture (Table 4.3), as would be expected with a gravel aggregate. The durability of this mixture becomes much worse as more moisture was present at mixing, probably due to weak bonding, low asphalt content and high voids in the mix.

For the specimens from the North Oakland-Sutherlin project the tendency for increased modulus with a small addition of moisture is probably due to increased aggregate density affected by improved workability, as would be expected with crushed rock aggregate with greater potential for improved packing than a gravel aggregate. Additional moisture increases the aggregate density and mix density (Table 4.3), but reduces interparticle interlock and friction and therefore the resilient modulus. This mixture is more durable than that from the Warren-Scappoose project due to the increased density and higher asphalt content, affected by improved workability.

An additional reason for the different behavior of the mixtures from the two projects is the absorption of the aggregate. The marginal aggregate from the North Oakland-Sutherlin project was much more absorptive and this could be an advantage in mixtures using moist aggregates where water might prevent asphalt absorption and thus render more asphalt available for coating. As reviewed in Chapter 2, moisture in aggregates would lower the asphalt absorption and, in effect, increase the volume of asphalt in the voids. Hence, air voids would be reduced. It should be noted that following the conditioning procedure, specimens from the Warren-Scappoose project had free water on the broken surface after fatigue test, whereas there was none on the surface of specimens from the North Oakland-Sutherlin project, indicating higher aggregate absorption but lower mixture absorption due to low air voids.

5.2.2 Fatigue Life Results

Fatigue test results can be presented in terms of repetitions to failure as a function of either the maximum tensile strain (Eq. (3.3)) as reviewed in Chapter 3, or the tensile stress (Eq. 3.4)) which is calculated from the applied load to a specimen and the dimension of a specimen directly (Eq. (5.1))

$$\sigma_t = \frac{2P}{\pi Dt} \tag{5.1}$$

where σ_t = Tensile stress, psi,

P = Load applied, pounds,

t = Thickness of specimen, inches, and

D = Diameter of specimen, inches.

The tensile strain that would be induced in a pavement structure is a function of both the applied load and the modulus of the asphalt mixture. Under a given loading, the mix having the higher modulus would have a lower tensile strain than the mix with a lower modulus. The decrease of modulus produces an increase of strain in a mix. The resulting strain increase due to modulus decrease results in a fatigue life decrease (35). Therefore, fatigue results based on tensile strain cannot be directly compared unless the modulus is the same, or unless the laboratory data are evaluated in conjunction with pavement analyses, where the asphalt mixture is included in a typical pavement structure (50).

The laboratory fatigue tests results can be interpreted using two approaches suggested by Barksdale (36). The elastic theory approach (42) involves using a suitable elastic layered theory, which makes several idealized assumptions, to calculate the tensile strain in the design pavement structure using the modulus of the asphalt concrete mix evaluated in the fatigue test. The repetitions of loading to cause failure of the pavement structure under the design load is then obtained directly from the experimentally evaluated fatigue curves presented in terms of tensile strain.

The method of intepretation of fatigue tests results based on applied load consists of determining for different mixes the repetitions required to cause failure by a constant repeated load applied to a specimen. The load method of interpretation gives a straight-forward, direct comparison of relative fatigue performance. From the standpoint of general pavement design, however, the strain approach is better than the load approach since the strain approach is suitable for use for widely varying conditions such as pavement geometry and condition of subgrade support.

In this study, both the strain approach calculated from applied load and the stress approach (rather than the load approach) are explored. Since the dimensions of specimens and temperature during a test are almost constant, better comparisons of relative performance would be obtained from the stress approach, which has direct relationship to load as shown in Eq. (5.2), and has a slightly lower, but still high, coefficient of determination (Table 5.1). In addition to the advantage of direct comparison, the stress approach could use the elastic theory, as presented by Gilmore et al. (5).

Figure 4.4 shows the effect of moisture on fatigue life for the Warren-Scappoose project using the strain approach. The fatigue lives of as-compacted specimens with 3% moisture for the Warren-Scappoose project are shorter than for specimens with no moisture or one percent moisture. Fatigue lives of as-compacted specimens with 1% moisture are longer than those with no moisture. After conditioning, specimens with 1% moisture again show the longest fatigue life.

For the North Oakland-Sutherlin project Figure 4.7 based on the strain approach shows that the fatigue lives of as-compacted specimens increase with increasing moisture content whereas those of conditioned specimens at zero moisture content and 1% moisture content are about the same with a substantial increase for 3%. Alternative fatigue plots are shown in Figure 5.1 where the number of load repetitions to failure at a measured tensile strain of 100

Table 5.1. Fatigue Data Based on the Stress ($N_f = C(\frac{1}{\sigma_t})^n$).

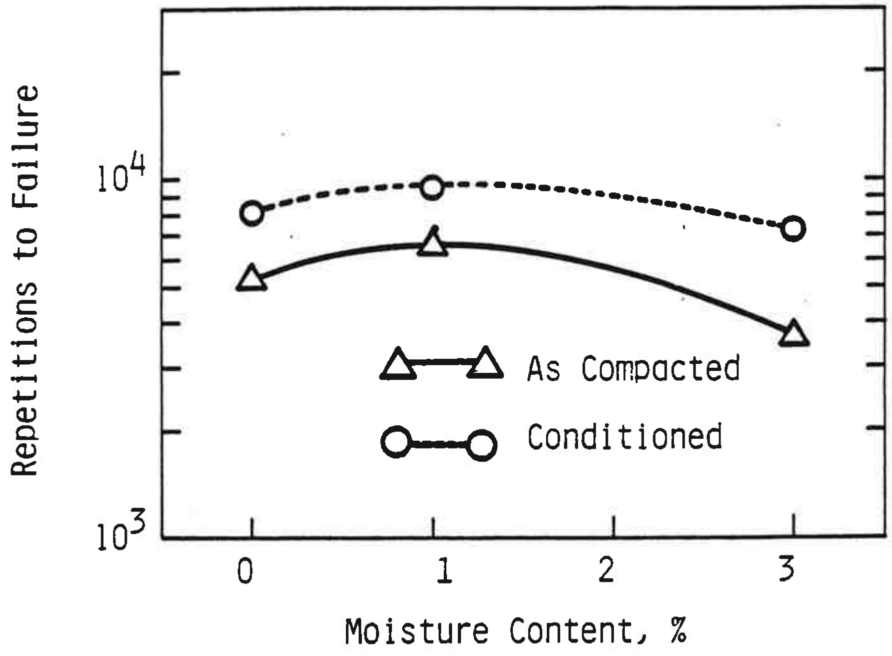
a. Warren-Scappoose

	As-Compacted			Conditioned		
	C	n	r^2	C	n	r^2
0% Moisture	1.339×10^8	3.104	.993	4.555×10^6	2.156	.924
1% Lime	2.223×10^8	3.153	.960	6.145×10^7	2.766	.883
0.5% Pavebond Special	4.012×10^7	2.621	.967	7.602×10^6	2.227	.916
1% Moisture	5.530×10^7	3.245	.915	7.415×10^6	2.401	.926
3% Moisture	2.778×10^5	1.837	.775	5.224×10^6	4.758	.892
3% Moisture/1% Lime	1.426×10^7	2.549	.876	2.290×10^7	2.485	.985
3% Moisture/0.5% Pavebond Special	2.342×10^5	1.805	.991	4.919×10^5	1.840	.999

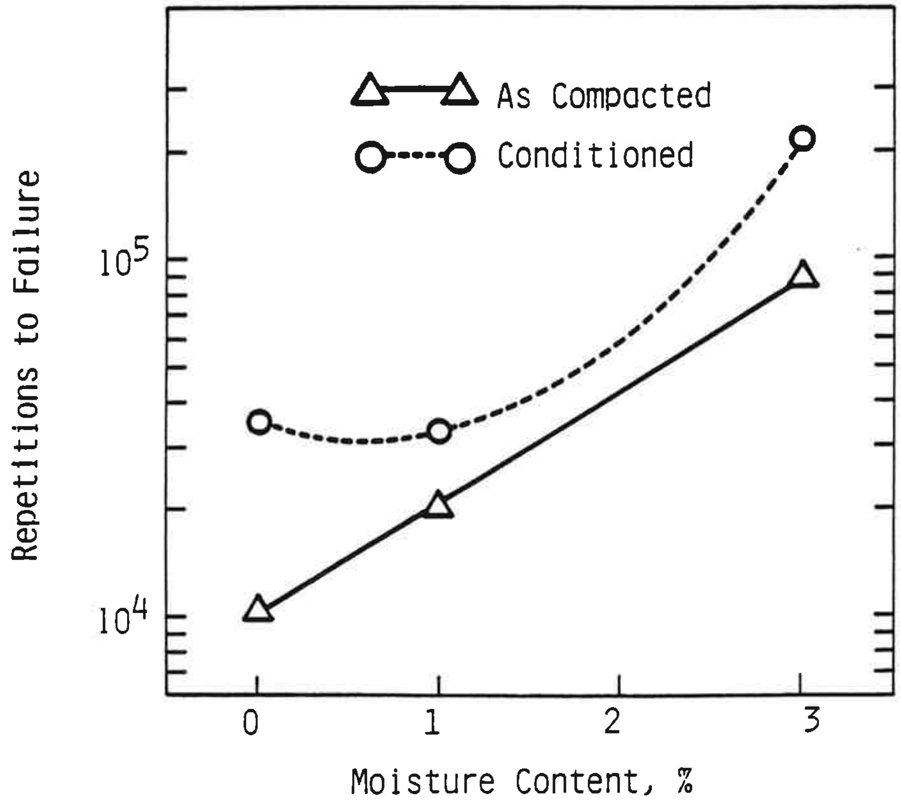
Table 5.1. Fatigue Data Based on the Stress ($N_f = C(\frac{1}{\sigma_t})^n$).

b. North Oakland-Sutherlin

	As-Compacted			Conditioned		
	C	n	r^2	C	n	r^2
0% Moisture	8.224×10^7	3.160	.994	1.254×10^8	3.034	.966
1% Lime	3.490×10^8	3.230	.884	4.589×10^9	3.971	.884
0.5% Pavebond Special	1.386×10^9	3.649	.986	6.186×10^{13}	6.611	.897
1% Moisture	2.163×10^9	3.759	.882	1.002×10^9	3.381	.973
3% Moisture	2.179×10^{11}	5.226	.995	5.592×10^7	2.397	.912
3% Moisture/1% Lime	4.538×10^8	3.226	.866	2.742×10^8	3.172	.913
3% Moisture/0.5% Pavebond Special	4.084×10^{10}	4.619	.929	9.145×10^9	4.194	.946



a. Warren-Scappoose

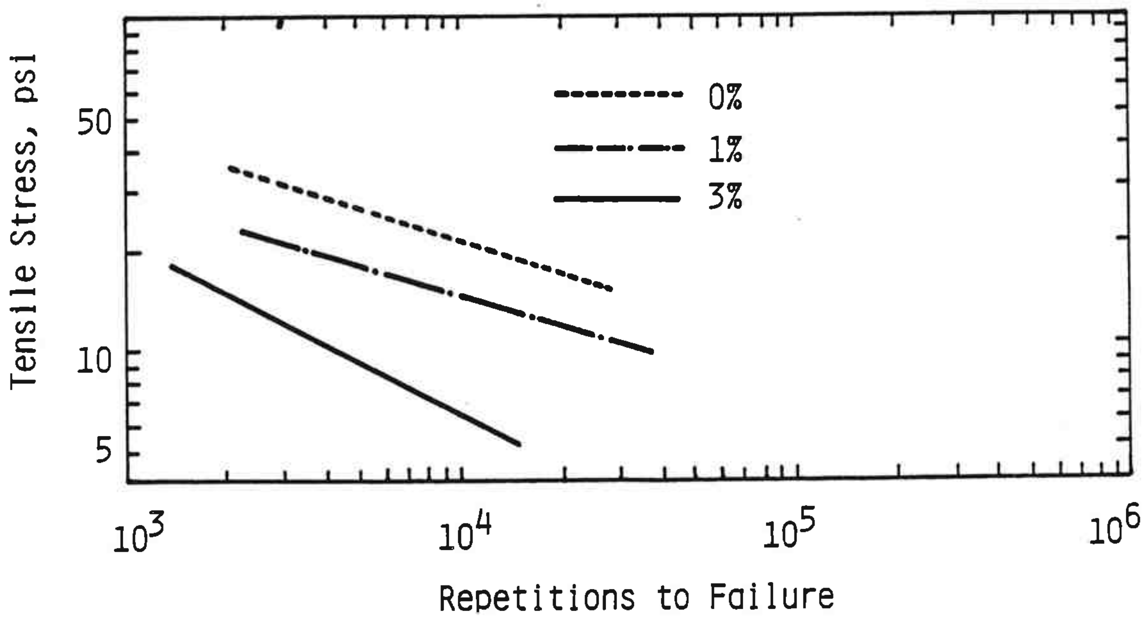


b. North Oakland-Sutherlin

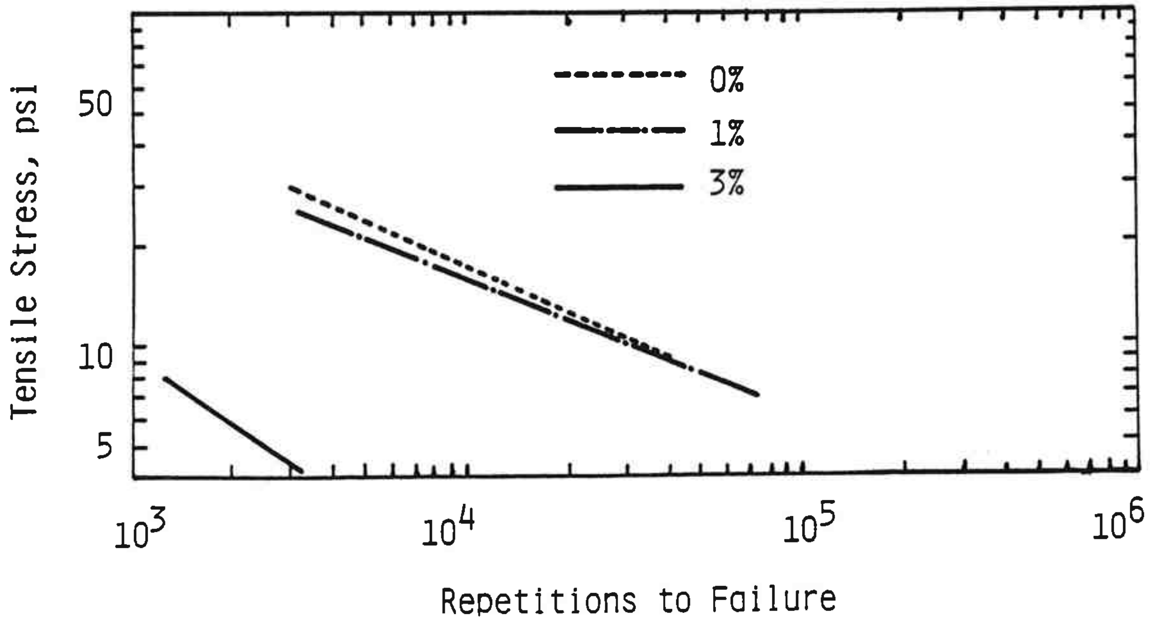
Figure 5.1 - Fatigue Life with Moisture at ε_t of 100 microstrain

microstrain are given for each project. These confirm the results reported above, and show quite clearly an "optimum" moisture content for the Warren-Scappoose project and an increase in fatigue life with moisture content for the North Oakland-Sutherlin project. For both projects fatigue lives were longer after conditioning for all moisture conditions (Figure 5.1) due to the reduced stiffness that occurred in all cases (Figure 4.1).

Figure 5.2 presents the effect of moisture on fatigue life for the Warren-Scappoose project based on the tensile stress. The trend shown in Figure 5.2 is clearly different from that shown in Figure 4.4. The moisture damage to the fatigue lives of mixtures is severe with increasing of moisture content. After conditioning, the fatigue lives of mixtures with one percent moisture which have low air voids are very close to those with no moisture. The results from Figure 5.2 affirm that modulus and air voids play predominant roles in determining the fatigue behavior of asphalt mixtures (31,40). Figure 5.3 shows a slightly different trend compared to Figure 4.7 for the North Oakland-Sutherlin project. As shown in Figure 4.7, however, moist specimens obtain much longer fatigue lives than the no moisture mix. The fatigue test results of the North Oakland-Sutherlin project shown in Figure 5.3 can be explained in terms of the air voids and modulus. For as-compacted mixtures, moduli values of mixtures with no moisture and 1% moisture do not show a big difference, but the fatigue behavior of those mixtures is much different, that is, with 1% moisture the mixtures obtain better fatigue performance. The specimens mixed with three percent moisture show the relatively best performance, due partially to the benefit from the low air voids and very small water absorption of mixtures during the conditioning phase as presented in Table 4.3. The different comparison methods, such as the stress approach and

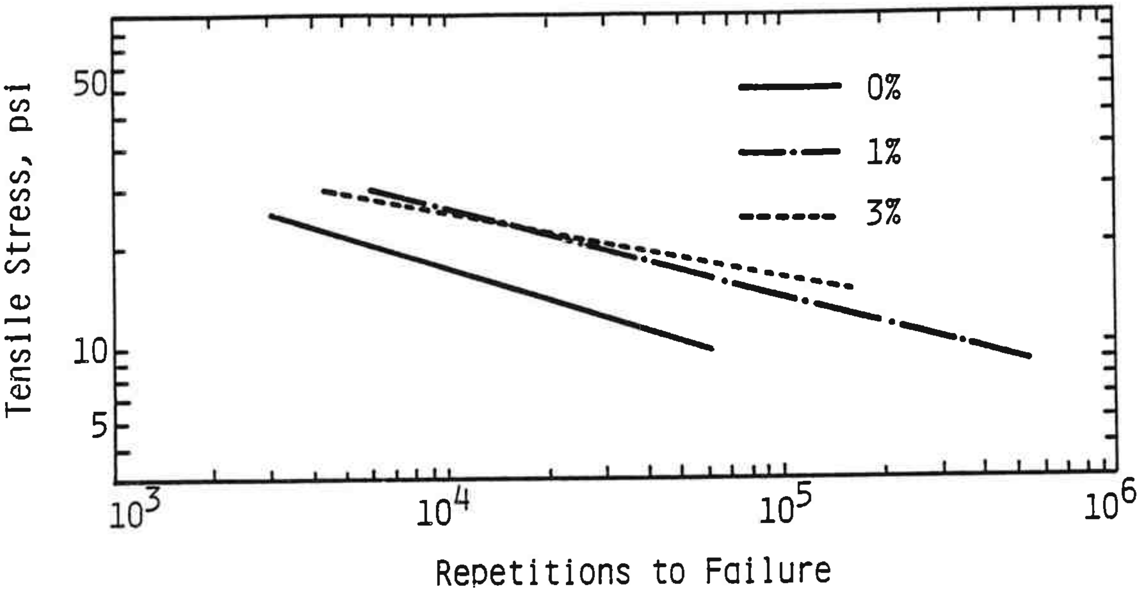


a) As-Compacted

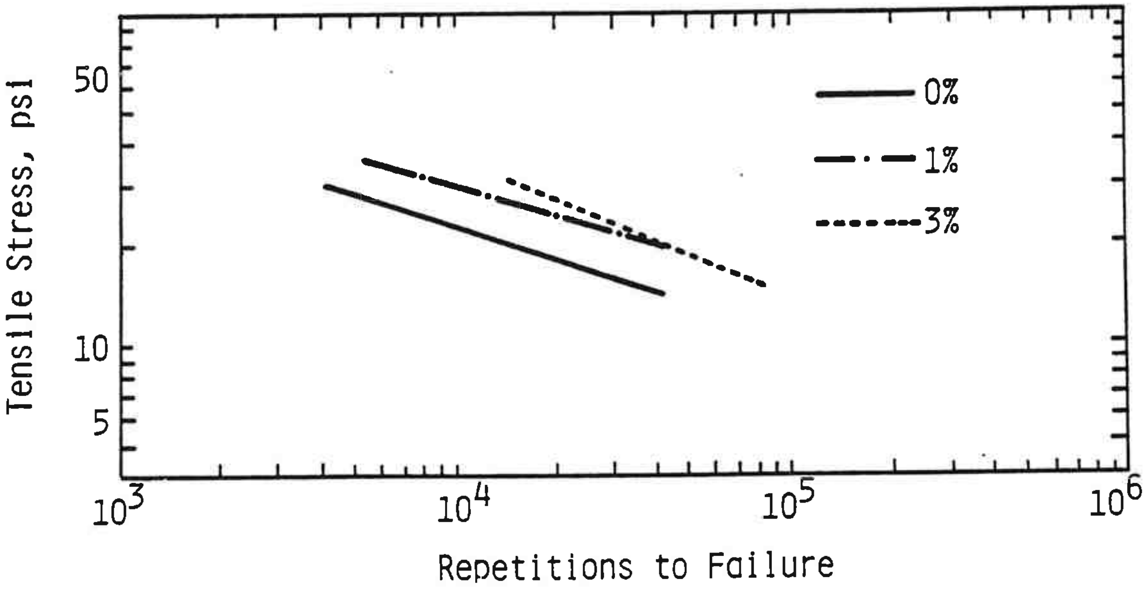


b) Conditioned

Figure 5.2 - Effect of Moisture on Fatigue Life of Warren - Scappoose Project - Based on the Stress



a) As-Compacted



b) Conditioned

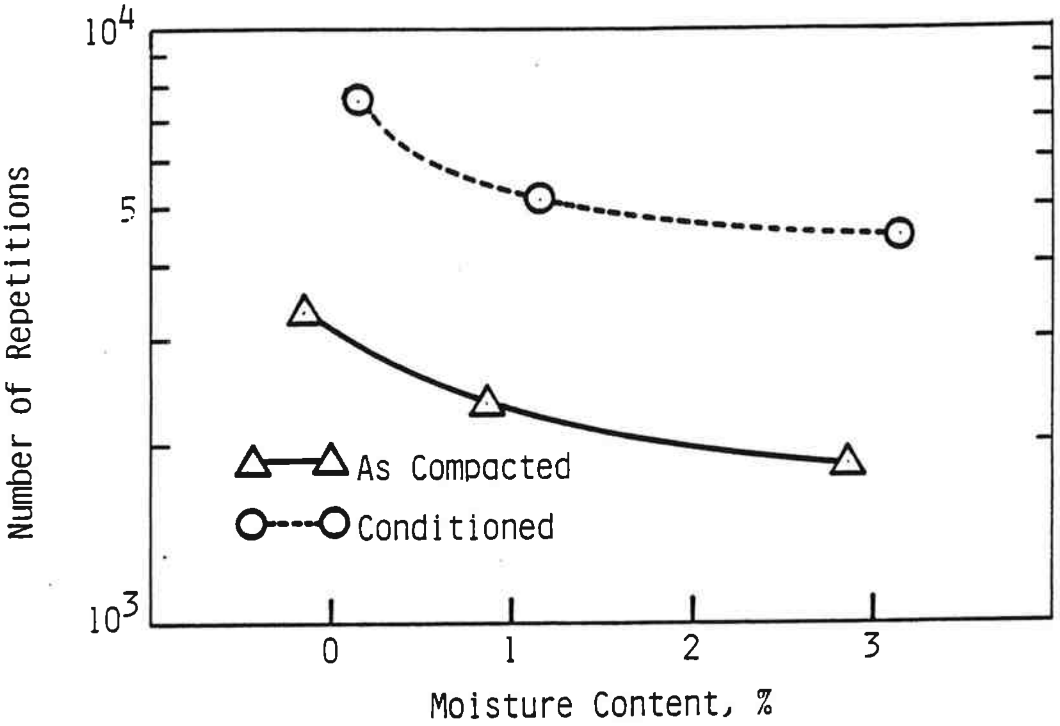
Figure 5.3 - Effect of Moisture on Fatigue LIfe of North Oakland - Sutherlin Project - Based on the Stress

the strain approach, result in different interpretation of fatigue results of mix, which depends on the modulus of the mix.

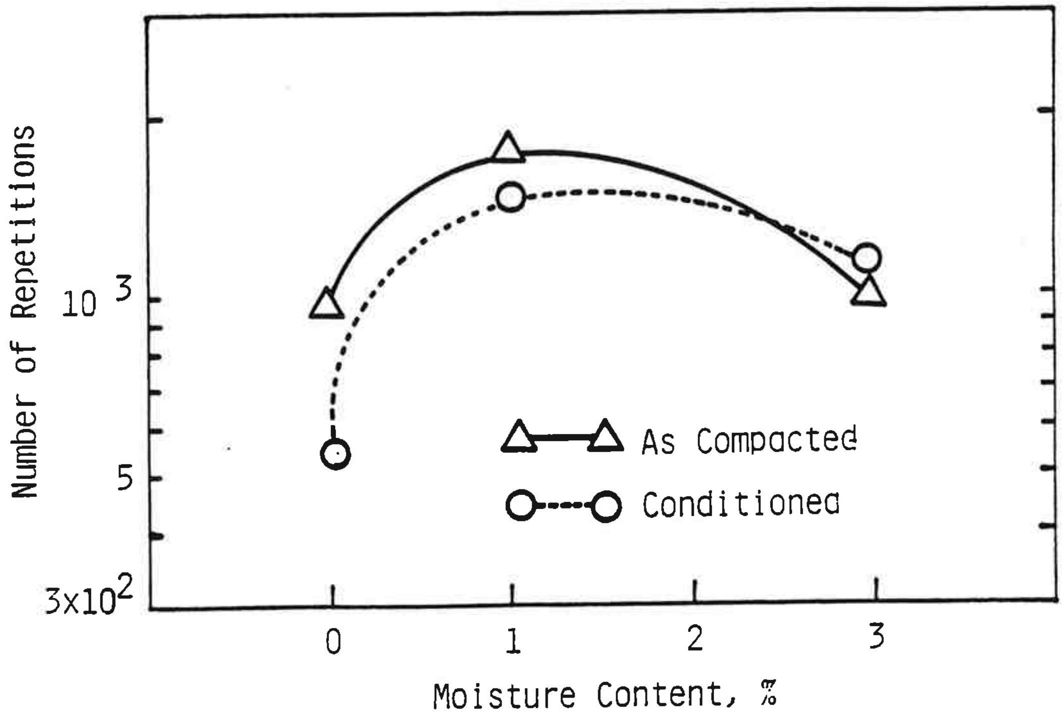
5.2.3 Permanent Deformation Results

The effect of moisture on permanent deformation of mixtures is presented in Figure 4.10 for the Warren-Scappoose project at tensile strain of 100 microstrain and Figure 4.13 for the North Oakland-Sutherlin project at tensile strain of 150 microstrain. For the Warren-Scappoose project, the as-compacted specimens with 3% moisture again performed the worst (less repetitions are required to reach a fixed compressive strain) and specimens with 0% moisture performed the best, (more repetitions are required to reach a fixed compressive strain) as shown in Figure 4.10. After conditioning, specimens with 1% moisture gave the worst results. For the North Oakland-Sutherlin project, as-compacted specimens with 1% moisture performed best, while those with 0% moisture performed worst, as demonstrated in Figure 4.13. After conditioning, the results again show that specimens with 1% moisture gave the best results while those with 0% moisture performed worst.

A comparison between the repetitions required to reach a vertical compressive strain of 1.2% for as-compacted and conditioned specimens, at a fixed initial tensile strain of 100 microstrain for the Warren-Scappoose project and 150 microstrain for the North Oakland-Sutherlin is shown in Figure 5.4. This level of permanent strain was chosen because it was close to the maximum recorded in all tests except those for specimens with 3% moisture for the Warren-Scappoose project. For the Warren-Scappoose project, the number of repetitions required decreased with increasing moisture content as noted with the results of modulus and fatigue life based on the tensile stress. The conditioned specimens required higher numbers of repetitions than as-compacted



a. Warren-Scappoose (ε_t of 100 Microstrain)



b. North Oakland-Sutherlin (ε_t of 150 Microstrain)

Figure 5.4 - Number of Repetitions with Moisture at ε_c of 1.2%

specimens because this comparison was based on the strain level of fatigue test as shown in fatigue life figure based on tensile strain (Figure 4.4). For the North Oakland-Sutherlin project, the greatest number of repetitions were obtained at 1% moisture content, and the conditioned specimens performed worse than the as-compacted specimens.

The above results are again related to the stiffness, voids, and asphalt content of the mixtures, although the results shown in Figure 5.4 for the Warren-Scappoose project are difficult to resolve. Stiffness is a major influence on permanent deformation resistance (38) and, therefore, the trend of decreasing resistance with decreasing stiffness is to be expected. However, the better performance of the conditioned specimens which were of lower stiffness (Figure 4.1) is not logical. This result can be explained by the comparison method based on the tensile strain level (100, 150 microstrain) rather than the stress level. Also, this anomaly may be due to the diametral mode of testing which is most suitable for stiffness and fatigue testing, but during tests the permanent strain is significantly influenced by various geometric and loading factors as well as the mixture variables. During tests it was found that the diametral permanent deformation test could be affected by local segregation or the presence of large aggregate as indicated by Wallace and Monismith (51). It should be noted that for the range of load repetitions used in the tests, the permanent strain for conditioned specimens is lower than for the as-compacted specimens (Figure 4.10) from the Warren-Scappoose project. The behavior of the specimens from the North Oakland-Sutherlin project is as expected with the stiffest mixtures performing best.

5.2.4 Summary - Effect of Moisture for Mixtures Without Additives

In summary, the effect of 3% mixture moisture on mix performance was most detrimental, particularly for the Warren-Scappoose project, but at 1% moisture content, mixtures from the North Oakland-Sutherlin project obtained better performance than mixtures with zero moisture content. With moisture, the North Oakland-Sutherlin project shows better performance than the Warren-Scappoose project which is largely because of improved stiffness due to smaller air voids and better durability due to richer asphalt content (39,40). It is found that it is difficult to compare the results of fatigue and permanent deformation based on the tensile strain due to different moduli values. The absorption of aggregate plays a predominant role in determining the air voids of moist mixtures resulting in the performance of mixtures.

5.3 Effect of Additives

5.3.1 Resilient Modulus Results

A major part of the testing program was aimed at evaluating the effect of lime (1%) and Pavebond Special (0.5%) on the performance of asphalt mixtures. The effect of additives on modulus for mixtures with no moisture is presented in Figure 4.2. For both projects, introduction of additives increases the modulus of as-compacted specimens very slightly. After conditioning, specimens with additives obtained a much higher modulus than the "no treatment" specimens and mixtures with 1% lime obtained the highest modulus.

With 3% moisture, the increase of modulus and retained modulus ratio by lime is substantial for the Warren-Scappoose project, and there is an improvement in retained modulus as shown in Table 4.4 and Figure 4.3. For the North

Oakland-Sutherlin project, the moduli of as-compacted and conditioned specimens with no additives are about the same as those with lime or Pavebond Special.

For the Warren-Scappoose project, without moisture there is little benefit from use of additives except with conditioned specimens. However, for mixtures with moisture, the effect of lime is superior to that of Pavebond Special, as indicated by the modulus and retained modulus ratio. For the North Oakland-Sutherlin project, there is little benefit shown from use of additives. However, the retained modulus ratios increase with introduction of additives.

For the mixtures with lime, the retained modulus ratios of the mixtures with moisture for both projects are greater than those with no moisture. This result indicates that lime is effective with the presence of moisture (2). It is noted that the retained modulus ratio increase of moist mixtures with Pavebond Special for the North Oakland-Sutherlin project is much greater compared to that of no moisture mixtures. This result can be explained in terms of air void. As presented in Table 4.3, air voids of moist mixtures with Pavebond Special for the Warren-Scappoose project is 10.05%, while that for the North Oakland-Sutherlin project is only 2.25%. Therefore, the air voids should be emphasized to reduce the moisture-induced damage.

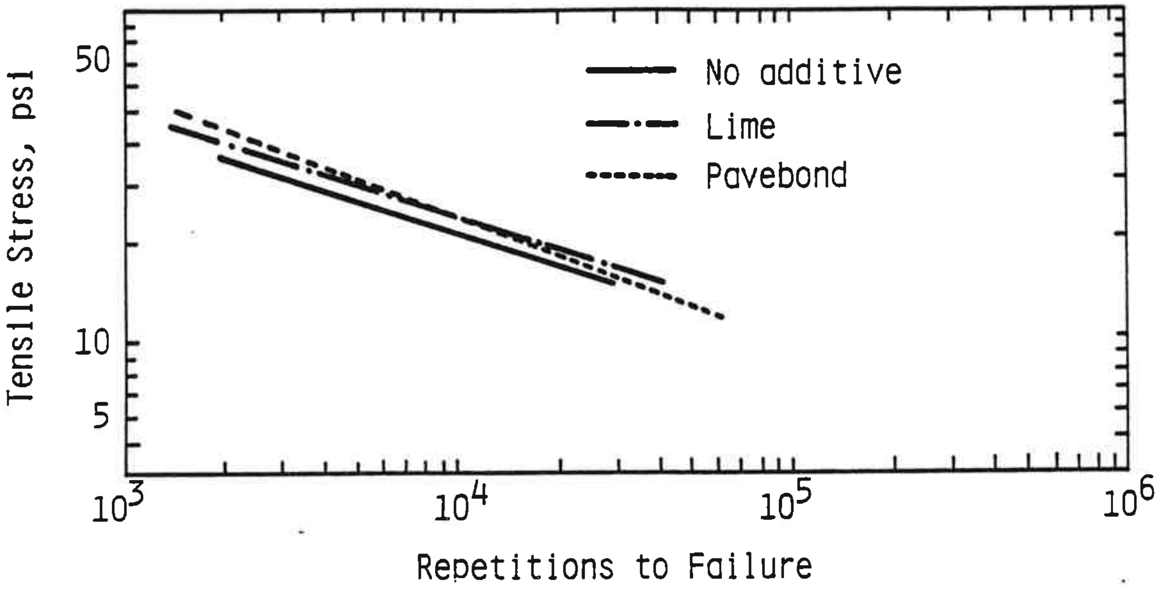
It can be seen that there is a partial stiffening effect on the specimens without moisture for the North Oakland-Sutherlin project and with moisture for the Warren-Scappoose project during a period of 7 weeks between as-compacted and conditioned tests (Figures 4.2 and 4.3).

5.3.2 Fatigue Life Results

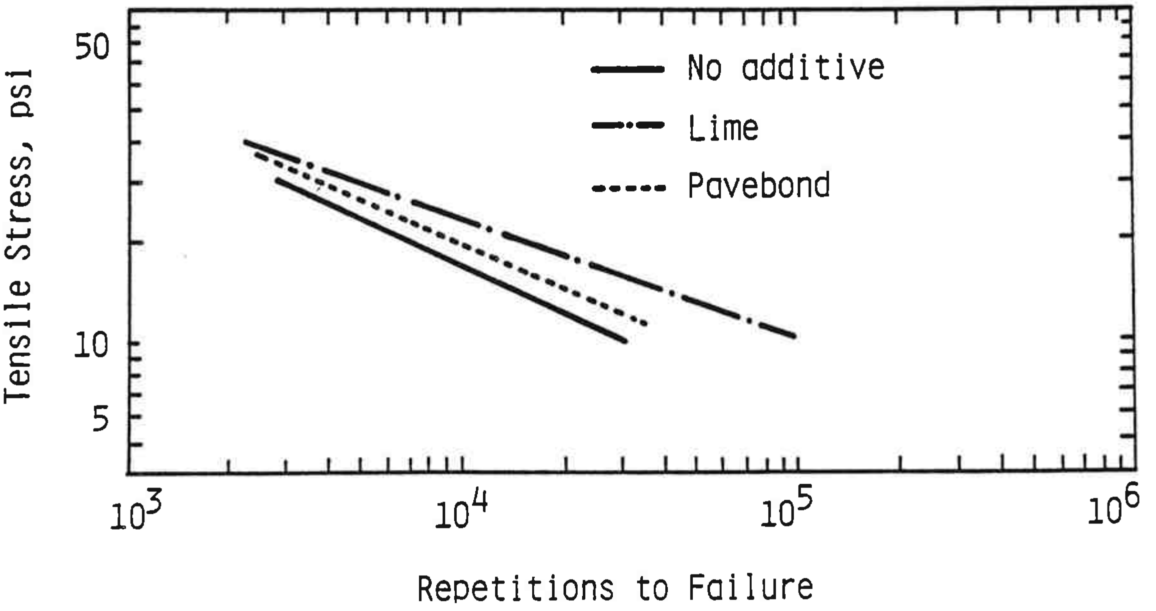
The effects of additives on fatigue life of specimens with and without moisture are presented in Figures 4.5 and 4.6 for the Warren-Scappoose project and Figures 4.8 and 4.9 for the North Oakland-Sutherlin project based on the tensile strain. As shown in Figure 4.5, there is little benefit from additives for mixtures without moisture for the Warren-Scappoose project, but below the 100 microstrain level, fatigue lives with lime are higher for as-compacted and conditioned specimens. The effect of lime on fatigue life of as-compacted specimens for the Warren-Scappoose project is much more significant for specimens with 3% moisture. As shown in Figure 4.6, the effect of lime is superior and Pavebond Special obtains better performance than no additive. After conditioning, lime addition still shows the best performance.

The comparison based on the tensile stress shows clearly better fatigue performance of mixtures with additives in Figure 5.5. As discussed previously, the result shown in Figure 5.5 reaffirms the fact that stiffness of mix plays a predominant role in determining the fatigue behavior of mixtures. With 3% moisture content, fatigue results represent the modulus results (Figure 5.6). As discussed in the modulus section, the effect of lime on the fatigue behavior of mixture is superior for both as-compacted and conditioned specimens as presented in Figure 5.6. Therefore, lime is more effective for increasing modulus, hence improves fatigue performance of mixtures, especially with moisture.

For the North Oakland-Sutherlin project Pavebond Special shows the best performance for specimens without moisture. As shown in Figure 4.8, the as-compacted specimen with no additive performs the worst and Pavebond Special achieves a slightly better performance than lime. After conditioning, Pave-

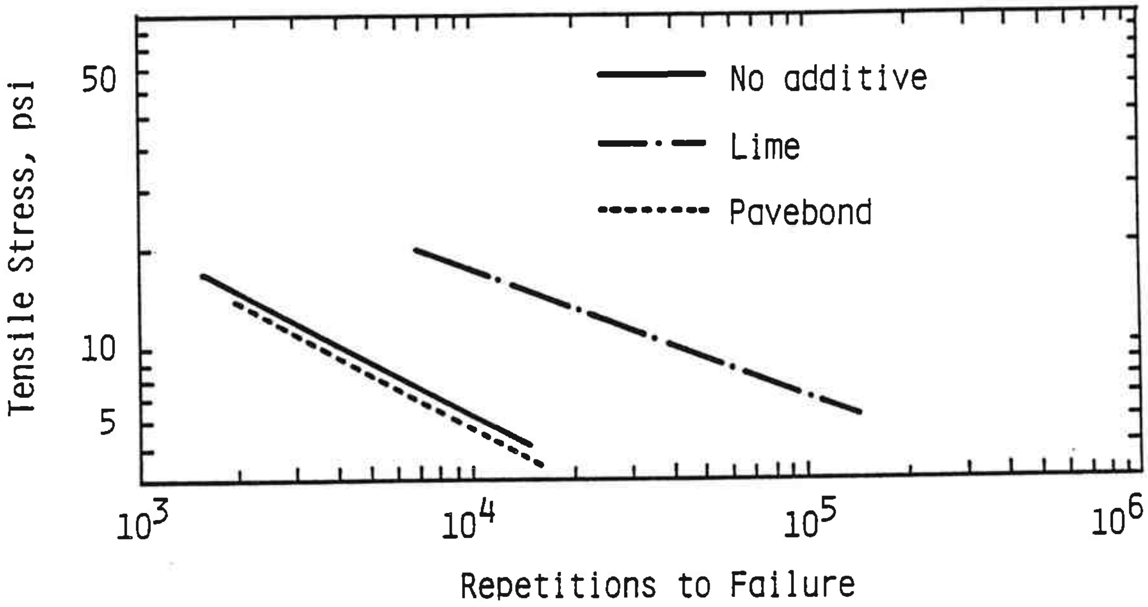


a. As-Compacted

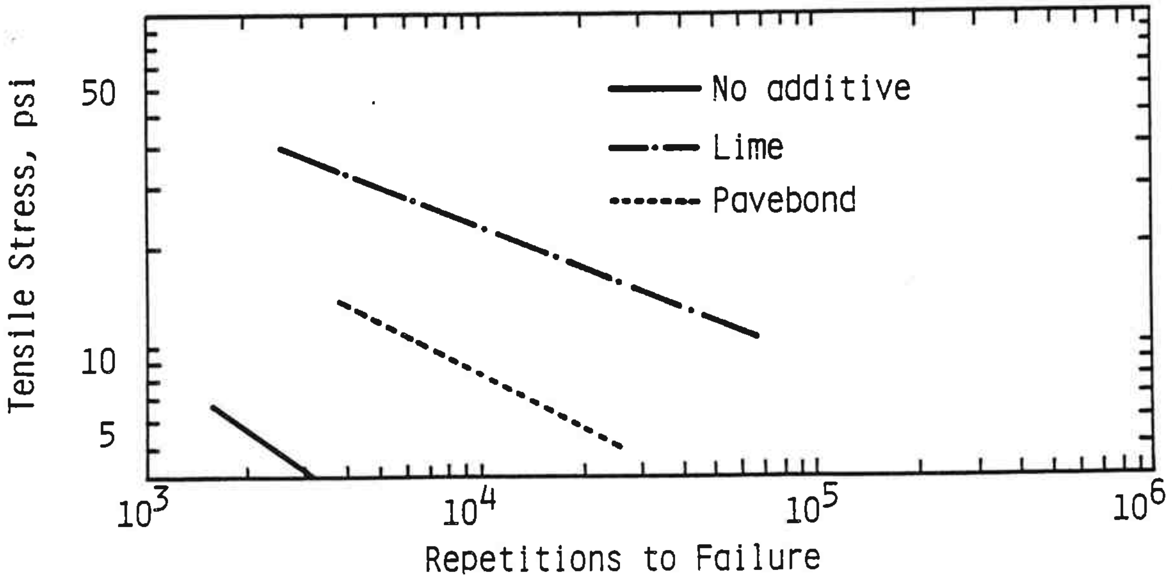


b. Conditioned

Figure 5.5 - Effect of Additives Without Moisture on Fatigue Life of Warren-Scappoose Project - Based on stress



a. As-Compacted



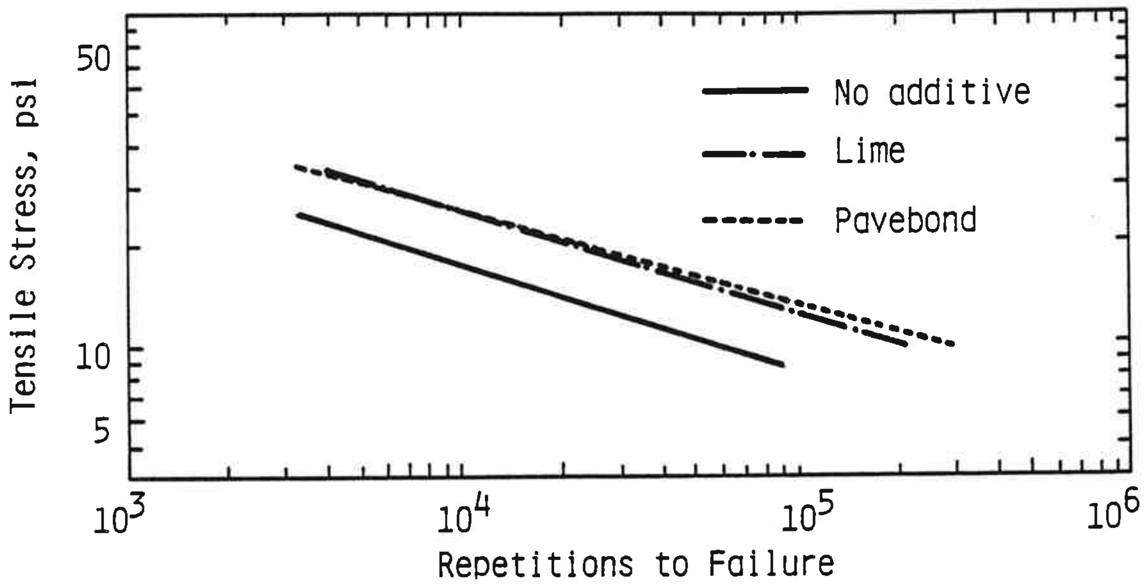
b. Conditioned

Figure 5.6 - Effect of Additives with Moisture on Fatigue Life of Warren - Scappoose Project - Based on the Stress

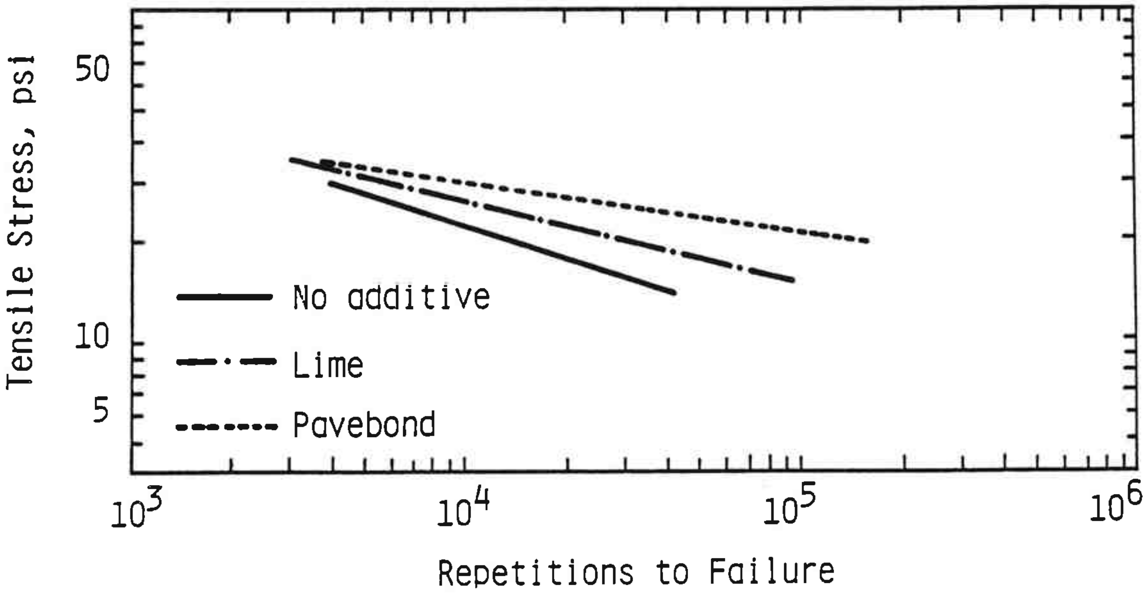
bond Special shows the best results but lime performs worse than specimens with no additive. With moisture, the result of no additive and lime is almost the same and is better than that of Pavebond Special, as shown in Figure 4.9. However, after conditioning, Pavebond Special again obtains better performance than no additive and lime below 150 microstrain level.

The fatigue results based on the tensile stress for the North Oakland-Sutherlin project gives similar trends to those based on the tensile strain (Figures 5.7 and 5.8) since the moduli values of each mix variable show little difference among them. Without moisture, Pavebond Special and lime improve the fatigue performance. The moduli values of mixtures with Pavebond Special for both as-compacted and conditioned specimens are almost the same as those with lime. However, the fatigue test results for mixtures with Pavebond Special show better performance due partially to smaller air voids and may be attributed to Pavebond Special. Therefore, smaller air voids contribute to improve the fatigue performance of mixtures if the moduli are the same. The fatigue result of mixtures with moisture reaffirms this fact. The moduli of mixtures with Pavebond Special are close to those with no additive and those with lime for as-compacted and conditioned specimens, respectively. In Figure 5.8, however, mixtures with Pavebond Special give better performance than each mixture mentioned above due to lower air voids.

Particularly, it is clear that for the Warren-Scappoose specimens, with no moisture, additives show a little benefit. When moisture is present, lime shows significant benefit. For the North Oakland-Sutherlin project, there is clear benefit from both additives, particularly Pavebond Special, for mixtures with no moisture. However, for this project, with 3% moisture, there is

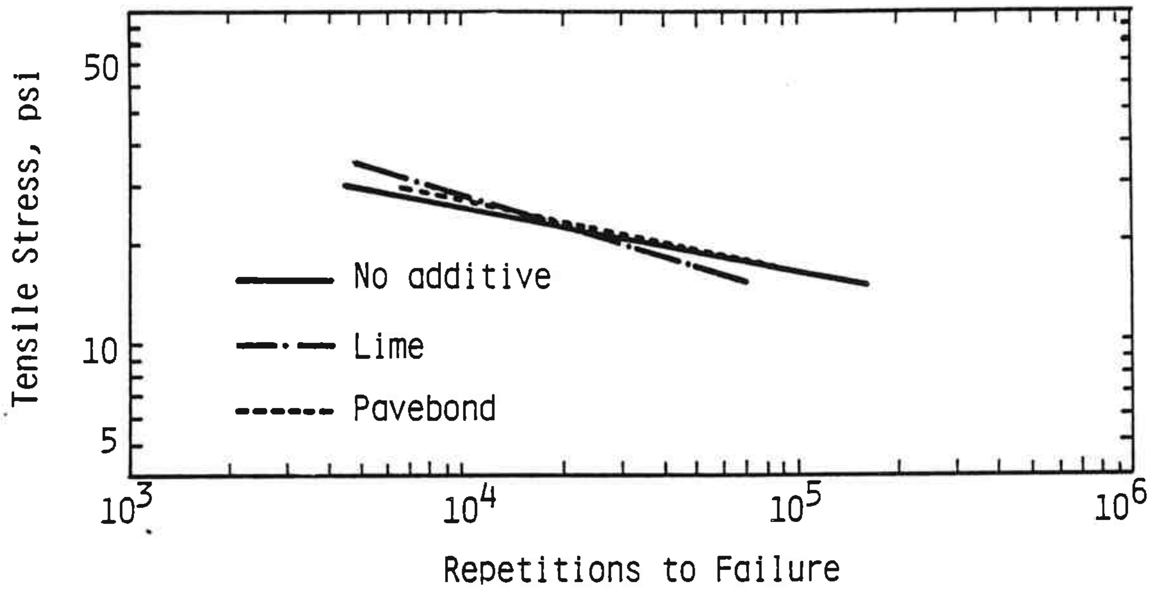


a. As Compacted

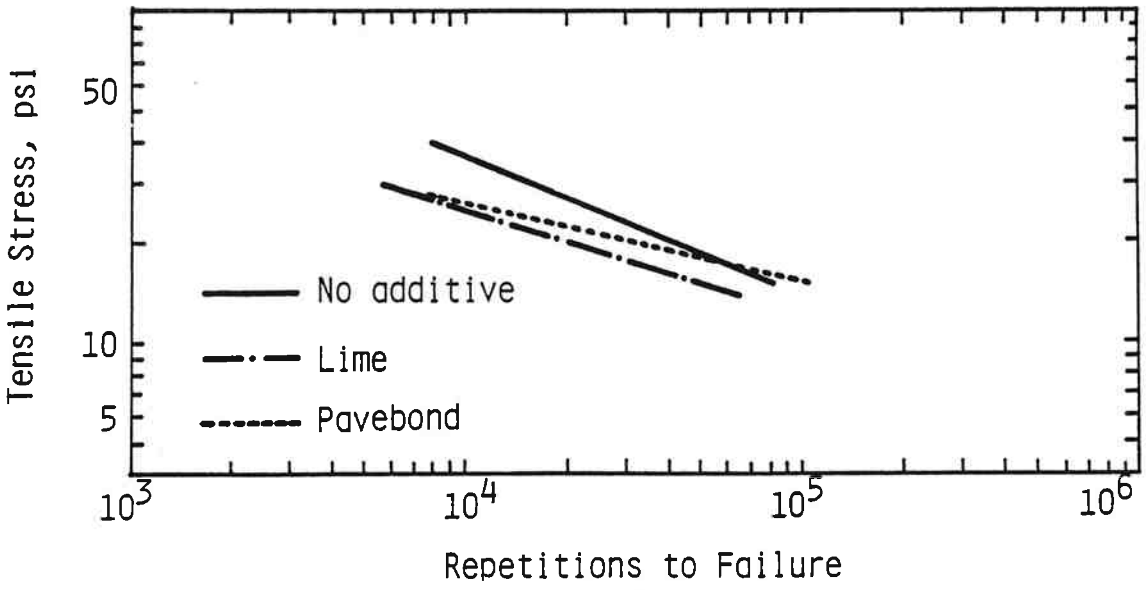


b. Conditioned

Figure 5.7 - Effect of Additives Without Moisture on Fatigue Life of North Oakland-Sutherlin Project - Based on Stress



a) As Compacted



b) Conditioned

Figure 5.8 - Effect of Addtive with Moisture on Fatigue Life of North Oakland-Sutherlin Project - Based on Stress

little benefit shown with lime and Pavebond Special when examining the results for as-compacted or conditioned mixtures.

The above results may be explained, in a similar manner to that done above, for mixtures without additives, in terms of modulus, voids, and coating of the mixtures (39,40). Figures 4.2 and 4.3 show moduli for the specimens with and without additives, and Table 4.3 shows the air void contents. Consideration of these data together with Figures 5.5, 5.6, 5.7, and 5.8, confirms the previous observation that the additives are only likely to be of significant benefit in mixtures with questionable durability, i.e., those with high voids and low asphalt content. Hence, lime shows a significant advantage for the Warren-Scappoose project, but neither additive shows an advantage for the North Oakland-Sutherlin project.

Fatigue life ratio, which is the ratio of fatigue life of mixtures after conditioning to that of as-compacted mixtures at tensile strain of 100 microstrain and tensile stress of 15 or 20 psi is presented in Table 5.2. Even though the ratios may not be used directly for evaluation of durability of mixtures since there was a difference of about 7 weeks between tests with as-compacted specimens and the conditioning test, the ratios show two interesting things. If the ratio based on the strain is greater than 1.0, the ratio based on the stress is less than 1.0, or vice versa due to the change of modulus after conditioning. Most of the ratios for the Warren-Scappoose project can be explained by the above reason.

Table 5.2. Fatigue Life Ratio*.

	Warren-Scappoose		North Oakland-Sutherlin	
	$\varepsilon_t = 100\text{x}10^{-6}$	σ_t = 15 psi	$\varepsilon_t = 100\text{x}10^{-6}$	σ_t = 20 psi
No Moisture	1.55	0.44	3.35	2.22
1% Lime	1.21	0.79	0.90	1.43
0.5% Pavebond Special	1.21	0.55	4.05	6.25
1% Moisture	1.46	1.32	1.62	1.44
3% Moisture	2.02	0	2.44	1.23
3% Moisture/1% Lime	0.43	1.91	0.69	0.71
3% Moisture/0.5% Pavebond Special	1.76	1.91	3.76	0.80

$$* \text{ Fatigue Life Ratio} = \frac{\text{Fatigue Life of Conditioned Specimens}}{\text{Fatigue Life of As-Compacted Specimens}}$$

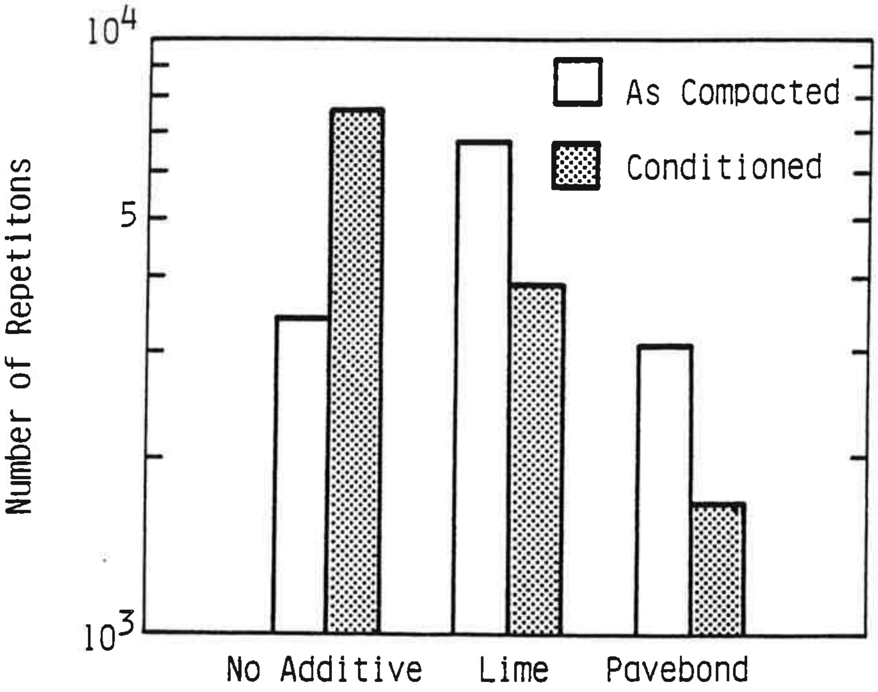
The ratio of mixtures greater than 1.0 based on both the strain and stress means that the conditioned mixtures are more durable to fatigue than as-compacted mixtures. For example, moduli of as-compacted and conditioned mixtures for the North Oakland-Sutherlin project are almost the same. The ratios of mixtures based on the stress as well as the strain are greater than 1.0. Because of the difference of seven weeks between tests, however, it cannot be said that the fatigue performance of mixtures for the North Oakland-Sutherlin project is improved after conditioning.

5.3.3 Permanent Deformation Results

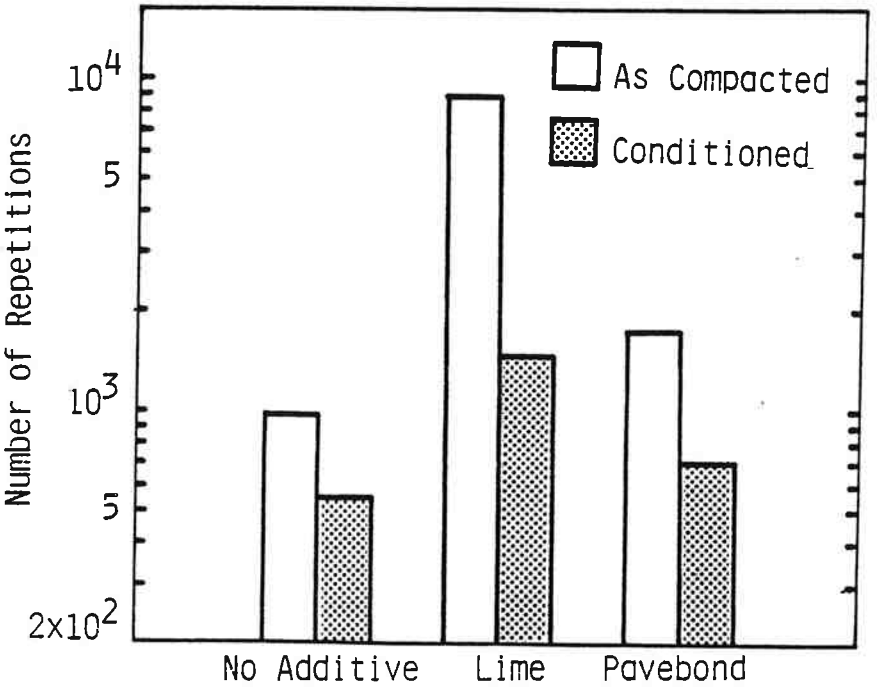
The effects of additives on permanent deformation of specimens with and without moisture are presented in Figures 4.11 and 4.12 for the Warren-Scappoose project and in Figures 4.14 and 4.15 for the North Oakland-Sutherlin project. For the Warren-Scappoose project, as-compacted specimens with no additive perform the worst as shown in Figure 4.11. Mixtures with Pavebond Special at low compressive strains and lime at high compressive strains perform best. After conditioning, mixtures with no additives having the lowest modulus perform the best, while specimens mixed with Pavebond Special perform the worst. For this project, the behavior of as-compacted specimens with moisture but no additive is similar to that of conditioned specimens without moisture as shown in Figure 4.12. After conditioning, specimens mixed with Pavebond Special again perform the worst, while specimens mixed with lime perform better than those with no additive. As discussed previously, the better performance of a mixture with lower modulus is not logical. This result may be due to the comparison model based on the tensile strain approach.

For the North Oakland-Sutherlin project, without moisture, specimens mixed with lime obtaining high modulus in Table 4.4 show the best performance for both as-compacted and conditioned specimens as shown in Figure 4.14. With moisture, specimens mixed with lime having relatively small moduli again show the best performance for both as-compacted and conditioned specimens, as shown in Figure 4.15. With and without moisture, mixtures with no additives show the worst performance. Again, these results indicate that it is difficult to interpret the result of permanent deformation based on the tensile strain approach.

A comparison between the repetitions required to reach a vertical compressive strain of 1.2% at a fixed initial tensile strain of 100 microstrain for the Warren Scappoose project and 150 microstrain for the North Oakland-Sutherlin project, for as-compacted and conditioned specimens, is shown in Figure 5.9 for specimens without moisture and Figure 5.10 for specimens with moisture. These figures illustrate more clearly the results discussed above. Figure 5.9 indicates poor durability (decreased resistance to deformation) for mixtures with additives but no moisture from the Warren-Scappoose project, since the conditioned results are inferior to the as compacted results. However, for the North Oakland-Sutherlin project, durability is improved for specimens with no moisture with additives. Figure 5.10 shows that there is an advantage to using Pavebond Special since mixtures from both projects with three percent moisture show improved deformation resistance. It should be noted that the required number of repetitions to reach a critical compressive strain of 5% is less than that to fatigue failure for both projects. A permanent strain of 5% was selected on the basis of the assumption that the tolerable permanent deformation of asphalt concrete layer be 0.5 inch

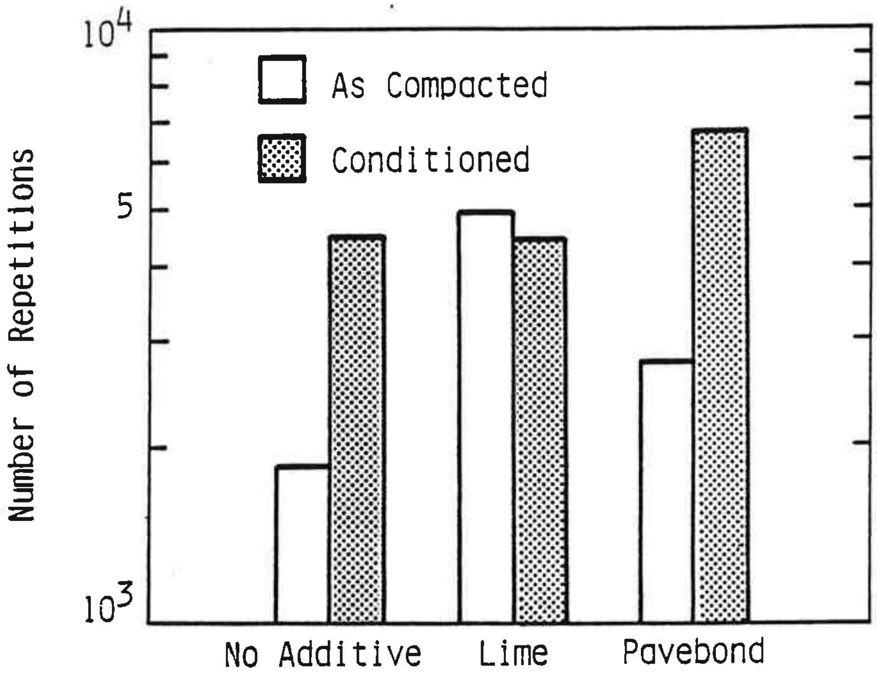


a. Warren-Scappoose (ε_t of 100 Microstrain)

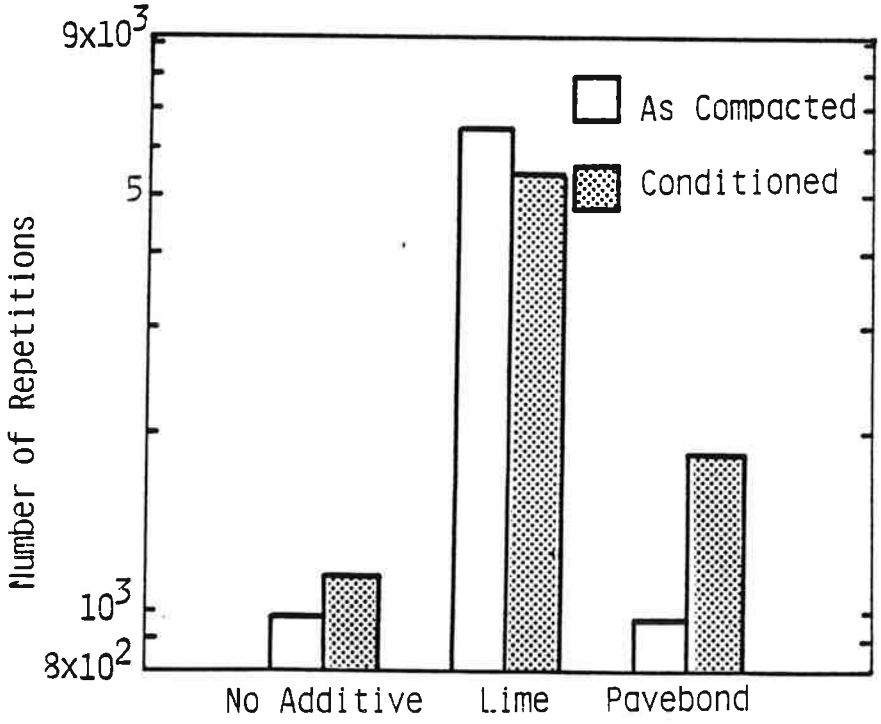


b. North Oakland-Sutherlin (ε_t of 150 Microstrain)

Figure 5.9 - Number of Repetitions with Additives at ε_c of 1.2% - No Moisture Content



a. Warren-Scappoose (ε_t of 100 Microstrain)



b. North Oakland-Sutherlin (ε_t of 150 Microstrain)

Figure 5.10 - Number of Repetitions with Additives at ε_c of 1.2% - 3% Moisture Content

(12.5 mm) and the depth of layer be 10 inches (254 mm). Therefore, fatigue is a more critical criterion than permanent deformation for judging mixture performance, at least under the conditions of this study. As mentioned in a previous section, deformation results at high strain levels should be treated with caution when obtained with a diametral device. Indeed, as in the evaluation of results for specimens without additives, the deformation results do not compare well with other data since the result of permanent deformation is based on the tensile strain level approach. For the North Oakland-Sutherlin project, however, it is noted that deformation resistance of the conditioned specimens mixed with additives is quite different between these mixtures even though the moduli values of these mixtues are almost the same (Figures 4.14 and 4.15 and Table 4.4).

5.3.4 Summary - Effect of Additives

Additives improved the performance of the Warren-Scappoose project by increasing stiffness and fatigue life. In particular, the performance after conditioning was improved. Lime treatment was particularly beneficial with Pavebond Special having little benefit. This appears to be due to the lower voids achieved in mixtures with lime which contributes to stiffness, fatigue resistance and durability. It was difficult to evaluate permanent deformation performance, but these do indicate improved performance for mixtures with lime.

There was little benefit shown from using additives in specimens for the North Oakland-Sutherlin project. Although a little improvement in permanent deformation resistance was indicated, there was no significant improvement in stiffness or fatigue resistance with moist mixtures. These results indicate that a dense mixture (low voids) which achieves good stiffness while having high binder content, can have good mechanical properties and durability without additives. The additives show benefit with problem mixtures. In this study, the Warren-Scappoose project had high void contents and a low asphalt content and showed inferior mechanical properties and durability to the North Oakland-Sutherlin project. It should also be noted that even with the improved performance by use of additives, the Warren-Scappoose project showed inferior performance to the North Oakland-Sutherlin project.

Finally, it is clear that the mix design must evaluate whether an additive is required, and if so, which one will be beneficial. As shown in this study, with limited data, it is not given that additives will improve performance or that one additive will always prove most beneficial. The current ODOT mix design procedure measures an index of retained strength; a low value results in selection of an additive. A preferred alternative would be to assess a retained modulus value as well as retained modulus ratio, since modulus reflects high performance with regard to fatigue and permanent deformation. Subsequent testing should be carried out to determine the most suitable additive. With regard to the comparison method for each mix variable, it was shown that the method based on the stress approach shows the difference of fatigue performance more clearly. Also, the comparison of permanent deformation results based on a given stress level, e.g. at 15 or 20 psi, might be preferable to a strain level, e.g. at 100 or 150 microstrain, unless the moduli are the same.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The effects of moisture and additives with asphalt mixtures used in the construction of two projects in Oregon were evaluated from dynamic testing of laboratory-compacted specimens. Mixture resilient moduli, fatigue lives and permanent deformations of as-compacted and conditioned specimens were determined for specimens prepared with the following range of variables:

1) Moisture content: 0%, 1%, and 3%.
2) Percent of additive and type: none, 1% lime, and 0.5% Pavebond Special.

The following major conclusions are drawn from the findings of this phase:

1. The results for mixtures with no additives showed that excess mixing moisture was detrimental for the Warren-Scappoose project, particularly with regard to reduction in stiffness after conditioning in the higher void content mixtures.
2. For the North Oakland-Sutherlin project, which utilized a marginal crushed rock aggregate, 1% moisture resulted in improved performance due to the substantial improvement in compaction that resulted.
3. Absorption of aggregate plays a predominant role in determining the air voids of moist mixtures and the resulting performance of mixtures.

4. For mixtures with additives, the detrimental effect of 3% moisture was substantially reduced by use of lime in the Warren-Scappoose project, with Pavebond Special showing limited benefit. Neither additive showed substantial benefit in the North Oakland-Sutherlin project.
5. The results of this study lead to the conclusion that additives are of limited benefit in mixtures with high density and which achieve good durability without additives, such as the North Oakland-Sutherlin project. Although this project used a marginal aggregate, the mix design produced a high performance mixture.
6. Additives, particularly lime, were of substantial benefit with the existence of moisture in the Warren-Scappoose project which had a high void content and low durability without the additives.
7. Resilient modulus plays a predominant role in determining the performance of mixtures. However, a lowering of modulus tends to increase fatigue life and deformation resistance based on the strain approach. Therefore, the comparison at a constant stress is the more logical approach, higher modulus higher performance.
8. Fatigue and deformation resistance of mixtures having the same resilient modulus achieved in different ways are quite different.
9. The results indicate that fatigue is a more critical criterion than permanent deformation under the conditions of this study.

10. The results indicate that if the mix design process indicates the need for an admixture, after every effort has been made to achieve high performance through a high mix density with maximum apshalt content, then further testing must be carried out to select the appropriate admixture.

6.2 Recommendations

The following recommendations can be made from the results of this phase of the study:

1) Since the limit of acceptable moisture content depending on the aggregate quality should be varied from one project to another, limiting values should be determined after the mix design.
2) It is recommended to use as much asphalt cement as possible to maximize durability and minimize the damage from moisture, while ensuring adequate resistance to permanent deformation.
3) Mix density should be maximized, commensurate with good mix design practice, to achieve good mechanical properties and durability.
4) Additives should be selected after appropriate tests have established values such as the retained modulus as well as the retained modulus ratio and fatigue life ratio.
5) It is necessary to establish test methods to determine the effect of residual moisture on mixtures. The procedures employed in this study, together with the specimen preparation techniques, are a good starting point.
6) A mix design should consider the fatigue or permanent deformation as well as strength or modulus.

7) Further research concerning the permanent deformation test using diametral test method is necessary.

8) Since the effect of moisture and effectiveness of additives are a complex functions of asphalt, aggregate, and additive interactions, it is necessary to establish a simple test to determine the compatibility of these components.

9) For comparison of mix variables in a laboratory, it is recommended to use the stress approach rather than strain approach for fatigue life and permanent deformation test, while strain approach is more useful for the design of a pavement structure.

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APPENDIX A

ORIGINAL MIX DESIGN (ODOT) TEST DATA

Table A.1 summarizes the average results of mix design for the 1978 asphalt concrete base layer of the North Oakland-Sutherlin project.

Table A.2 summarizes the original mix design for the Warren-Scappoose project. This mix design was used for both the base and the wearing layers.

Table A.1. Mix Design for 1978 Paving (ODOT)

Asphalt Concrete Base Layer, -B- Mix
North Oakland-Sutherlin Project

Asphalt Content (AR 8000)	5.5	6.0	6.5	7.0	7.5
Asphalt Film Thickness	Suff.	Suff.	Suff.	Suff.-Thick	Thick
Stability Value, 1st Compaction	32	34	35	38	39
Bulk Spec. Gravity, 1st Compaction	2.23	2.25	2.27	2.29	2.31
Percent Voids, 1st Compaction	11.2	9.6	8.1	6.5	4.9
Stability Value, 2nd Compaction	49	50	50	49	52
Bulk Spec. Gravity, 2nd Compaction	2.32	2.34	2.35	2.36	2.38
Percent Voids, 2nd Compaction	7.6	6.0	4.9	3.7	2.1
Rice Gravity (AASHTO T-209)	2.51	2.49	2.47	2.45	2.43
Index of Retained Strength (AASHTO T 165):					
AR 8000	11	-	20	-	45
AR 8000 + 1% Sucon (No Strip)	62	-	79	-	82
AR 8000 + 1% Pavebond Special	64	-	81	-	84
AR 4000	16	-	25	-	53

Mix Gradation: Percent passing 3/4" - 100; 1/2" - 86; 1/4" - 60; No. 10 -25; No. 40 -12; No. 200 - 5

Recommended Asphalt Content (AR 8000 - % of total mix): 6.9%

Table A.2. Original Mix Design (ODOT) Test Data
Warren-Scappoose Project

Asphalt Content - Shell AR 4000	4.5	5.0	5.5	6.0	6.5
Asphalt Film Thickness	Suff.	Suff.	Suff.	Suff.-Thick	Thick
Stablility Value, 1st Compaction	47	39	40	41	37
Bulk Spec. Gravity, 1st Compaction	2.30	2.33	2.35	2.37	2.39
Percent Voids, 1st Compaction	9.1	7.2	5.6	4.0	2.8
Stability Value, 2nd Compaction	50	45	47	49	34
Bulk Spec. Gravity, 2nd Compaction	2.39	2.41	2.43	2.45	2.46
Percent Voids, 2nd Compaction	5.5	4.0	2.4	0.8	0.0
Rice Gravity (AASHTO T-209)	2.53	2.51	2.49	2.47	2.46
Index of Retained Strength (AASHTO T 165)	90	-	93	-	100+

APPENDIX B

SUMMARY OF CORE DATA

Table B.1 summarizes the average results of tests on the North Oakland-Sutherlin project. Ten cores were taken from Station 1655+85, 5 cores from station 1735+95, 2 cores from station 1700+00 and 1705+00, and 2 cores from station 1740+00 and 1781+00.

Table B.2 summarizes core data taken across the panel at two locations on the Warren-Scappoose project. Locations are given in Table B.2.1. Table B.2.2 summarizes the results of individual tests on the cores.

Table B-1 - Summary of Average Test Results

*Station 1655+85

**Station 1700 and 1705

Paving Tested:	*Wearing Surface Class "E"	*Top Lift Class "B"	**Bottom Lift Class "B"
Mix Property:			
Bulk Sp. Gr. In place	2.09	2.24	2.17
Bulk Sp. Gr. R. Compacted	2.29	2.39	2.45
Max. Sp. Gravity	2.52	2.51	2.51
% Voids, In place	17.2	10.0	15.7
Gradation, % passing			
1/4 "	61	62	60
No. 10	16	30	31
No. 200	3.9	6.3	8.2
Asphalt Content	6.5	7.2	7.2
Modulus, ksi Lab. Compacted	218	468	-

Table B-1 - Summary of Average Test Results (cont.)

*Station 1753+95

**Station 1740 and 1781

Paving Tested:	*Wearing Surface Class "E"	*Top Lift Class "B"	**Bottom Lift Class "B"
Mix Property:			
Bulk Sp. Gr. In place	2.09	2.28	2.11
Bulk Sp. Gr. Re Compacted	2.24	2.40	2.42
Max. Sp. Gravity	2.52	2.47	2.49
% Voids, In place	17.2	8.0	15.5
Gradation, % passing			
1/4 "	64	67	65
No. 10	18	34	31.5
No. 200	3.6	6.4	8.7
Asphalt Content	7.0	7.1	7.7
Modulus, ksi Lab. Compacted	220	476	232

Table B-2-1 - Location of Asphalt Cores

(a) Station 908 + 00

Location	I.D. Core No.	Lift	Thickness	Remarks
$24\overset{0'}{-}$ RT	1	Top	2.1"	Light tack coat. Poor adhesion between lifts. 80% coated - Dry - SUFF - Gradation OK
	1	Base	2.2"	75% coated - Stripping on Large Agg. - SUFF - Very sticky - Fine Gradation
$26\overset{0'}{-}$ RT	2	Top	2.0"	70% coated - Stripping on Large Aggregate - Coarse Gradation Light Tack Coat - Poor Adhesion
	2	Base	2.2"	90% coated - SUFF - Mealy Looking
$27\overset{5'}{-}$RT	3	Top	2.1"	Light tack coat - 90% coated - SUFF - Stripping on Large Aggregate. Very bony - Large aggregate segregated to bottom of lift
	3	Base	2.1"	95% coated - SUFF - Fine Gradation
$30\overset{0'}{-}$ RT	4	Top	2.2"	90% coated - Mealy looking - Coarse Aggregate segregated to bottom of lift - Dry - SUFF - Very poor adhesion between lifts
	4	Base	2.1"	95% coated - Dry - SUFF - Gradation looks good - Slight stripping
$31\overset{5'}{-}$ RT	5	Top	2.0"	95% coated - Dry - SUFF - Fine Gradation - Very little stripping - Poor adhesion
	5	Base	2.1"	85% coated - Some stripping on coarse aggregate - Dry - SUFF

Table B-2-1 - Location of Asphalt Cores (cont.)

(b) Station 1051 + 00

Location	I.D. Core No.	Lift	Thickness	Remarks
$23^{\underline{0'}}$ RT	6	Top	2.0"	85% Coated - Some Stripping - Dry - Mealy looking - Very poor adhesion between lifts
	6	Base	2.5"	80% Coated - Slight stripping - Very Dry
$25^{\underline{0'}}$ RT	7	Top	1.9"	95% coated - SUFF - Very fine gradation - Very little stripping - Fair adhesion
	7	Base	2.4"	95% coated - SUFF - Very fine gradation
$27^{\underline{0'}}$ RT	8	Top	2.0"	85% coated - Dry - SUFF - Very fine Gradation - Poor adhesion
	8	Base	2.2"	95% Coated - SUFF - Fine Gradation
$29^{\underline{0'}}$ RT	9	Top	2.1"	95% Coated - Dry - SUFF - Very Fine Gradation - Poor adhesion
	9	Base	2.0"	75% Coated - Very Dry - Stripping on CA - Very dirty
$31^{\underline{0'}}$ RT	10	Top	2.0"	95% Coated - SUFF - Segregation of CA to bottom of lift
	10	Base	2.1"	Fine Gradation - Poor adhesion - 95% Coated - SUFF -

Table B-2-2 - Summary of Test Results

(a) Station 908 + 00

	Location									
	24'RT		26'RT		27.5'RT		30'RT		31.5'RT	
Mix Property	Top	Base	Top	Base	Top	Base	Top	Base	Top	Base
Bulk Specific Gravity, In Place	2.19	2.25	2.22	2.36	2.18	2.36	2.15	2.32	2.23	2.30
Bulk Specific Gravity, Recompacted	2.36	2.42	2.37	2.45	2.35	2.44	2.35	2.45	2.39	2.42
Real Gravity	2.50	2.47	2.50	2.47	2.53	2.48	2.51	2.49	2.53	2.48
% Voids, in place	12.4	8.9	6.3	4.5	13.8	4.8	14.3	6.8	11.9	7.3
Gradation, % passing										
1/4"	63.2	69.3	55.5	62.8	51.2	63.9	61.7	64.1	70.2	60.6
No. 10	29.3	33.9	25.9	31.9	23.7	32.8	28.6	33.3	32.2	30.5
No. 200	6.5	7.3	6.0	7.2	5.3	7.2	6.0	7.3	6.7	6.8
Asphalt Content, %	5.4	6.3	4.9	6.0	4.7	6.1	5.4	6.2	5.7	5.9
Water content, %	0.67	0.79	0.68	0.67	0.69	0.75	0.91	0.74	0.83	0.64
Modulus, ksi	312	240	324	309	232	302	239	346	253	295

Table B-2-2 - Summary of Test Results (cont.)

(b) Station 1051 + 00

	Location									
	23'RT		25'RT		27'RT		29'RT		31'RT	
Mix Property	Top	Base	Top	Base	Top	Base	Top	Base	Top	Base
Bulk Specific Gravity, In Place	2.17	2.30	2.15	2.22	2.15	2.22	2.19	2.23	2.22	2.26
Bulk Specific Gravity, Recompacted	2.35	2.39	2.35	2.37	2.37	2.36	2.35	2.38	2.38	2.40
Real Gravity	2.51	2.49	2.49	2.50	2.49	2.49	2.48	2.52	2.49	2.50
% Voids, in place	13.5	7.6	13.7	11.2	13.7	10.8	11.7	11.5	10.8	9.0
Gradation, % passing										
1/4"	64.5	65.5	70.4	62.1	73.0	62.3	64.8	53.1	70.5	68.5
No. 10	30.2	33.0	33.0	29.6	33.5	29.8	30.1	26.5	33.2	34.0
No. 200	6.4	7.4	6.6	6.8	6.8	6.9	6.2	6.6	6.8	7.7
Asphalt Content, %	5.1	5.9	5.6	5.3	5.7	5.4	5.2	4.9	5.9	5.8
Water content, %	0.76	0.81	0.78	1.0	0.67	0.70	0.87	0.87	0.73	0.87
Modulus, ksi	309	401	236	404	221	457	246	450	248	355