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16. Abstract This report summarizes the findings of Project 3-9-72-183, "Tensile Characterization of Highway Pavement Materials," and describes a series of research activities related to indirect tensile testing, tensile and repeated-load properties of inservice materials, engineering properties of asphalt mixtures, and design of asphalt mixtures. The report contains a summary of activities related to the development, application, and use of the indirect tensile test to obtain engineering properties related to pavement distress. A detailed test procedure is contained in Research Report 183-14 and an ASTM test procedure was developed to determine the resilient modulus of asphalt mixtures. Information related to the engineering properties of pavement materials from inservice pavements in Texas is also summarized. This includes mean values and the variation which actually occurs which are intended for use in elastic and stochastic pavement design systems. Finally, information related to the engineering properties of asphalt mixtures and the design of asphalt mixtures is provided.			
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TENSILE CHARACTERIZATION OF
HIGHWAY PAVEMENT MATERIALS

by

Thomas W. Kennedy

Research Report Number 183-15F

Tensile Characterization of Highway Pavement Materials
Research Project 3-9-72-183

conducted for

Texas

State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

July 1983

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

This report is the fifteenth and final in a series of reports for Project 3-9-72-183, "Tensile Characterization of Highway Pavement Materials," which was active over a period of nine years. The work accomplished and summarized in this report has been subdivided into the following functional categories:

- o Indirect Tensile Testing
- o Tensile and Repeated-Load Properties of Inservice Materials
- o Engineering Properties of Asphalt Mixtures
- o Design of Asphalt Mixtures

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Appreciation is also extended to District personnel who supplied material and worked closely with the project and to the staff of the Center for Transportation Research, whose assistance has been essential to the conduct of the study.



LIST OF REPORTS

There are fifteen reports from this project, numbered 183-1 through 183-15F. They are listed below in functional groups, for easy reference, rather than in numerical order.

INDIRECT TENSILE TESTING

Report No. 183-3, "Cumulative Damage of Asphalt Materials Under Repeated-Load Indirect Tension," by Calvin E. Cowher and Thomas W. Kennedy, summarizes the results of a study on the applicability of a linear damage rule, Miner's Hypothesis, to fatigue data obtained utilizing the repeated-load indirect tensile test.

Report No. 183-4, "Comparison of Fatigue Test Methods for Asphalt Materials," by Byron W. Porter and Thomas W. Kennedy, summarizes the results of a study comparing fatigue results of the repeated-load indirect tensile test with the results from other commonly used tests and a study comparing creep and fatigue deformations.

Report No. 183-7, "Permanent Deformation Characteristics of Asphalt Mixtures by Repeated-Load Indirect Tensile Test," by Joaquin Vallejo, Thomas W. Kennedy, and Ralph Haas, summarizes the results of a preliminary study which compared and evaluated permanent strain characteristics of asphalt mixtures using the repeated-load indirect tensile test.

Report No. 183-14, "Procedures for the Static and Repeated-Load Indirect Tensile Test," by Thomas W. Kennedy and James N. Anagnos, summarizes indirect tensile testing and recommends testing procedures and equipment for determining tensile strength, resilient properties, fatigue characteristics, and permanent deformation characteristics.

TENSILE AND REPEATED-LOAD PROPERTIES OF INSERVICE MATERIALS

Report No. 183-1, "Tensile and Elastic Characteristics of Pavement Materials," by Bryant P. Marshall and Thomas W. Kennedy, summarizes the results of a study on the magnitude of the tensile and elastic properties of highway pavement materials and the variations associated with these properties which might be expected in an actual roadway.

Report No. 183-2, "Fatigue and Repeated-Load Elastic Characteristics of Inservice Asphalt-Treated Materials," by Domingo Navarro and Thomas W. Kennedy, summarizes the results of a study on the fatigue response of highway pavement materials and the variation in fatigue life that might be expected in an actual roadway.

Report No. 183-9, "Fatigue and Repeated-Load Elastic Characteristics of Inservice Portland Cement Concrete," by John A. Crumley and Thomas W. Kennedy, summarizes the results of an investigation of the resilient elastic and fatigue behavior of inservice concrete from pavements in Texas.

ENGINEERING PROPERTIES OF ASPHALT MIXTURES

Report No. 183-5, "Fatigue and Resilient Characteristics of Asphalt Mixtures by Repeated-Load Indirect Tensile Test," by Adedare S. Adedimila and Thomas W. Kennedy, summarizes the results of a study on the fatigue behavior and the effects of repeated tensile stresses on the resilient characteristics of asphalt mixtures utilizing the repeated-load indirect tensile test.

Report No. 183-8, "Resilient and Fatigue Characteristics of Asphalt Mixtures Processed by the Dryer-Drum Mixer," by Manuel Rodriguez and Thomas W. Kennedy, summarizes the results of a study to evaluate the engineering properties of asphalt mixtures produced using a dryer-drum plant.

Report No. 183-12, "The Effects of Soil Binder and Moisture on Blackbase Mixtures," by Wei-Chou V. Ping and Thomas W. Kennedy, summarizes the results of a study to evaluate the effect of soil binder content on the engineering properties of blackbase paving mixtures.

Report No. 183-13, "Evaluation of the Effect of Moisture Conditioning on Blackbase Mixtures," by James N. Anagnos, Thomas W. Kennedy, and Freddy L. Roberts, summarizes the results of a study to evaluate the effects of moisture content on the engineering properties of blackbase paving mixtures.

DESIGN OF ASPHALT MIXTURES

Report No. 183-6, "Evaluation of the Resilient Elastic Characteristics of Asphalt Mixtures Using the Indirect Tensile Test," by Guillermo Gonzalez, Thomas W. Kennedy, and James N. Anagnos, summarizes the results of a study to evaluate possible test methods for obtaining elastic properties of pavement materials, to recommend a test method and preliminary procedure, and to evaluate properties in terms of mixture design.

Report No. 183-10, "Development of a Mixture Design Procedure for Recycled Asphalt Mixtures," by Ignacio Perez, Thomas W. Kennedy, and Adedare S. Adedimila, summarizes the results of a study to evaluate the fatigue and elastic characteristics of recycled asphalt materials and to develop a preliminary mixture design procedure.

Report No. 183-11, "An Evaluation of the Texas Blackbase Mix Design Procedure Using the Indirect Tensile Test," by David B. Peters and Thomas W. Kennedy, summarizes the results of a study evaluating the elastic and repeated-load properties of blackbase mixes determined from current blackbase design procedures using the indirect tensile test.

SUMMARY

Report No. 183-15F, "Tensile Characterization of Highway Pavement Materials," by Thomas W. Kennedy, summarizes the findings and activities of the total research project which are reported in the interim research reports.



ABSTRACT

This report summarizes the findings of Project 3-9-72-183, "Tensile Characterization of Highway Pavement Materials," and describes a series of research activities related to indirect tensile testing, tensile and repeated-load properties of inservice materials, engineering properties of asphalt mixtures, and design of asphalt mixtures.

The report contains a summary of activities related to the development, application, and use of the indirect tensile test to obtain engineering properties related to pavement distress. A detailed test procedure is contained in Research Report 183-14 and an ASTM test procedure was developed to determine the resilient modulus of asphalt mixtures.

Information related to the engineering properties of pavement materials from inservice pavements in Texas is also summarized. This includes mean values and the variation which actually occurs which are intended for use in elastic and stochastic pavement design systems.

Finally, information related to the engineering properties of asphalt mixtures and the design of asphalt mixtures is provided.

KEY WORDS: Asphalt mixtures, portland cement concrete, indirect tensile test, pavement materials, drum mixers, recycled asphalt mixtures, elastic properties, permanent deformation, fatigue, resilient modulus, tensile strength, mixture design



SUMMARY

The indirect tensile test is a practical and effective test for determining the elastic tensile properties and distress related properties of asphalt mixtures. The test has gained wide acceptance and should be implemented as quickly as possible.

The properties of pavement materials vary significantly in actual pavements. This variation should be considered in the design and performance evaluation of pavements. Information related to the mean values of various engineering properties and the variation of these properties is contained in the report.

Attention should also be given to the engineering properties of asphalt mixtures and their relationship to performance and mixture design.

Information and recommendations related to the above concepts are summarized in the report. Many of the findings have already been considered and implemented.



IMPLEMENTATION STATEMENT

Many of the findings related to indirect tensile testing, the engineering properties of pavement materials and the variation of these properties, the engineering properties of asphalt mixtures, and the design of asphalt mixtures have already been implemented or have provided a background for developments in subsequent research projects which have in turn been implemented.

Of particular importance is the use of the indirect tensile test which was developed for use primarily as part of Research Project 3-9-72-183, "Tensile Characterization of Highway Pavement Materials," and a previous project, Project 3-8-66-98, "Evaluation of Tensile Properties of Subbases for use in New Rigid Pavement Design." As a result of these developments and interactions with other researchers, the test has gained wide acceptance and has led to an ASTM Standard for determining the resilient modulus of asphalt mixtures. Steps should be taken to begin to routinely use the test in Texas for construction control and mixture design.

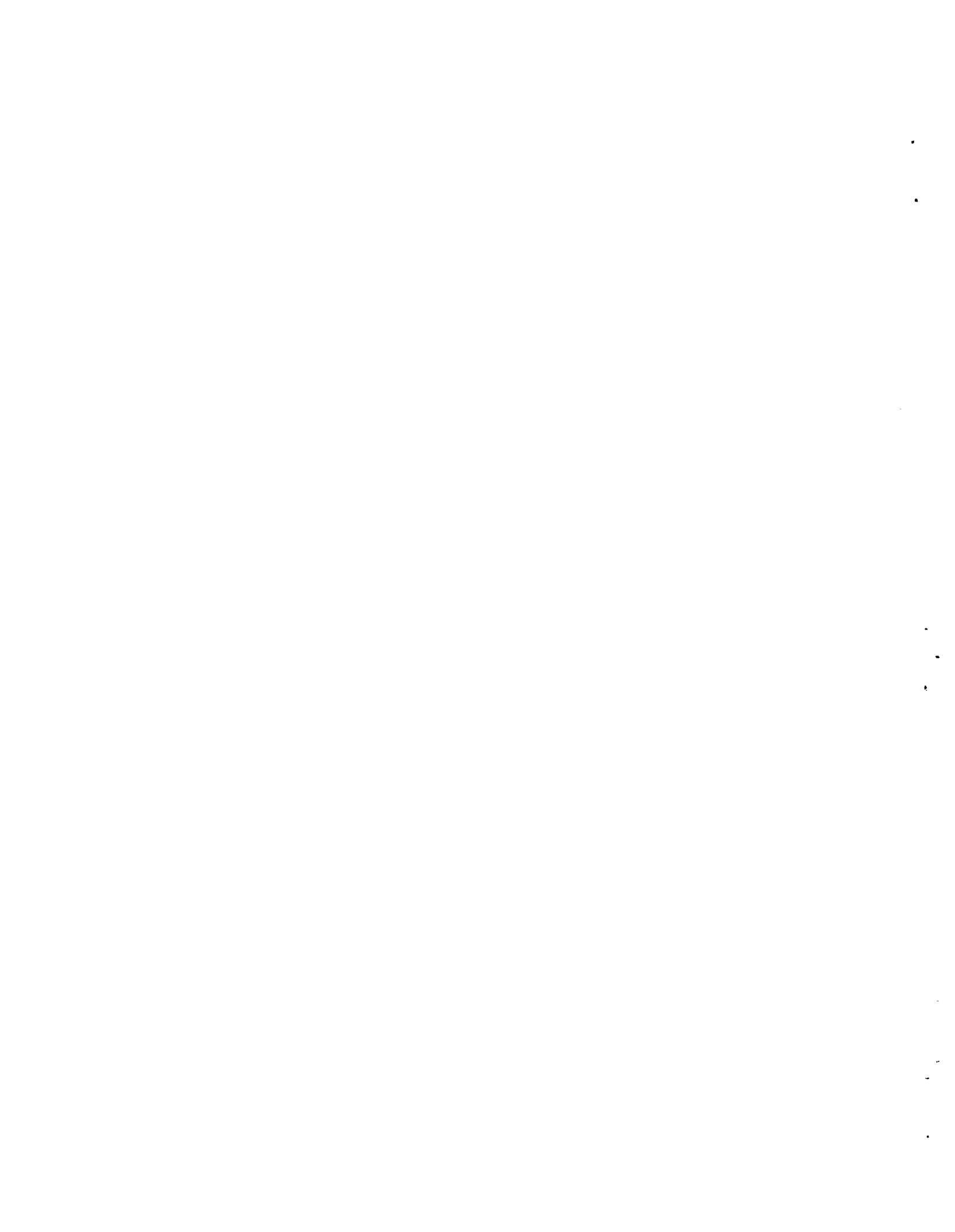


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CHAPTER 1. INTRODUCTION

Tensile stresses and strains are created in the individual layers of pavements by moving traffic and by thermal or shrinkage effects. As the pavement structure deflects, tensile stresses are created in the lower portions of the layers beneath the loads and to a certain extent in the upper portions preceding and following a transient wheel load. These stresses and strains can lead to fatigue cracking or, if large enough, to cracking under a single load. In addition, tensile stresses are created when a pavement material attempts to shrink but is restrained by friction with the other layers or subgrade. Closely associated is reflection cracking in pavement layers with low tensile strengths caused by cracks and movements in underlying layers, the combination of which causes these cracks to propagate upward through the overlying layers.

In recognition of the importance of the tensile properties of pavement materials, Project 3-9-72-183, "Tensile Characterization of Highway Pavement Materials," was sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration and was conducted through the Center for Transportation Research at The University of Texas at Austin in order to develop information on the tensile and variational characteristics of pavement materials.

In addition, a number of other related studies were incorporated into the overall objectives of the study. These additional aspects related to the engineering properties of asphalt mixtures including those produced by drum mixers, the effect of soil binder and moisture on asphalt mixtures, and the design of asphalt mixtures.

The purpose of this report is to briefly summarize the activities, findings, and recommendations of this project. These findings are covered in more detail in a series of fourteen reports dealing with different phases of the project at various stages during the active period of the overall study. Those wishing more detail on any given aspect of the project should consult the appropriate report.

CHAPTER 2. INDIRECT TENSILE TESTING

This chapter summarizes the findings related to the development and use of the indirect tensile test which are contained in five Research Reports numbered 183-3, 183-4, 183-7, and 183-14 (Refs 3, 4, 7, and 14), and to a small extent 183-6 (Ref 6).

INTRODUCTION

The ability to characterize pavement materials in terms of fundamental properties has become increasingly important, partially due to the fact that many agencies are beginning to use mechanistic pavement design methods based on elastic or viscoelastic theory. Empirical tests required for previous design procedures do not provide fundamental engineering properties required by these newer design procedures and generally cannot be used to evaluate new materials that have no performance history. In addition, it is desirable to be able to evaluate the material properties that are related to three important pavement distress modes:

- (a) thermal or shrinkage cracking,
- (b) fatigue cracking, and
- (c) permanent deformation, or rutting.

One of the important inputs to these mechanistic evaluations is the response of the various materials when subjected to tensile stresses or strains, especially repeated tensile stresses or strains. For each material the following basic materials properties are required as inputs for an elastic layer analysis of a flexible pavement:

- (a) modulus of elasticity and Poisson's ratio, including variations with temperature and rate of loading,
- (b) tensile strength, which is primarily required for thermal or shrinkage cracking analysis, and
- (c) repeated-load characteristics of the materials, which include the fatigue and permanent deformation characteristics.

In addition, a viscoelastic analysis may include other properties such as creep compliance or the properties, GNU and ALPHA, used in the VESYS design system.

Most structural design methods and the various elastic or viscoelastic programs have been developed semi-independently resulting in the use of a wide variety of different field and laboratory tests. Because field testing is usually time consuming and not always practical, laboratory methods have received considerable emphasis. Many of the more commonly used laboratory tests are empirical and used primarily for one material, making it difficult to compare materials, evaluate new materials, or provide input into elastic or viscoelastic design and analysis procedures except through the use of correlations.

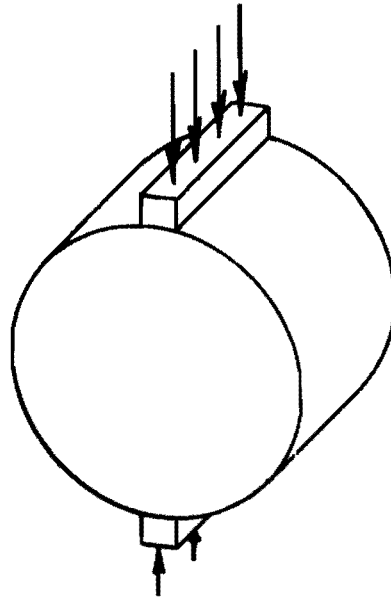
Thus, there has been a need for simple, effective laboratory tests for characterizing materials in terms of the required fundamental properties. As a result the static and repeated-load indirect tensile tests were developed to evaluate the engineering properties of pavement materials.

INDIRECT TENSILE TEST

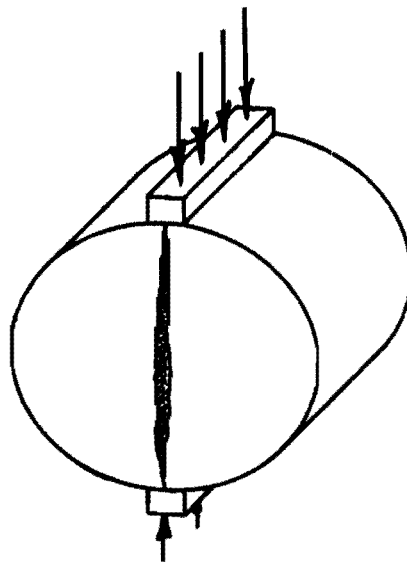
The indirect tensile test is conducted by loading a cylindrical specimen with a single or repeated compressive load which acts parallel to and along the vertical diametral plane (Fig 1). This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane, which ultimately causes the specimen to fail by splitting along the vertical diameter.

The indirect tensile test has been described under a series of names including: Brazilian Split Test, Split Test, Splitting Tensile Test, Diametral Test, Resilient Modulus Test, Schmidt Test, as well as Indirect Tensile Test. In addition, the test can be performed in a repeated-load configuration or as a static, single load to failure, mode. The equipment and setup prescribed for use in various supporting documents will vary somewhat but the results are the same in terms of strength and the elastic or viscoelastic properties.

The development of stresses within a cylindrical specimen subjected to a line load was reported by Kennedy and Hudson (Refs 25 and 26). The



(a) Compressive load being applied.



(b) Specimen failing in tension.

Fig 1. Indirect tensile test loading and failure.

significant stress distributions along the horizontal and vertical axes are shown in Figure 2.

Under conditions of a line load, the specimen would fail near the load points due to compressive stresses and not in the center portion of the specimens due to tensile stresses. However, these compressive stresses are greatly reduced by distributing the load through a loading strip, which not only reduces the vertical compressive stresses but changes the horizontal stresses along the vertical diameter from tension to compression near the points of load application. In addition, as previously noted, a biaxial state of stress is developed within the specimen. At the center of the specimen, the vertical compressive stress is approximately three times the horizontal tensile stress. A 0.5-inch curved loading strip has been used because the stress distributions are not altered significantly in a 4-inch diameter specimen* and because calculations of modulus of elasticity and Poisson's ratio are facilitated by maintaining a constant loading width rather than a constantly changing loading width, which would occur with a flat strip.

Equations were developed that permit the computation of the tensile strength, tensile strain, modulus of elasticity, and Poisson's ratio (Refs 15 and 27). These equations required that the calculations be carried out using a computer program; however, for a given diameter and width of loading strip the equations can be simplified and used without the aid of a computer. These equations and input coefficients for various specimen sizes are contained in Research Report 183-14 (Ref 14).

Test Procedures

In the static test a cylindrical specimen is loaded generally at a rate of 2 inches of deformation per minute. Slower rates can be used, especially for colder temperatures, since the material behaves more elastically and since loads or deformation associated with thermal cracking develop slowly, and for the more brittle materials such as portland cement-concrete. The testing temperature normally has been at room temperature, approximately 75°F, to eliminate the need for special heating

*A 0.75-inch-wide loading strip is used for 6-inch-diameter specimens.

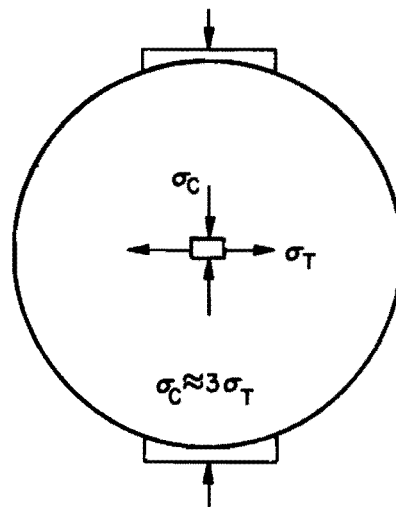
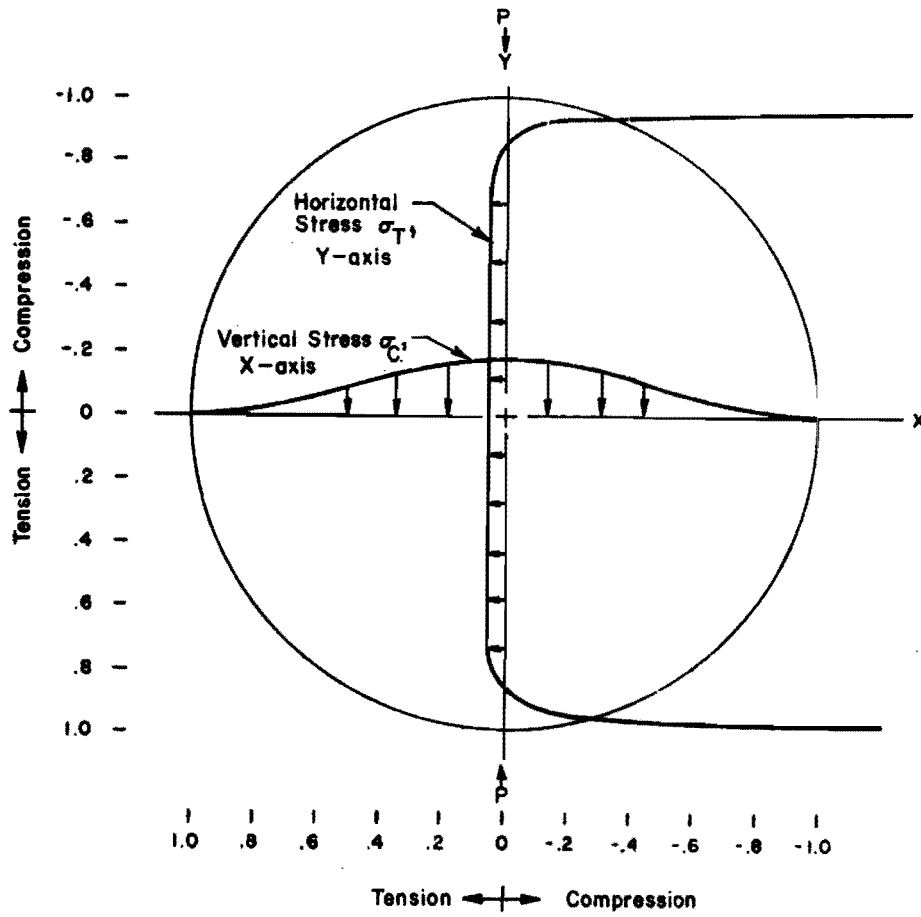


Fig 2. Relative stress distributions and center element showing biaxial state of stress for the indirect tensile test.

or cooling facilities, however other temperatures can be used. To completely characterize a material such as asphalt concrete at least three temperatures, e.g. 39, 75 (room temperature), and 102°F, should be used to obtain the effects of temperature. The total horizontal (tensile) deformations and vertical (compressive) deformations should be measured continuously during loading.

In the dynamic, or repeated-load, indirect tensile test method, the same basic equations are used but it is not necessary to characterize the entire load-deformation relationship. A resilient modulus of elasticity can be obtained by measuring the recoverable vertical and horizontal deformations and assuming a linear relationship between load and deformation. In addition, this method can also provide an estimate of permanent deformation which occurs under repeated loads. Generally, the repeated stress is applied in the form of a haversine and a small preload is used in order to maintain constant contact between the loading strip and specimen. Typical load-time pulse and deformation-time relationships are shown in Figures 3 and 4. It is recommended that a shorter load duration be used if adequate recording equipment is available. Other load-time pulses, e.g., square wave or trapezoidal wave forms, can also be used.

Based on work at The University of Texas at Austin, the detailed test procedures were developed and reported in Research Report 183-14 (Ref 14).

PROPERTIES RELATED TO DISTRESS

In addition to the basic elastic and viscoelastic inputs, properties related to the basic distress modes of thermal and shrinking cracking, fatigue cracking, and permanent deformation are required and can be obtained using the static and repeated-load indirect tensile tests.

Thermal or Shrinkage Cracking

Tensile strengths required by the thermal or shrinkage cracking subsystem can be obtained using the direct tension or the static indirect tensile test. The direct tension test, however, is extremely difficult and time-consuming to conduct while the indirect tensile test is simple and can be conducted at a rate of 25 tests per hour. Values for asphalt concrete

a = Duration of loading during one load cycle
 b = Recovery time
 c = Cycle time

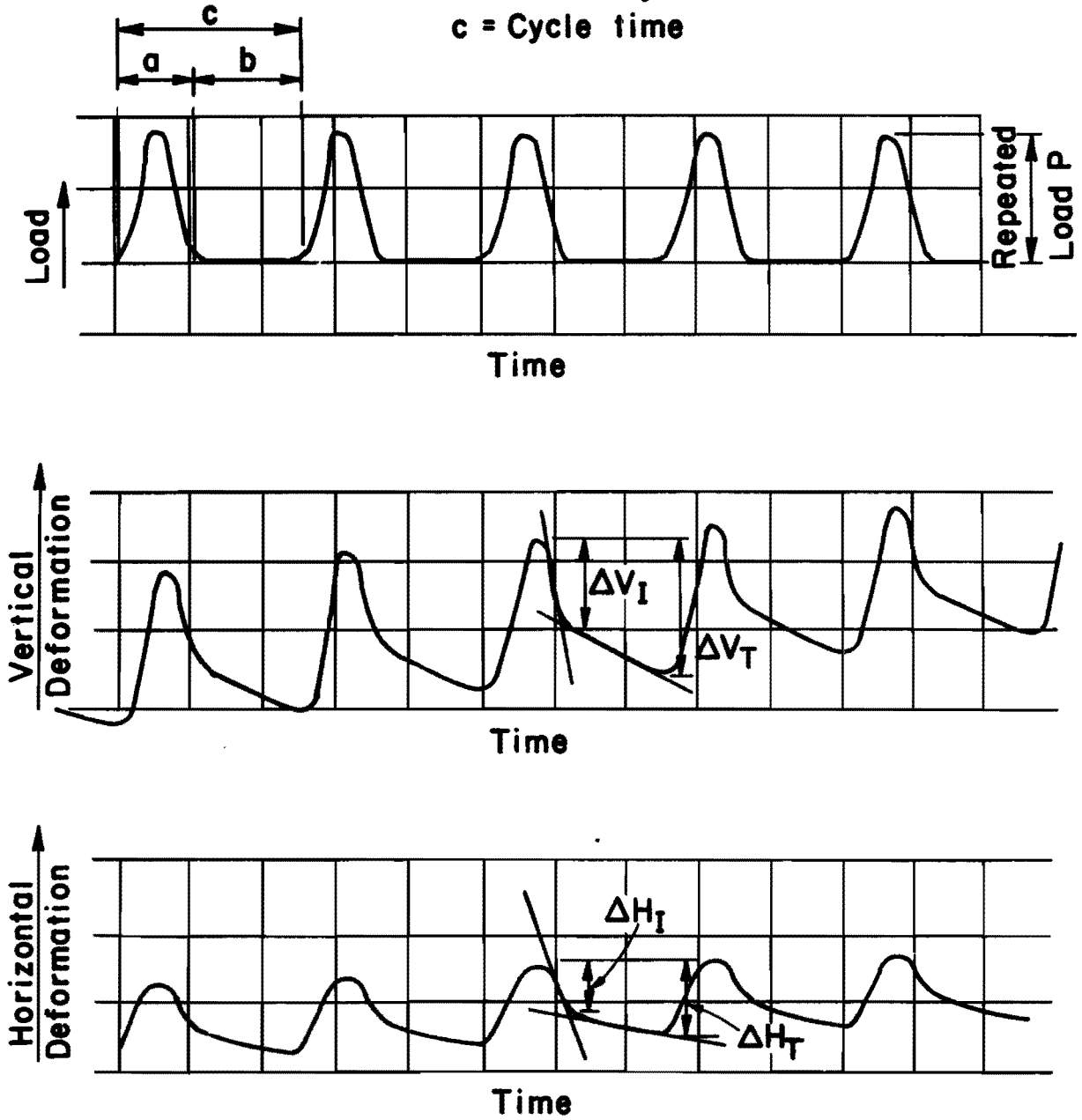


Fig 3. Load pulse and associated deformation relationships for the repeated-load indirect tensile test.

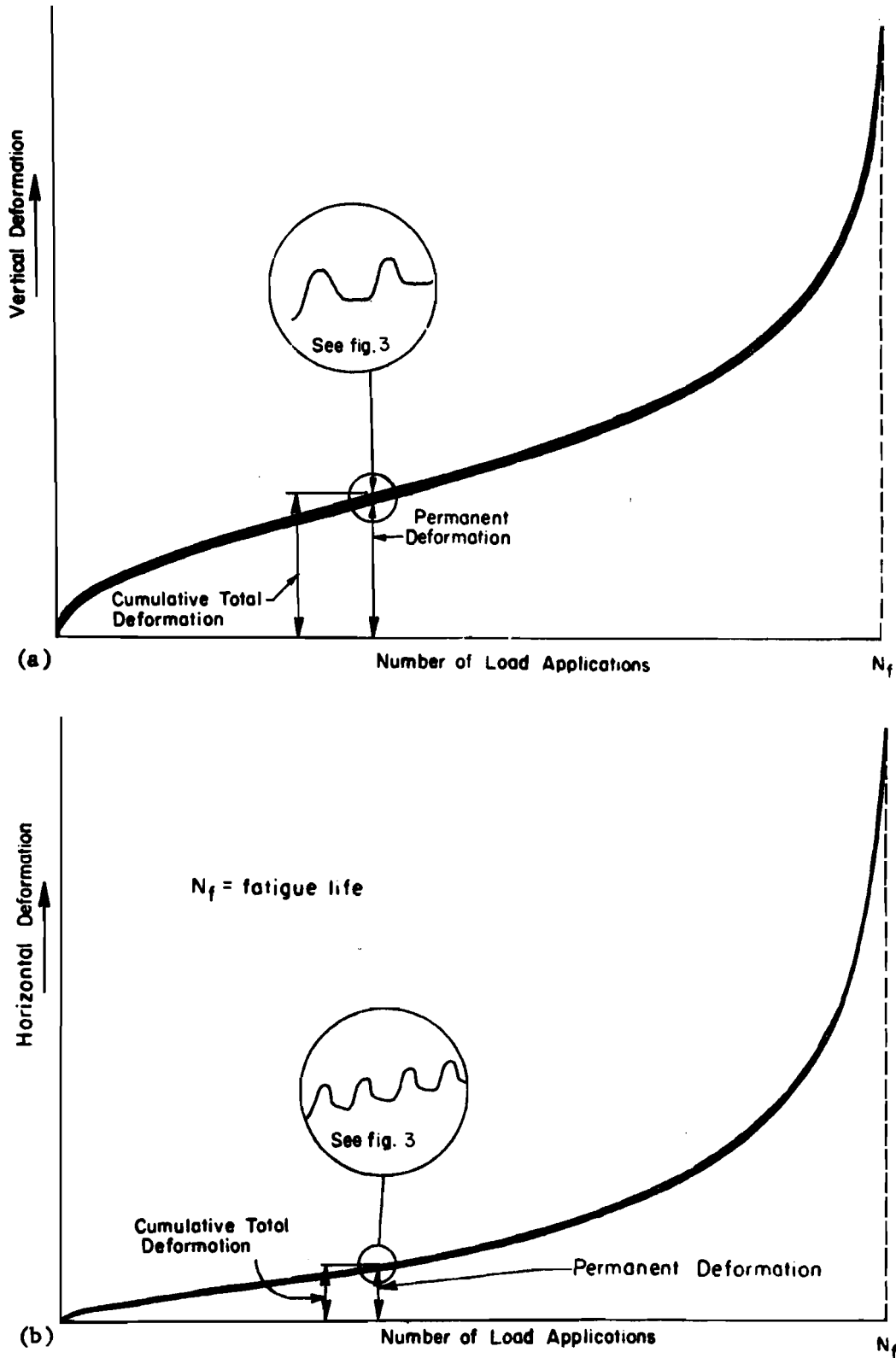


Fig 4. Relationships between number of load applications and vertical and horizontal deformation for the repeated-load indirect tensile test.

generally have varied from 50 to 600 psi depending on the temperature. At 75°C, values generally have been in the range of 100 to 200 psi. These strengths are typical and realistic for asphalt concrete. Realistic values have also been obtained for portland cement concrete and other materials.

Because of the ease of conducting the static test, the test can be used for quality control and has definite application for the evaluation of pavement materials in areas which do not have easy access to testing laboratories. It is also possible that tensile strength or the static modulus of elasticity can be related to the behavior under repeated loads, or that mixture designs can be based on static tests.

Fatigue Cracking

Various types of tests have been used to study the fatigue behavior of asphalt mixtures and other pavement materials. Those tests which have been used significantly for asphalt materials are the flexure test, rotating cantilever test, axial load test, and repeated-load indirect tensile test.

In addition, two basic types of loading are used in laboratory tests, controlled-strain or controlled-stress. Controlled-strain tests involve the application of repeated-loads which produce a constant repeated deformation or strain. In the controlled-stress tests a constant stress or load is repeated. Materials in thick flexible pavements are best tested using controlled-stress. The controlled-strain test is more applicable to thin flexible pavements.

In all of the above tests, a linear relationship is assumed to exist between the logarithm of the applied tensile stress and the logarithm of fatigue life, which can be expressed in the form

$$N_f = K_2 \left(\frac{1}{\sigma_\tau} \right)^{n_2} \quad (2.1)$$

where N_f = fatigue life,
 σ_τ = applied tensile stress,
 n_2 = slope of the logarithmic relationship between fatigue life and tensile stress, and
 K_2 = antilog of the intercept of the logarithmic relationship between fatigue life and tensile stress.

It was found (Refs 2 and 5) that values of n_2 obtained using the indirect tensile test compared favorably with those reported by other investigators using other test methods (Refs 16,17, and 18); however, the values of K_2 were significantly smaller, resulting in much lower fatigue lives. Thus, the results obtained from other test methods were analyzed and compared with the characteristics of these tests and it was concluded that the results obtained from the repeated-load indirect tensile test were compatible if the applied stress was expressed in terms of stress difference, or deviator stress, to account for the biaxial state of stress which exists in the indirect tensile test (Fig 2). Figure 5 illustrates the relationships between fatigue life and stress difference for various tests. The dashed line illustrates the relationship between fatigue life and stress. For the indirect tensile test, stress difference is approximately equal to $4\sigma_\tau$ while stress difference for the uniaxial tests is equal to the applied stress. As seen in Figure 5, the differences in the results were greatly reduced.

Expressing fatigue life in terms of stress difference merely shifts the position of the stress-fatigue life relationship and does not change the slope. Therefore, the K_2 values are significantly increased but values of n_2 are not affected and the relationship can be expressed in the form

$$N_f = K_2' \left(\frac{1}{\Delta\sigma} \right)^{n_2} \quad (2.2)$$

where $\Delta\sigma$ = stress difference, and

K_2' = the antilog of the intercept value of the logarithmic relationship between fatigue life and stress difference.

Values of K_2' , which are based on stress difference, were found to be comparable to values obtained for similar mixtures using other test methods.

In addition, fatigue life is significantly increased if the duration of the applied stress is reduced. In the above tests, the duration was 0.4 seconds, which ideally should be reduced to about 0.1 seconds. Such a change will improve the fatigue life predictive capabilities since laboratory fatigue tests underestimate the actual fatigue life of inservice pavements.

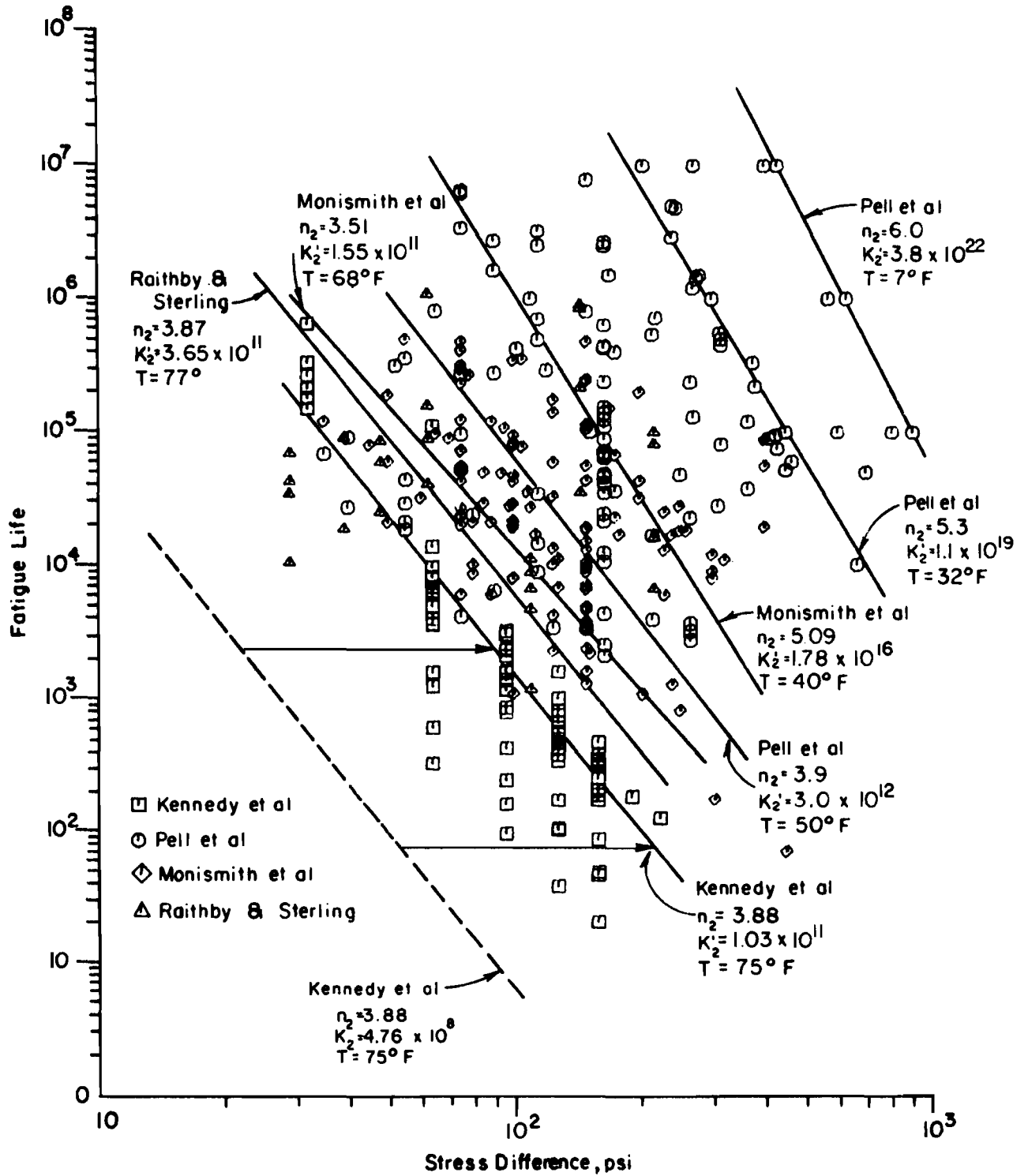


Fig 5. Typical stress difference-fatigue life relationships for various test methods.

The relationship between initial strain and fatigue life can also be expressed as

$$N_f = K_1 \left(\frac{1}{\epsilon_i} \right)^{n_1} \quad (2.3)$$

where ϵ_i = initial tensile strain,
 n_1 = slope of the logarithmic relationship between fatigue life and initial strain, and
 K_1 = antilog of the intercept of the logarithmic relationship between fatigue life and tensile strain.

Values of K_1 compared favorably with previously reported values for similar mixtures with the same asphalt contents and tested at the same temperature.

Thus, it has been demonstrated in a number of studies that the fatigue characteristics obtained using the repeated-load indirect tensile test are comparable to the results obtained from other tests if stress is expressed in terms of stress difference or strain. This is significant since the repeated-load indirect tensile test is easier and more rapid to conduct than other commonly used fatigue tests and uses cylindrical specimens and cores.

Permanent Deformation

Three basic repeated-load tests have been used to obtain permanent strain information for asphalt materials. These tests are the:

- (a) triaxial compression test,
- (b) triaxial test in which the axial stress is tension, and
- (c) repeated-load indirect tensile test.

On the basis of a comparison of values obtained for the Brampton Road Test (Ref 19) with values obtained using the repeated-load indirect tensile test, it was concluded that the repeated-load indirect tensile test and the triaxial test in which the axial stress is tension provides reasonable estimates of permanent strain (Ref 7).

In addition to normal permanent strain characteristics, the permanent strain properties used by VESYS can be determined using the repeated-load indirect tensile test and the triaxial test. Two basic parameters, GNU and

ALPHA, are used to describe the permanent deformation characteristics of asphalt mixtures and to predict rutting.

The theory (Ref 20) assumes that the logarithmic relationship between the number of repeated loads and permanent strain is essentially linear over a range of load applications (Fig 6) and can be described by the equation

$$\epsilon_{\alpha} = IN^S \quad (2.4)$$

where ϵ_{α} = accumulated permanent strain,
 I = intercept with permanent strain axis (arithmetic strain value, not log value) (Fig 6),
 N = number of load applications, and
 S = slope of the linear portion of the logarithmic relationship.

GNU is defined as
$$\mu = \frac{IS}{\epsilon_r} \quad (2.5)$$

and ALPHA is defined as
$$\alpha = 1 - S \quad (2.6)$$

where ϵ_r = resilient strain, which is considered to become constant after a few load applications (Fig 7).

An evaluation of the three tests listed above (Ref 7) indicated that the permanent strain relationships for the latter two tests, which involve tensile stresses, are similar but different from those for the triaxial compression tests. Typical compressive and tensile test relationships are shown in Figure 8.

For compressive tests, the semilogarithmic relationship has a linear portion; however, the logarithmic relationship is nonlinear. For the tensile tests, the arithmetic relationship has a significant linear portion, but, as with the compressive stress relationship, the logarithmic relationship is nonlinear. This behavior is characteristic of the relationships obtained from both the repeated-load indirect tensile test and the triaxial test in which the axial stress is tensile (Refs 19, 21 and 22).

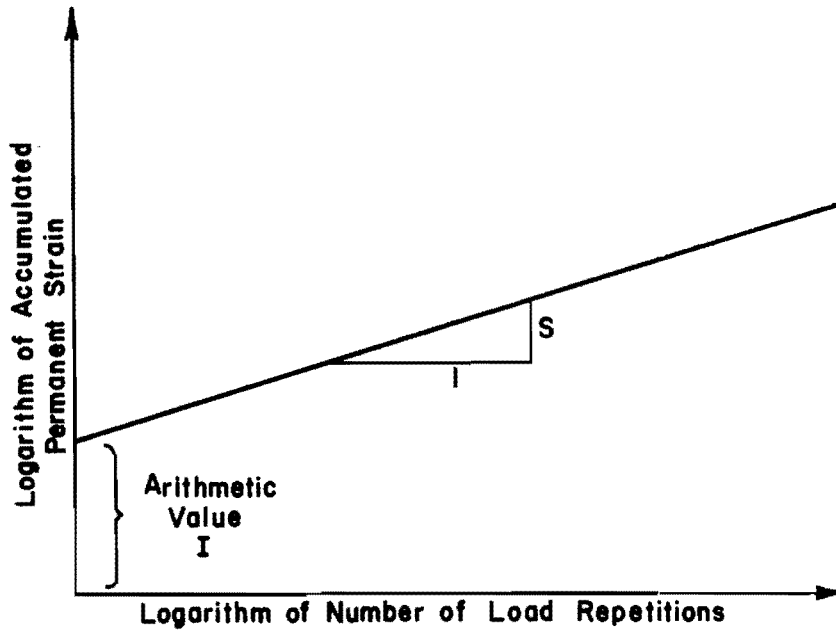


Fig 6. Assumed logarithmic relationship between permanent strain and number of load repetitions (Ref 20).

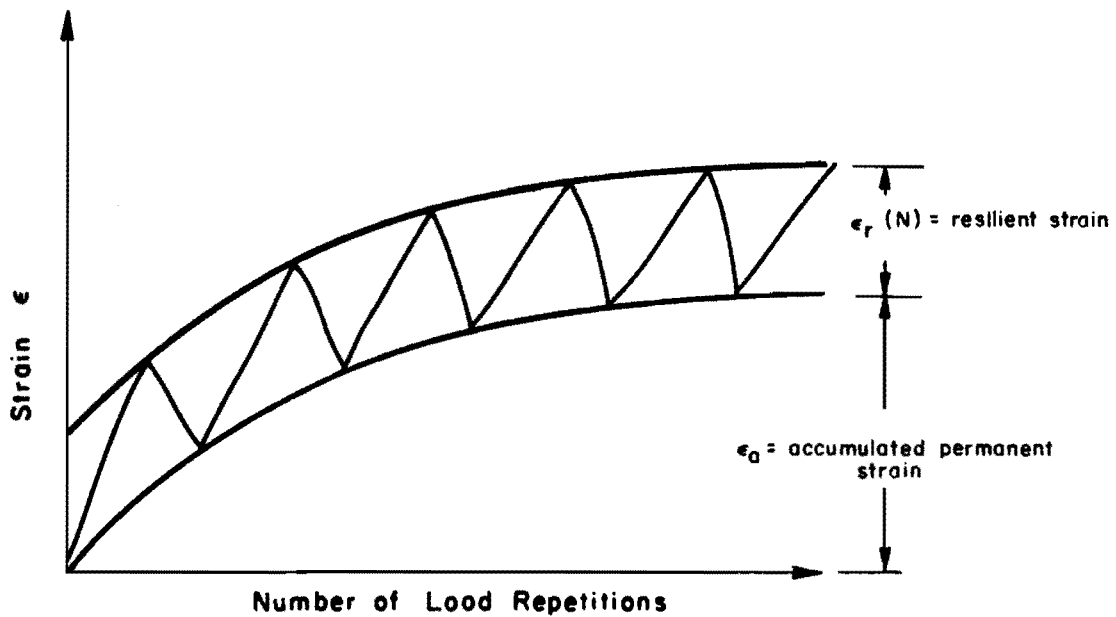


Fig 7. Typical relationship between strain and number of load repetitions (Ref 20).

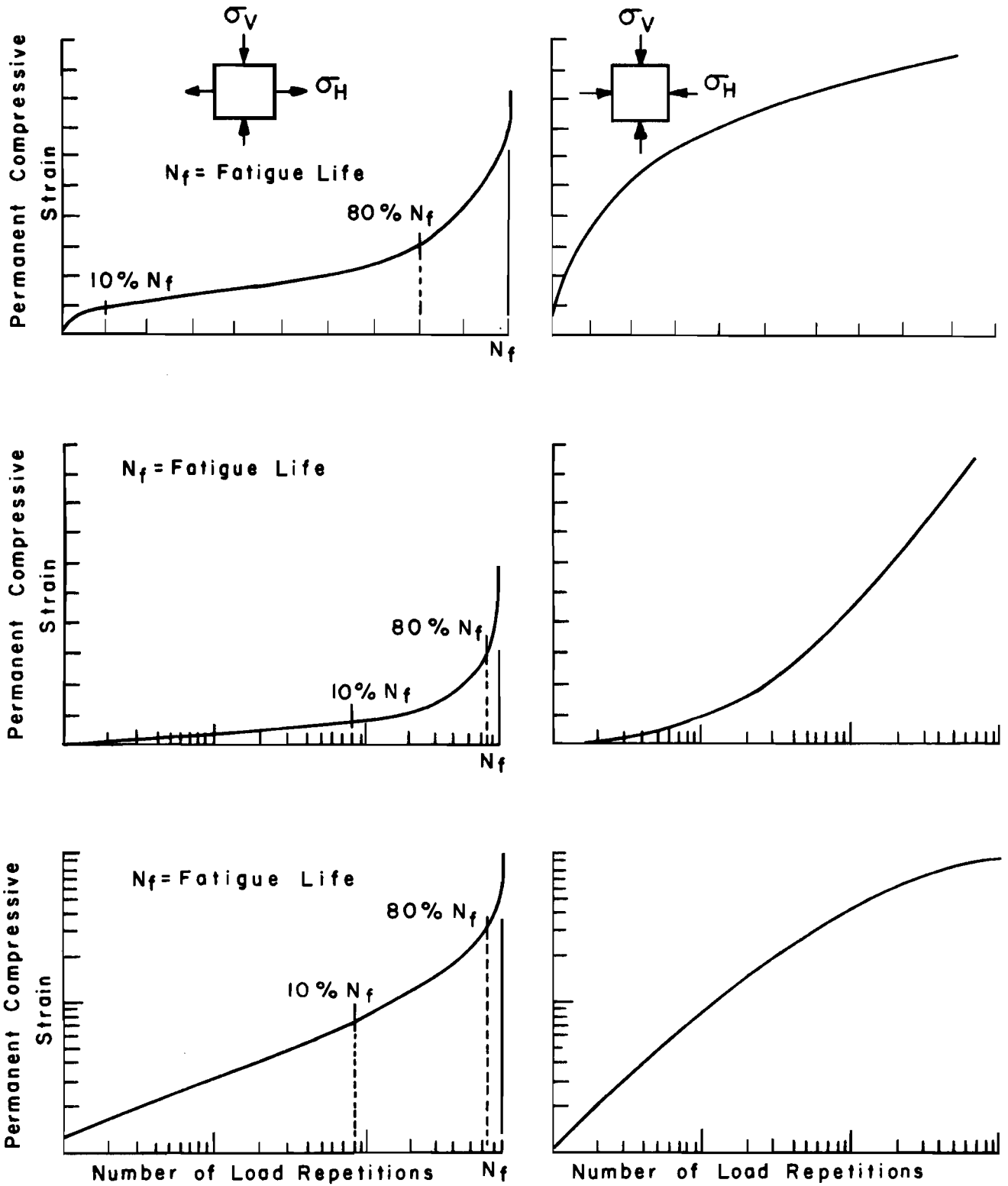


Fig 8. Typical arithmetic and logarithmic permanent strain relationships for relationships for tensile and compressive tests (Ref 7).

Because of the differences in the permanent strain relationships for the various tests and the fact that all three differ from the assumed relationship, the concept of GNU and ALPHA should be re-evaluated in order to improve the ability to characterize the permanent strain relationships of asphalt mixtures for use in VESYS. Nevertheless, the indirect tensile test can be used to obtain acceptable values for GNU and ALPHA by characterizing the initial portion of the logarithmic relationship for permanent strain.

Choice of Test Method

Table 1 contains a subjective comparison of various test methods currently used to obtain fundamental materials' characteristics inputs. The various tests, as commonly conducted, are evaluated and summarized in terms of their ability to provide elastic and viscoelastic properties plus information related to the distress modes in terms of the previously discussed criteria.

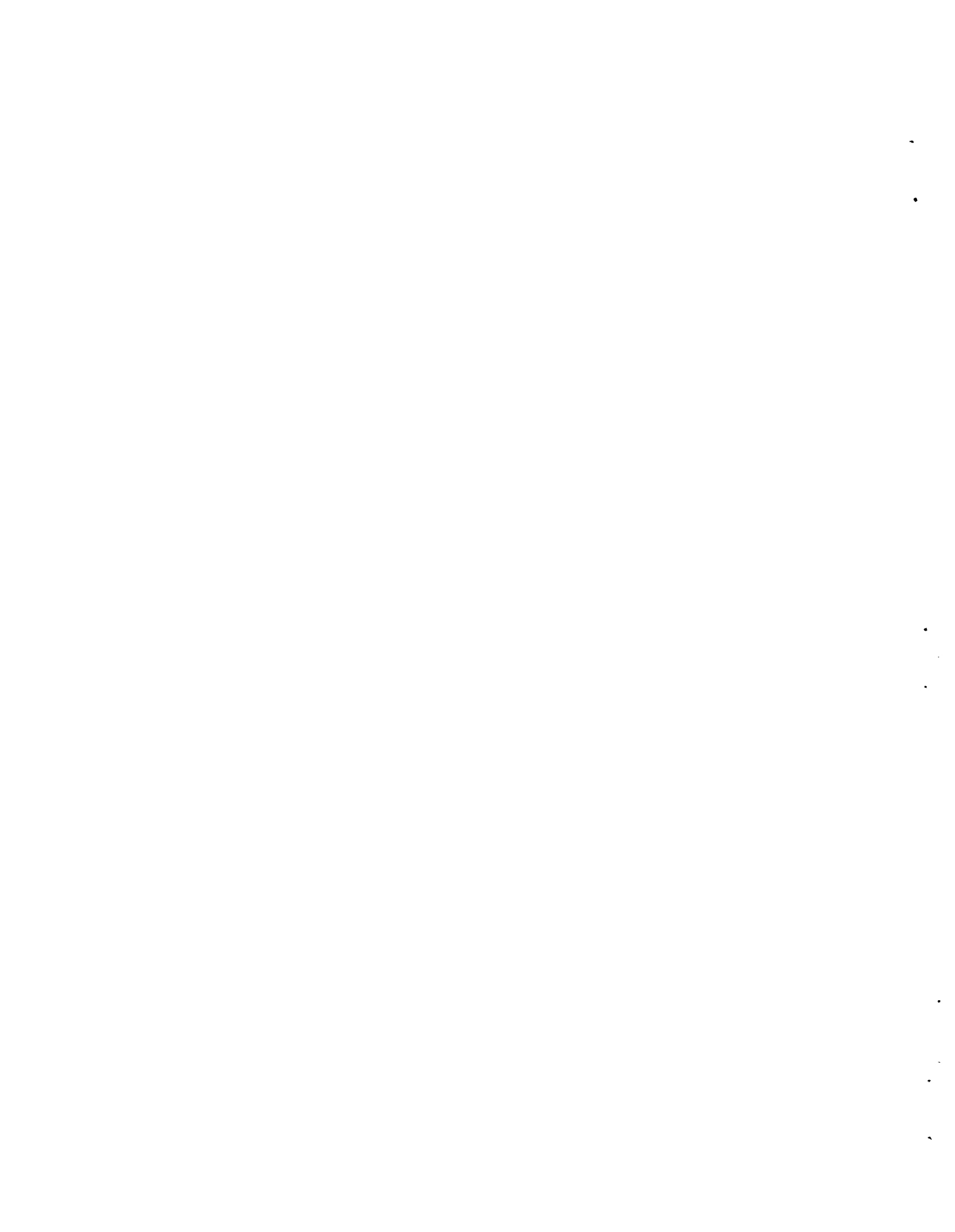
An examination of the comparisons suggests that the indirect tensile test has certain advantages of economy and simplicity for bound, or cohesive, materials. In the case of unbound materials, the triaxial test remains the only variable method for laboratory evaluation, although a triaxial form of indirect tensile test is currently being developed.

Prior to 1965, the indirect tensile test was used primarily to measure the tensile strength of concrete. Because of the many practical advantages of the test, however, beginning in 1965 the test was used to evaluate other pavement materials. The test also has been used to evaluate sulphur-asphalt and recycled asphalt mixtures.

In addition, during the past few years, the indirect tensile test has been used extensively to evaluate the engineering properties of asphalt mixtures, and an ASTM standard (Ref 23) for the determination of the resilient modulus of elasticity and Poisson's ratio is available.

TABLE 1. COMPARISON OF COMMON TEST METHODS (REF 24)

	Basic Test	Variations of Basic Test	Fundamental Properties Usually Determined By Test	Relationships Test Commonly Used For	Structural Subsystem Applicability			Criteria		Remarks
					Fatigue	Permanent Deformation	Low-Temperature Cracking	Ease of Testing and Economy	Reproducibility	
Tests for Elastic Properties	Indirect Tensile Test	Static	Stiffness Modulus, S	Fatigue Permanent Deformation Strain vs Temperature	Yes	Yes	Yes	Excellent	Good	Easy acquisition of specimens (i.e., from Marshall test or field cores)
		Dynamic Repeated	Resilient Modulus, E_R							
	Triaxial	Complex Modulus Test ¹	Complex Modulus, E		No	Yes	No	Good	Good	Output of test used for layer analyses rather than for fatigue, permanent deformation, or cracking relationships
		Resilient Modulus Test ²	Resilient Modulus, M_R							
	Beam Bending		Stiffness Modulus, S	Fatigue	Yes	No	No	Fair	Fair	
	Direct Tension	Triaxial ³		Permanent Deformation	Yes	Yes	No	Poor	Good	Specimen preparation usually requires sawing
Beam Test		Stiffness Modulus, S	Strain vs Temperature	Yes	No	Yes	Good	Poor		
Tests for Viscoelastic or Time-Dependent Properties	Triaxial	Static Creep ⁵	Creep Compliance	Permanent Deformation	No	Yes	No	Good	Good	Limited experience in applying this test to viscoelastic materials
		Dynamic Repeated	GNU and ALPHA ⁶							
	Indirect Tensile Test ⁷	Static Creep ⁵	Creep Compliance	Permanent Deformation	Yes	Yes	No	Excellent	Good	
		Dynamic Repeated	GNU and ALPHA ⁶							



CHAPTER 3. TENSILE AND REPEATED-LOAD
PROPERTIES OF INSERVICE MATERIALS

This chapter summarizes the work reported in Research reports 183-1, 183-2, and 183-9 (Refs 1, 2, and 9) and is concerned with the properties and variational characteristics of inservice materials used in newly constructed Texas pavements.

INTRODUCTION

Most pavement design procedures are largely empirical and deterministic in nature, using exact values of input and presenting the results as exact values. At a 1970 workshop on the structural design of asphalt pavements (Ref 28), one of the most pressing areas of research need was established to be the application of probabilistic or stochastic concepts to pavement design. The workshop stated the problem as follows:

So that designers can better evaluate the reliability of a particular design, it is necessary to develop a procedure that will predict variations in the pavement system response due to statistical variations in the input variables, such as load, environment, pavement geometry, and materials properties including the effects of construction and testing variables. As part of this research, it will be necessary to include a significance study to determine the relative effect on the system response of variations in the different input variables.

Research at The University of Texas led to design procedures for both rigid and flexible pavements in which the systems approach was used to consider all phases of design, construction, and inservice performance to arrive at an acceptable pavement design. Trial use of these design systems revealed a definite need to consider the random or stochastic nature of many of the input variables so that the design reliability can be estimated.

In addition, these design systems were empirical, and it was felt that attempts should be made to apply theory of elasticity or other more fundamental design approaches. A necessary first step was the determination of

the elastic and tensile properties of pavement materials and the variations in these properties as they exist in the roadway.

The principal objectives of the research effort summarized in this chapter and in Research Reports 183-1, 183-2 and 183-9 (Refs 1, 2, and 9) were (1) to characterize highway paving materials in terms of their tensile, elastic and fatigue properties, specifically tensile strength, Poisson's ratio, modulus of elasticity, and fatigue life; and (2) to establish an estimate of the variation in these properties which can be expected for an in-place pavement but not necessarily to establish the cause of the variation. To accomplish these objectives, field cores of various highway paving materials from construction projects in the state of Texas were tested using the static and repeated-load indirect tensile test. The fatigue lives, resilient elastic properties, and the variation about mean values were estimated using the repeated-load indirect tensile test; values of strength, modulus of elasticity, and Poisson's ratio were determined using static loading.

Roadway designers have traditionally assumed that the properties of paving material are constant along a design length of roadway, where design length can be defined as a specific length along a roadway which is designed for uniform thickness and materials type. However, even under closely controlled laboratory conditions there is a random variation in the properties of replicate specimens. This variation represents inherent material variation plus some amount of testing error. In comparing the laboratory environment with a construction project, it would be expected that more variation would result from the relatively uncontrolled construction process.

The variation in material properties introduced along the road includes inherent material variation as well as variation introduced by the environment, changes in the constituents of the mixture, changes in contractor or construction technique, and various other factors. This variation was estimated by testing cores sampled randomly along the design length of the project and samples were clustered in one location. In addition to the variation which occurs horizontally in the pavement, the variation which occurred vertically was determined for specimens taken from the upper and lower portions of the cores or for the various layers.

DESCRIPTION OF PROJECTS TESTED

It was originally anticipated that several different types of pavement material would be available for testing, including portland cement concrete, blackbase, asphalt concrete, asphalt-treated materials, cement-treated materials, and lime-treated materials. However, due to the lack of newly completed construction projects using some of these materials or the difficulty in obtaining an intact core, only four materials were tested with most testing involving portland cement concrete and blackbase which were most commonly used in paving projects. Other materials were asphalt concrete and cement-treated base material. Figure 9 shows the geographical distribution of the Highway Department districts from which the pavement cores were obtained.

CORE SAMPLING PLAN UTILIZED IN THIS STUDY

Cores from newly constructed pavements are routinely taken in order to determine pavement thickness. These cores are taken at approximately regular intervals unless a thin section is encountered, i.e., a section of pavement in which the depth is less than design depth. When this occurs, cores are taken at closer intervals until the depth again reaches design depth (Fig 10). With this systematic sampling technique, the cores can be considered to have been randomly sampled from the pavement. This sampling plan is based on the assumption that samples obtained in a systematic fashion can be considered to be random when the sampling function does not coincide with any variation distribution function that may exist in the pavement.

As previously discussed, one method of estimating the additional variation due to construction would be to test cores clustered at approximately the same location in the pavement. Considered with the total length of a project, a group of cores obtained at close intervals approximates a cluster. The variation introduced during construction (along-the-road variation) as a result of changes in pit source, weather, etc., can be estimated with the cores obtained over longer longitudinal distances.

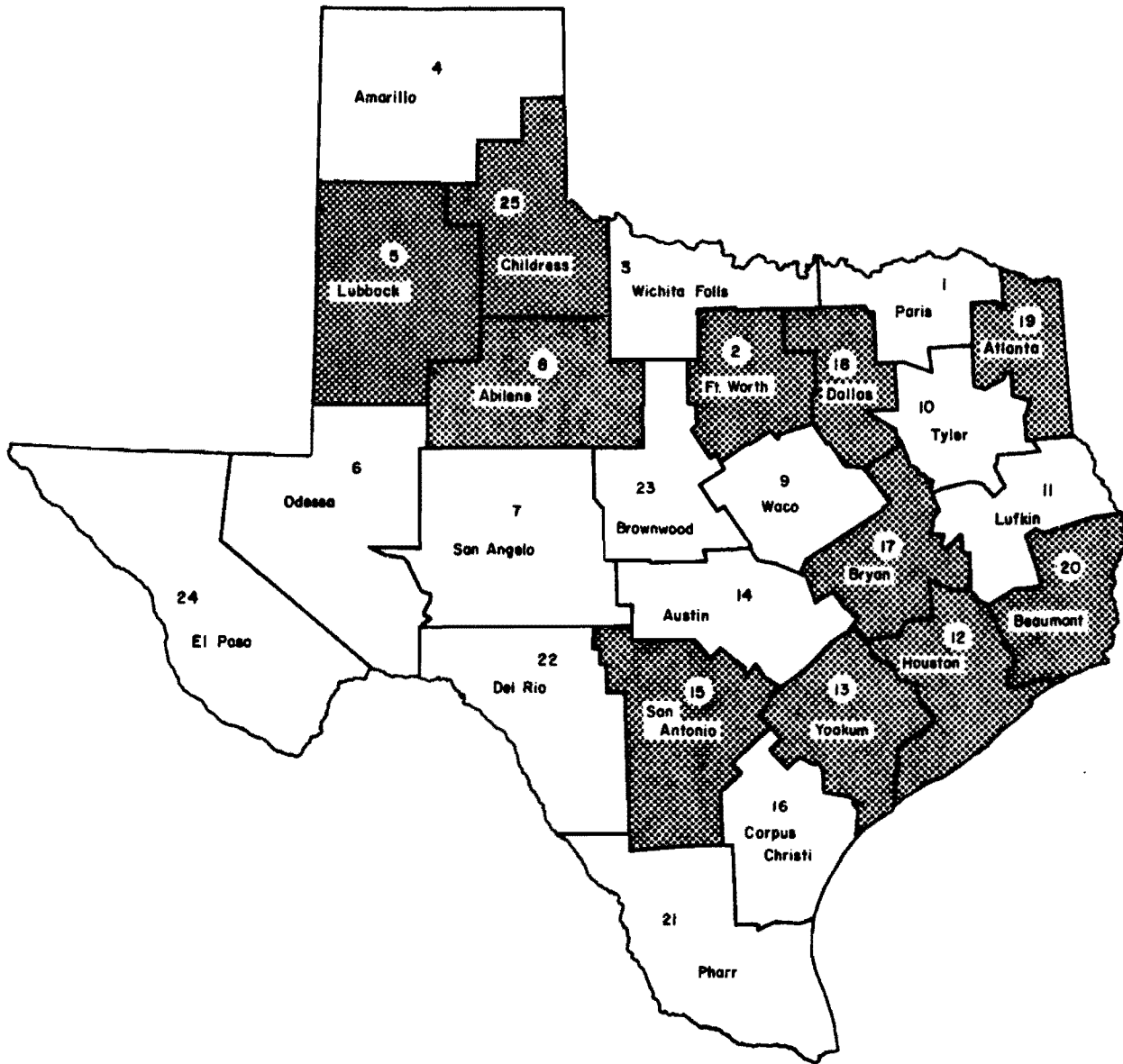


Fig 9. Districts (SDHPT) from which cores were obtained.

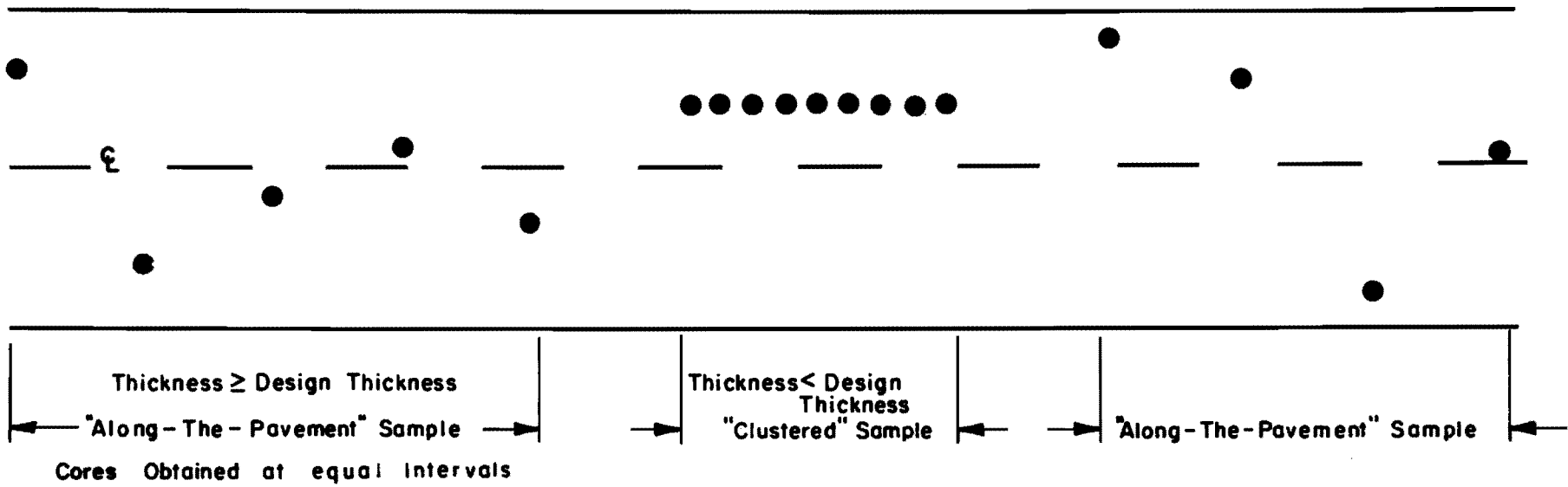


Fig 10. Typical core sampling plan.

TEST PROGRAM

All portland cement concrete cores were obtained with a 4-inch inside diameter core barrel from 8-inch or 9-inch nominal depth pavements. Since many projects involved a large number of cores, and due to time restrictions, not all cores could be tested. Therefore, a portion of the cores were selected at random to represent the along-the-road sample and, where present, the clustered sample for a given project. The concrete paving projects were typically multilane roadways in which the two main directional lanes (i.e., northbound and southbound) were treated as separate roadways for sampling purposes.

To investigate differences with respect to depth in the pavement, normally three specimens were cut from each concrete core, one from the top, center, and bottom of the core. Each specimen was approximately 2 inches thick, with a 4-inch diameter.

Both 4-inch and 6-inch diameter blackbase cores were tested. The cores were sawed at the interface between lifts whenever possible, so that each specimen represented only one lift.

Before the specimen was tested, its dimensions were accurately measured and the specimen was weighed so that its density could be estimated.

The tensile and elastic properties of the paving materials studied were estimated using the indirect tensile test procedures summarized in Chapter 2.

ANALYSIS AND EVALUATION OF TEST RESULTS

The primary objective of this study was to synthesize information on the elastic and tensile characteristics and their variations for various highway pavement materials in order to provide preliminary estimates of materials properties for the design of pavements. The materials tested and evaluated were portland cement concrete, blackbase, asphalt concrete, and cement-treated base.

Portland Cement Concrete

Cores were obtained from a total of ten projects from six Texas Highway Department districts. Three of these projects had clustered samples involving cores obtained at 10-foot intervals. Each core was generally sawed to obtain three specimens. These specimens were tested using the indirect tensile test to estimate tensile strength, static and resilient modulus of elasticity, and fatigue life. In addition, the variation in pavement thickness was determined for the projects for which this information was available and densities were estimated by measuring the dimensions and weight of the specimens. A summary of the test results is contained in Research Reports 183-1 (Ref 1) and 183-9 (Ref 9).

Tensile Strength. Tests involved the individual specimens, regardless of whether the specimen was cut from the top, center, or bottom of the core. Mean tensile strength values varied from 390 psi to 580 psi and averaged 470 psi. The coefficient of variation for the mean tensile strength values for each project was 13 percent, and, while this value was not large, it did indicate that there were differences between projects. Coefficients of variation within given projects were very consistent at about 20 percent. This magnitude of variation is comparable to that found for flexural and compressive strength in previous studies. In addition, the coefficients for the clustered samples were comparable.

A comparison of the strengths of the top, center, and bottom specimens indicated that there was a general increase in strength with depth. However, only the specimens cut from the bottom of the cores had significantly higher tensile strengths than the specimens from the top and center portions of the cores. These strength differences ranged from 20 to as much as 150 psi. The strengths of the center and top specimens were not significantly different from each other. Thus, a portion of the within-project variation can be attributed to the variation due to differences with depth in the layer or in the core.

The repeated-load or fatigue results in Research Report 183-9 (Ref 9) were obtained from specimens which were capped to minimize surface irregularities. Thus, separate static tests were conducted on four projects to determine the effects of the capping process.

The strengths of the capped specimens were approximately 30 percent greater than the strength of the uncapped specimens. The range of tensile strength for uncapped specimens was 400 to 560 psi as compared to a range of 520 to 710 psi for the capped specimens from the same projects.

A comparison of the coefficients of variation indicated that generally the coefficients were much less for the capped specimens than for the uncapped specimens, indicating that a large portion of the previously measured variation was due to testing errors related to surface irregularities of the specimens. Coefficients from the capped specimens ranged from 8 to 16 percent compared to about 20 percent for uncapped specimens.

Static Modulus of Elasticity. A value of 0.20 was assumed for Poisson's ratio in order to calculate modulus. Results of a sensitivity analysis indicated that a 25 percent change in Poisson's ratio (0.18 to 0.24) produced a 12 percent change in the computed modulus value (3.6×10^6 to 4.1×10^6 psi). The coefficient of variation, however, did not change.

Comparison of the top, center, and bottom specimens from each core revealed that in most cases there was an increase in modulus with depth and that the bottom specimens generally had a higher modulus than the centers and tops although the trend was not as pronounced as that for tensile strength. As with strength comparisons, there were generally no significant differences between center and top specimens.

The range in mean modulus values for the ten projects tested was not large. The values for all ten projects ranged from 3.4×10^6 psi to 5×10^6 psi and averaged 4×10^6 psi. The coefficient of variation of the mean modulus values was 13 percent, which is approximately the same as for strength. The variation in modulus within a given project was low to moderate, with coefficients of variation ranging from 22 percent to 42 percent. The average coefficient for all ten projects was 34 percent. The coefficients of variation for the clustered samples were not significantly different from the coefficients for the along-the-roadway samples.

Resilient Modulus of Elasticity. The resilient moduli of elasticity were calculated from horizontal deformation measurements and an assumed Poisson's ratio of 0.20. A typical relationship between resilient modulus

and the number of load applications for concrete produced with normal weight aggregate is shown in Figure 11.

Generally all specimens exhibited a slight decrease in modulus with increased load applications between 10 and 75 percent of the fatigue life. At approximately 75 percent of the fatigue life, the resilient modulus began to decrease. Between 25 and 75 percent of the fatigue life the mean resilient modulus decreased between 3 and 38 percent. The normal weight aggregates decreased between 3 and 23 percent while the light weight aggregate decreased much more with a value of 38 percent.

Fatigue Life. Specimens from one project were subjected to repeated loads at several stress levels in order to evaluate the linearity of the relationship between the logarithm of fatigue life and stress/strength ratio. The typical S-N relationship is shown in Figure 12. Since nearly all previous investigators have agreed that the S-N relationship is linear, only two stress levels were used for the three remaining test series.

For comparison purposes the S-N relationships for all four projects, which differed in strength by 35 percent, are shown in Figure 13 along with the results of other investigators who tested laboratory specimens using various test procedures.

As shown, the slopes of the four relationships were approximately equal but are displaced vertically. Thus the change in fatigue life produced by a change in stress/strength ratio was approximately the same although the actual fatigue life differed. Similarly, the fatigue lives for the cores tested were less than the fatigue lives of the other laboratory specimens; however, the differences in the slopes of the relationships were relatively small which is significant, considering that different test methods were used.

As might be expected, the variations in test results were larger for the cores than for the laboratory specimens. The coefficients of variations ranged from 16 to 38 percent, which were based on the logarithm of fatigue life since the distribution of fatigue life is generally log-normal.

Density and Pavement Thickness. Project densities ranged from 133.1 pcf to 146.2 pcf. Coefficients of variation were generally very

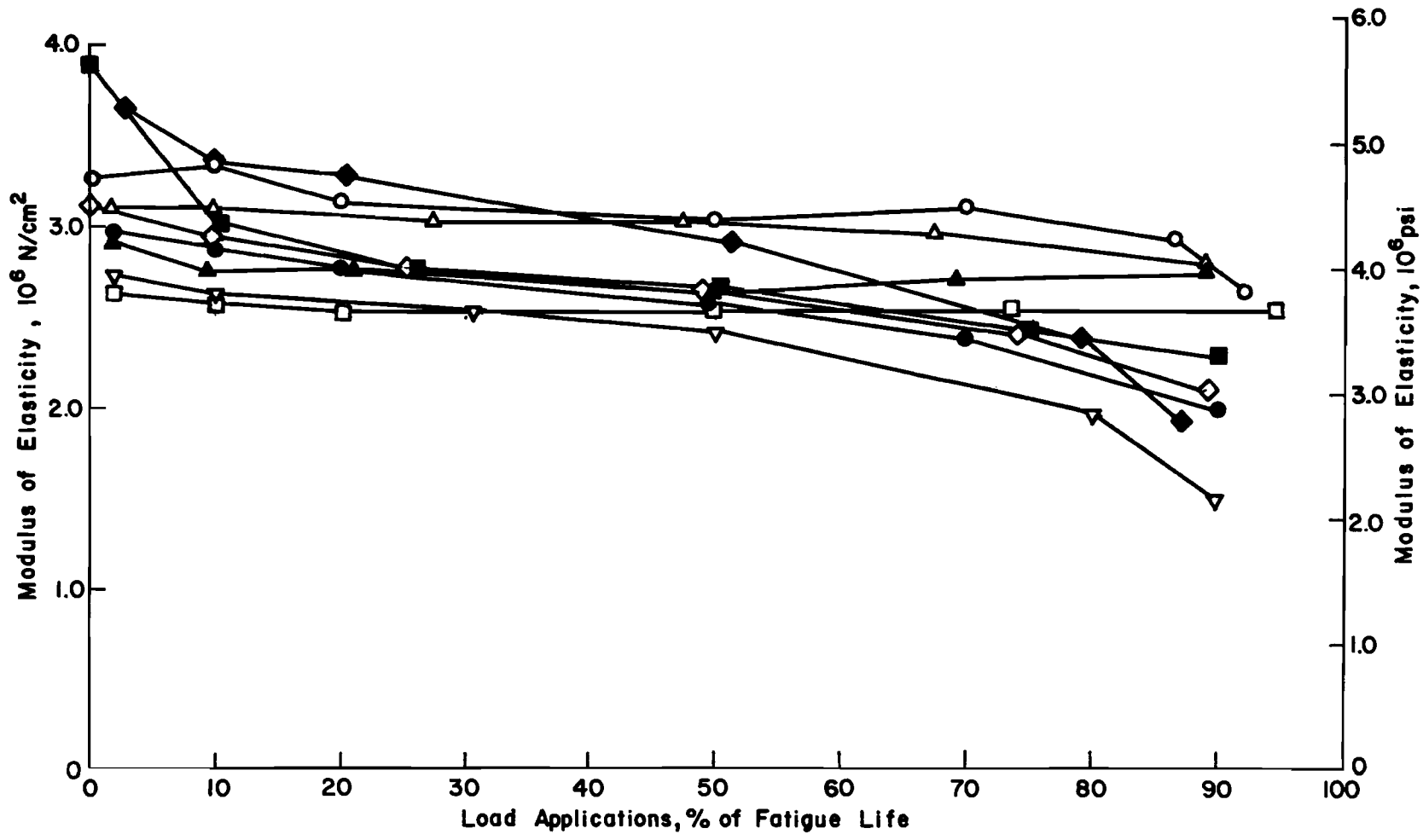


Fig 11. Typical relationships between modulus of elasticity and load applications for portland cement concrete (Ref 9).

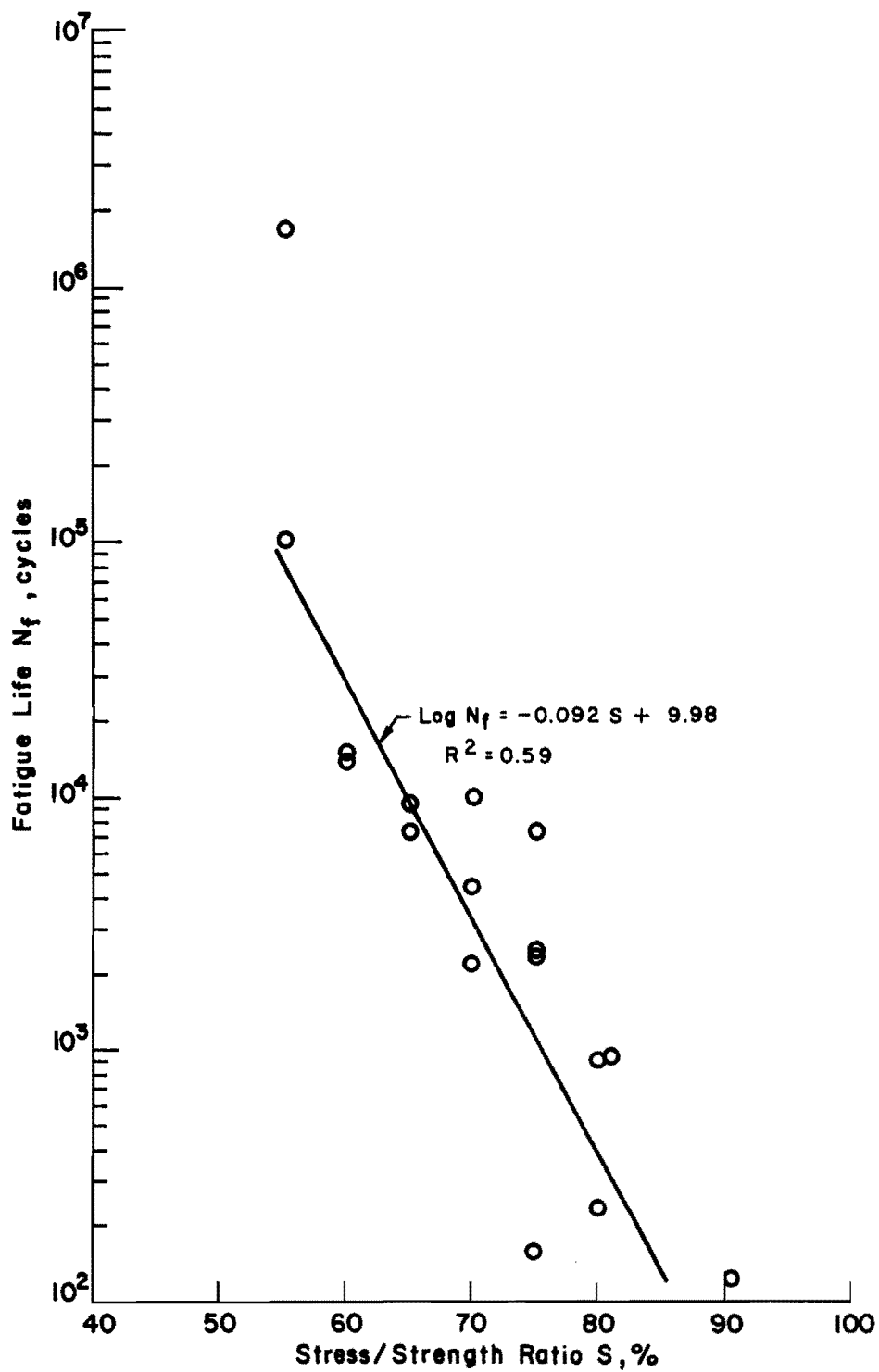


Fig 12. Typical S-N relationship for inservice concrete (Ref 9).

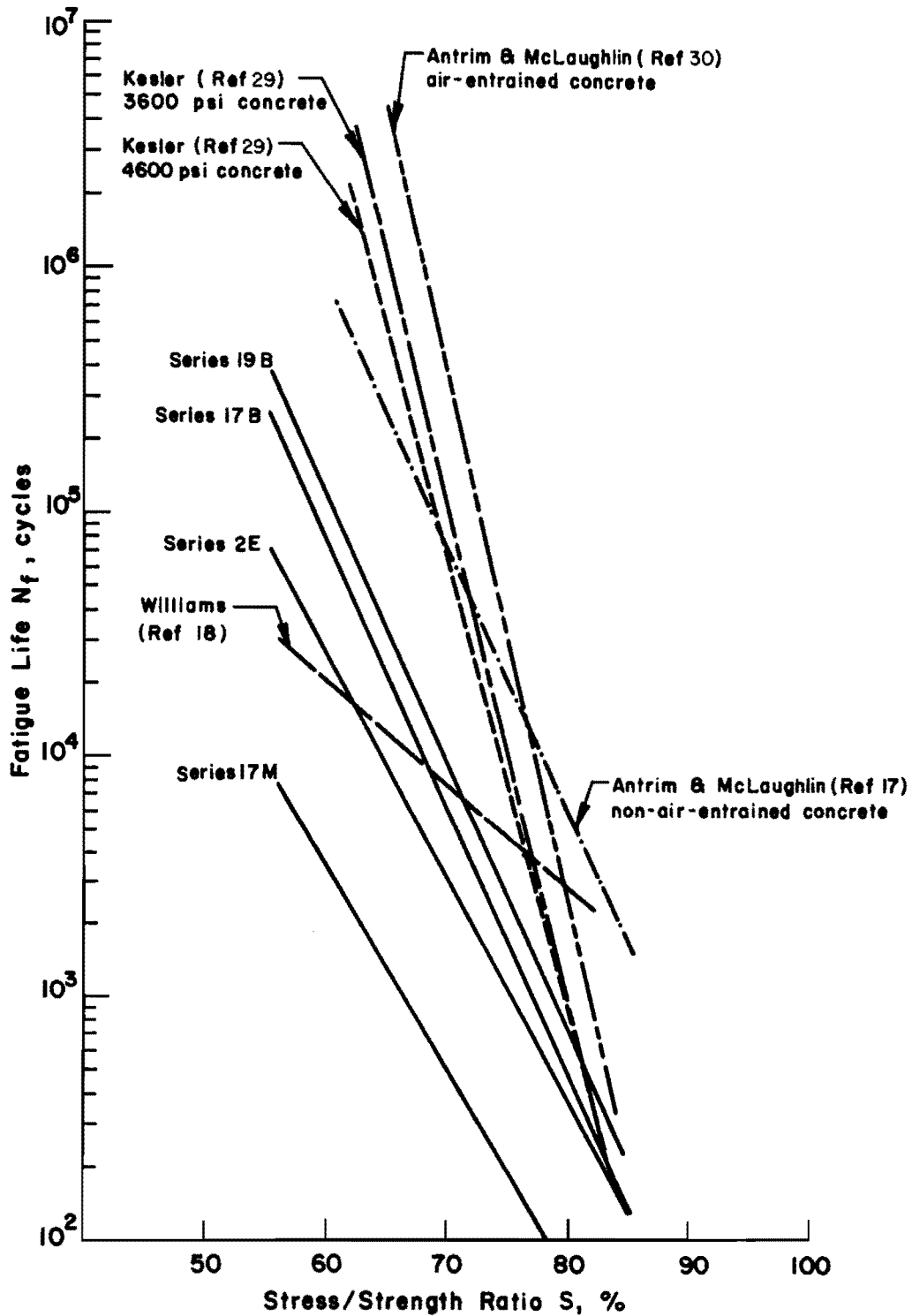


Fig 13. Comparison of relationships between fatigue life and stress/strength ratio for portland cement concrete (Ref 9).

small, averaging 1.7 percent. Pavement thickness measurements indicated minimal variation. Coefficients of variation were generally less than 3 percent for the 8-inch design depth pavements. The magnitudes of these variations are consistent with values reported from previous studies which indicated low coefficients of variation for pavement thickness and density.

Cement-Treated Base

Specimens from four projects in three districts were tested. The results tend to demonstrate that an obvious characteristic of this material is its highly variable nature.

Tensile Strength. Mean tensile strengths normally ranged from 83 psi to 120 psi; however, one project, which might appropriately be classified as a lean concrete, exhibited a strength of 210 psi. The coefficients of variation within each project were moderate to high, ranging from 23 percent to 49 percent. Clustered samples appeared to have small coefficients.

Static Modulus of Elasticity. Since experimental estimates of Poisson's ratio for cement-treated bases could not be obtained experimentally, a Poisson's ratio of 0.22 was assumed. Mean modulus values varied from 0.60×10^6 psi to 1.80×10^6 psi, and averaged 1.10×10^6 psi. Excluding the high modulus material, the average modulus was 0.77×10^6 psi and the range was from 0.60×10^6 to 1.05×10^6 psi. The variation for the individual projects was moderate to high, with coefficient of variation values ranging from 57 percent to 83 percent, and averaging 68 percent. As with strength the variation within clustered samples was generally less.

Density. Densities were subject to much less variation than either tensile strength or modulus. Coefficients of variation for density ranged from 1.9 percent to 3.9 percent, and averaged approximately 3.2 percent, which, as previously noted, is comparable to those found in previous studies.

Blackbase

Cores from ten blackbase projects were tested. Summaries of the test results are contained in Research Reports 183-1 (Ref 1) and 183-2 (Ref 2). Only two of the projects had clustered samples. The parameters estimated using the indirect tensile test were tensile strength, static and resilient modulus of elasticity, Poisson's ratio, and fatigue life. Density was estimated by measuring the dimensions and weights of the specimens.

Tensile Strength. The mean tensile strengths for the various projects generally ranged from 84 psi to 157 psi and averaged 105 psi. In addition to a variation in strength, the various projects also had different coefficients of variation. These coefficients generally ranged from 14 percent to 27 percent and averaged 21 percent. The average was comparable to that obtained for tensile strength of concrete cores. Coefficients were generally smaller for clustered samples as expected. A comparison of strength differences between layers at the same location indicated that there was no significant difference in the tensile strength of the specimens from the various layers.

Static Modulus of Elasticity. Mean modulus values varied from 39.0×10^3 psi to 92×10^3 psi and averaged 58×10^3 psi. The coefficient of variation of the mean modulus values was 36 percent, indicating project differences. Coefficients of variation within projects generally ranged from 24 percent to 59 percent and averaged 40 percent with smaller values being observed for clustered cores. A comparison of the moduli of the layers comprising a given core indicated no differences existed between layers.

Instantaneous Resilient Modulus of Elasticity. The mean instantaneous resilient moduli were consistent for the various projects, ranging from 220×10^3 to 615×10^3 psi which is much larger than the static moduli. More important, however, is the consistency within a given project and the fact that the modulus value was not overly sensitive to the magnitude of the applied stress for the range of stresses used in testing. As a result, the coefficients of variation were low, ranging from 4 to 28 percent, which was less than the values for static modulus probably due to errors associated

with surface irregularities which would not affect repeated load measurements as much.

A comparison of the mean static moduli and the mean resilient moduli is shown in Figure 14. From this figure it is evident that the dynamic moduli were significantly larger than the static moduli. The ratio of the resilient and static moduli ranged from 10.5 to 2.3, with the higher values associated with the materials with low static moduli.

Static Poisson's Ratio. Mean Poisson's ratio values generally ranged from 0.16 to 0.34, with an average of 0.27. The coefficient of variation of these means was 25 percent, which was approximately the same magnitude as the coefficient obtained for strength. The variation in Poisson's ratio for each project was found to be large, ranging from 39 to 67 percent, with an average of 48 percent. The variation for clustered samples was smaller. This large range of coefficients is probably due to the fact that the calculation of Poisson's ratio is very sensitive to small errors in the deformation measurements.

Instantaneous Resilient Poisson's Ratio. Values of resilient Poisson's ratio were fairly consistent, generally ranging from 0.10 to 0.22. These values tend to be lower than those for similar materials which were previously tested using the static indirect tensile test; however, a comparison of the static Poisson's ratio indicates that the resilient and static Poisson's ratios were essentially of the same magnitude. In most projects the mean values tended to increase with increasing stress.

Coefficients of variation for Poisson's ratio were high, generally ranging from 18 to 57 percent. Nevertheless, these coefficients are lower for the static Poisson's ratios for similar materials.

Density. The coefficients of variation of the densities for each project were generally small, ranging from 1.7 to 3.6 and averaging 2.4 percent. The magnitudes of these variations are consistent with values reported from previous studies, which indicated low coefficients of variation for density.

Fatigue Life. Cores from seven projects were subjected to a minimum of three different stress levels to measure fatigue life and the associated

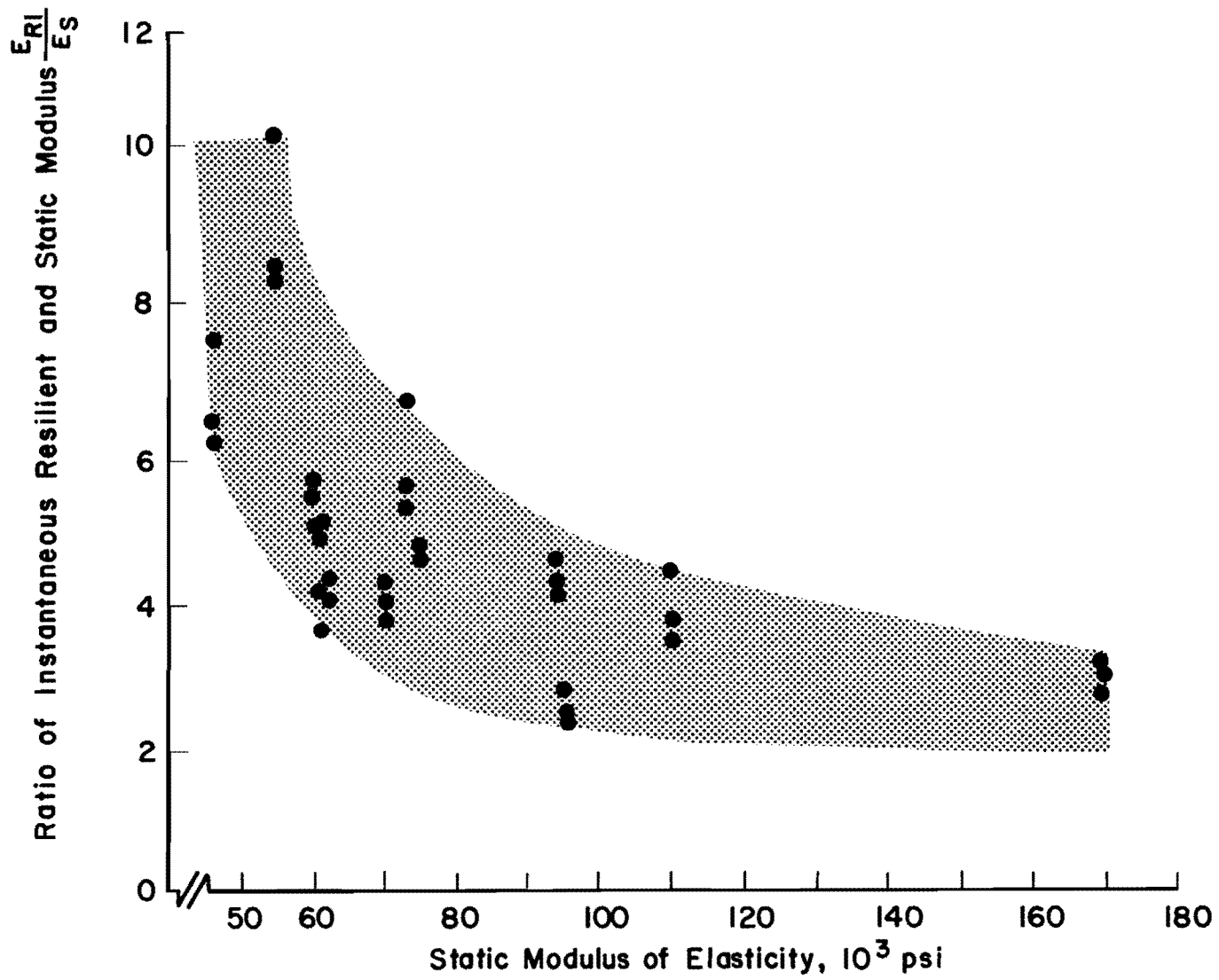


Fig 14. Relationship between static modulus and the ratio of static and instantaneous resilient moduli for asphalt mixtures (Ref 2).

variation. The relationships (Eq 2.1) between the logarithm of tensile stress and the logarithm of fatigue life were essentially linear, but the slopes varied, indicating that the relationships were material, or project, dependent.

The values of n_2 , the slope, were fairly consistent (Fig 15). Values generally ranged from 3.18 to 5.08, which are consistent with previously reported values of 1.85 to 6.06. In addition, there was some evidence that n_2 was a function of the stiffness of the mixture.

Previously reported values of K_2 were 8.00×10^7 and 4.10×10^{18} . Values in this study were smaller, ranging from 2.79×10^5 to 7.13×10^{12} . Thus, the fatigue lives for the materials tested are generally smaller than values previously reported. While a number of contributing factors were identified, a large portion of the difference was attributed to the fact that the indirect tensile test involves a biaxial state of stress while most of the other test methods involve a uniaxial state of stress and that stress should be expressed in terms of a stress difference.

The relationships between the logarithm of fatigue life and the logarithm of stress difference (Eq 2.2) are shown in Figure 16. Values of n_2 did not change since the lines were merely shifted along the X axis. Values of the K coefficient, designated K_2' , however, were significantly larger than K_2 , ranging from 2.5×10^6 to 8.2×10^{15} , with the majority of the values in the range of 10^{10} to 10^{13} . These values are consistent with the previously reported values of K_2 for tests with uniaxial stress.

The coefficients of determination R^2 indicate that a great deal of the variation in data could not be explained by the linear relationships. In addition, the coefficients of variation were not constant but, rather, were stress and project dependent. Coefficients ranged from 26 to 84 percent; however, a portion of this variation can be accounted for by stress since the coefficients increased with increasing stress or decreasing fatigue life.

Since there were significant differences in the coefficients of variation for the various projects and stress levels, no definite recommendation can be made concerning an exact value for the expected coefficient of variation, but it is possible to establish a range of values to be expected.

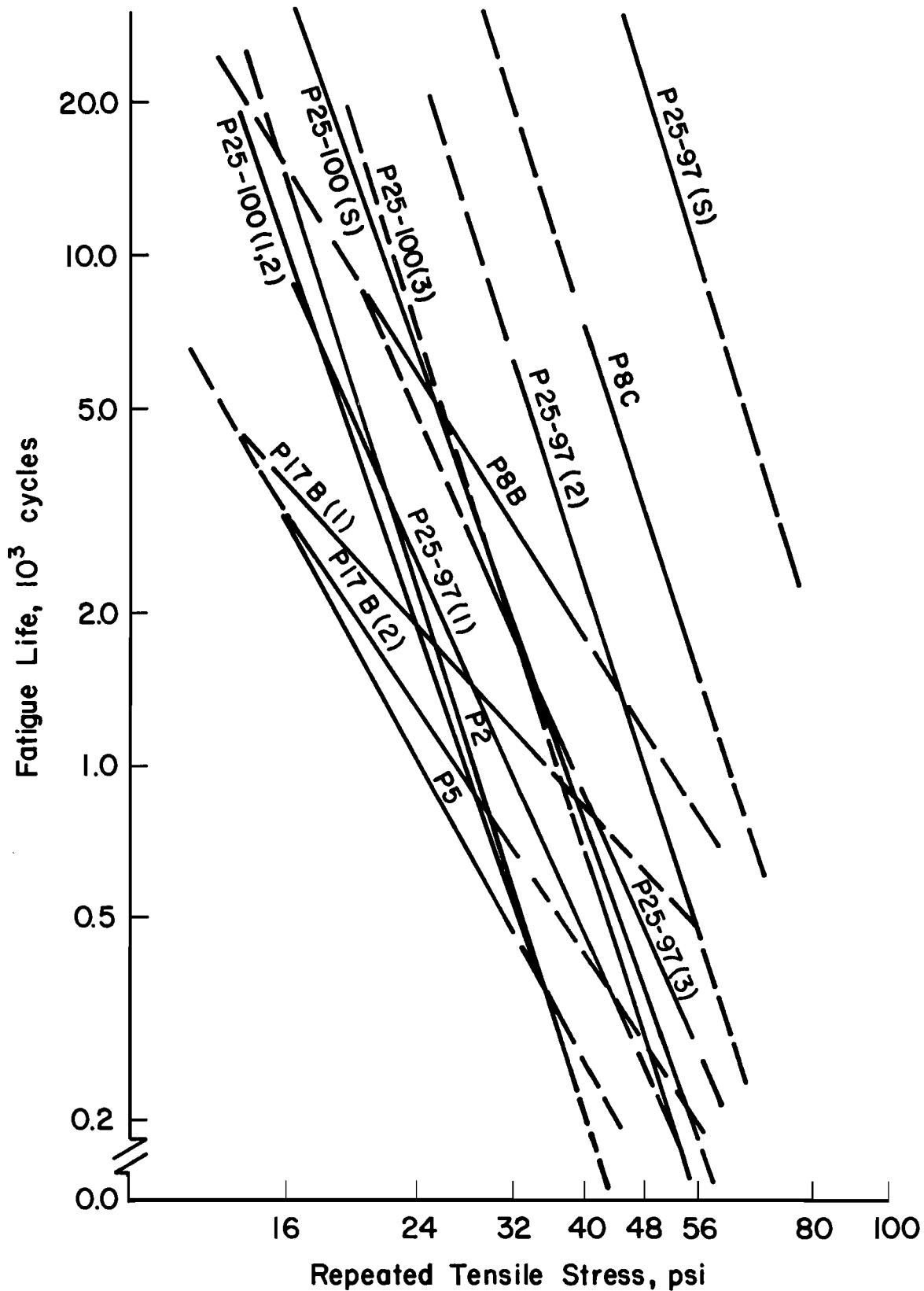


Fig 15. Relationships between the logarithms of tensile stress and fatigue life for asphalt mixtures (Ref 2).

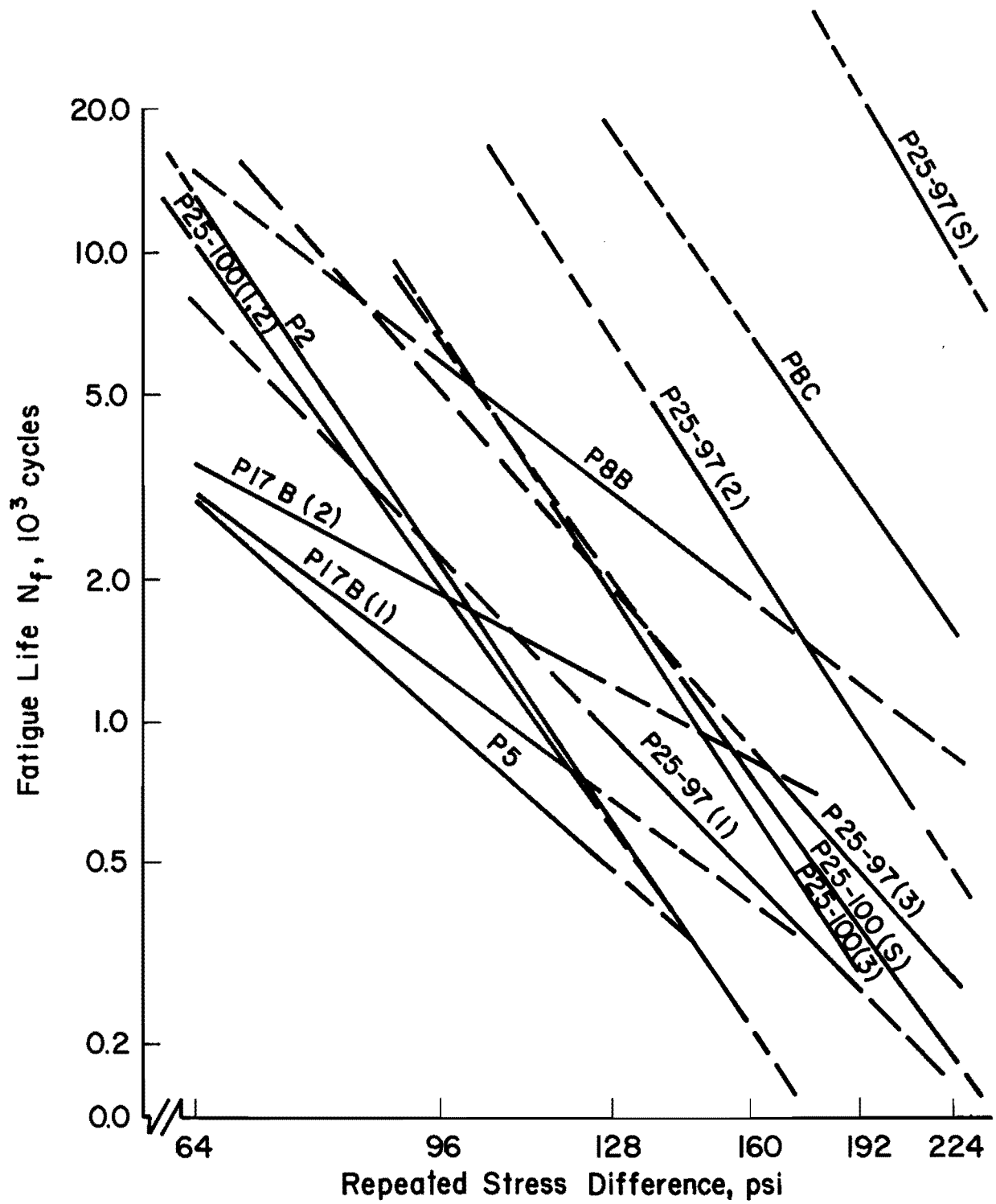


Fig 16. Relationships between the logarithms of stress difference and fatigue life for asphalt mixtures (Ref 2).

Correlations with Fatigue Life. Possible correlations between various static test values were investigated in an attempt to reduce the need for costly long term fatigue tests.

No correlations were found between fatigue life and static modulus of elasticity nor between fatigue life and resilient modulus of elasticity except that higher moduli tended to have longer fatigue lives.

Correlations were found between fatigue life and the ratio of repeated tensile stress and tensile strength and between the logarithm of fatigue life and the logarithm of tensile strain, i.e., repeated tensile stress divided by the resilient modulus. However, because of the large errors which could be expected neither of these two correlations should be used to estimate fatigue life.

Asphalt Concrete

Only one asphaltic concrete project was tested. The mean values for tensile strength, modulus of elasticity, and Poisson's ratio were 77 psi, 42.0×10^3 psi, and 0.40, respectively. The coefficients of variation for the same properties were 16 percent, 29 percent, and 27 percent, respectively. These values were generally smaller than those obtained for blackbase. As with the other materials, the variation in densities was small, 3.7 percent, for a mean density of 133.5 pcf.

CHAPTER 4. ENGINEERING PROPERTIES OF ASPHALT MIXTURES

A series of four studies were conducted to evaluate the properties of asphalt mixtures. One extensive study was conducted to evaluate the fatigue and resilient characteristics of laboratory prepared asphalt mixtures using the repeated load indirect tensile test which is reported in Research Report 183-5 (Ref 5). In addition, two studies were conducted to evaluate the effect of moisture and soil binder on the properties of blackbase mixtures, the findings of which are reported in Research Reports 183-12 and 183-13 (Refs 12 and 13). A special limited study was conducted to evaluate the resilient and fatigue characteristics of mixtures produced using drum mixers, reported in Research Report 183-8 (Ref 8).

PROPERTIES OF ASPHALT MIXTURES (Research Report 183-5)

The mixtures evaluated were prepared in the laboratory and consisted of either crushed limestone or rounded river gravels and an AC-10 grade of asphalt cement. Asphalt contents ranged from 4 to 8 percent by weight of the total mixture. These specimens were tested using the static indirect tensile test and repeated load indirect tensile test at temperatures of 50, 75, and 100°F. Repeated loads involved tensile stress ranging from 8 to 120 psi.

Tensile Strength

The average strength varied with asphalt content, testing temperature, and aggregate type and ranged between 7 and 584 psi.

Typical relationships showing the effect of asphalt content and testing temperature is shown in Figures 17 and 18. The maximum strengths for the two aggregate mixtures were approximately equal; however, the optimum asphalt contents were different and tended to decrease with increased temperature. It was also found that the effect of temperature tends to decrease at the higher temperatures and that the effect of asphalt content is less at higher temperatures. Thus, the selection of the asphalt

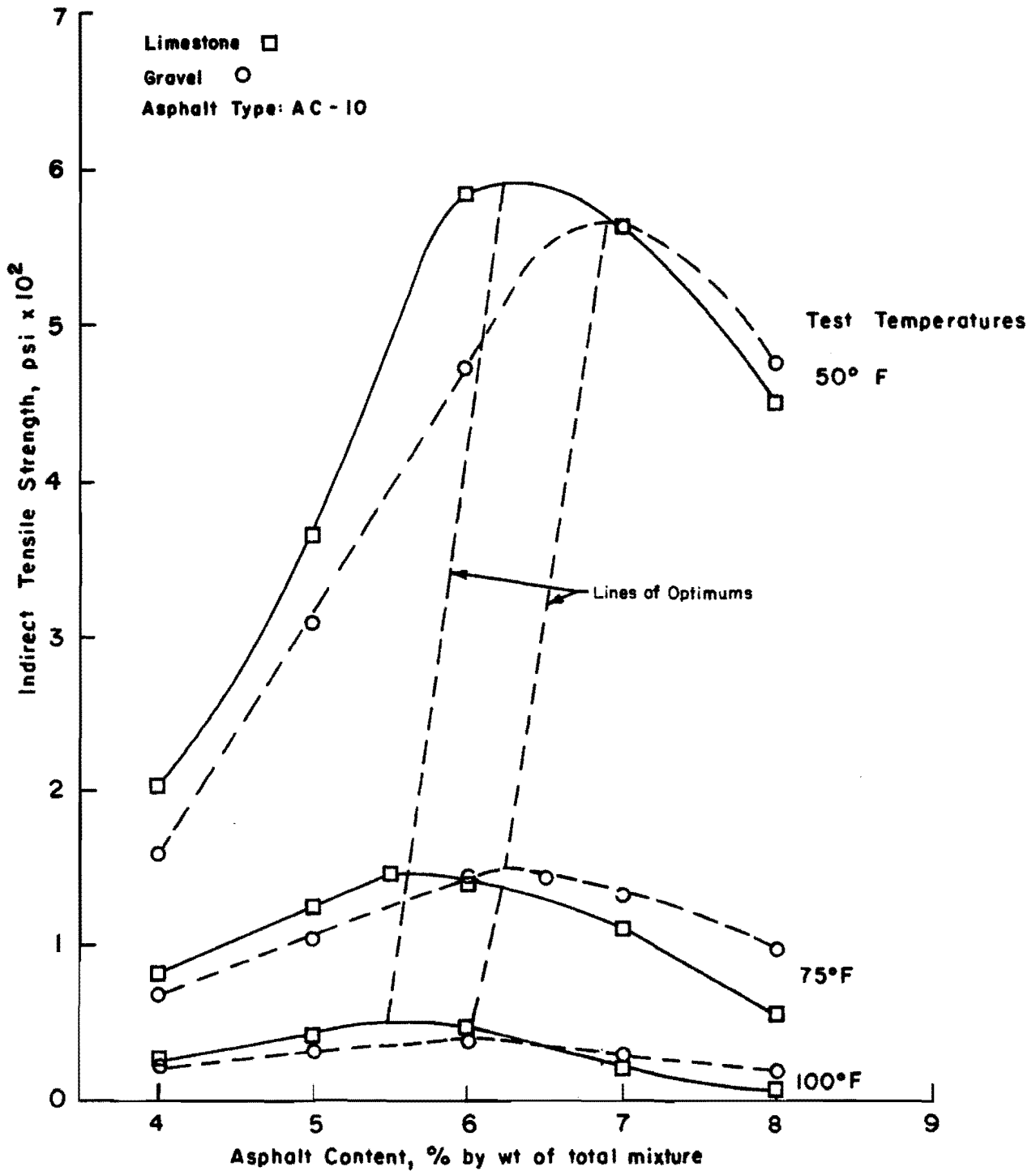


Fig 17. Relationships between average indirect tensile strengths and asphalt content for limestone and gravel asphalt mixtures (Ref 5).

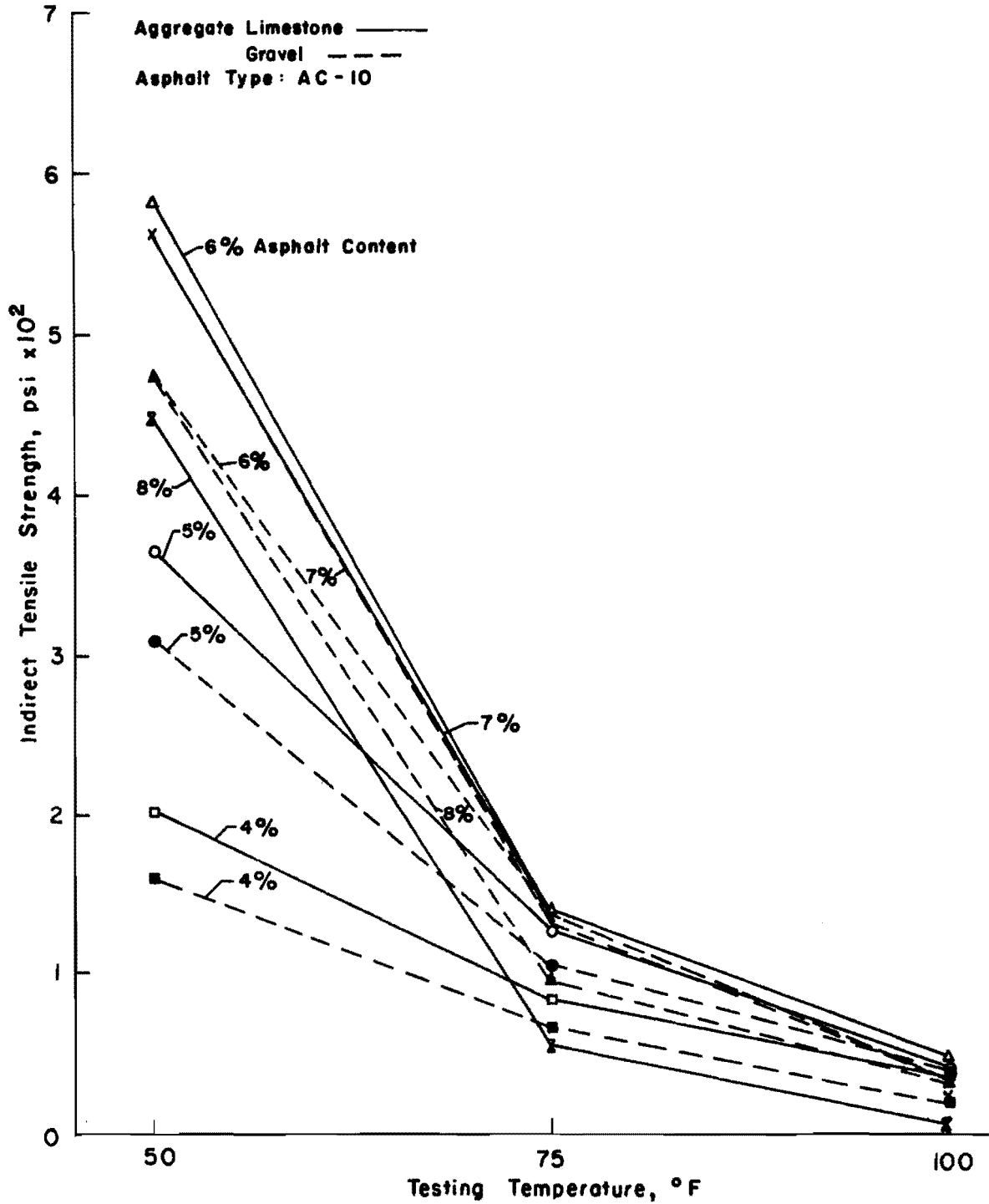


Fig 18. Effect of testing temperature on average indirect tensile strength of asphalt mixtures (Ref 5).

content would be expected to be less critical for high temperature conditions. It should also be noted that the optimum asphalt content for density was not necessarily the same as the optimum for strength (Fig 19).

Static Modulus of Elasticity

The static modulus of elasticity for the mixtures and testing temperatures used in the study ranged from 5,000 to 625,000 psi. The effect of asphalt content and testing temperature is illustrated in Figures 20 and 21. The basic trends with respect to asphalt content, testing, temperature, and optimum asphalt content (Fig 19) were similar to those observed for tensile strength.

Static Poisson's Ratio

Poisson's ratios varied widely, ranging from values of zero for tests conducted at 50°F to values of about 0.5 for tests conducted at 100°F. At approximately optimum asphalt for strength and modulus and at a testing temperature of 75°F, values were 0.18 for gravel and 0.14 for limestone. However, no consistent relationship between Poisson's ratio and asphalt content was evident.

Relationships Between Static Properties

Results from this study indicated a possible correlation between tensile strength and static modulus of elasticity. Other analyses indicated that there was no strong correlation between the two properties of tensile strength and modulus of elasticity and the mixture properties of density and air void content.

Fatigue Life

A linear relationship was found to exist between the logarithm of applied stress and the logarithm of fatigue life expressed in the form of Equation 2.1, Chapter 2. Values of K_2 varied between 3.26×10^5 and 1.90×10^{13} while n_2 varied between 2.66 and 5.19 depending on the mixture and temperature. As in previous evaluations discussed in Chapters 2 and 3, the

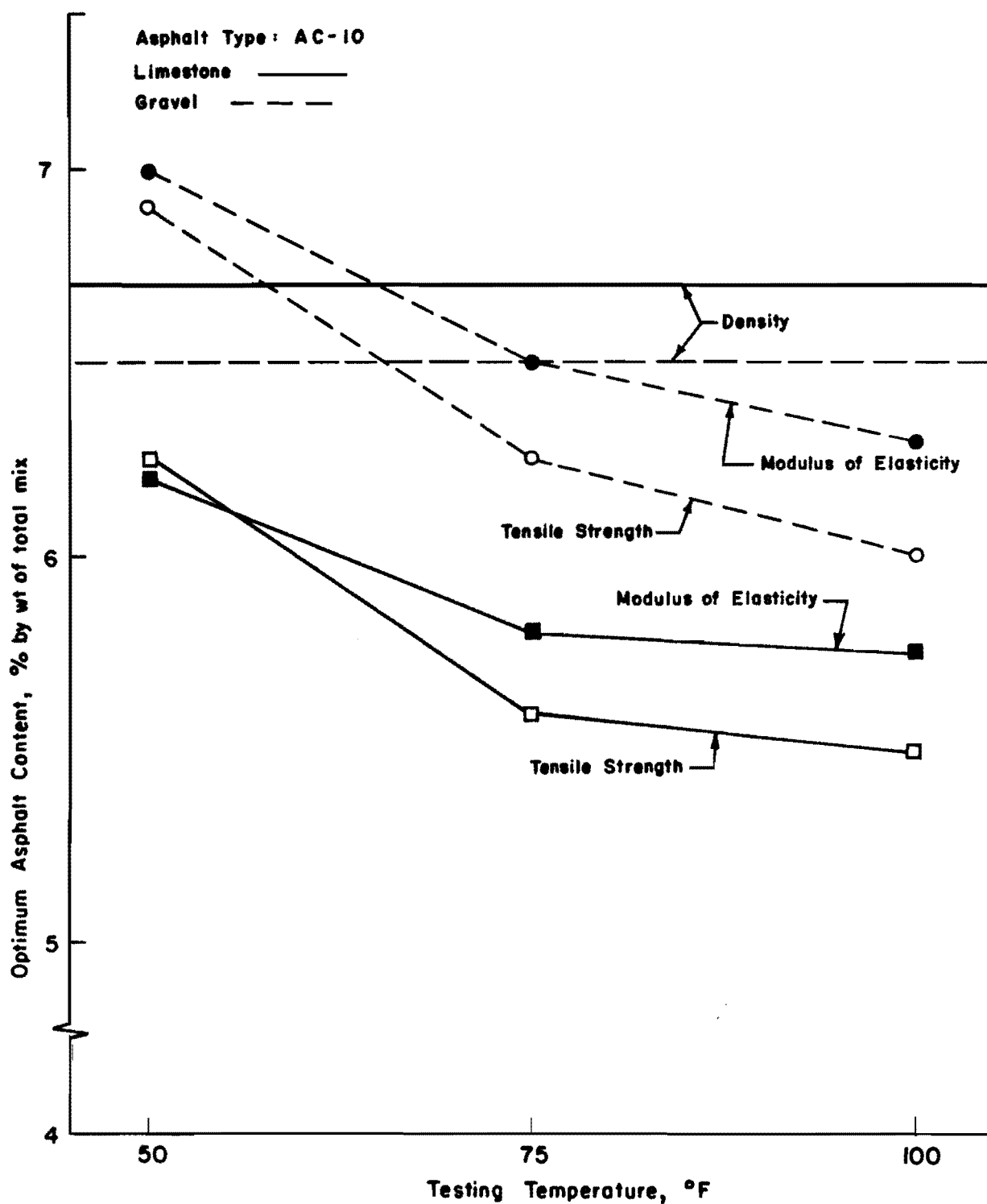


Fig 19. Comparison of optimum asphalt contents for density and static properties for asphalt mixtures (Ref 5).

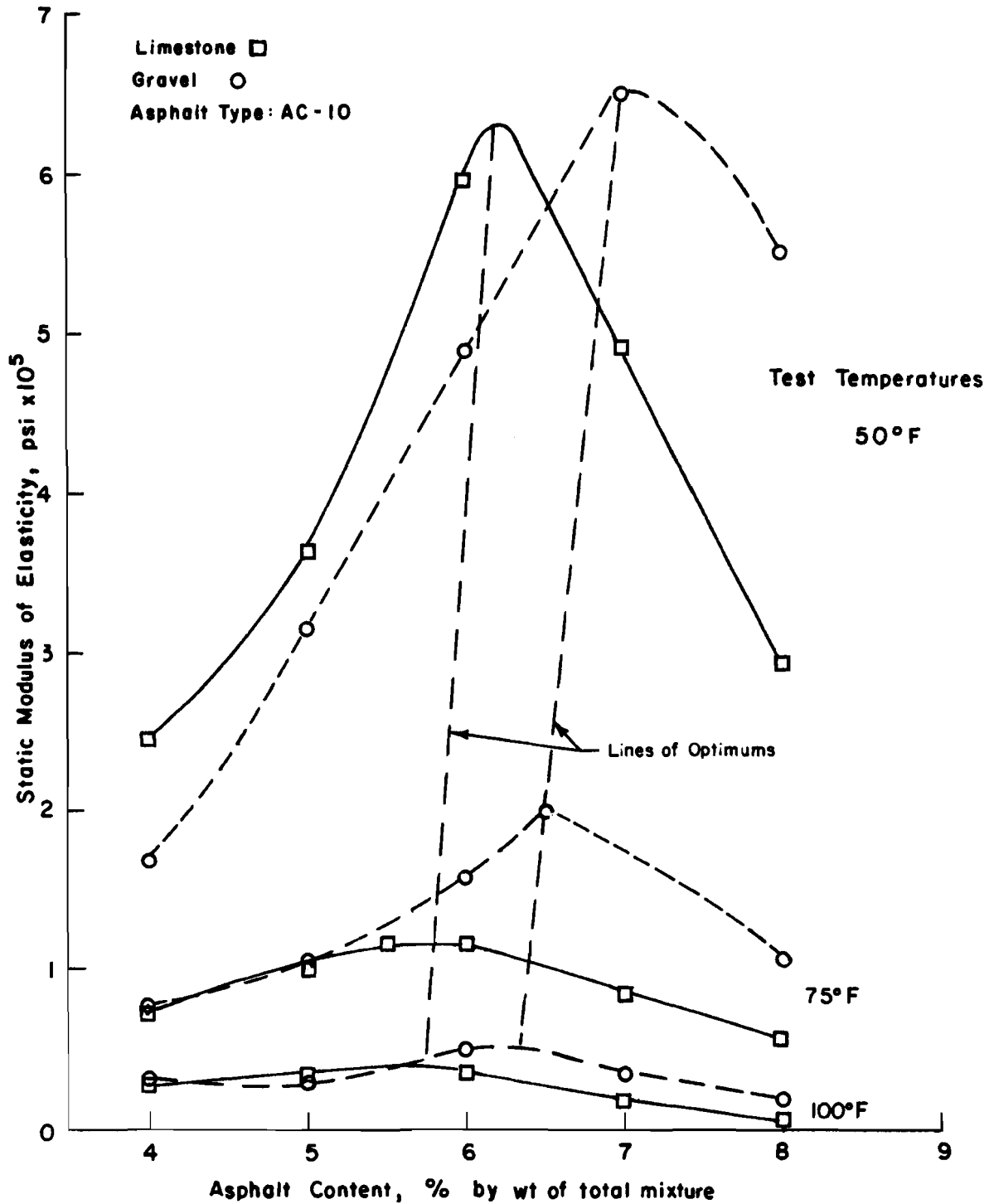


Fig 20. Relationships between average static modulus of elasticity and asphalt content for limestone and gravel asphalt mixtures (Ref 5).

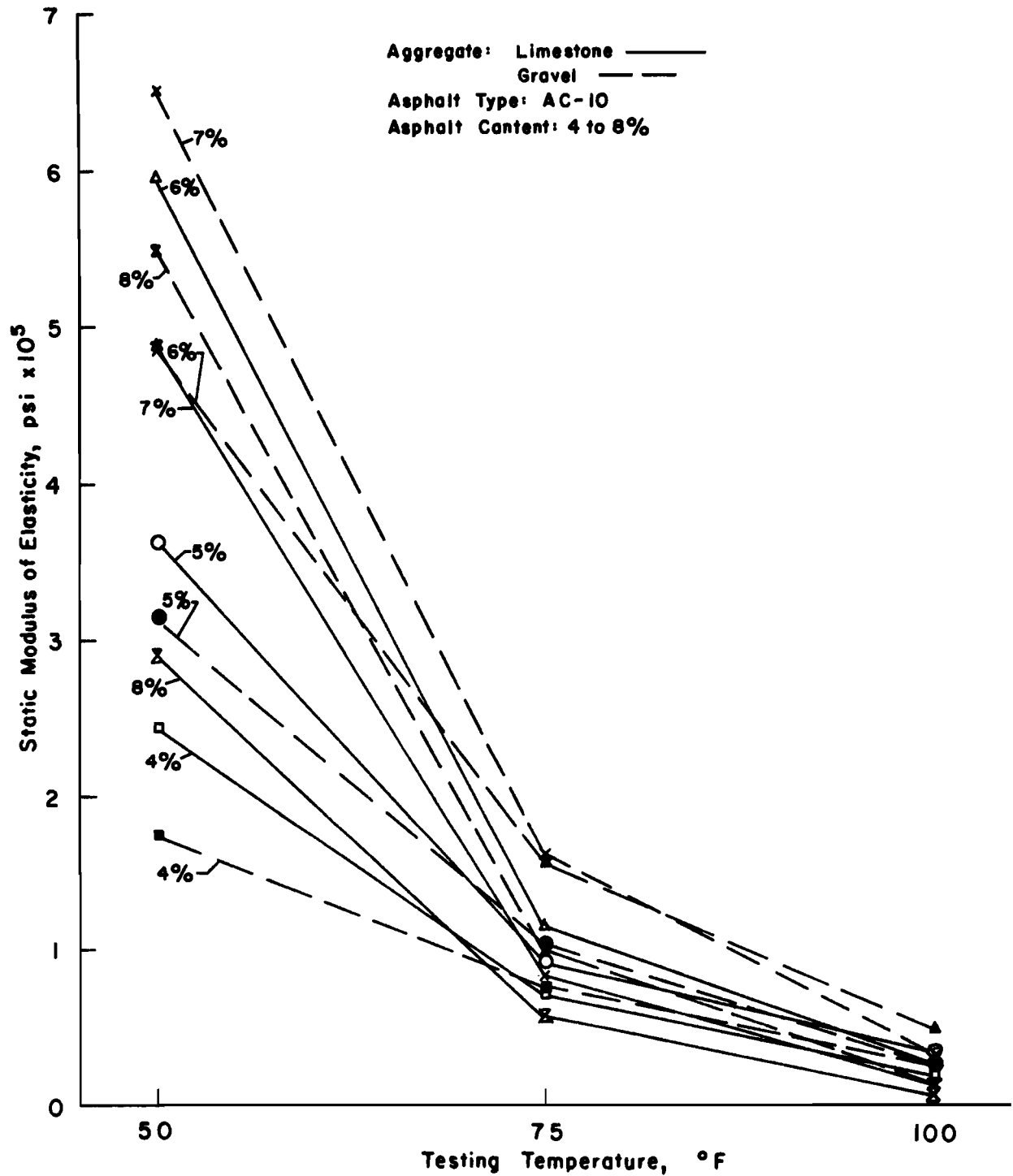


Fig 21. Effect of testing temperature on average static modulus of elasticity of asphalt mixtures (Ref 5).

values of n_2 compare favorably with values reported using other test methods; however, values of K_2 were significantly smaller. Thus the relationships were analyzed in terms of stress difference (Eq 2.2) as discussed in Chapter 2.

Values of K_2' ranged from 1.41×10^7 to 2.53×10^{16} . While these still are generally smaller than those reported for other test methods, they are similar, and the differences can be attributed to the higher testing temperatures and longer load durations used in this study.

Fatigue life relationships are often expressed in terms of initial strain. A number of methods of estimating initial strain were evaluated; however, the best relationships were obtained between the logarithm of fatigue life and the logarithm of initial strain which was estimated by dividing repeated stress by the average static modulus of elasticity. Relationships were developed in the form of Equation 2.3, Chapter 2. Values of K_1 ranged from 5.65×10^{17} to 5.01×10^7 and of n_1 ranged from 2.66 to 5.19. These values were comparable to those obtained previously using other test methods.

Relationships Between Fatigue Constants, n and K. Approximate linear relationships were found to exist between n_2 and the logarithm of K_2' and between n_1 and the logarithm of K_1 for a variety of mixtures and test methods. These relationships are shown in Figures 22 and 23. Because of the high correlation coefficient, it appears that a relationship exists between the fatigue constants, irrespective of mixture properties and test method.

Factors Affecting Fatigue Life. It is evident that asphalt content, aggregate type, and testing temperature had a significant effect on fatigue life and that there were optimum asphalt contents for maximum fatigue life. The effect of aggregate, however, was minimal in this study.

An analysis was also conducted to determine the effect of these three factors on the values of the fatigue constants, n and K.

The maximum value of n_1 and the minimum value of K_1 occurred at an asphalt content which was slightly higher than the optimum asphalt content for maximum fatigue life. Maximum values of K_2 , K_2' , and n_2 occurred at the same asphalt content.

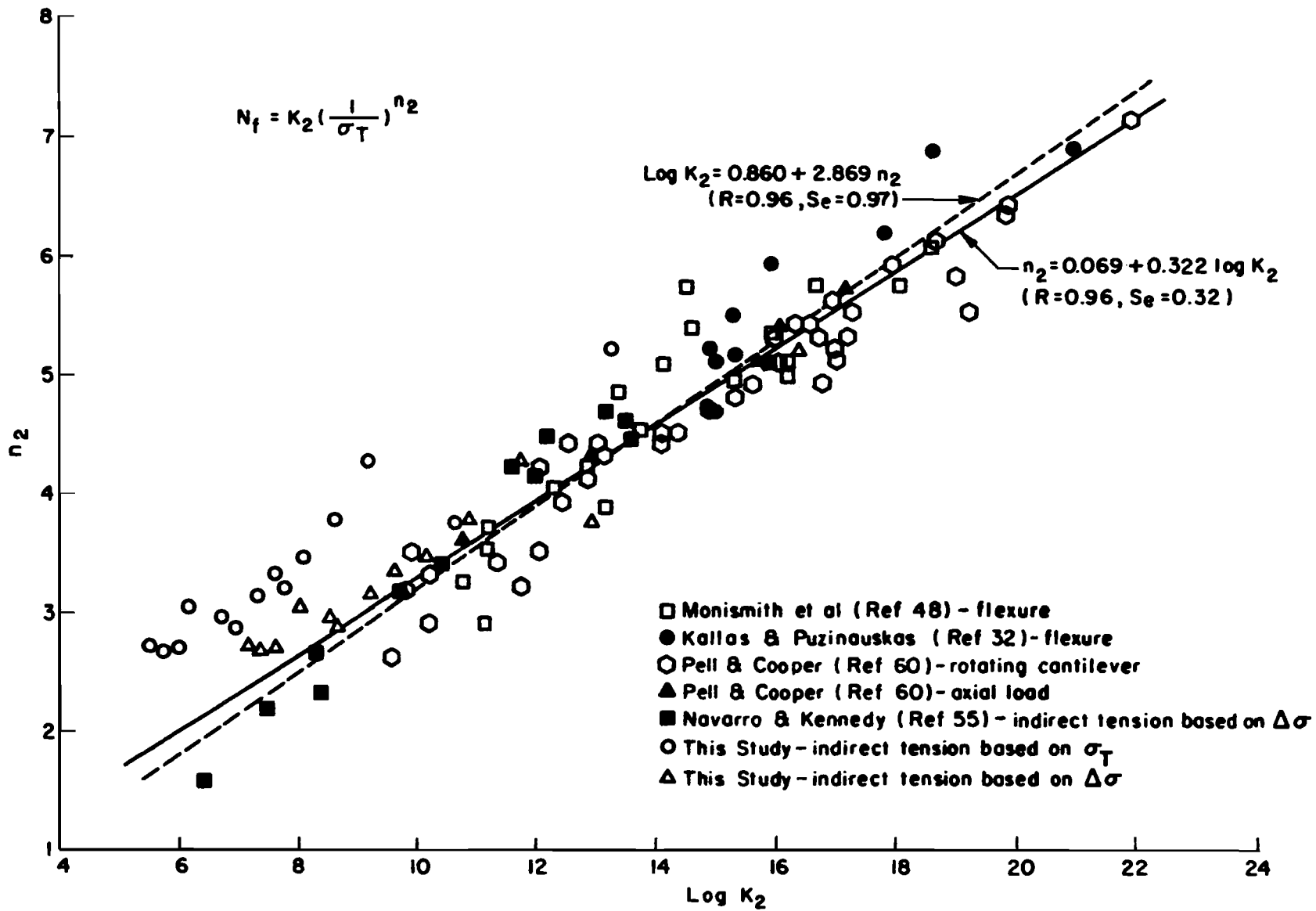


Fig 22. Relationships between n_2 and K_2 from various studies.

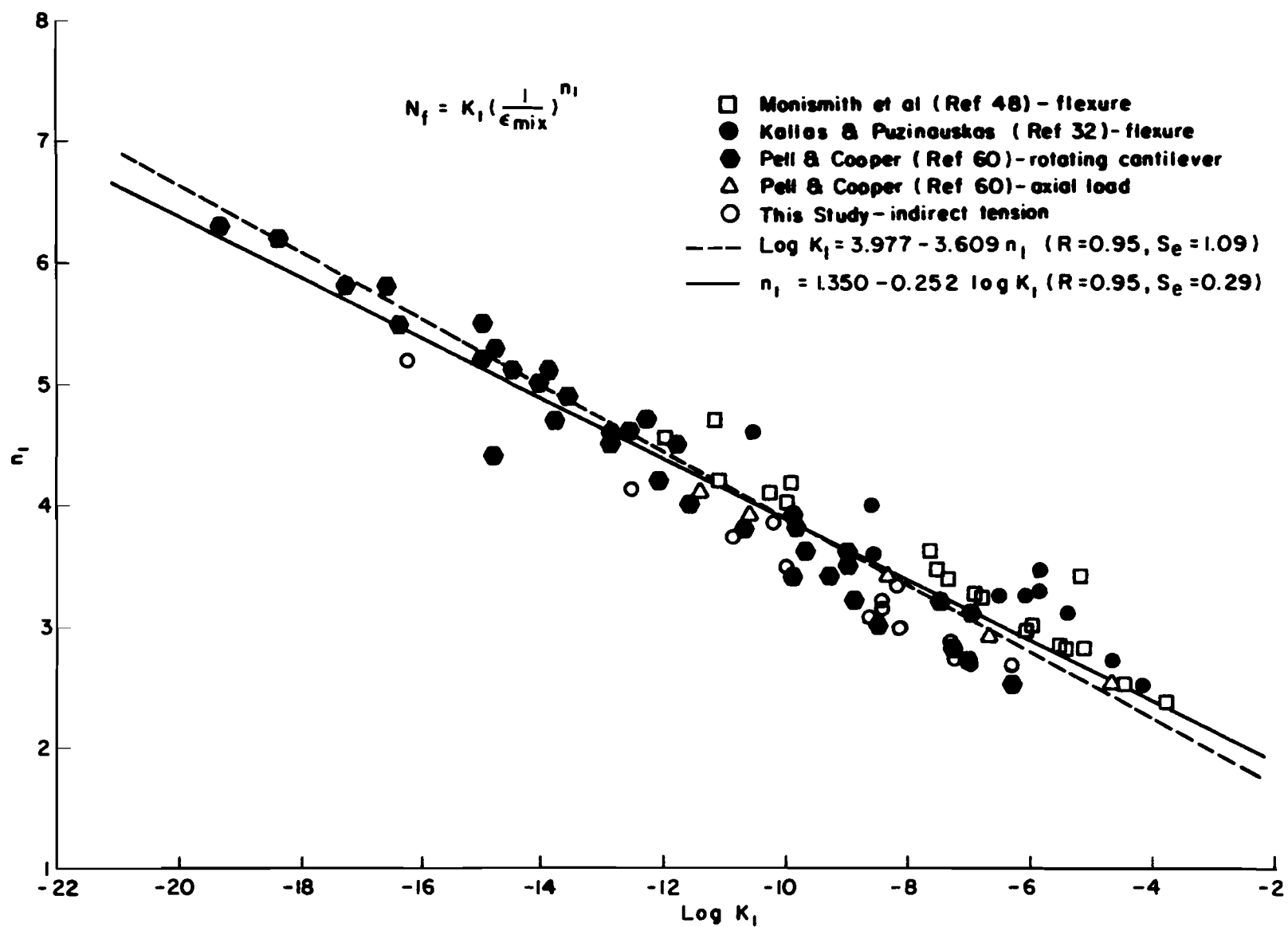


Fig 23. Combined relationships between n_1 and K_1 from various studies.

Gravel mixtures exhibited higher values of n_1 and lower values of K_1 than the limestone mixtures. In terms of stress relationships, the gravel exhibited higher values of n_2 , K_2 , and K_2' than the limestone mixtures.

In terms of temperature, an increase in testing temperature produced an increase of K_1 and a decrease of n_1 . An increase in temperature produced a decrease for K_2 , K_2' and n_2 .

Effect of Repeated Loads on Load-Deformation Properties

An effort was made to determine the effects of repeated loads on strain, modulus of elasticity, and Poisson's ratio.

Strain. The effect of repeated loads on the following four types of strain were evaluated.

- (1) Total resilient strain, based on total recovered deformation per cycle,
- (2) Instantaneous resilient strain, based on instantaneous recovered deformation per cycle,
- (3) Individual total strain, based on total deformation per cycle, and
- (4) Permanent strain, based on cumulative total permanent strain.

An approximately linear relationship was found to exist between total resilient strain and the number of load applications, up to about 60 to 70 percent of the fatigue life, at which time resilient strain increased more rapidly until failure occurred (Fig 24). The relationships between instantaneous and individual total tensile strain and the number of load applications were similar to the total resilient strain relationships (Fig 25).

The relationships (Fig 26) between load applications and both the horizontal and vertical permanent strains were divided into the following three zones:

- (1) Zone of initial adjustment--the first 10 percent of the fatigue life,
- (2) Zone of stable condition--the portion between 10 and 70 percent of the fatigue life, during which the relationship is linear, and

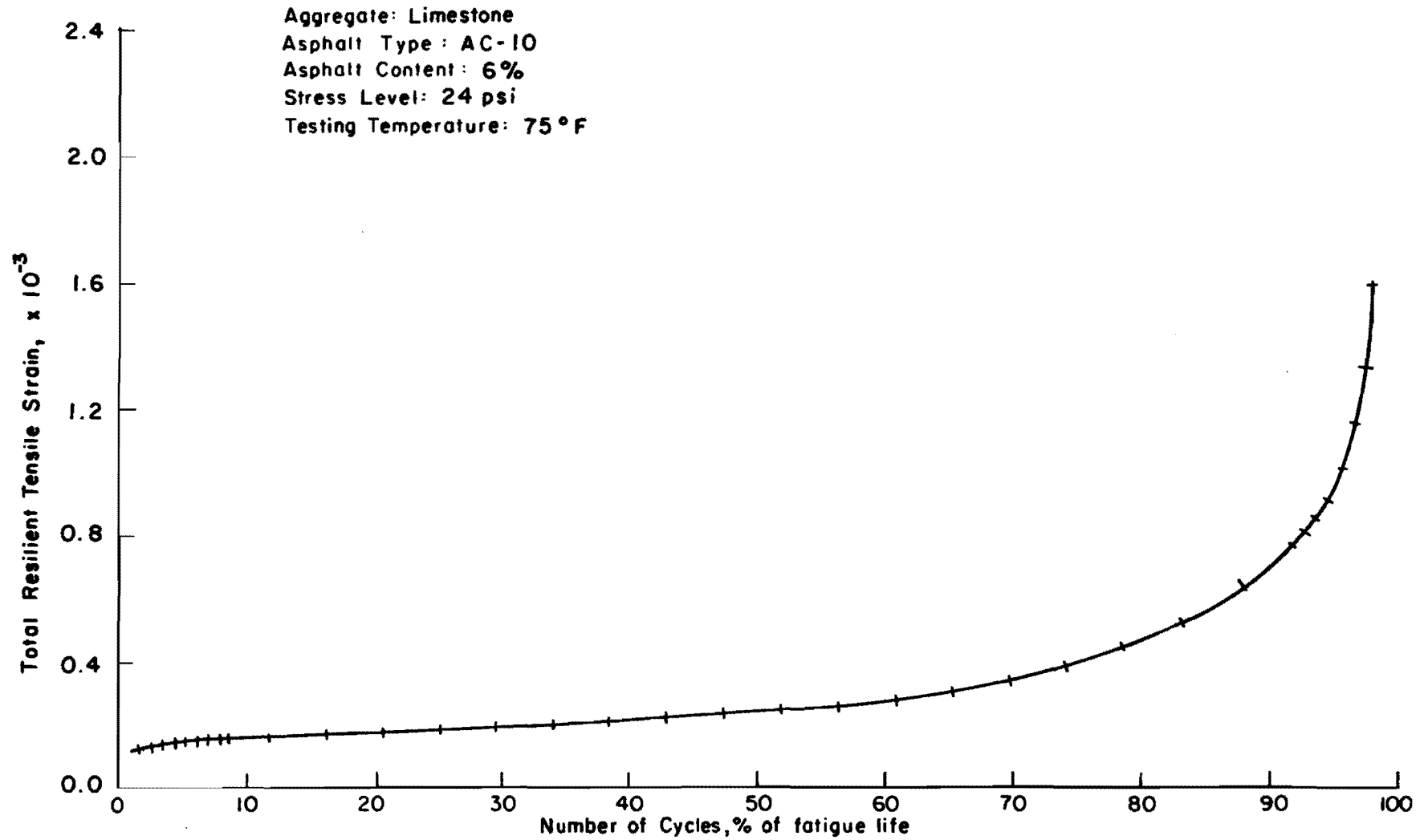


Fig 24. Effect of repeated loads on total resilient tensile strain for asphalt mixtures (Ref 5).

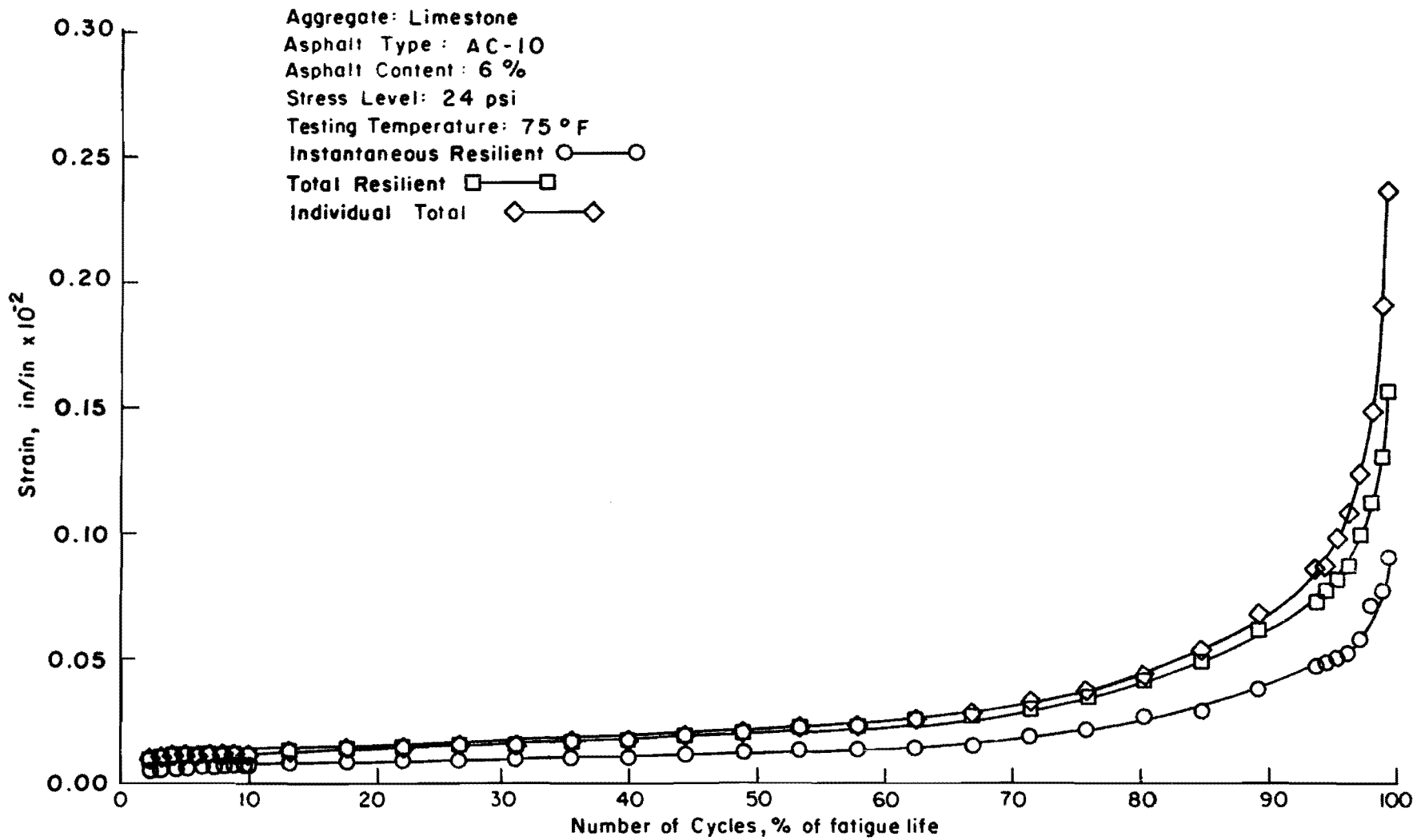


Fig 25. Comparison of instantaneous resilient, total resilient, and individual total tensile strains for asphalt mixtures (Ref 5).

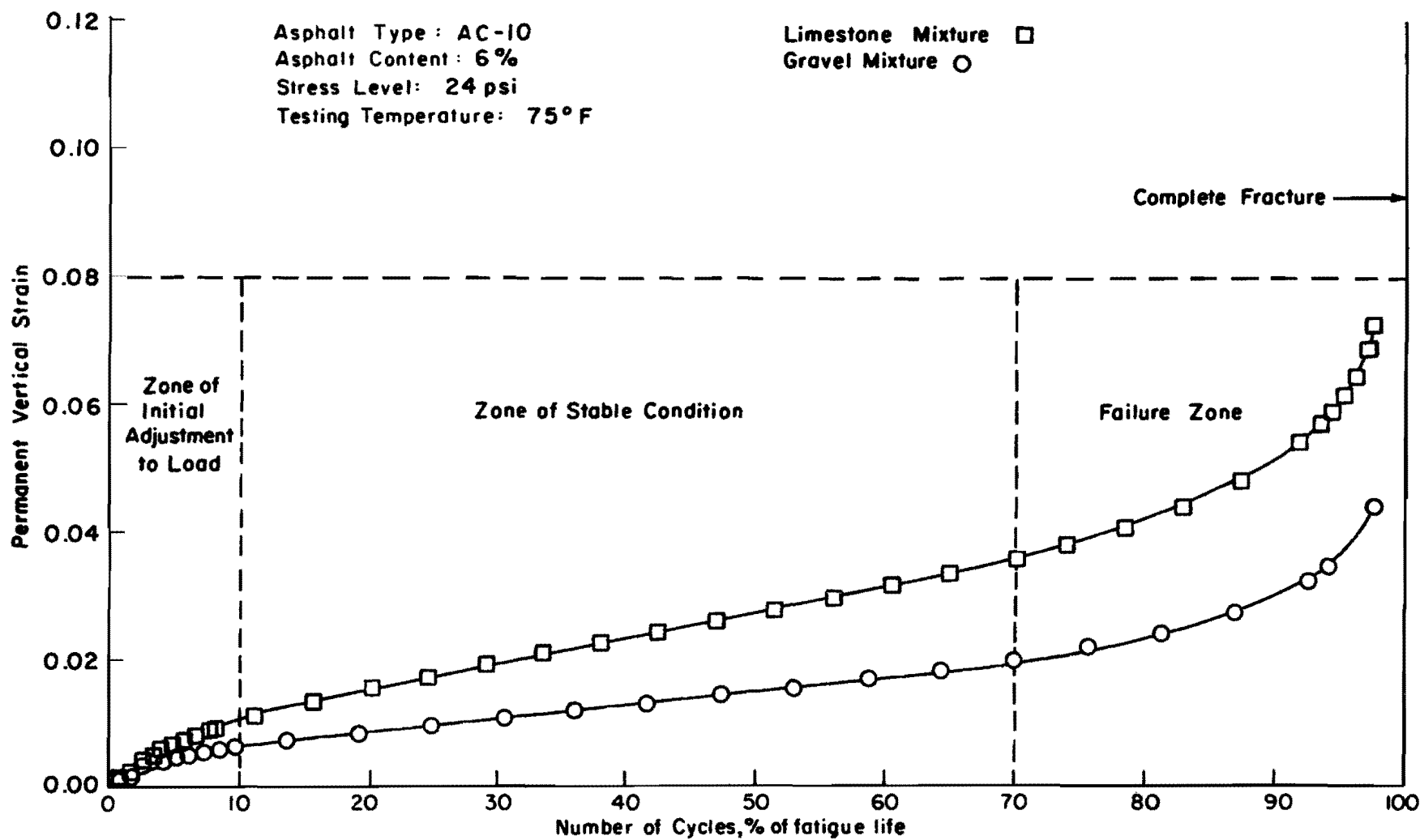


Fig 26. Effects of repeated loads on vertical permanent strain for asphalt mixtures (Ref 5).

- (3) Failure zone--the zone from about 70 percent of fatigue life to actual failure in which excessive permanent strain develops.

Modulus. The effect of repeated loads on the following moduli were investigated:

- (1) instantaneous resilient modulus, based on instantaneous resilient strain,
- (2) total resilient strain, based on total resilient strains,
- (3) modulus of individual total deformation, based on individual total strains, and
- (4) modulus of cumulative total deformation, based on cumulative total strains.

The shapes of the relationships were the same as for strain and can be divided into the same three zones. While the shapes of the relationships were similar (Fig 27), the relative magnitude of the values differs, with the instantaneous resilient moduli having the largest values and the moduli of individual total deformation having the lowest value.

Information related to the deterioration of modulus due to repeated loads was also developed. Deteriorations ranged between 7 and 3000 psi/load cycle for the instantaneous resilient moduli and between 5 and 1000 psi/load cycle for the total resilient moduli. The rate of deterioration increased with increased stress and higher slopes. In addition, the rate of deterioration was minimum at the optimum asphalt content for maximum fatigue, which indicates that longer fatigue lives are associated with smaller rates of deterioration of both the instantaneous and total resilient moduli.

Moduli values occurring at approximately 50 percent of the fatigue life ranged between 126,000 and 920,000 psi for the instantaneous resilient modulus and 90,000 and 800,000 psi for the total resilient moduli. These values compare favorably with values obtained in other studies.

Studies were also conducted to evaluate the effect on resilient modulus of asphalt content, temperature, stress level, and aggregate type.

Poisson's Ratio. There was a gradual increase in Poisson's ratio with an increase in the number of load applications until, at about 70 to 80

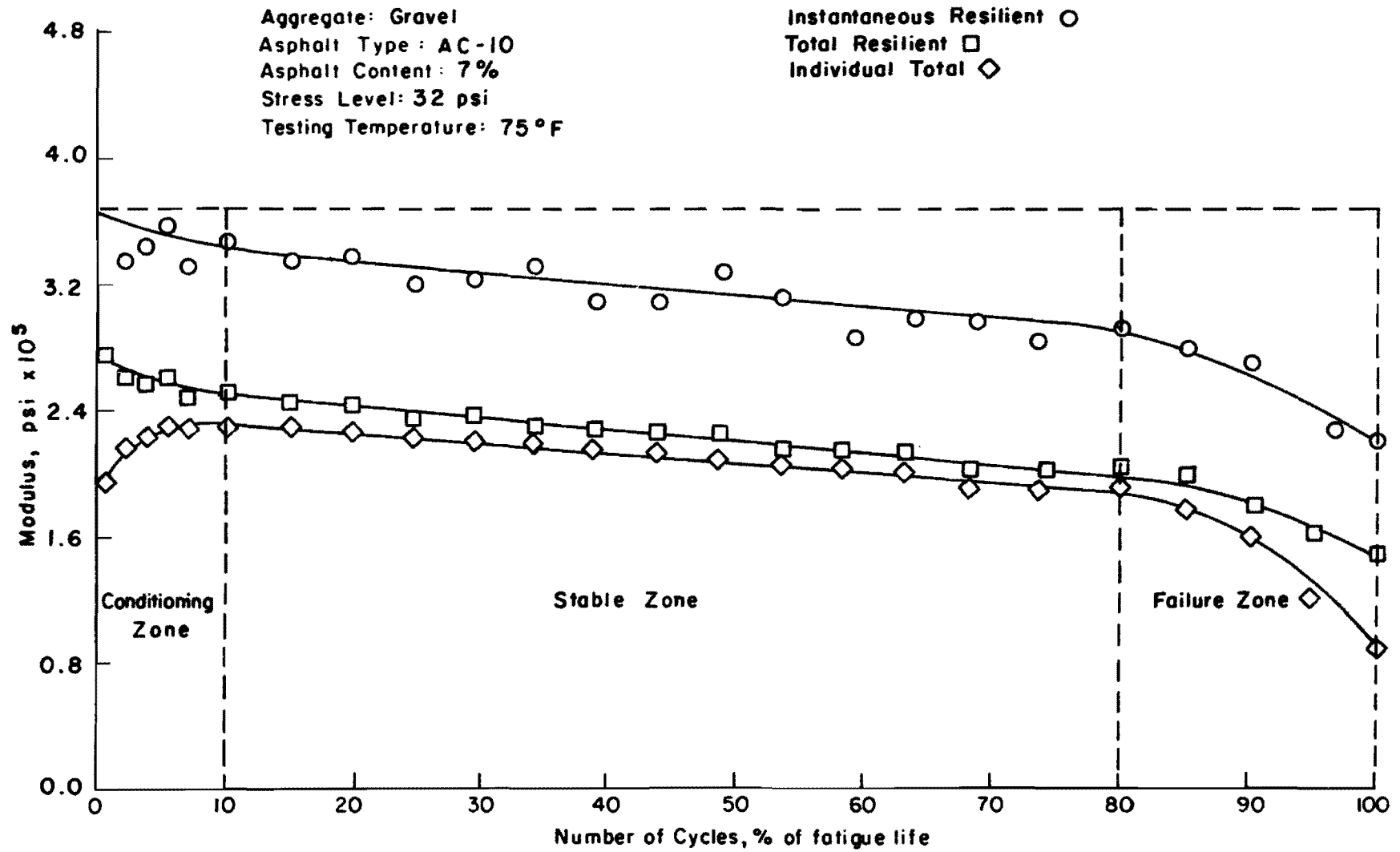


Fig 27. Comparison of instantaneous resilient, total resilient, and individual total modulus for gravel asphalt mixtures (Ref 5).

percent of the fatigue life, the value of Poisson's ratio increased quite rapidly.

SOIL BINDER AND MOISTURE IN BLACKBASE (Research Report 183-12)

The purpose of this study was to investigate the effect of the amount of soil binder on the engineering properties of asphalt-treated materials. Two aggregates, a gravel and crushed limestone, were used with gradations that varied in binder content (amount of minus No. 40 material).

The experimental approach was to determine the relationships between asphalt content and the above engineering properties and determine the optimum asphalt content for each property. These relationships and optimums were then evaluated with respect to soil binder content to determine whether properties could be improved by controlling the binder content. Finally, the effect of moisture on these relationships was evaluated.

AVR Design Optimum Asphalt Content and Density

The total air voids were calculated using the in-mold AVR density and zero air void density and relationships between asphalt content and total air voids were determined for each aggregate gradation. From these relationships the laboratory AVR design optimum asphalt content for each aggregate gradation was determined according to Test Method Tex-126-E (Ref 32). The laboratory AVR design optimum asphalt contents were slightly greater than the asphalt contents corresponding to the inflection point on the straight line section of the AVR curves.

The relationships between asphalt content and total air voids indicated that as the amount of soil binder decreased the total air voids decreased, and then the total air voids increased appreciably as the amount of soil binder continued to decrease below about 5 to 10 percent (Fig 28). Similarly, maximum density occurred at the binder contents which produced minimum air voids.

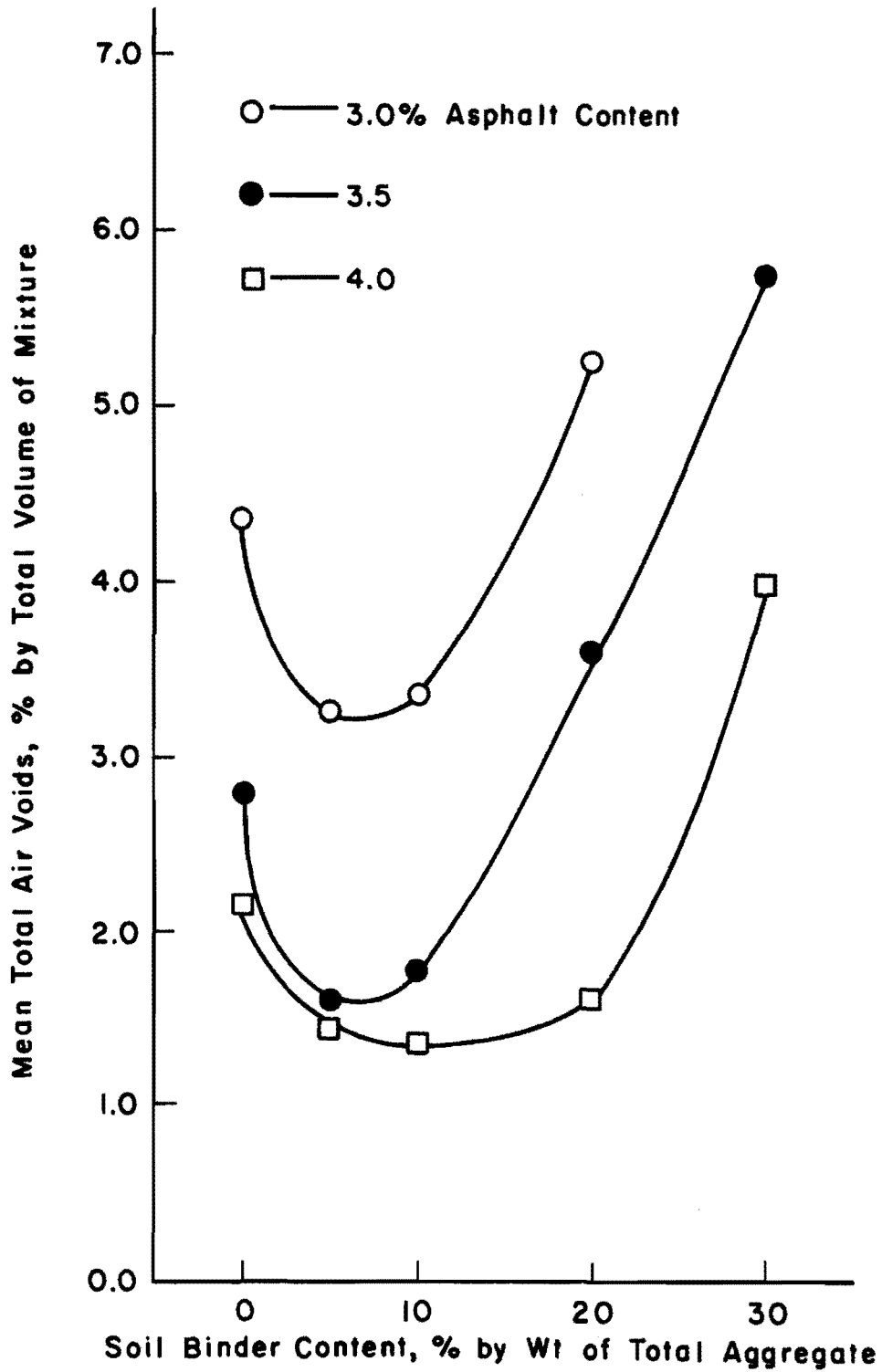


Fig 28. Relationships between soil binder content and total air voids for Eagle Lake gravel asphalt mixtures (Ref 12).

Static Indirect Tensile Test Results

The tensile strength and static modulus of elasticity were estimated using the static indirect tensile test.

Tensile Strength. Optimum asphalt contents were found for each soil binder content and each aggregate type. In addition, the maximum tensile strength occurred at a binder content of 5 percent.

For the purpose of comparison, the relationships between binder content and tensile strength per 1 percent optimum asphalt content were evaluated (Fig 29). It can be seen that the gravel mixture with 5 percent soil binder content produced the maximum ultimate tensile strength per unit percent of optimum asphalt content while the limestone mixture with 10 percent binder content produced the maximum tensile strength per unit percent of optimum asphalt content.

Static Modulus of Elasticity. For all mixtures there were optimum asphalt contents for maximum static moduli of elasticity. For the gravel and limestone mixtures the optimum binder content for maximum static modulus of elasticity was found to be 5 and 10 percent, respectively.

The relationships between soil binder content and modulus per one percent of optimum asphalt content were similar to those observed for tensile strength. The modulus per one percent optimum asphalt content was maximum at binder contents of 5 and 10 percent for the gravel and limestone mixtures, respectively.

Repeated-Load Indirect Tensile Test Results

Repeated-load indirect tensile tests were conducted to evaluate the fatigue life, resilient modulus of elasticity, and resistance to permanent deformation.

Fatigue Life. An optimum asphalt content for maximum fatigue life was found for each of the gravel and limestone mixtures. The optimum soil binder content for maximum estimated fatigue life was 5 percent for both types of aggregate which also produced the minimum optimum asphalt content (Fig 30).

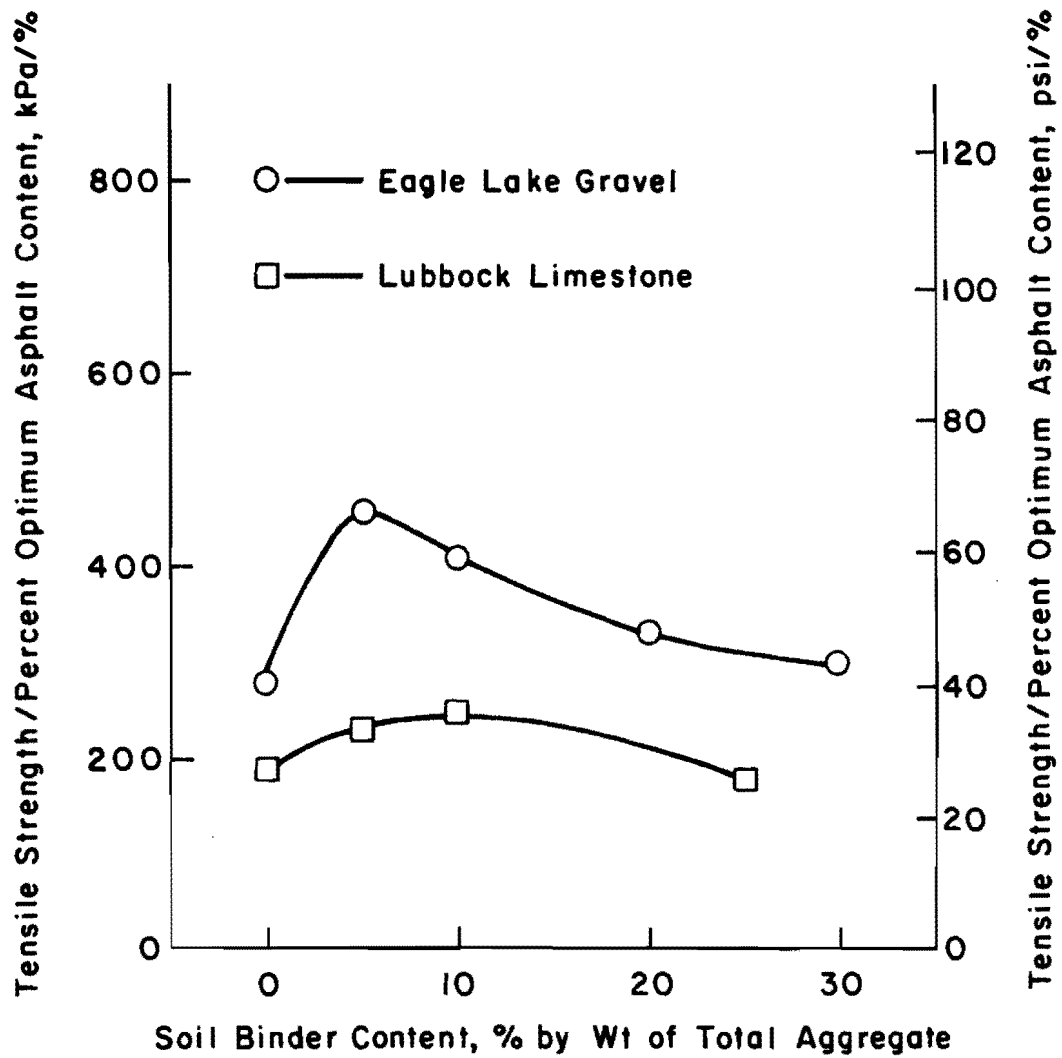


Fig 29. Relationship between binder content and the tensile strength per unit percent of optimum asphalt content for gravel and limestone asphalt mixtures (Ref 12).

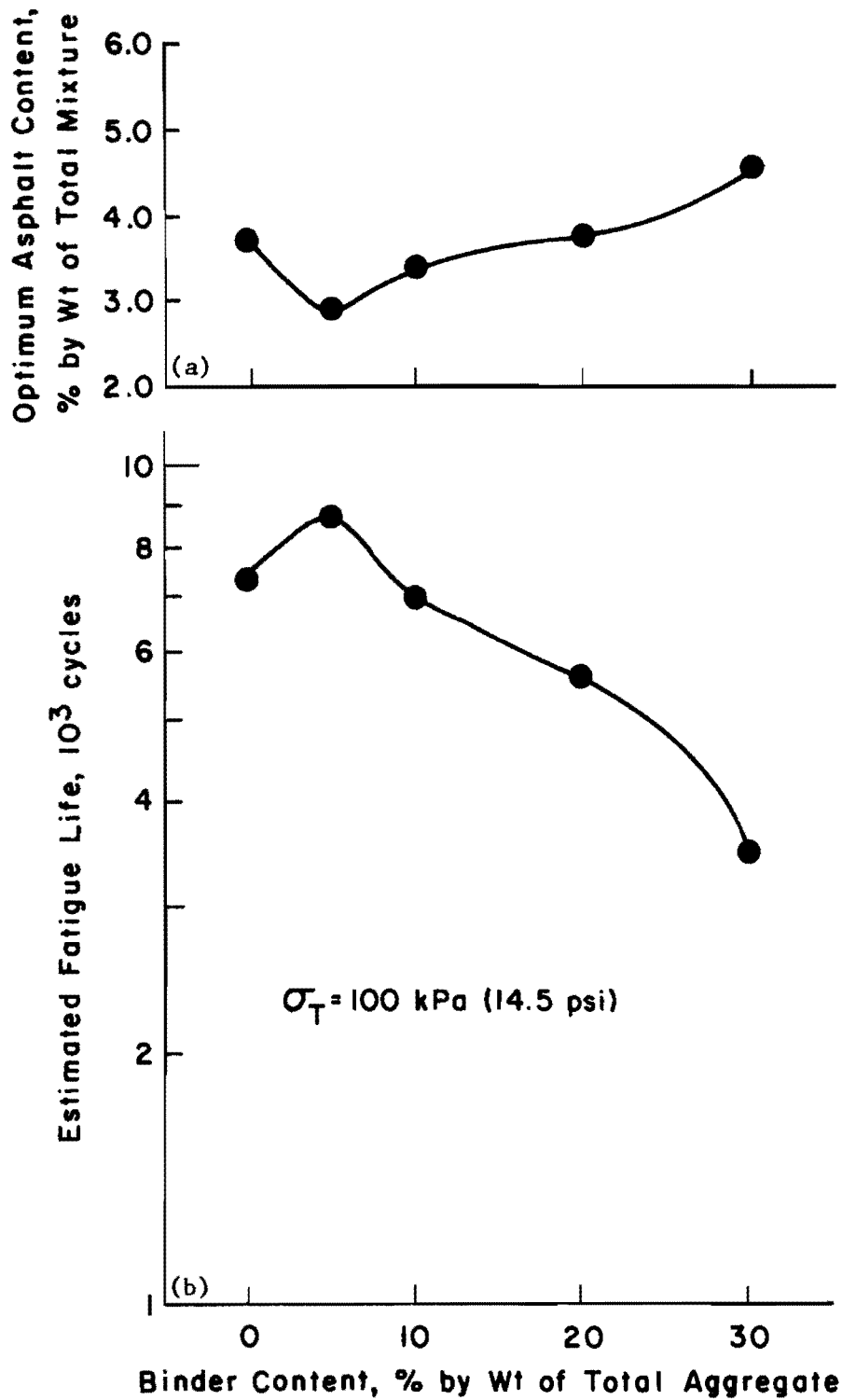


Fig 30. Relationships between binder content and both optimum asphalt content and the corresponding fatigue life for gravel asphalt mixtures (Ref 12).

The relationships between binder content and estimated fatigue life per one percent optimum asphalt content indicate maximum economy occurred at binder contents between 5 and 10 percent for the limestone mixtures and at approximately 5 percent for the gravel mixtures.

Resilient Modulus of Elasticity. The relationships between asphalt content and the resilient modulus of elasticity indicated that the optimum asphalt content for maximum resilient modulus is not well defined, with most of the relationships being flat. This behavior is consistent with the behavior reported by other investigators (Refs 1 and 26). The optimum binder content for maximum resilient modulus of elasticity for the limestone mixtures was 10 percent while the optimum of the gravel was about 5 percent.

Permanent Deformation. An optimum asphalt content for minimum rate of permanent deformation was found to occur, but appeared to be stress dependent. The optimum binder contents were again 5 and 10 percent for the gravel and limestone.

Moisture Damage

This study generally indicated that the optimum soil binder contents for maximum engineering properties were relatively low, in the range of 5 to 10 percent. In addition, these low binder contents required less asphalt and therefore improved the economy of the mixtures. However, the specimens were tested dry and had not been subjected to moisture. Thus, it was necessary to evaluate the effects of water on the engineering properties of the two materials. A series of specimens for each aggregate type at the optimum asphalt content for the maximum ultimate tensile strength were subjected to pressure wetting and then were tested to obtain static indirect tensile results and the resilient moduli of elasticity.

Total air voids and densities of tested specimens were not exactly the same as those obtained from the specimens used to establish the laboratory AVR relationships, but the values were close. The asphalt contents of tested specimens were lower than the optimum asphalt contents for the maximum densities and thus the corresponding densities were less than the maximum densities and the air void contents were higher. Water contents

after pressure wetting were proportional to the total air voids, i.e., the higher the total air voids, the higher the water contents.

There was a definite effect of moisture on the ultimate tensile strength and the static modulus of elasticity (Fig 31). A strength loss of about 36 psi occurred for the gravel mixtures with 5 percent soil binder and of about 72 psi for mixtures with 30 percent soil binder. For the limestone mixtures the losses varied from 110 psi to 58 psi. The effect of pressure wetting on static modulus of elasticity was more significant (Fig 31a). Losses in modulus for the gravel mixtures ranged from 14,500 psi to slightly less than 145,000 psi. Similarly, for the limestone the losses ranged from about 58,000 psi to 145,000 psi. No consistent relationships were observed for the resilient modulus of elasticity. In most cases the pressure wetted specimens exhibited higher moduli than the dry specimens. This was especially true for the limestone mixtures.

A comparison of the density relationships for tested specimens with the curves of the ultimate tensile strength and the static modulus of elasticity after pressure wetting indicates that the shapes are similar.

Thus, it would appear that moisture damage was dependent on the density of the mixture, or air void content, which in turn was related to water content. It was found that the highest density for gravel mixtures was achieved at 5 percent soil binder content and for limestone mixtures at 10 percent soil binder content. This would suggest that as long as the mixture has adequate density substantial damage will not occur.

MOISTURE CONDITIONING OF BLACKBASE (Research Report 183-13)

Based on the results of the study to evaluate the effects of soil binder content on the behavior of blackbase mixtures, a second study was conducted to evaluate moisture effects at lower asphalt and soil binder contents.

The same aggregates used in the previous study (Ref 12) were selected for additional study. These aggregates were a rounded river gravel and a crushed caliche limestone. The asphalt cement was an AC-20. Gradations were varied by adding or removing material finer than the No. 40 sieve while maintaining the amount of material retained on the No. 40 sieve. Binder contents ranged from 0 to 30 percent.

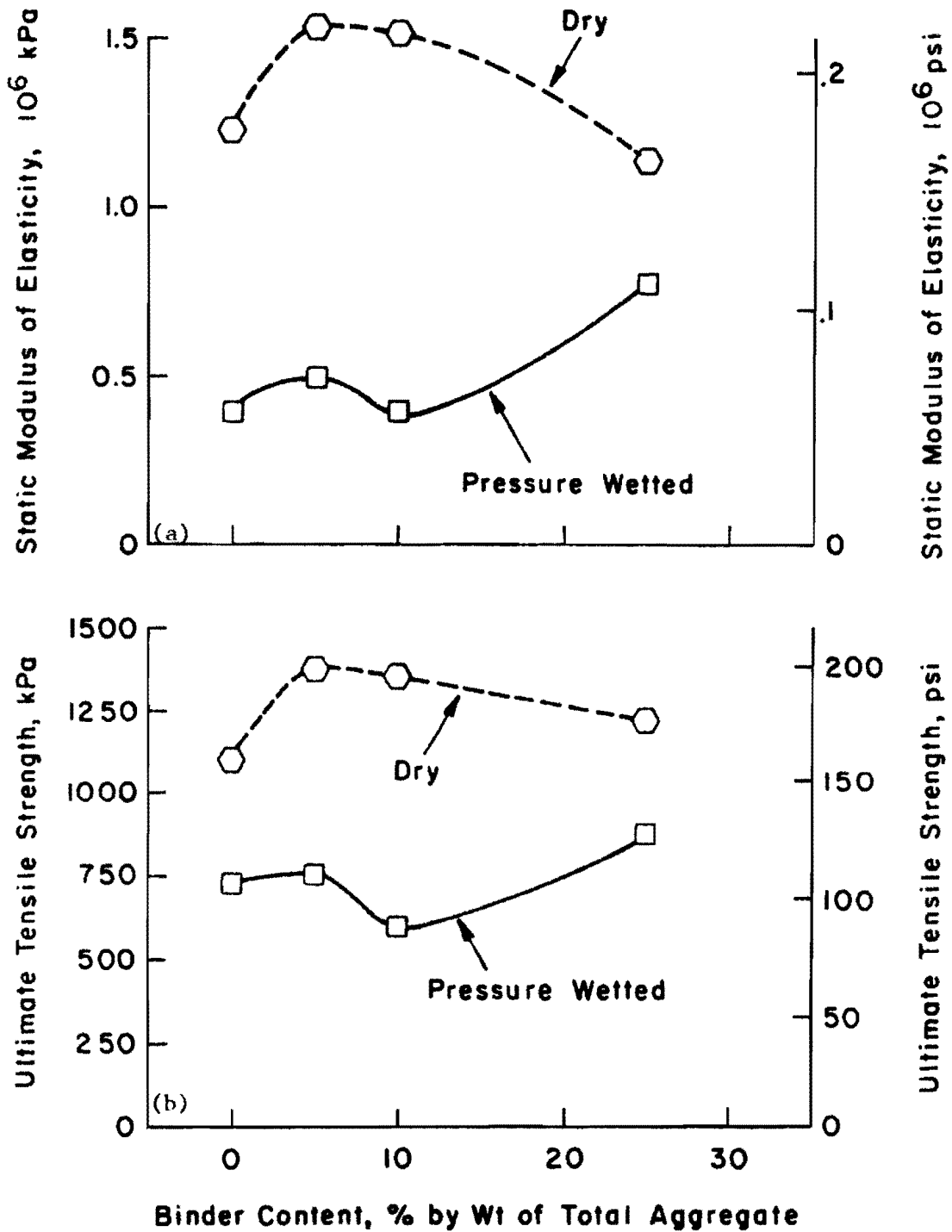


Fig 31. Relationships between binder content and moisture content on the ultimate tensile strength and the static modulus of elasticity for limestone asphalt mixtures (Ref 12).

To evaluate the effects of moisture, specimens were tested in either a dry or wet condition. The dry condition involved curing the specimens at 75°F for 4 days prior to testing. The wet condition involved immersing the specimens in distilled water at 75°F, applying a 4-inch (mercury) vacuum for 30 minutes, and subjecting the specimens to a freeze-thaw cycle prior to testing. All specimens were tested using the indirect tensile test to obtain estimates of tensile strength and static modulus of elasticity.

Two parameters were utilized to evaluate moisture effects. These parameters were the tensile strength ratio (TSR) and static modulus of elasticity ratio (MER), which are defined as follows:

$$\text{TSR} = \frac{S_{T\text{wet}}}{S_{T\text{dry}}} \quad (4.1)$$

where $S_{T\text{wet}}$ = tensile strength of the wet specimens, and
 $S_{T\text{dry}}$ = tensile strength of the dry specimens;

$$\text{MER} = \frac{E_{S\text{wet}}}{E_{S\text{dry}}} \quad (4.2)$$

where $E_{S\text{wet}}$ = modulus of elasticity of the wet specimens, and
 $E_{S\text{dry}}$ = modulus of elasticity of the dry specimens.

Values of TSR and MER

Values of TSR ranged from 0.59 to 1.5 for the gravel mixtures and 0.19 to 0.56 for the caliche mixtures as compared to 0.14 to 1.04 and 0.26 to 1.17 as reported by Lottman (Ref 35) and Maupin (Ref 36).

Values of MER ranged from 0.37 to 1.52 for the gravel mixtures and from 0.05 to 0.22 for the caliche mixtures which are in the same general range as the values of TSR.

Factors Affecting TSR

The test results from this study were used to investigate the changes in TSR as a result of changes in binder content, asphalt content, air void content, and moisture content for both aggregate types and test methods.

Soil Binder Content. The gravel mixtures exhibited little loss of strength due to moisture except at 0 percent soil binder. The TSR generally were approximately 1.0, with the highest ratios occurring between 10 and 20 percent soil binder content. The caliche limestone mixtures, on the other hand, exhibited large losses of the tensile strength ratio at all soil binder contents.

Asphalt Content. For the gravel mixtures there was an optimum asphalt content for maximum TSR which depended on the soil binder content. However, for the limestone mixtures there was an apparent increase in TSR with an increase in asphalt content.

Air Void Content. The previous study (Ref 12) indicated that moisture damage is dependent on the relative density or the air void content of the mixtures. Generally, mixtures having high air void contents are more adversely affected by moisture than mixtures with low air void contents. Similarly, in this study the TSR decreased as the air void content increased.

Water Content. The amount of water absorbed by each specimen during moisture conditioning was measured before testing and expressed as a percentage of the dry weight of the specimen. Water contents ranged from 0.1 to 2.0 percent for the gravel mixtures and from 3.9 to 7.9 percent for the caliche mixtures. As water content increased, TSR decreased.

Aggregate Type. Results indicated that the moisture susceptibility of the caliche limestone mixtures was much greater than that of the gravel mixtures. The TSR values for the caliche mixtures were consistently much smaller than the values for the gravel mixtures. The caliche limestone mixtures also had higher moisture contents and air void contents than did the gravel mixtures. After compaction both mixtures had about the same air void contents, 1.7 to 8.2 percent for the caliche and 1.5 to 11.3 percent for the gravel. After moisture conditioning, however, the air void contents for the gravel were the same as before conditioning but for the caliche mixture the air voids had increased to 5.6 to 12.5 percent, indicating a volume change.

EVALUATION OF DRYER-DRUM MIXTURES (Research Report 183-8)

The objective of this study was to evaluate the fatigue and elastic properties of asphalt mixtures produced using a dryer-drum plant. This evaluation involved a comparison of these properties with the properties of asphalt mixtures produced by a conventional plant. Mixtures with high moisture contents were not available. In fact, the water contents were approximately equal to those which might be expected in conventional plants. Factors which could be evaluated were curing treatment and mixing temperature.

Fatigue Properties

Values of the constants n_2 , K_2 , and K_2' were obtained by linear regression. Values of n_2 were fairly constant, ranging from 1.24 to 2.28. More important, however, is the fact that these values are low compared to previously reported values for field cores of mixtures produced using a conventional plant. Monismith (Ref 16) reported values ranging from 1.85 to 6.06 and Navarro and Kennedy (Ref 2) reported values ranging from 1.58 to 5.08. Since $\frac{1}{\sigma}$ is always less than 1.0, lower values of n_2 generally would indicate higher values of fatigue life, but the higher values would tend to occur at higher stress levels.

Values of K_2' ranged from 7.05×10^5 to 2.52×10^8 . These values are small compared to previously reported values of K_2' for mixtures produced using conventional plants, which should indicate lower fatigue lives. Navarro and Kennedy (Ref 2) reported values of K_2' ranging from 1.38×10^6 to 1.24×10^{15} . Monismith (Ref 14) reported values in the range of 4.02×10^7 to 4.31×10^{17} . Adedimila and Kennedy (Ref 5), for laboratory specimens at the optimum asphalt content, reported values of K_2' of 3.68×10^9 for gravel mixtures and 1.44×10^9 for limestone mixtures.

The logarithmic relationships generally indicated that the dryer-drum mixtures had lower fatigue lives for the range of stress shown; however, the reverse would probably occur at very high stress levels.

Static Test Results

Values of tensile strength, modulus of elasticity, and Poisson's ratio obtained for dryer-drum mixtures were approximately the same as values obtained previously for conventional mixtures. Thus, in terms of static elastic and strength properties, the dryer-drum mixtures should perform as well as conventional asphalt mixtures.

Repeated-Load Test Results

The resilient elastic properties were obtained for cycles corresponding to 30, 50, and 70 percent of fatigue life and were averaged to obtain a mean value for the life of the mixture.

Instantaneous Resilient Modulus of Elasticity. The values of the mean instantaneous resilient modulus of elasticity for each project ranged from 186×10^3 to 506×10^3 psi with the coefficient of variation ranging from 4 to 25 percent. Navarro and Kennedy (Ref 2) reported values of modulus for mixes produced with a conventional plant ranging from 220×10^3 to 615×10^3 psi with a coefficient of variation ranging from 4 to 28 percent. For both studies, the moduli were consistent within each project; therefore, the coefficients of variation for each project were small. Thus, the moduli obtained for dryer-drum mixtures tested in this study were essentially equal to those reported in previous studies of conventional mixtures.

Instantaneous Resilient Poisson's Ratio. The mean values of instantaneous resilient Poisson's ratios ranged from 0.05 to 0.38, with the larger values occurring at the high stress levels. Previously reported values (Ref 2) of instantaneous resilient Poisson's ratio for field cores of asphalt concrete mixes produced by the conventional plant were 0.44 and 0.57. Adedimila and Kennedy (Ref 5) reported values of instantaneous resilient Poisson's ratio for laboratory-prepared specimens of asphalt concrete ranging from 0.04 to 0.20. Thus, the values of the instantaneous resilient Poisson's ratio found in this study, even though they were generally smaller, were within the range of values previously reported for conventional plants.

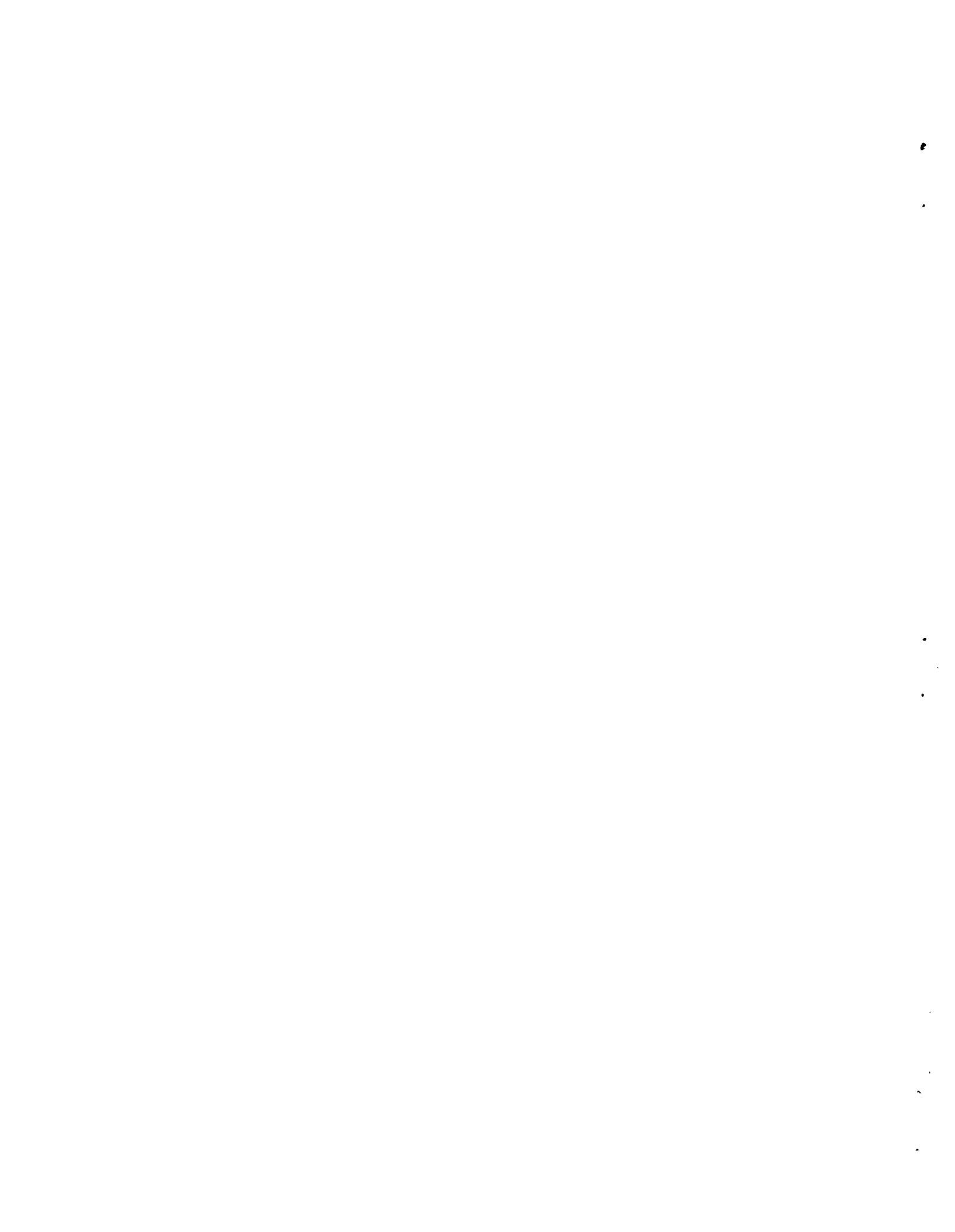
Effect of Mixing Temperature

An evaluation of the effect of the mixing temperature on the fatigue and elastic properties was made by testing specimens from one district. The specimens were produced at four different mix temperatures and asphalt contents using a dryer-drum plant.

An increase in mixing and compaction temperature caused a small decrease in the tensile strength. The static modulus of elasticity and the static Poisson's ratio did not show significant change with a change in mix temperature.

Values of n_2 and K_2' were approximately equal for a group of specimens produced with 5.5 percent asphalt content at 205°F and those produced with 5.3 percent asphalt content at 225°F. Nevertheless, there were significant differences in the values of n_2 and K_2' for the mixtures containing 4.7 and 4.9 percent asphalt and mixed at 215°F and 250°F, respectively. The value of n_2 was smaller and the value of K_2' was larger for the 250° mixing temperature. No consistent change in the value of the modulus was observed with a change in mix temperature.

The number of comparisons in the study was quite small and also involved changes in asphalt content. Thus, it is difficult to arrive at any definite conclusion concerning the effect of mixing temperature.



CHAPTER 5. MIXTURE DESIGN

Three studies were conducted which were directly applicable to mixture design. The study, findings, and recommendations are contained in Research Reports 183-6 (Ref 6), 183-10 (Ref 10), and 183-11 (Ref 11) and are summarized in this chapter.

ELASTIC CHARACTERISTICS OF ASPHALT MIXTURES (Research Report 183-6)

The basic data utilized in this study were obtained from an experimental program which was described in Research Report 183-5 (Ref 5). These data were analyzed further in an attempt to establish a technique for estimating the modulus of elasticity and Poisson's ratio from the repeated-load indirect tensile test and to further investigate the repeated-load elastic characteristics and fatigue characteristics for purposes of mixture design of asphalt mixtures.

Two types of aggregate were included in the test program, an angular and relatively porous crushed limestone and a relatively nonporous gravel, with a medium gradation basically conforming to the State Department of Highways and Public Transportation standard specification for hot mix asphalt concrete Class A. The asphalt was an AC-10 asphalt cement, and the asphalt contents varied from 4 to 8 percent by weight of the total mixture.

All specimens were approximately 4 inches in diameter by 2 inches high. Maximum density of the limestone mixtures was 146 pcf at the optimum asphalt content of 6.7 percent. The maximum density and the optimum asphalt content for the gravel mixtures were 144 pcf and 6.5 percent. Specimens were tested using the static and repeated-load indirect tensile test at 50, 75, and 100°F.

Test properties analyzed were static modulus of elasticity, static Poisson's ratio, instantaneous resilient modulus of elasticity, instantaneous resilient Poisson's ratio, and fatigue life.

The static modulus of elasticity E_s and Poisson's ratio ν_s were estimated from the slopes of load-deformation relationships. The instantaneous resilient modulus of elasticity and Poisson's ratio were

calculated from the instantaneous resilient horizontal and vertical deformations (Fig 3) and the applied stress. Static modulus and Poisson's ratio were similarly calculated assuming that the relationship between load and deformation was linear. Thus only the maximum and minimum deformations were required.

Fatigue life was defined as the number of cycles required to produce complete fracture of the specimen.

Relationships Between Resilient Modulus, Static Modulus, and Poisson's Ratio

In previous studies Navarro and Kennedy (Ref 2) and Adedimila and Kennedy (Ref 5) found no correlation between the resilient modulus of elasticity and the static modulus of elasticity. Nevertheless, since the static modulus of elasticity can be obtained quickly and easily, it was felt that the possibility of correlations between the instantaneous resilient modulus and static modulus should be investigated further.

Instantaneous Resilient versus Static Modulus. The instantaneous resilient moduli were significantly larger than the static moduli and it is obvious that no correlation existed. The ratio of the instantaneous resilient modulus and the mean static modulus to the static modulus of elasticity ranged from 0.9 to 5.1 for gravel mixtures and from 1.0 to 10.7 for limestone mixtures, with higher values occurring for materials with the lower static moduli. These ratios are approximately the same as those obtained for inservice blackbase and asphalt concrete as shown in Figure 14 of Chapter 3 (Ref 2).

Instantaneous Resilient versus Static Poisson's Ratio. The instantaneous resilient Poisson's ratios tend to be larger than the static values. The majority of the instantaneous resilient Poisson's ratios for the gravel and limestone specimens were in the range of 0.11 to 0.54 and 0.10 to 0.70, respectively, while for the static Poisson's ratio the range was 0.13 to 0.35 for gravel and 0.08 to 0.36 for limestone.

Test Procedure to Determine the Instantaneous Resilient Modulus

One of the principal objectives of this investigation was to develop a method to obtain a representative value of the instantaneous resilient modulus of elasticity of an asphalt mixture without conducting long-term repeated-load tests. The instantaneous resilient modulus changes continuously throughout the life of the specimen and is subject to large variations during the first 10 percent of the fatigue life of the specimen. In order to evaluate the possible error associated with estimating the instantaneous resilient modulus at a low percentage of the fatigue life, estimates of the instantaneous resilient modulus were made at approximately 0.1, 0.5, 1.0, 5.0, 10, 30, 50, and 70 percent of the fatigue life.

Average relationships for both aggregates at 6.0 percent and test temperatures of 50, 75 and 100°F are shown in Figure 32. The resulting relationships indicated that the moduli after the first 10 percent of the fatigue life generally were not significantly different from the values obtained after additional load applications. Thus, the instantaneous resilient moduli at any given percentage of the fatigue life were expressed in terms of a ratio with the modulus at $0.5 N_f$, which was assumed to be the average modulus during the life of the specimen. A typical relationship between this ratio and the logarithm of percent fatigue life is shown in Figure 33. Analysis of the various relationships indicated that at one percent of the fatigue life the estimated instantaneous resilient modulus generally was from 1.01 to 1.16 times as large as the modulus value at 50 percent of the fatigue life. At 75°F, the average modulus at $.001 N_f$ would be 1.22 and 1.05 times the modulus at $0.5 N_f$ for the gravel and limestone mixtures, respectively.

Thus, it would appear that a reasonable estimate of the modulus could be obtained after 0.1 to 1.0 percent of the fatigue life. However, the amount of scatter increased significantly as the number of load applications was reduced, which could be a problem especially at high test temperatures.

Based on the fact that it was difficult to estimate the instantaneous resilient modulus at $.001 N_f$ at 50°F and 100°F, it was concluded that the resilient modulus should be estimated at $.01 N_f$ or greater. However, since the actual number of cycles will vary with the fatigue life, which is a

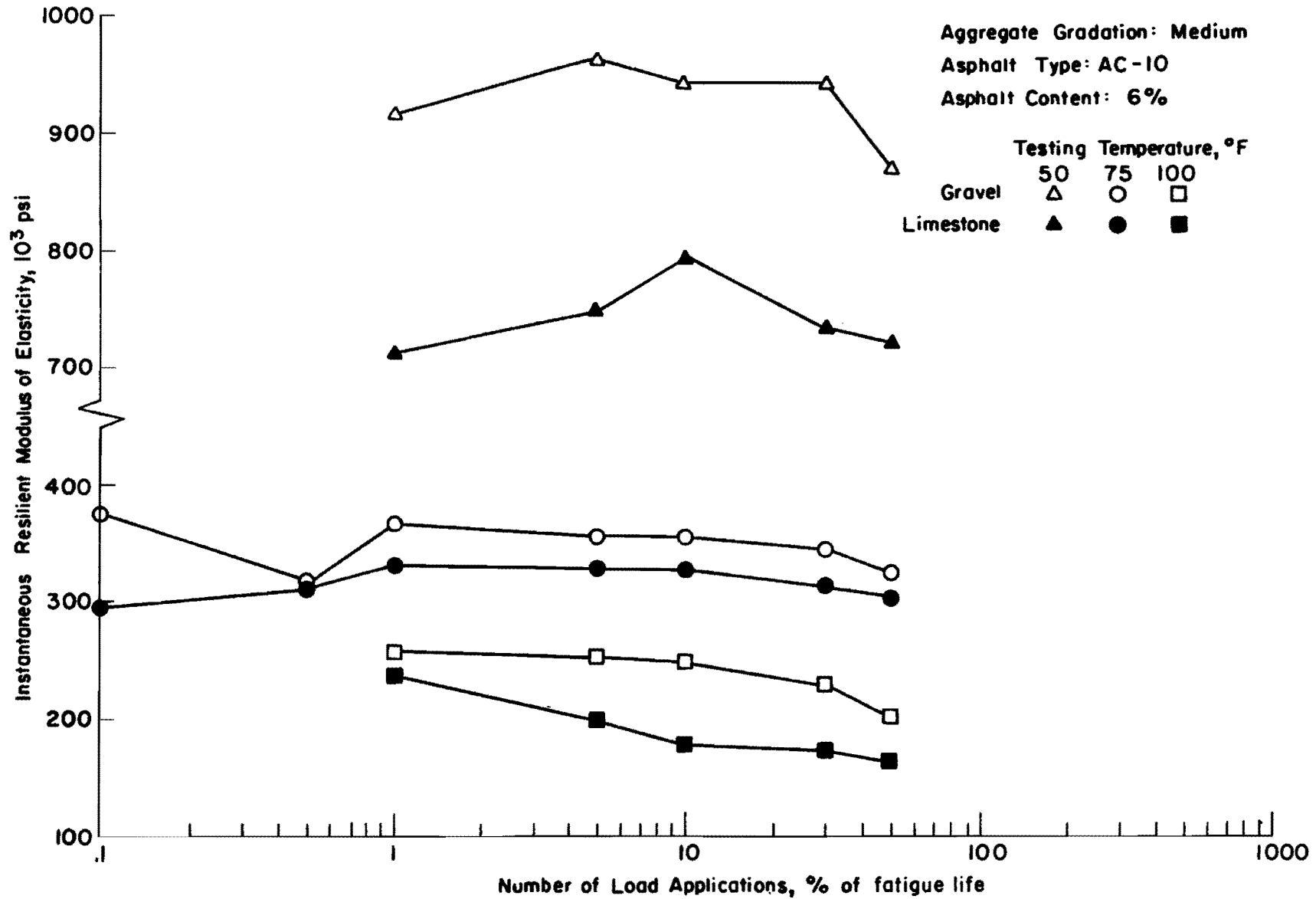


Fig 32. Average relationships between instantaneous resilient modulus of elasticity and number of load applications for asphalt mixtures (Ref 6).

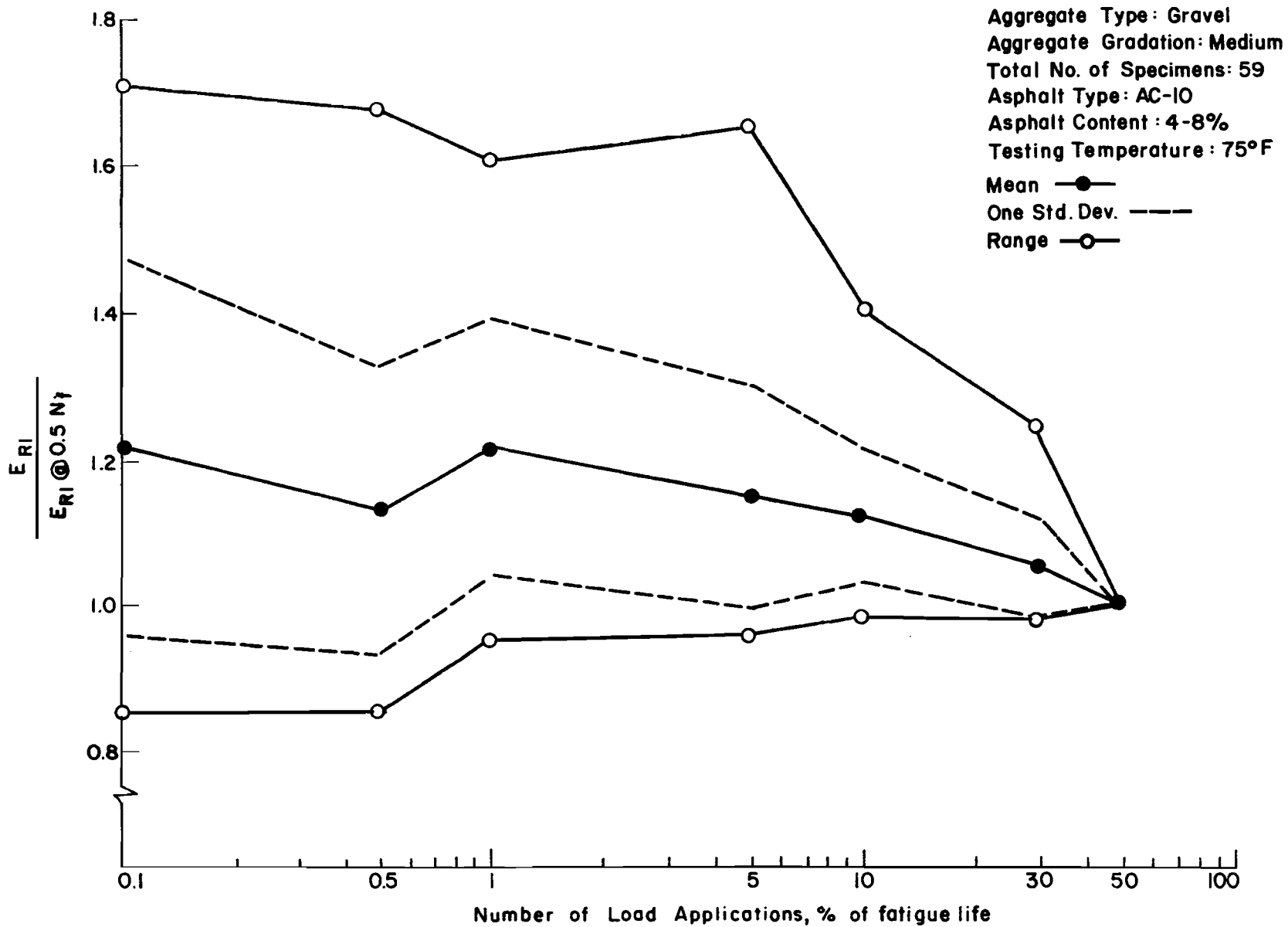


Fig 33. Relationship between resilient modulus and number of load applications for gravel asphalt mixture tested at 75° F (Ref 6).

function of stress as well as other mixture construction variables, it was necessary to obtain an estimate of the required number of load applications.

Adedimila and Kennedy (Ref 5) and Moore and Kennedy (Refs 33 and 34) concluded that fatigue life could be estimated in terms of stress-strength ratio with reasonable accuracy and that such a relationship minimized the effects of test temperature. From an evaluation of the relationship between stress-strength ratio and fatigue life as reported in Reference 5 along with the relationships for various percentages of fatigue life, it was concluded that the specimen should be subjected to a minimum of 25 load applications before estimating the instantaneous modulus of elasticity.

Relationship Between Properties and Optimum Asphalt Contents

Previous work (Refs 2, 5, 33, and 34) have shown no correlation between fatigue life and the static modulus of elasticity or the instantaneous resilient modulus of elasticity. Navarro and Kennedy (Ref 2) investigated the possibility of such a relationship for cores from inservice pavements while Adedimila and Kennedy (Ref 5) evaluated the relationship for the laboratory prepared specimens used in this study.

Further evaluation in this study confirmed the fact that there was no definite relationship which would allow fatigue life to be estimated from a single value of either the static or the instantaneous resilient modulus of elasticity. These relationships do have significance if considered in terms of increasing asphalt contents.

The relationships between fatigue life and static modulus of elasticity for the gravel and limestone mixtures are shown in Figures 34 and 35, respectively. Similar relationships between fatigue life and instantaneous resilient modulus of elasticity are shown in Figures 36 and 37. In addition to the actual data points, these figures include estimated points at the optimum asphalt contents for maximum fatigue life and the maximum static modulus of elasticity.

Optimum Asphalt Content for Maximum Fatigue Life. A definite optimum asphalt content for maximum fatigue life existed for the mixtures and stress levels used in this study; stress level had no apparent effect on

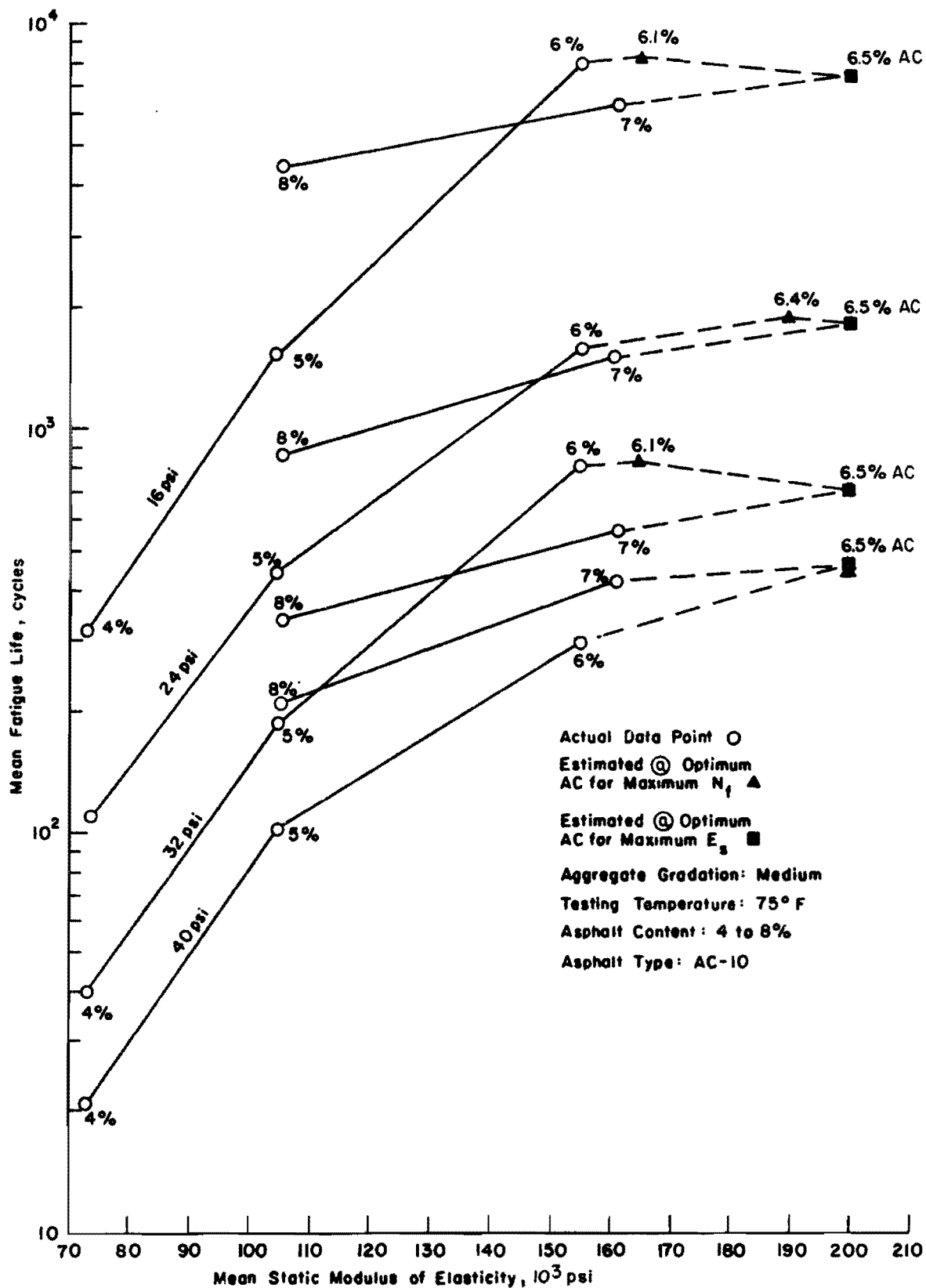


Fig 34. Relationship between static modulus of elasticity and fatigue life for gravel asphalt mixtures (Ref 6).

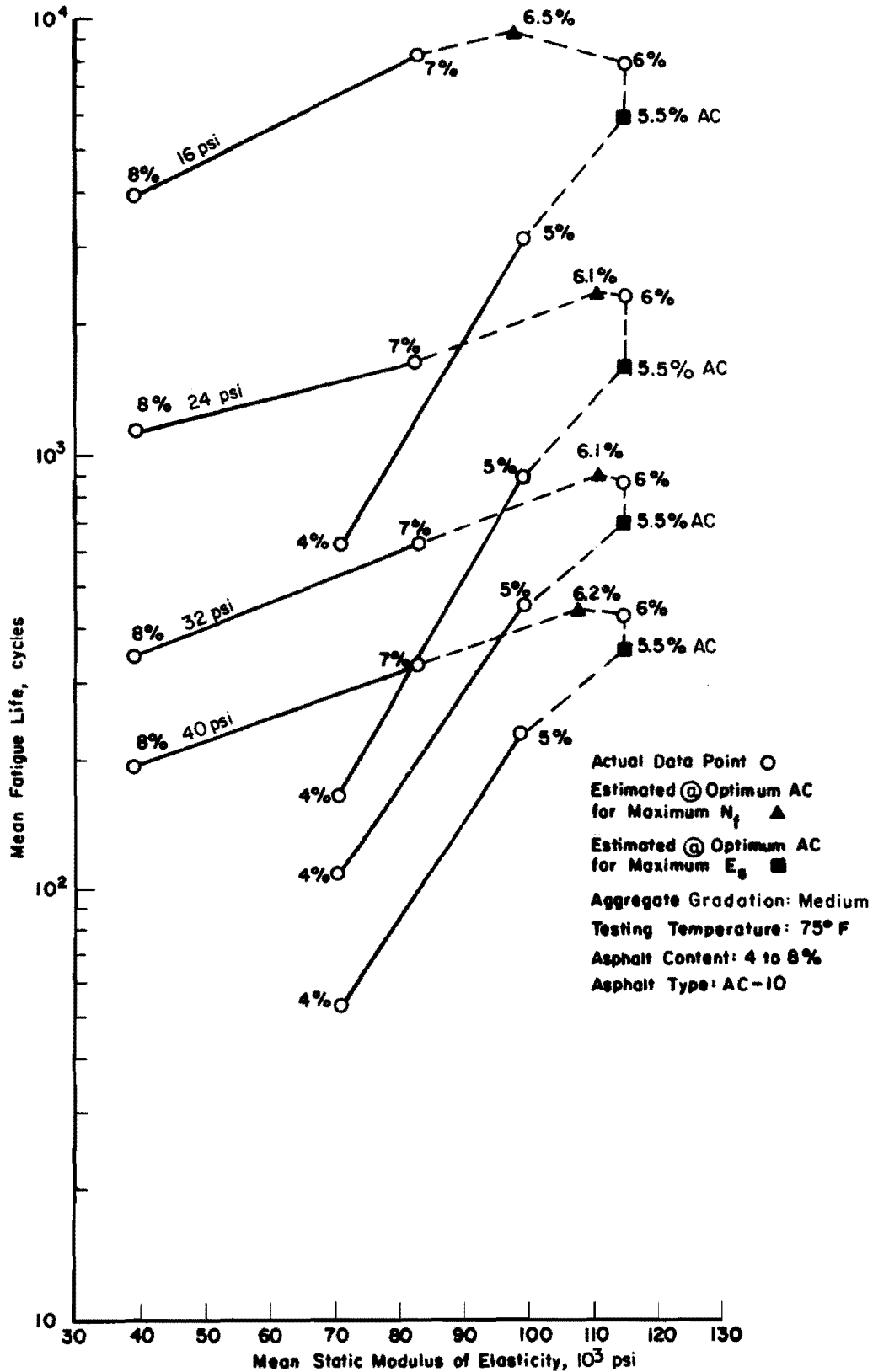


Fig 35. Relationship between static modulus of elasticity and fatigue life for limestone asphalt mixtures (Ref 6).

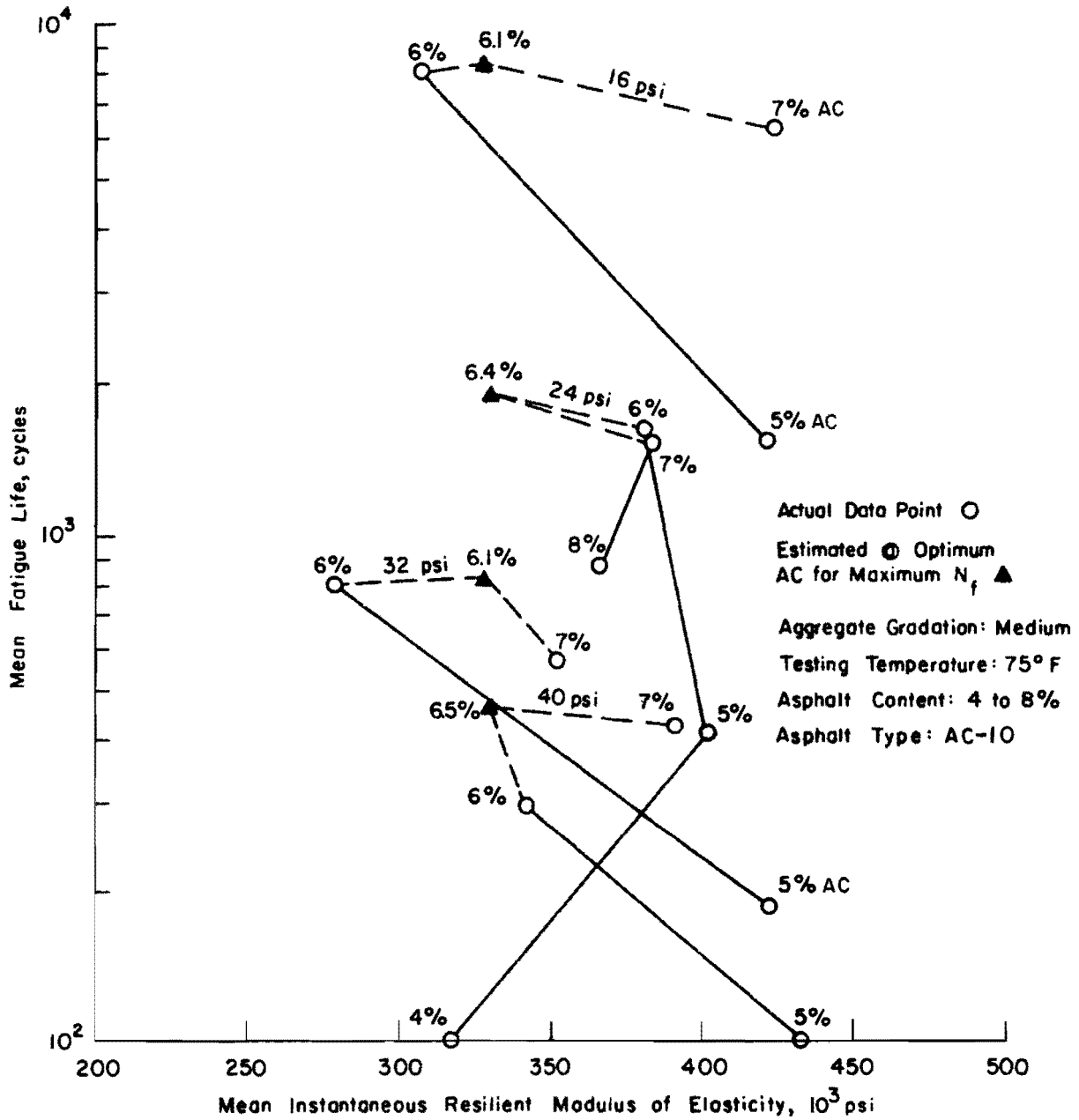


Fig 36. Relationship between instantaneous resilient modulus of elasticity and fatigue life for gravel asphalt mixtures (Ref 6).

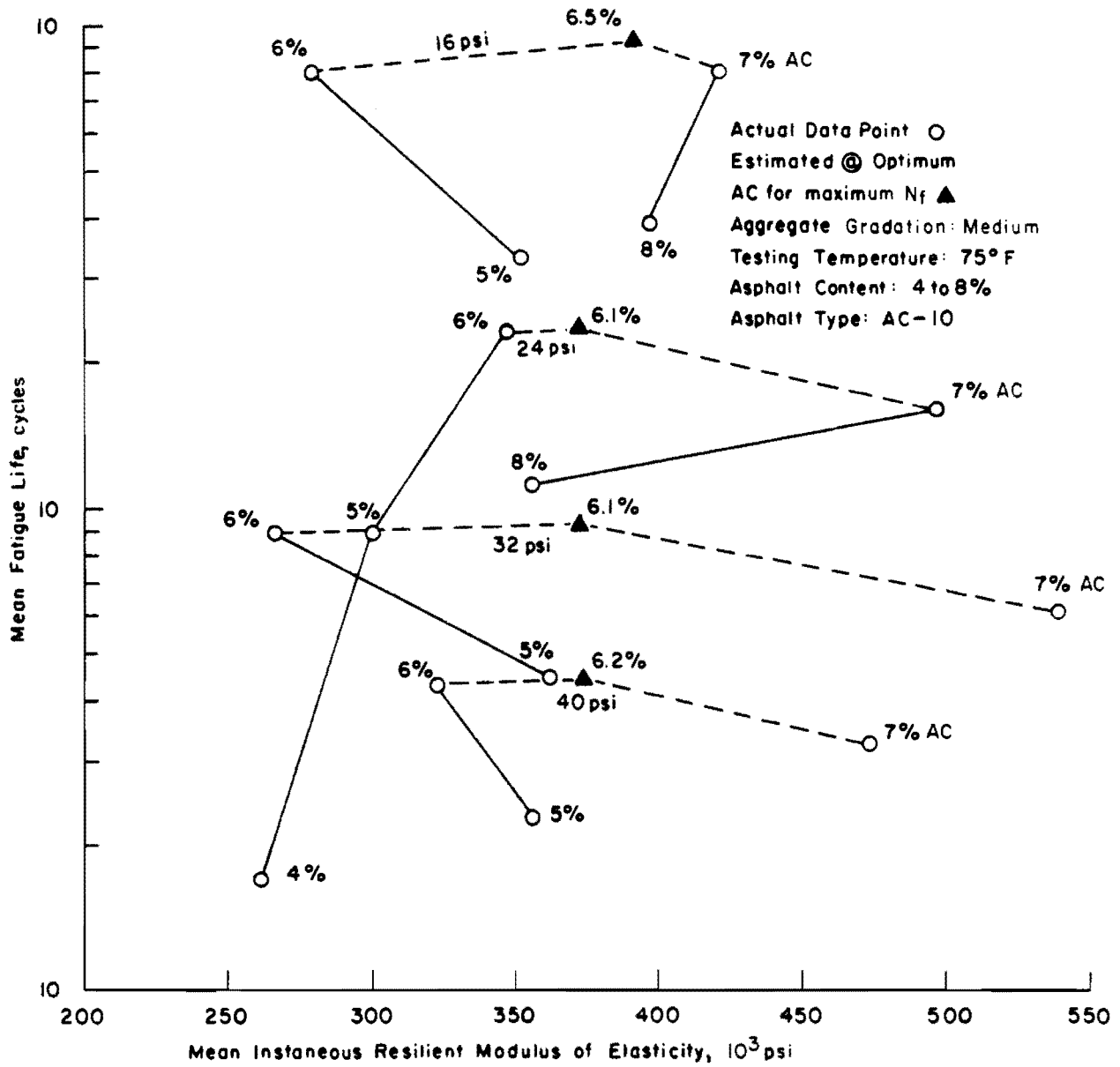


Fig 37. Relationship between instantaneous resilient modulus of elasticity and fatigue life for limestone asphalt mixtures (Ref 6).

the optimum asphalt content. The optimum asphalt contents were generally less than the optimum for maximum density.

Optimum Asphalt Content for Maximum Static Modulus of Elasticity. The optimum asphalt content tended to increase slightly with decreased testing temperature. In addition, at the higher temperatures the optimum was not well defined indicating that the actual choice of the optimum is much more critical at lower temperatures. In addition, the optimum asphalt contents for maximum static modulus generally were slightly less than the optimum asphalt content for maximum fatigue life. However, Figures 34 and 35 indicate that while for limestone the above statement is true, for gravel the reverse is true, although the optimums are much closer.

Optimum Asphalt Content for Maximum Instantaneous Resilient Modulus. Although maximum moduli did occur, there was no well defined optimum asphalt content. Thus the instantaneous resilient modulus was relatively insensitive to asphalt content. Similar relationships were also obtained in another study (Ref 5), in which it was also reported that Schmidt detected an optimum asphalt content for maximum resilient modulus but that the optimum occurred on a plateau, thus indicating that the choice of asphalt content was not critical.

Evaluation of Relationships Between Fatigue Life and Static Modulus. Maximum fatigue life for limestone mixtures occurred at an asphalt content which was larger than the asphalt content for maximum static modulus. However, for gravel mixtures the optimum asphalt contents for maximum fatigue life were slightly less than or equal to the optimums for maximum static modulus (Figs 34 and 35). Since, according to Adedimila and Kennedy (Ref 5), the optimums for maximum tensile strength and static modulus are essentially equal, it would appear that the optimum asphalt content for maximum fatigue life generally was larger than for maximum tensile strength. Hence, these relationships indicate that the final choice of the optimum asphalt content for fatigue life was not overly critical. Nevertheless, if a large error in asphalt content can be expected, then the error should be on the wet side of the optimum for maximum fatigue life since the effect is much less for a change in asphalt content on the wet side.

The relationships between fatigue life and instantaneous resilient modulus (Figs 36 and 37) have a slightly different shape which can be attributed to the fact that the resilient modulus was relatively insensitive to changes in asphalt content and, therefore, the actual value is probably determined by other more important factors. However, these figures do indicate that small changes in asphalt content, near the optimum asphalt content for maximum fatigue life, did not produce large reductions in fatigue life. However, for large or small changes, the losses were generally less on the wet side. Probably more important is the fact that the instantaneous resilient modulus increased with an increase in asphalt content above the optimum for maximum fatigue life.

Choice of Asphalt Content. From the above discussion, it would appear that mixtures similar to the ones used in this study should be designed at or above the optimum asphalt content for maximum fatigue life. If the design is to be based on static tests, the asphalt content should be slightly above the optimum for maximum modulus of elasticity or maximum tensile strength.

Additional mixtures involving other aggregates, gradations, and asphalt types need to be studied before a definite conclusion can be made. In addition, consideration of other characteristics such as permanent deformation, or rutting, may require that the asphalt content be altered.

Nevertheless, it is apparent that the optimum asphalt contents for various properties are different and that this fact should be recognized and considered in the design of asphalt mixtures.

MIXTURE DESIGN FOR RECYCLED ASPHALT MIXTURES (Research Report 183-10)

This report summarizes the findings of a study to evaluate the fatigue and elastic characteristics of recycled asphalt pavement materials and to develop a preliminary mixture design procedure.

Mixtures with different types and amounts of additives for three recycling projects in Texas were evaluated. The primary method of evaluation was the indirect tensile test. This basic test was conducted using a single load to failure and repeated loads. Estimates of tensile

strength, resilient elastic characteristics, and fatigue characteristics were obtained.

Fatigue Properties

The linear relationship between fatigue life and stress were expressed in the forms of Equations 2.1 and 2.2 (Fig 38). Previous studies (Refs 2, 4 and 5) have shown that results from Equation 2.2 are more useful and comparable with results from other test methods. For the indirect tensile test, stress difference is approximately equal to $4\sigma_T$ at or near the center of the specimen.

Values of n_2 ranged from 2.15 to 8.07. These values were in the same range, although slightly higher than those previously reported for conventional pavement materials. Values of K_2' ranged from 3.96×10^8 to 1.11×10^{23} . These values were also higher than those for previously reported mixtures produced using conventional methods and materials. Thus, the fatigue lives generally were longer for the recycled mixtures, as indicated by the K_2' values. However, a small increase in the stress level would substantially increase the fatigue life as evidenced by the large n_2 values.

Strength and Static Elastic Properties

Estimates of tensile strength, modulus of elasticity, and Poisson's ratio were determined using the static indirect tensile test. Strength and moduli obtained for recycled mixtures generally were slightly larger than values obtained previously for conventional mixtures. Thus, in terms of static elastic and strength properties, the recycled material should perform as well as the conventional mixtures.

Repeated-Load Test Results

The resilient elastic properties were determined at approximately 50 percent of fatigue life.

Resilient Modulus of Elasticity and Poisson's Ratio. The resilient modulus of elasticity for each project ranged from 249×10^3 to 1003×10^3 psi, with the coefficient of variation ranging from 2 to 27 percent. Thus,

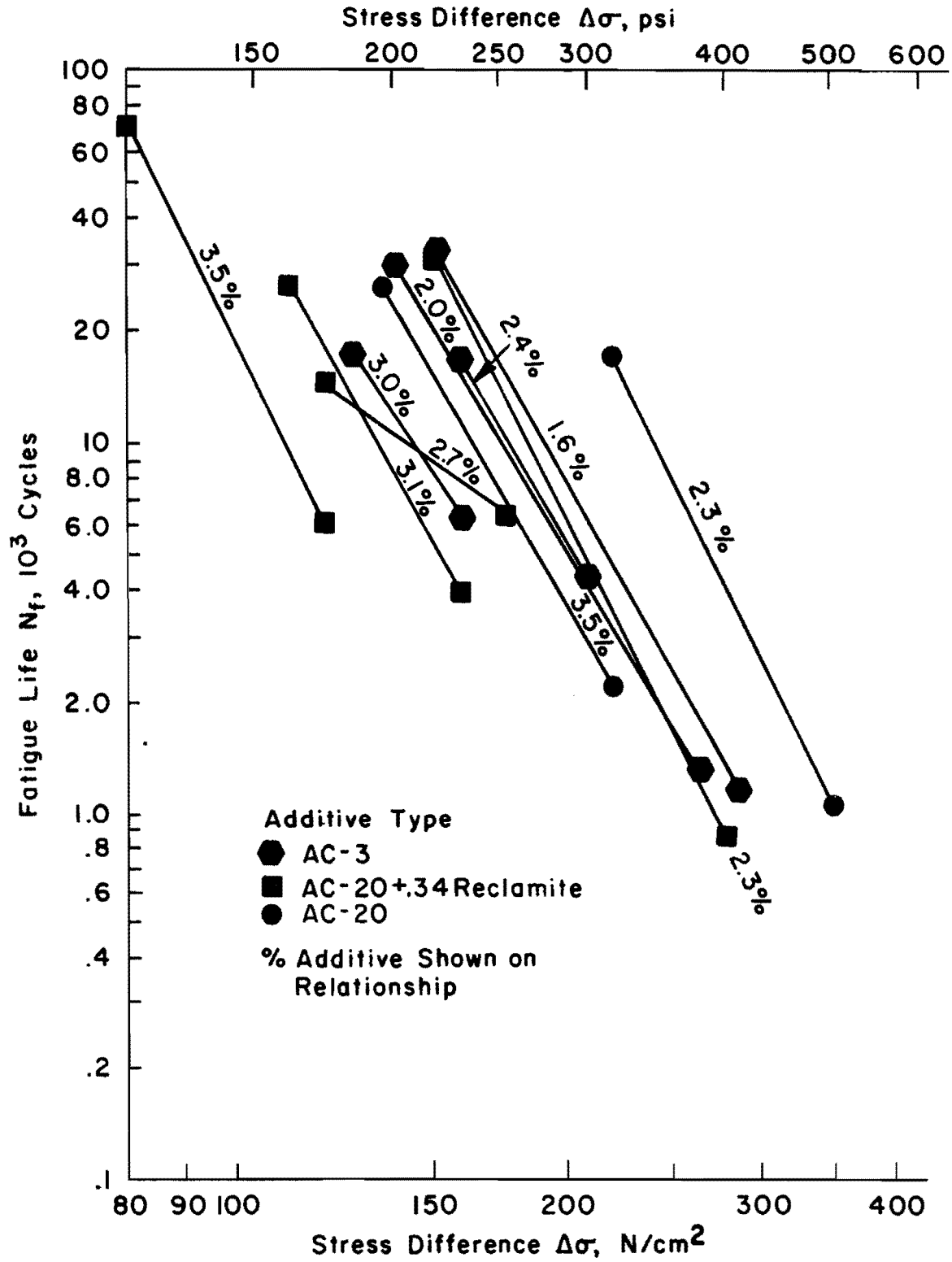


Fig 38. Relationships between the logarithms of fatigue life and stress difference for recycled asphalt mixtures (laboratory specimens) (Ref 10).

the moduli for this study were higher than those reported in previous evaluations of conventional mixtures. The values for resilient Poisson's ratio ranged from 0.04 to 0.68. These values overlapped values previously reported for conventional mixtures.

Effect of Additive Content

The effects of the amount and type of additive on the tensile strength, static modulus of elasticity, resilient modulus of elasticity, and fatigue life for the three projects are summarized in Figures 39, 40, 41, and 42. Generally, all four properties decreased linearly with an increase in the amount of additive.

Preliminary Mixture Design Procedure

The following recommendations were developed on the basis of the experience of project personnel to date, are preliminary in nature, and will require modifications as additional information and experience are developed.

The design problem involves (1) bringing the asphalt to its optimum composition for durability, (2) restoring the asphalt characteristics to a consistency level appropriate for the mixture, and (3) meeting the asphalt content requirement of the mixture design procedure.

The steps necessary for the design of recycled asphalt mixtures have been subdivided into three categories: general, preliminary design, and final design.

General. The following information is required prior to beginning the design process.

- (1) Determine the gradation of the aggregate in the mixture to be recycled.
- (2) Determine the amount of asphalt in the asphalt mixture to be recycled.
- (3) Determine the final aggregate conditions, e.g., final gradation after the addition of new aggregate.
- (4) Determine the maximum size of the mixture particles after pulverization.

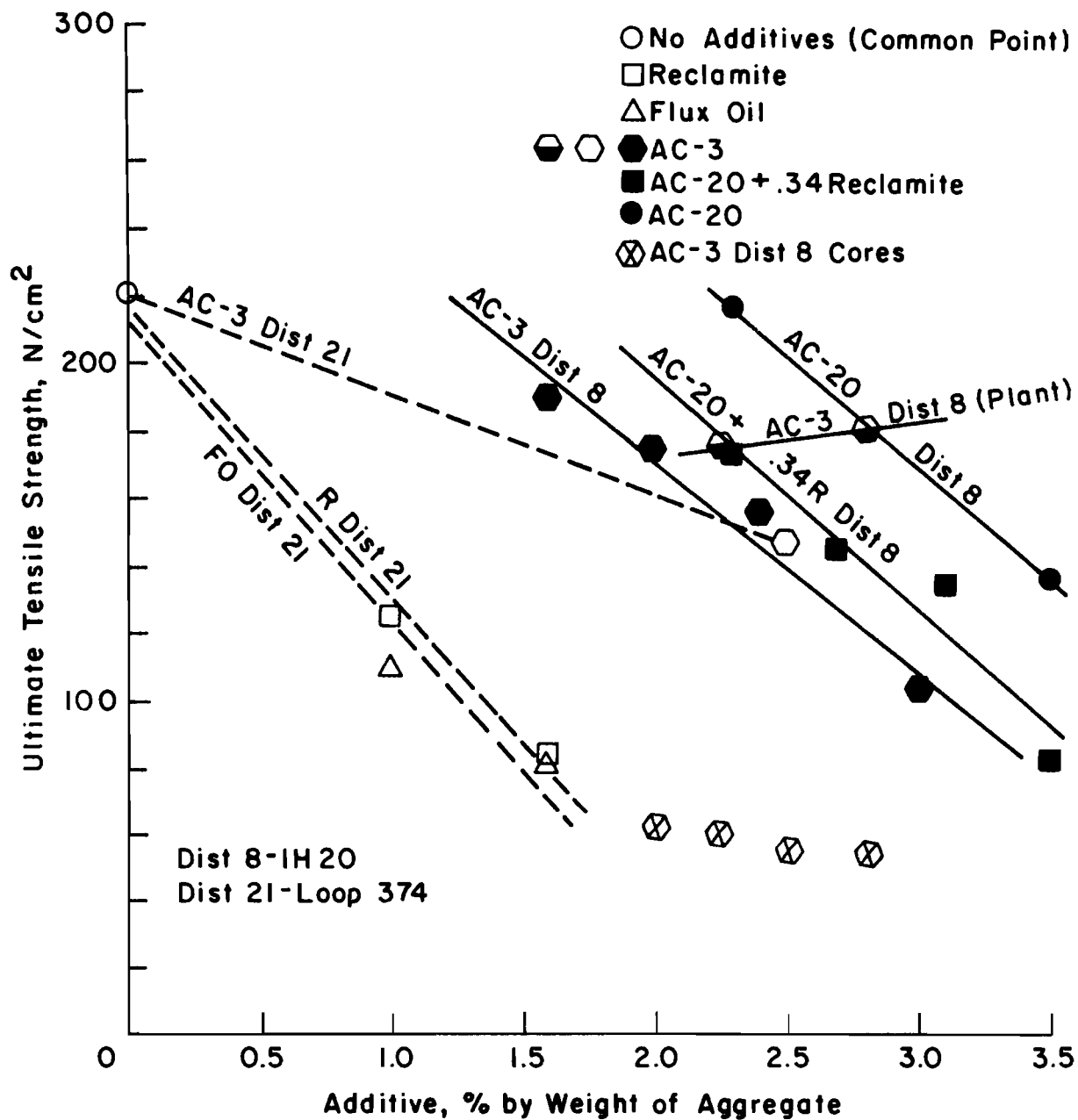


Fig 39. Effects of the amount of additive on tensile strength of laboratory and field recycled asphalt mixtures (Ref 10).

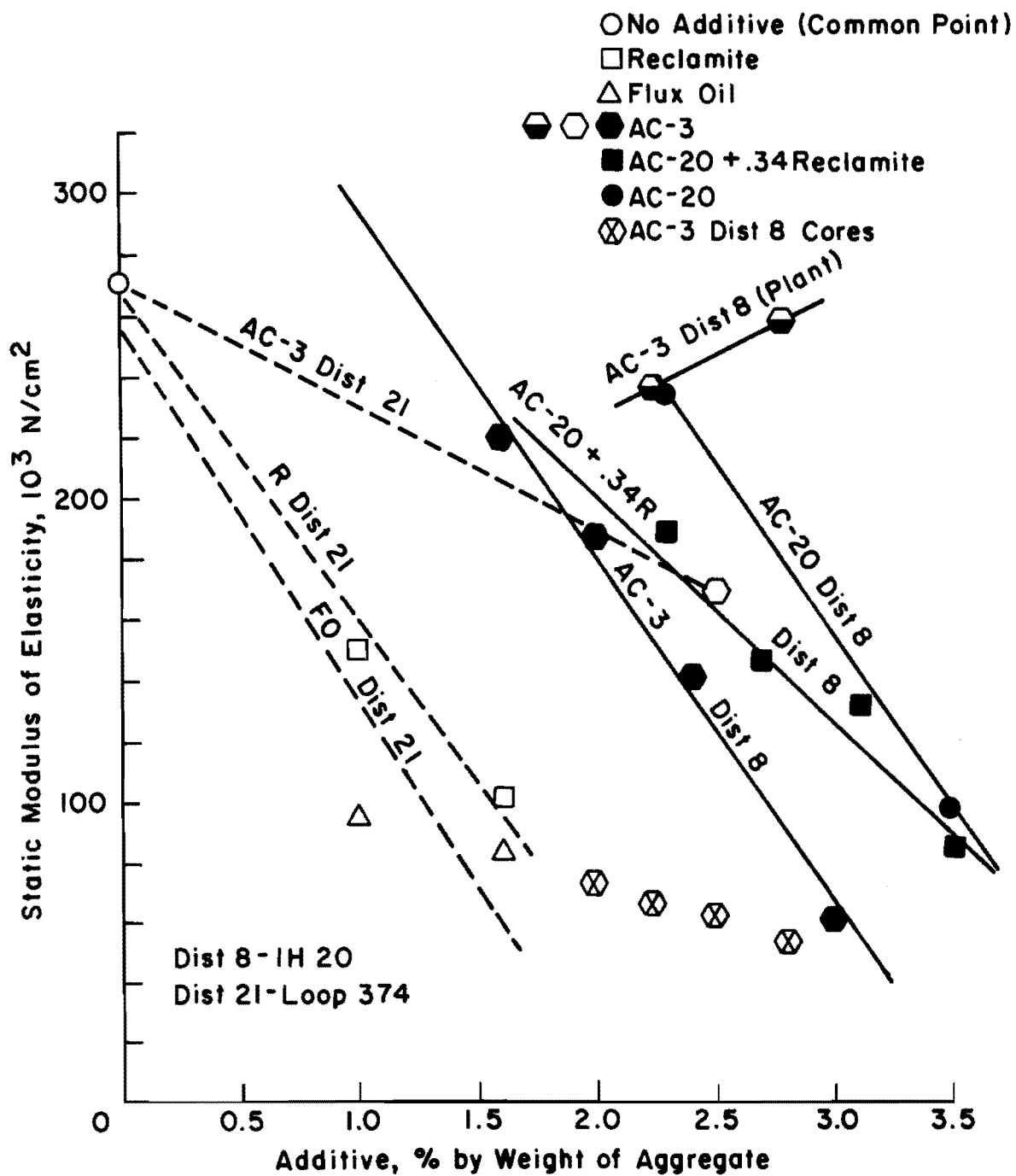


Fig 40. Effects of the amount of additive on static modulus of elasticity of laboratory and field recycled asphalt mixtures (Ref 10).

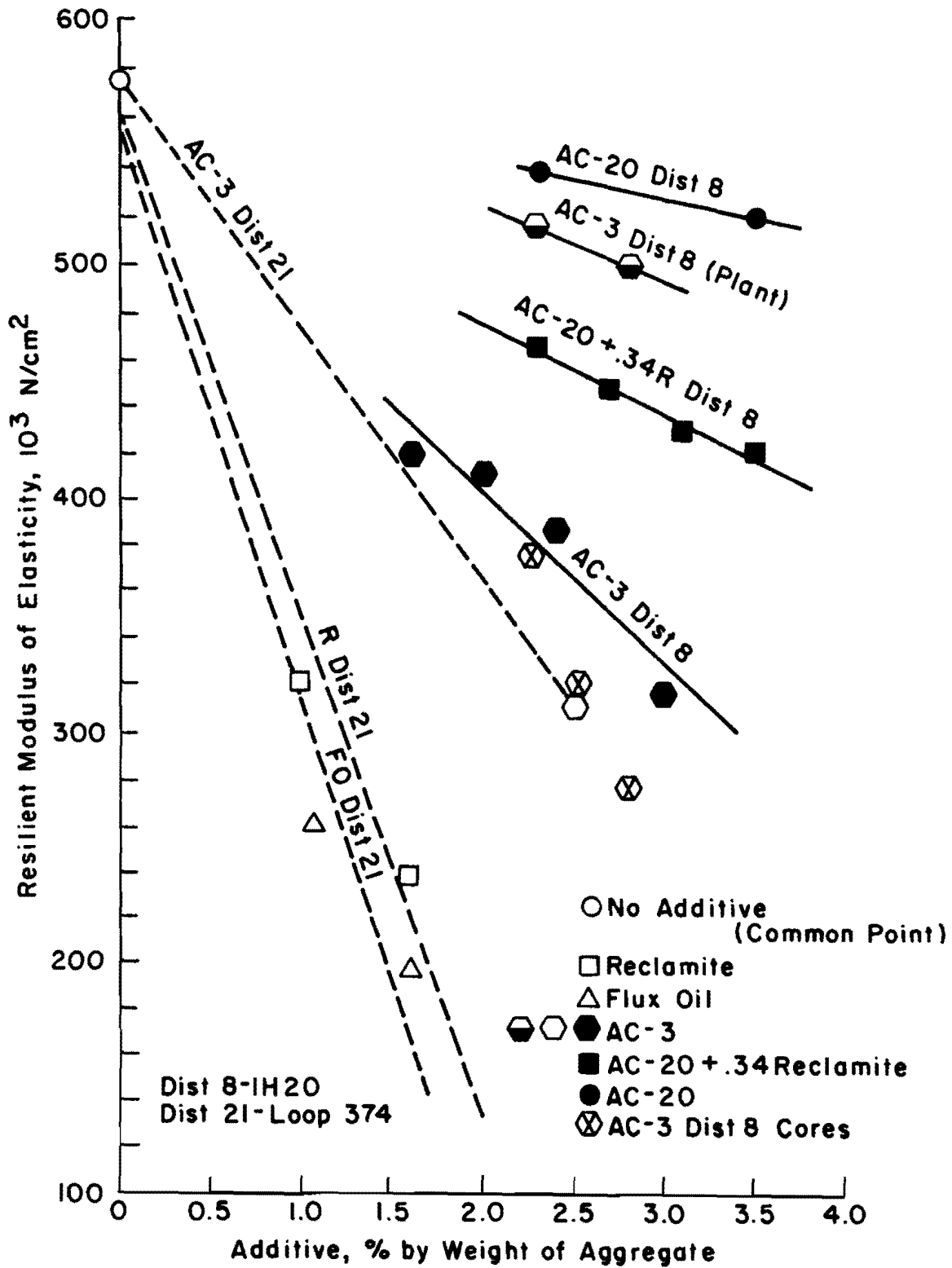


Fig 41. Effects of the amount of additive on resilient modulus of elasticity of laboratory and field recycled asphalt mixtures (Ref 10).

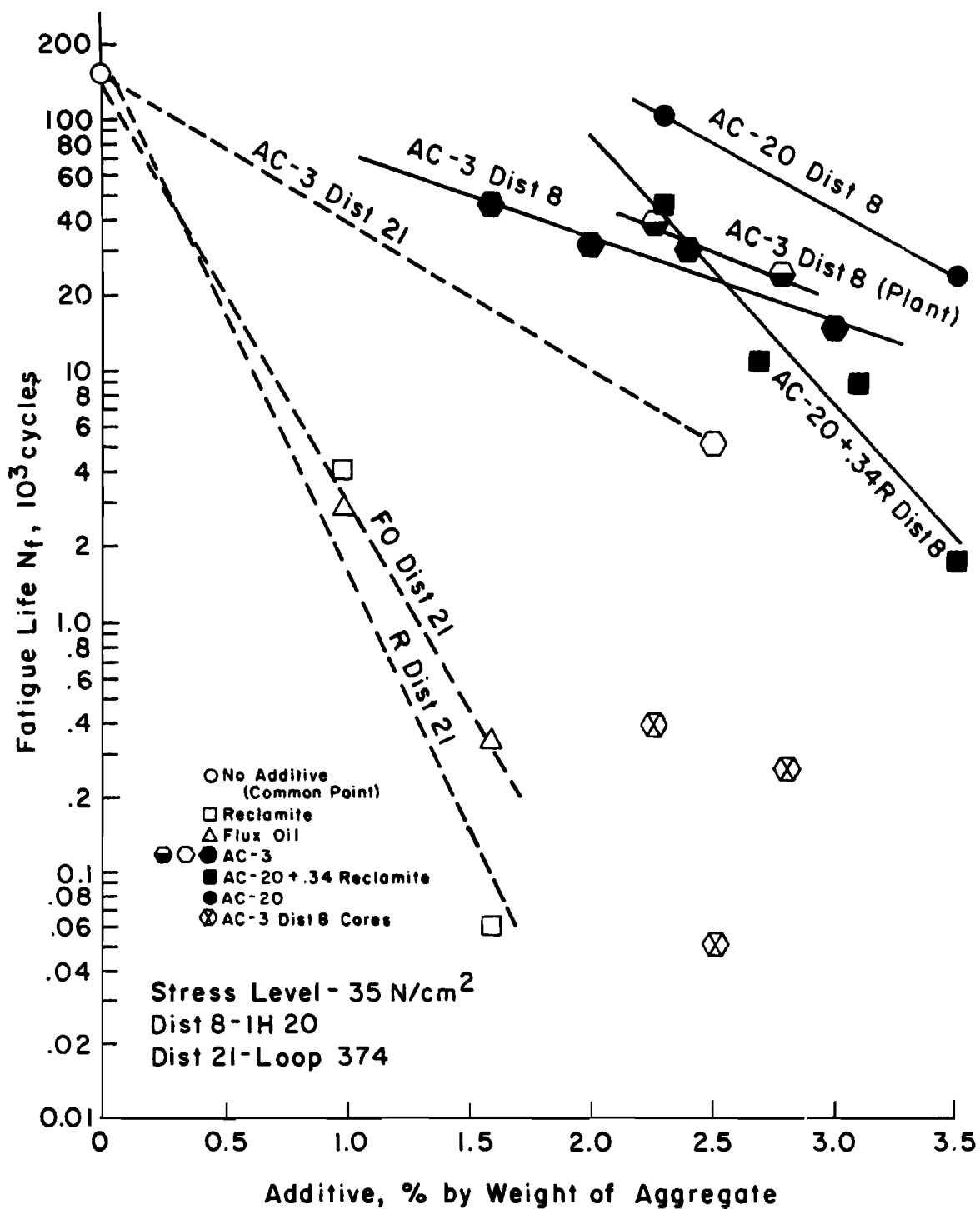


Fig 42. Effects of the amount of additive on fatigue life of laboratory and field recycled asphalt mixtures (Ref 10).

Preliminary Design. The primary objective of this preliminary procedure is to select the types and amounts of additives which can be used to recondition the asphalt in the mixture being recycled and involves the selection of an additive which will soften the existing asphalt. A variety of materials are available, such as a soft asphalt, flux oil, commercially available softening agents, and combinations of these materials. The primary criterion is to reduce the viscosity or increase the penetration of the asphalt until it reaches an acceptable or specific range. Suggested steps for this evaluation are summarized as follows:

- (1) Extract and recover asphalt from a sample of the mixture to be recycled (Tex-211-F).
- (2) Mix the extracted asphalt with the selected types and amounts of additives.
- (3) Measure the viscosity (Tex-513-C, Tex-528-C) and/or penetration (Tex-502-C) of each sample of the treated asphalt.
- (4) Develop curves describing the relationships between the amount of additive and the viscosity and/or penetration over the range of each additive.
- (5) Select those combinations which will produce a binder of the desired consistency, i.e., penetration and/or viscosity.
- (6) Select those combinations which warrant further evaluation. This selection can be based on cost, availability, construction considerations, past reliability and experience, etc.

Final Design. The materials selected in the preliminary design should be evaluated further in order to select the final type and amount of additive and to determine whether the resulting engineering properties are acceptable. The following steps are suggested:

- (1) Prepare duplicate specimens of mixtures containing various percentages of the selected additives in the approximate range determined in the preliminary design and compatible with variations in field application procedures.
- (2) Test according to the Standard Tests used by the Texas State Department of Highways and Public Transportation:
 - (a) for blackbase - Tex-126-E, unconfined compression; and
 - (b) for asphalt concrete - Tex-208-F, stabilometer.

Other agencies should test using their standard tests.

- (3) Compare the results with those required in the specifications for conventional mixtures. For the Standard Tests used by the Texas State Department of Highways and Public Transportation, these values are
 - (a) for blackbase - Test Method Tex-126-E: for the best base material, the unconfined compressive strength should not be less than 50 psi at a slow loading rate and 100 psi at a fast loading rate; for the poorest acceptable base material, the unconfined compressive strength should not be less than 30 psi at a slow loading rate and 100 psi at a fast loading rate.
 - (b) for asphalt concrete - Test Method Tex-208-F: the stability value should not be less than 35 percent at 97 percent density.
- (4) Test using the static and repeated-load indirect tensile tests. Tentative test procedures for the static and repeated-load tests are contained in Reference 14. Tentative test procedures for the repeated-load indirect tensile test are being developed.
- (5) Compare the indirect tensile test results with those obtained for conventional mixtures. Properties to be considered are
 - (a) tensile strength,
 - (b) static modulus of elasticity,
 - (c) fatigue life, and
 - (d) resilient modulus of elasticity.

The relationships between the above properties and the amount of additive should be developed as shown in Figures 38 through 41. The resulting values should then be compared to desired values for which there is a limited amount of information. Most specifications specify minimum values of strength, etc. For recycled asphalt mixtures, values normally need to be reduced below some maximum since the asphalt is extremely stiff and brittle.

- (6) Evaluate the workability of the mixture by visual inspection and make necessary adjustments.

BLACKBASE DESIGN EVALUATION (Research Report 183-11)

The basic approach used to evaluate the Texas method of blackbase mixture design was to compare the various engineering properties for a range of asphalt contents with the engineering properties at the AVR design optimum asphalt content.

Design Asphalt Contents

A laboratory design asphalt content, or an air voids ratio (AVR) design optimum, was determined for each material from the relationship between asphalt content and total air voids. Total air voids were calculated using the in-mold AVR density and zero air void density as described in Chapter 2. The AVR design optimum asphalt content was chosen slightly greater than the asphalt content corresponding to the inflection point on the straight line section of the AVR curve (Fig 43). The AVR design optimums were 4.5, 7.3, and 7.5 for the gravel, limestone, and sand mixtures which differed from the field values actually used by the state.

Density

An analysis of the relationships between density and asphalt content for the three mixtures the AVR densities were generally greater than the densities obtained for specimens cut from the top and bottom of the compacted specimen. This can be explained by the fact that the AVR densities were determined while the specimens were still in the mold and subjected to a compressive stress of 500 psi while the densities for the top and bottom specimens were determined after the large compacted specimens had been removed from the mold and sawed, which allowed some expansion of the specimen.

Unconfined Compression Tests

Unconfined compression tests were performed on specimens at or near the AVR optimum asphalt content for both the fast and the slow rates of deformation in order to determine whether the mixture satisfied the unconfined compressive strength requirements of Test Method Tex-126-E. The

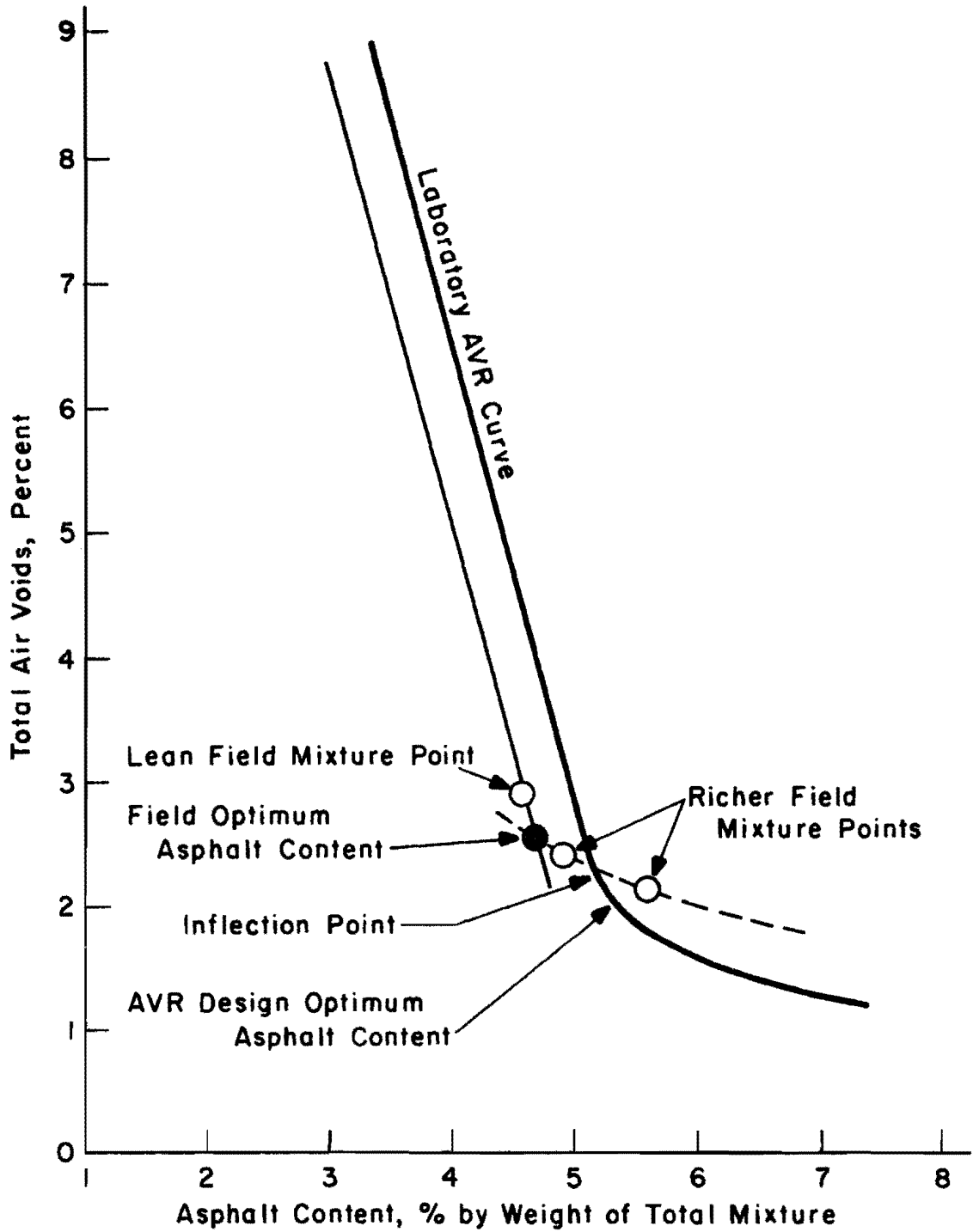


Fig 43. Relationship between asphalt content and total air voids (Ref 37).

unconfined compressive strengths of the three mixtures did not satisfy strength specifications.

The strengths for the gravel mixture were far below the minimum strength requirements for the poorest grade of blackbase (Grade 3) at both the fast and the slow speeds.

The limestone mixture exceeded the strength requirements at the slow speed but failed to meet the strength requirements for the poorest grade of blackbase at the fast loading rate. In addition, the pressure pycnometer, which was used to saturate the specimens, produced severe damage to the specimens containing sand.

In conclusion, according to Test Method Tex-126-E all mixtures failed to satisfy minimum unconfined compressive strength standards. Nevertheless, according to district personnel of the Department of Highways and Transportation all mixtures have provided satisfactory pavement performance.

Static Indirect Tensile Test Results

Two engineering properties, tensile strength and static modulus of elasticity, were estimated using the static indirect tensile test.

Tensile Strength. For the range of temperatures studied, the optimum asphalt content for ultimate tensile strength was found to increase slightly with a decrease in temperature for all three mixtures, which agrees with previous findings.

The optimum asphalt contents for maximum tensile strength for all mixtures and temperatures were less than the optimum AVR design asphalt content by as much as 0.2 to 2.5 percentage points, depending on the material and temperature. The maximum tensile strength for the gravel mixture ranged from about zero to 25 percent greater than the tensile strength at the laboratory AVR optimum; for the limestone mixture the maximum tensile strength ranged from about zero to 50 percent greater than the value at the AVR design optimum; and for the sand mixture, depending on the temperature, the estimated maximum tensile strength was from 100 to 200 percent greater than the estimated values at the AVR design optimum of 7.5 percent.

Static Modulus of Elasticity. The optimum asphalt contents for maximum static moduli of elasticity for all mixtures and temperatures were less than the AVR design optimum asphalt contents by as much as 0.1 to 2.7 percentage points, depending on the mixture and temperature. The optimums for static moduli of elasticity for the gravel and limestone mixtures were from 0.1 to 1.1 percentage points less than the laboratory AVR design optimum. For the sand mixture alone the optimums were from 1.5 to 2.7 percentage points less than the AVR design optimum.

As a result of these differences, the maximum static modulus of elasticity for the gravel mixture ranged from about 15 to 125 percent greater than the value at the AVR optimum. For the limestone mixture, the value of maximum static modulus of elasticity did not exceed the value at the AVR optimum by more than about 25 percent. Although the static modulus of elasticity was not obtained at the AVR optimum for the sand mixture, it appeared that the maximum values of static modulus of elasticity are probably significantly greater than the values of the AVR optimum, depending on the temperature.

Repeated-Load Indirect Tensile Test Results

Repeated-load indirect tensile tests were conducted to evaluate the fatigue life, resilient modulus of elasticity, and resistance to permanent deformation of the materials being studied.

Fatigue Life. An optimum asphalt content for maximum fatigue life was found for all three mixtures and all test conditions studied, which is consistent with previous findings.

Depending on the temperature, the optimum asphalt content for maximum fatigue life of the gravel ranged from 0.1 percentage point more to 0.5 percentage point less than the AVR design optimum. For the limestone mixture the optimum asphalt content was 7.5 percent, regardless of temperature, which was approximately 0.2 percentage point greater than the AVR design optimum. However, for the sand mixture the optimum ranged from 1.0 to 2.0 percentage points less than the AVR design optimum. Thus, the optimum asphalt content for maximum fatigue life tended to be less than the AVR design optimum asphalt content for the sand mixture.

Because of these differences, the maximum fatigue life for the gravel mixture was as much as 60 percent greater than the fatigue life at the AVR optimum, depending on the temperature. For the limestone mixture, the values of maximum fatigue life were 15 to 200 percent greater than the fatigue life at the AVR design optimum, with the larger differences occurring at the lower temperatures. For the sand mixture, it was estimated that the maximum fatigue life could be anywhere from 150 to 1000 percent greater than the value at the AVR design optimum.

Resilient Modulus of Elasticity. While an optimum asphalt content for maximum resilient modulus of elasticity was evident for most of the mixtures studied, the actual value was not well defined, indicating that with this range asphalt content did not have a significant effect on resilient modulus. This agrees with the findings of other investigators.

There was little or no difference between the maximum value and the value at the AVR optimum in most cases, because the relationship between asphalt content and resilient modulus of elasticity generally tended to be poorly defined or flat except at low temperatures. Therefore, it was felt that asphalt content, within the range of typical design values, had little effect on resilient modulus of elasticity.

Permanent Deformation. The analysis of permanent deformation was limited since normalization of the applied stress was different for the various mixtures and test conditions. Since the relationship between permanent deformation and applied stress is not well established, it was not possible to obtain permanent deformation information for the same stress conditions. Therefore, the analysis primarily involved comparing the optimum asphalt contents for maximum resistance to permanent deformation to the AVR design optimum asphalt content. The parameter used to analyze permanent deformation was the permanent vertical deformation per cycle.

For the gravel mixture the optimum asphalt content for maximum resistance to permanent deformation ranged from 4.0 to 4.5 percent; for the limestone mixture the range was from 7.1 to 7.4 percent; and for the sand mixture the range was from 5.3 to 6.5 percent.

The optimum asphalt contents for maximum resistance to permanent deformations were from 0.1 percentage point greater to 2.2 percentage

points less than the AVR design optimum. The optimums for the gravel and limestone mixtures ranged from zero to 0.5 percentage point less than the AVR design optimum. For the sand mixture alone, the optimums were from 1.0 to 2.2 percentage points less than the AVR design optimum. Thus, the maximum resistance to permanent deformation usually occurred at asphalt contents below the AVR design optimum. For the gravel and sand mixtures the rate of increase in permanent deformations was larger on the wet side of the optimum asphalt content than on the dry side.

Comparison of Optimum Asphalt Contents

Test results indicated that optimum asphalt contents existed for various engineering properties, i.e., indirect tensile strength, static modulus of elasticity, fatigue life, minimum permanent deformation, and, to a certain extent, resilient modulus of elasticity. These optimums were different, however, and in addition were not the same as the AVR design optimum or the optimum for in-mold AVR density.

The relationships between optimum asphalt contents and test temperature for these properties are shown in Figures 44, 45, and 46. For comparison, the laboratory AVR design asphalt content and the optimum asphalt content for maximum in-mold AVR density are also shown.

From the preceding discussion and from Figures 44, 45, and 46, it may be concluded that the optimum asphalt content for static and repeated-load properties is generally less than the optimum asphalt content obtained by using Test Method Tex-126-E. These test results indicate that for the engineering properties discussed herein, optimum performance for various properties would be found generally at asphalt contents less than the design optimum asphalt content, depending upon the property under consideration and the aggregate.

The effect of moisture at these lower asphalt contents was not considered in this investigation but may have a significant effect on the performance of an asphalt mixture with reduced asphalt contents. Consequently, a study evaluating the effects of moisture at these asphalt contents should be undertaken before making a judgment on the field performance of these materials at lower asphalt contents than the design optimum asphalt content.

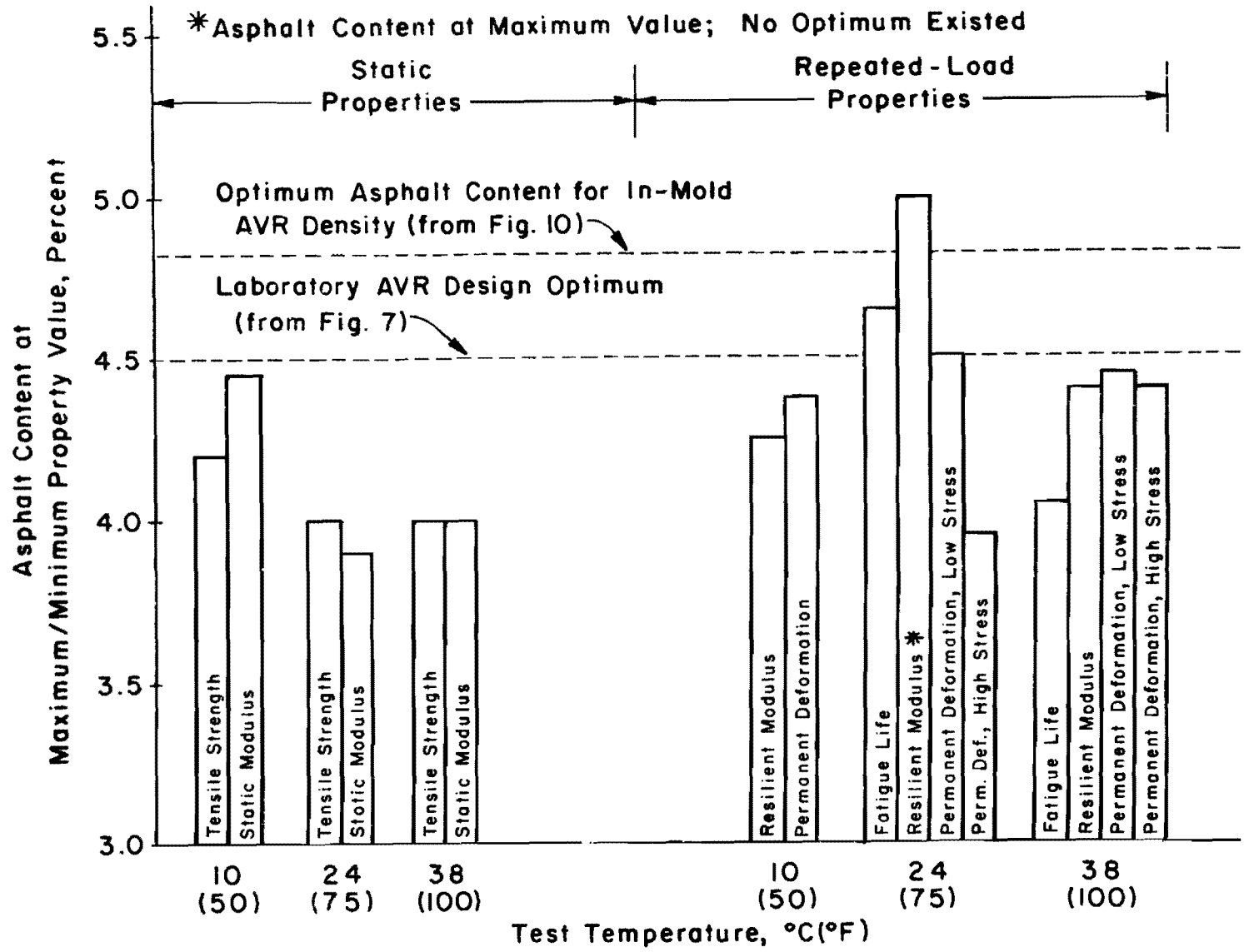


Fig 44. Relationship between testing temperature and the optimum asphalt contents for engineering properties of gravel asphalt mixtures (Ref 11).

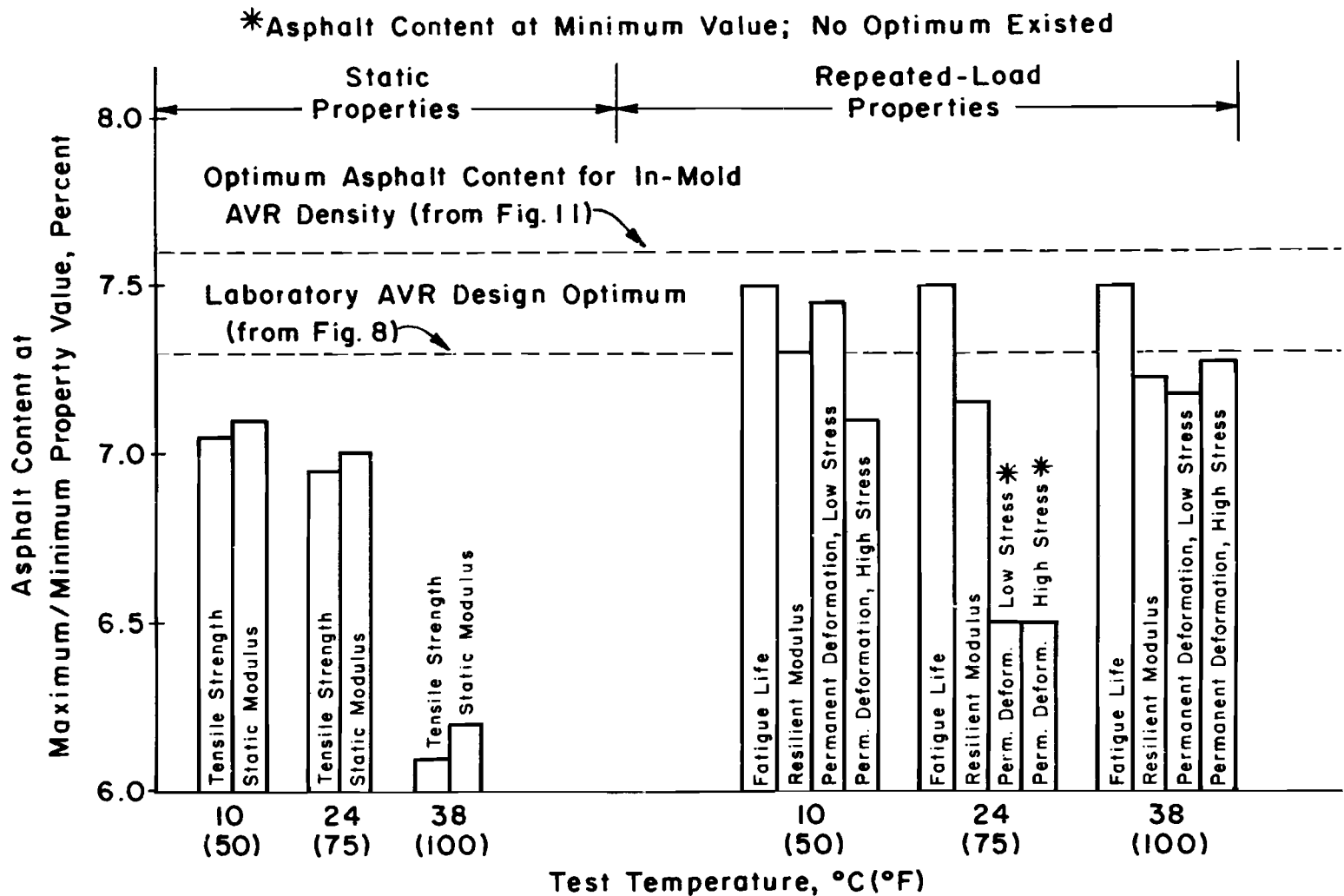


Fig 45. Relationship between testing temperature and optimum asphalt contents for engineering properties of limestone asphalt mixtures.

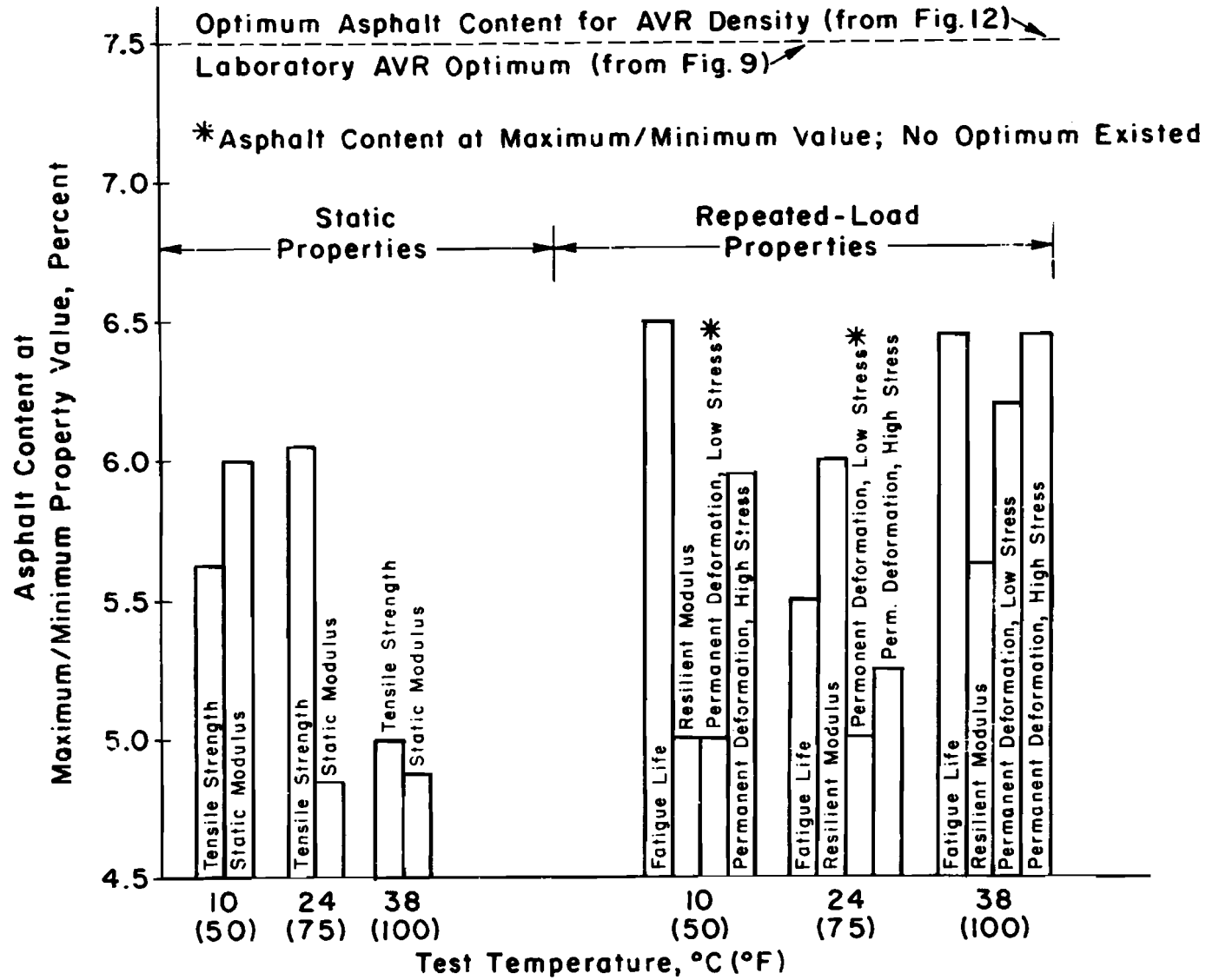


Fig 46. Relationship between testing temperature and optimum asphalt contents for engineering properties of sand asphalt mixtures (Ref 11).

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Because of the complexity of the study, only the major conclusions and recommendations are contained in this report. The reader is referred to the individual interim reports for more detail.

CONCLUSIONS AND FINDINGS

The major findings and conclusions are summarized below.

Indirect Tensile Testing (Reports 183-3, 183-4, 183-7, and 183-14)

1. The static and repeated-load indirect tensile tests can be used to obtain estimates of the tensile and elastic characteristics and the properties related to pavement distress for asphalt mixtures as well as other basic paving materials.
2. Properties which can be estimated are
 - Tensile strength,
 - Static modulus of elasticity,
 - Static Poisson's ratio,
 - Resilient modulus of elasticity,
 - Resilient Poisson's ratio,
 - Fatigue life and characteristics,
 - Permanent deformation characteristics, and
 - Strains.
3. Values of the various engineering properties obtained using the indirect tensile test are compatible with values obtained using other test methods.
4. The repeated-load indirect tensile test provides fatigue results which are comparable to other commonly used test methods when the results are expressed in terms of stress difference (Eq 2.2) or initial strain (Eq 2.3).
5. Miner's hypothesis was valid for the asphalt mixtures tested.

6. Fatigue service life, the number of load applications at which it is assumed that irreversible damage has occurred in the form of cracking, was equal to 75 to 85 percent of fatigue life.
7. The static indirect tensile test
 - a. is easy, rapid, and inexpensive to conduct,
 - b. does not require expensive instrumentation and equipment,
 - c. provides strength and elastic properties with little variation due to testing,
 - d. has a well developed theory,
 - e. has become accepted nationally,
 - f. can be used for quality control, and
 - g. involves cylindrical specimens.
8. The repeated-load indirect tensile test is more difficult to conduct than the static test but is still easier and faster to conduct than most repeated-load tests.
9. Resilient modulus of elasticity can be easily obtained and an ASTM procedure (ASTM D 4013-81) has been developed.

Tensile and Repeated-Load Properties of Inservice Materials

10. The engineering properties of inservice materials vary in accordance with a normal distribution.
11. The magnitude of the variation associated with the various estimated properties depended on the material and the property estimated. Relatively small variations were found for portland cement concrete, moderate variations were associated with blackbase and asphalt concrete, and large variations were found to exist for cement-treated materials. Variations were small for pavement thickness and density, moderate for tensile strength, and relatively large for modulus and fatigue life.
12. The coefficients of variation, which is the standard deviation divided by the mean, for the various properties were

density	< 3%
pavement thickness	< 3%

portland cement concrete

tensile strength (uncapped specimens)	≈ 20%
tensile strength (capped specimens)	8 - 16%
static modulus of elasticity	22 - 42%
resilient modulus of elasticity (capped specimens)	7 ± 54%

blackbase and asphalt concrete

tensile strength	14 - 27%
static modulus of elasticity	24 - 59%
static Poisson's ratio	27 - 67%
logarithm fatigue life	26 to 84%
resilient modulus of elasticity	4 to 28%
resilient Poisson's ratio	18 to 57%

cement-treated base

tensile strength	23 to 49%
static modulus of elasticity	57 to 83%

13. A great deal of the variation can be attributed to testing error. As the complexity of the measurements tended to increase the amount of variation increased.
14. The range of engineering properties for inservice materials tested at 75°F was

portland cement concrete

tensile strength (uncapped specimens)	400 - 560 psi
tensile strength (capped specimens)	520 - 710 psi
static modulus of elasticity uncapped specimens)	3.4 - 5.0 x 10 ⁶ psi
resilient modulus of elasticity (capped)	2.4 - 4.1 x 10 ⁶ psi

blackbase and asphalt concrete

tensile strength	77 - 157 psi
static modulus of elasticity	39 to 92 x 10 ³ psi
static Poisson's ratio	0.16 - 0.40
resilient modulus of elasticity	220 - 615 x 10 ³ psi
resilient Poisson's ratio	.10 - 0.22

cement-treated base

tensile strength	83 - 120 psi
static modulus of elasticity	0.6 to 1.05 x 10 ⁶ psi

Engineering Properties of Asphalt Mixtures

15. Optimum asphalt contents exist for maximum tensile strength, static and resilient modulus, and fatigue life and for minimum permanent deformation.
16. The optimum asphalt contents for the various engineering properties were different and were not necessarily the same as the optimum for maximum density or the design asphalt content.
17. A linear relationship existed between the logarithm of fatigue life and the logarithm of
 - a. tensile stress,
 - b. stress difference, and
 - c. initial strain.
18. The fatigue constants for asphalt mixtures ranged as follows:

K_1	$5.65 \times 10^{17} - 5.01 \times 10^{-7}$
n_1	2.66 - 5.19
K_2	$3.26 \times 10^5 - 1.90 \times 10^{13}$
n_2	2.66 - 5.19
K_2'	1.41×10^7 and 2.53×10^{16}
19. Linear relationships existed between n_1 and the logarithm of K_1 and between n_2 and the logarithm of K_2 or K_2' .
20. Both instantaneous and total resilient tensile strains exhibited a slight linear increase with an increase in the number of repeated stresses up to about 70 percent of the fracture life, at which point a more rapid increase occurred for additional stress repetitions, until complete fracture occurred.
21. The relationship between permanent horizontal and vertical strains, and number of stress applications, could be divided roughly into 3 zones:

- (a) a conditioning zone, represented by the first 10 percent of the fracture life in which a rapid increase in strain occurred;
 - (b) a relatively stable zone, lying between about 10 and 70 percent of the fracture life, in which there was a gradual and linear increase of strain with additional repeated stresses; and
 - (c) a failure zone, represented by the last 30 percent of fracture life in which there was a rapid increase in strain with additional stress applications.
22. The relationships between instantaneous resilient modulus, total resilient modulus, or modulus of individual total deformation, and the number of stress applications, could also be divided into three zones. During the first 10 percent of the fracture life, the shape of the relationship was uncertain due to initial adjustment to load and possible additional compaction. However, between about 10 and 80 percent, the moduli decreased linearly with increasing stress applications. Beyond about 80 percent the moduli decreased very sharply until complete fracture.
23. The rate of deterioration or decay of total resilient modulus with stress applications, evaluated in terms of the slope of the approximately linear portion, ranged between 5 and 990 psi/cycle. For instantaneous resilient modulus the slopes ranged between 7 and 3,000 psi/cycle. For both instantaneous and total resilient moduli, the rate of moduli decay increased with increasing stress level and increasing testing temperature, and there was an optimum asphalt content for minimum rate of decay, which corresponded to the optimum for fatigue life.
24. The relationship between modulus of cumulative total deformation and number of stress applications indicated an initial rapid drop in modulus, followed by a prolonged period of gradual decrease, and a final sharp drop in the failure zone.
25. Average values of modulus of cumulative total deformation were generally low, ranging from 1,200 to 76,600 psi. These values

increased with decreasing asphalt content, increasing stress level, and decreasing testing temperature.

26. Average values of instantaneous and total resilient moduli were higher than average values of static modulus of elasticity and modulus of cumulative total deformation.
27. The ratio of the instantaneous resilient and static moduli of elasticity ranged from 10.5 to 2.3, with the higher values associated with materials with low static moduli.

Recycled Asphalt Mixtures (Report 183-8)

28. The engineering properties of the dryer-drum mixtures evaluated in this study generally were equal to those of previously evaluated inservice and laboratory-prepared mixtures.
29. Based on the findings of this study and the experience and findings of others, it is felt that satisfactory mixtures can be produced with the dryer-drum. The only question relates to the effect of moisture and it would appear from previous experience that moisture produces little if any adverse effect.

Effect of Soil Binder and Moisture in Blackbase (Reports 183-12 and 183-13)

30. Optimum soil binder contents for two aggregate types were found to occur between 5 and 10 percent by weight. These optimums produced maximum density, tensile strength and fatigue life and minimum permanent deformation.
31. Optimum asphalt contents generally increased with increased binder contents above the optimum binder contents.
32. Moisture damage appeared to be directly related to the total air voids in the asphalt mixture which were minimum at the optimum binder contents. Thus, moisture damage was minimum at the optimum binder content.
33. Values of TSR* appeared to be maximum at the optimum binder content and optimum asphalt content.
34. Values of TSR* decreased with increased air void contents and moisture contents.

*TSR--ratio of dry and wet tensile strengths.

Design of Blackbase Materials (Report 183-11)

35. Based on the findings of the study and information supplied by the SDHPT, Test Method 126-E did not consistently predict the pavement performance of the asphalt mixtures.
36. The AVR design optimum asphalt contents generally were higher than the optimum asphalt contents for the engineering material properties of tensile strength, static modulus of elasticity, resilient modulus, fatigue life, and permanent deformation characteristics as measured using the static and repeated-load indirect tensile test.
37. Optimum asphalt contents were found to occur for the following material properties:
 - (a) tensile strength,
 - (b) static modulus of elasticity,
 - (c) fatigue life, and
 - (d) permanent deformation.

Well defined optimums did not consistently occur for resilient modulus except at low temperatures.

38. Generally, the optimum asphalt contents for static tensile properties were less than the optimums for the repeated-load properties.
 - (a) The optimum for static modulus of elasticity was generally less than the optimum for tensile strength.
 - (b) The optimum for fatigue life was larger than the optimums for the other engineering properties.
 - (c) The optimums for permanent deformation and instantaneous resilient modulus of elasticity were generally less than the optimum for fatigue life and larger than the optimum for static tensile properties.
39. The static and repeated-load indirect tensile tests can be used to evaluate materials for mix design purposes.

Design of Recycled Asphalt Mixtures (Report 183-10)

40. The engineering properties of the recycled mixtures evaluated in this study generally were slightly higher than those of conventional mixtures which have been previously evaluated.
41. It is concluded that satisfactory mixtures can be obtained with recycled mixtures based on the findings of this study and on the experience and findings of others.
42. A preliminary mixture design procedure was developed which will be modified as additional experience is obtained.

Elastic Characteristics of Asphalt Mixtures (Report 183-6)

43. An estimate of resilient modulus can be obtained without conducting a long-term repeated-load test.
44. Reasonable estimates of the modulus could be obtained after about 1.0 percent of the fatigue life.
45. A test specimen should be subjected to a minimum of 25 load applications before estimating the modulus.
46. Definite optimum asphalt contents existed for tensile stress, fatigue life, and static modulus of elasticity. No well defined optimum asphalt content was evident for maximum instantaneous resilient modulus, indicating that resilient modulus was not sensitive to changes in asphalt content. This is consistent with previous findings by the project and other investigators.

RECOMMENDATIONS

1. The State Department of Highways and Public Transportation should begin to use the static indirect tensile test. This test can be conducted in district laboratories.
2. The State Department of Highways and Public Transportation should develop the capability to conduct the repeated-load indirect tensile test and to make load-deformation measurements. Initially the development of this capability should be restricted to the Materials and Tests Division.

3. Static and repeated-load indirect tensile tests should be used in the design of blackbases and asphalt concrete surface courses as a means of determining the design asphalt contents and to evaluate aggregate and aggregate gradation effects. The department will need to establish minimum and/or maximum values for the various engineering properties for the various materials.
4. The information obtained from this project on the properties of inservice pavement materials should be used in the development and application of stochastic pavement design procedures based on elastic theory.
5. The information related to mixture properties should be evaluated in terms of mixture design and performance.
6. Recycled asphalt mixtures should be considered to be a viable alternative for rehabilitation of existing asphalt concrete pavements and overlays and for blackbase.
7. Generally guidelines at 75°F are as follows:

Tensile Strength	100 - 250 psi
Static Modulus of Elasticity	100,000 - 500,000 psi
Resilient Modulus of Elasticity	250,000 - 1,000,000

These moduli were established using a 0.4 sec load duration and probably should be increased for shorter load durations, e.g., 0.1 - 0.2 sec.



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