TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CFHR 3-9-72-183-7		

4. Title and Subtitle	5. Report Date
PERMANENT DEFORMATION CHARACTERISTICS OF ASPHALT MIXTURES BY REPEATED-LOAD INDIRECT TENSILE TEST	June 1976
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Joaquin Vallejo, Thomas W. Kennedy, and Ralph Haas	Research Report 183-7
9. Performing Organization Name and Address	10. Work Unit No.
Center for Highway Research The University of Texas at Austin Austin, Texas 78712	11. Contract or Grant No. Research Study 3-9-72-183
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas State Department of Highways and Public Transportation - Transportation Planning Division P. O. Box 5051 Austin, Texas 78763	Interim
	14. Sponsoring Agency Code

15. Supplementary Notes

Work done in cooperation with the Department of Transportation, Federal Highway Administration.
Research Study Title: "Tensile Characterization of Highway Pavement Materials"

16. Abstract

This report reviews the basic concepts of the permanent deformation structural subsystem, the properties required, and the possible methods required to obtain these properties. Special consideration is given to the permanent deformation parameters given by VESYS IIM.

The results of this study suggest that the repeated-load indirect tensile test can be used to obtain the permanent deformation characteristics or properties required for the structural design and analysis of pavements. It was also found that the permanent deformation behavior obtained using the repeated-load indirect tensile test is similar to that obtained using a triaxial test with an axial tensile stress.

17. Key Words	18. Distribution Statement
repeated-load indirect tensile test, rutting, permanent deformation, VESYS IIM, asphalt concrete	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	84	

Form DOT F 1700.7 (8-69)

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by

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Thomas W. Kennedy
Ralph Haas

Research Report Number 183-7

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
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

June 1976

PREFACE

This is the seventh in a series of reports dealing with the findings of a research project concerned with the tensile characterization of pavement materials for use in mixture and structural design. This report summarizes the results of a preliminary study which compared and evaluated permanent deformation results obtained using the repeated-load indirect tensile test and triaxial tests. This comparison included consideration of the permanent deformation parameters used in VESYS IIM.

Previous work indicated that the indirect tensile test could be used to obtain the elastic properties needed as inputs in elastic layer structural analyses and the properties needed for the thermal and fatigue cracking structural subsystems. The results of this study indicate that the test can also be used for the permanent deformation, or rutting, subsystem.

The study was financed by the State Department of Highways and Public Transportation as a part of the Cooperative Highway Research Program. Special appreciation is extended to Messrs. Avery Smith, Gerald Peck, and James L. Brown of the State Department of Highways and Public Transportation, who provided technical liason for the project, and to Messrs James N. Anagnos and Victor N. Toth for their assistance with the testing program.

Joaquin Vallejo
Thomas W. Kennedy
Ralph Haas

June 1976

LIST OF REPORTS

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 In-Service 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. 183-3, "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. 183-5, "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. 183-6, "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. 183-7, "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.

ABSTRACT

This report reviews the basic concepts of the permanent deformation structural subsystem, the properties required, and the possible methods required to obtain these properties. Special consideration is given to the permanent deformation parameters used by VESYS IIM.

The results of this study suggest that the repeated-load indirect tensile test can be used to obtain the permanent deformation characteristics or properties required for the structural design and analysis of pavements. It was also found that the permanent deformation behavior obtained using the repeated-load indirect tensile test is similar to that obtained using a triaxial test with an axial tensile stress.

KEY WORDS: repeated-load indirect tensile test, rutting, permanent deformation, VESYS IIM, asphalt concrete.

SUMMARY

This report summarizes the findings of a study to compare and evaluate the permanent deformation properties and characteristics obtained using the repeated-load indirect tensile test and triaxial tests. This comparison includes consideration of the permanent deformation parameters used in VESYS IIM.

Laboratory prepared specimens of two asphalt mixtures containing either gravel or limestone aggregates and various percentages of asphalt cement (AC-10) were tested at either 10, 24, or 38° C (50, 75, or 100° F) using the repeated-load indirect tensile test. Permanent and elastic strains were measured and the relationships between permanent strain and the number of load applications were developed. The characteristics of these relationships were then compared with the characteristics obtained using other test methods and with realistic values.

The repeated-load indirect tensile test can be used to estimate the permanent strain characteristics of asphalt materials. Realistic values of the permanent strain properties used in VESYS IIM can be obtained; however, the two properties are dependent on whether the stresses are compressive or tensile and are dependent on which portion of the relationship between permanent strain and number of load applications is used. Predictive equations developed by Haas which successfully predicted rutting at the Brampton Road Test were able to predict the permanent compressive strains obtained using the repeated-load indirect tensile test.

IMPLEMENTATION STATEMENT

This limited study showed that the repeated-load indirect tensile test can be used to evaluate the permanent strain characteristics of asphalt mixtures. This is significant since the test is easier to conduct than other commonly used tests and can be used to evaluate cylindrical specimens and cores. In addition, the repeated-load indirect tensile test also allows the calculation of resilient elastic properties such as the resilient modulus of elasticity and resilient Poisson's ratio. The test also provides information related to fatigue and shrinkage cracking.

It is recommended that the State Department of Highways and Public Transportation begin to use the static and repeated-load indirect tensile test to obtain strength, elastic, fatigue, and permanent strain properties of asphalt materials. In addition, it is recommended that the permanent strain characteristics be considered in pavement and mixture design.

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CHAPTER 1. INTRODUCTION

The ability to characterize pavement materials in terms of fundamental properties is becoming more important. This is partially due to the fact that many agencies are beginning to use pavement design procedures based on elastic or viscoelastic theory. Also important is the fact that previous empirical tests do not provide the information required to evaluate new materials such as recycled pavement mixtures and sulphur-asphalt mixtures.

Fatigue and shrinkage cracking have been studied to a relatively large extent compared to the effort devoted to the study of pavement rutting. Thus, it is desirable to be able to estimate the actual amount of rutting which will occur under a given set of conditions. This requires that the pavement material be characterized in terms of its permanent strain characteristics. A proposed method of obtaining the necessary permanent deformation characteristics of asphalt materials is the repeated-load indirect tensile test. This test has previously been used to characterize pavement materials in terms of tensile strength, elastic properties, and fatigue characteristics. If information on the permanent deformation characteristics can be obtained, all information required for elastic analysis and consideration of the three basic distress modes can be estimated from this one simple test.

The primary objective of this study was to evaluate the potential use of the repeated-load indirect tensile test as a means of determining the permanent deformation characteristics of asphalt materials for use in pavement and mixture design. Chapter 2 summarizes information on pavement rutting: the mechanism concerning the permanent deformation subsystem and materials characterization techniques. The experimental program and the data used to evaluate the repeated-load indirect tensile test are described in Chapter 3. The findings are presented and discussed in Chapter 4. Chapter 5 contains the conclusions and recommendations.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

Elastic and viscoelastic structural analyses of pavements as layered systems are increasingly becoming a part of working design practice. This is largely due to the ease with which such analyses can be done by readily available computer programs and the easy understandability of the results. Moreover, there is growing evidence that the results of these analyses can be directly related to observed field performance.

Examples of operational programs available for elastic layer analysis of flexible pavements include (1) BISTRO and BISAR, developed by Shell Oil Co., (2) CHEVRON, developed by Chevron Co., and (3) FEPAVE II and FEPAVE IV, developed at the University of California, Berkeley. VESYS IIM is a design system developed for the Federal Highway Administration which includes a visco-elastic layer analysis method.

In addition to the use of these computer programs for research purposes, attempts are being made to use them in pavement management and design systems.

The original work which led to the acceptance of the Pavement System Concept was carried out as a part of NCHRP 1-10, conducted by Hudson, McCullough, Finn, et al (Refs 24, 25, and 26). At about the same time, Haas and Hutchinson (Refs 16 and 28) were conducting similar studies in Canada. As a result of this initial work, plus subsequent efforts, a number of working pavement design and management systems have been developed.

While these systems have generally considered pavement behavior on an overall basis, they have recognized that there are three basic modes of distress which need to be checked in design:

(1) thermal or shrinkage cracking,
(2) fatigue cracking from repeated traffic loadings,
(3) rutting, or permanent deformation, from repeated traffic loading.

An extensive amount of work has been done on fatigue cracking, with lesser efforts devoted to shrinkage cracking and permanent deformation.

Closely associated with the development and use of structural subsystems is the need for simple, effective tests for characterizing materials in terms of the fundamental properties required by the various structural subsystems. Most of the models for the various structural subsystems have been developed semi-independently, resulting in the need to conduct a variety of different tests both in the field and in the laboratory. Because field testing is usually time consuming and not always practical, laboratory methods have received considerable emphasis. However, even though a fundamental property is being evaluated, different types of tests can give widely different results. It follows then that the predicted structural response of the pavement can similarly vary widely, depending upon what test results are used. In addition many of these tests are complex, time consuming, and require expensive and sophisticated equipment.

Materials testing technology in the pavement field has been largely built on a comparative basis, using index-type tests. Such index testing is useful for comparison of similar materials but it is often inadequate for comparison of different materials, especially when nonconventional materials are being considered. In addition, index-type tests do not provide the fundamental materials properties needed for structural analysis.

Previous work in this project has demonstrated that the repeated-load and static indirect tensile tests can be used to characterize asphalt materials in terms of their elastic properties and in terms of the properties required for consideration of fatigue and shrinkage, or thermal, cracking. The remainder of this chapter is devoted to a review of permanent deformation concepts and the techniques for characterizing materials.

THE PERMANENT DEFORMATION SUBSYSTEM

Permanent deformation, or rutting, has been found to be one of the more significant structural distress modes and causes of serviceability loss on asphalt pavement structures. The Austin Workshop (Ref 22) and the Third International Conference on Structural Design of Asphalt Pavements (Ref 57) stressed the importance of this distress mode.

Several problems can be caused by excessive permanent deformation in asphalt pavements; i.e., loss of serviceability, loss of safety, high maintenance costs, and user delays. Studies made on rutting in asphalt pavements

(Refs 7, 21, and 43) demonstrated that excessive permanent deformation leads to longitudinal depressions in the wheel paths, followed by longitudinal cracking. Subsequently, water can penetrate and the pavement will deteriorate due to loss of load carrying capacity (Fig 1). Permanent deformation can also reduce safety, especially on high volume highways in which lane changes at high speeds become dangerous and uncomfortable. The lateral forces between tires and pavement are very high and may cause loss of control of the vehicle. Extensive maintenance of this type of road on which traffic is high is costly and may cause user delays.

Morris (Ref 43) listed the following structural, economic, and safety reasons for developing a permanent deformation predictive technique:

(1) Axle loads, tire pressure, and load repetitions on highways and airfields are increasing rapidly.

(2) Multi-wheel landing gears on aircraft are increasing in complexity and size. These assemblies produce higher stresses in the lower, weaker layers of the pavement structure.

(3) Shrinkage cracking can be reduced by using softer asphalts, which increases susceptibility to permanent deformation during the hot summer periods.

(4) A means of predicting permanent deformation-time relationships is required to make an economic evaluation of the system.

(5) Excessive permanent deformation decreases driving comfort and can lead to icing or hydroplaning when water collects in the wheel paths.

Permanent Deformation Mechanisms

During the AASHO Road Test (Ref 21), special trenching studies were performed in order to investigate the rutting phenomenon. Based upon these studies, three basic conclusions concerning permanent deformations were made:

(1) Permanent deformation occurs in all layers of the pavement system.

(2) Permanent deformation is primarily a result of lateral distortion of the pavement materials, rather than densification.

(3) The deformation consists of a continuous accumulation of incrementally small movements from each load application.

Figure 2 shows a typical transverse profile at the AASHO Road Test and Table 1 gives the depth and percentage of permanent deformation found in each layer. Average values from 51 sections trenched in 1960 indicate that

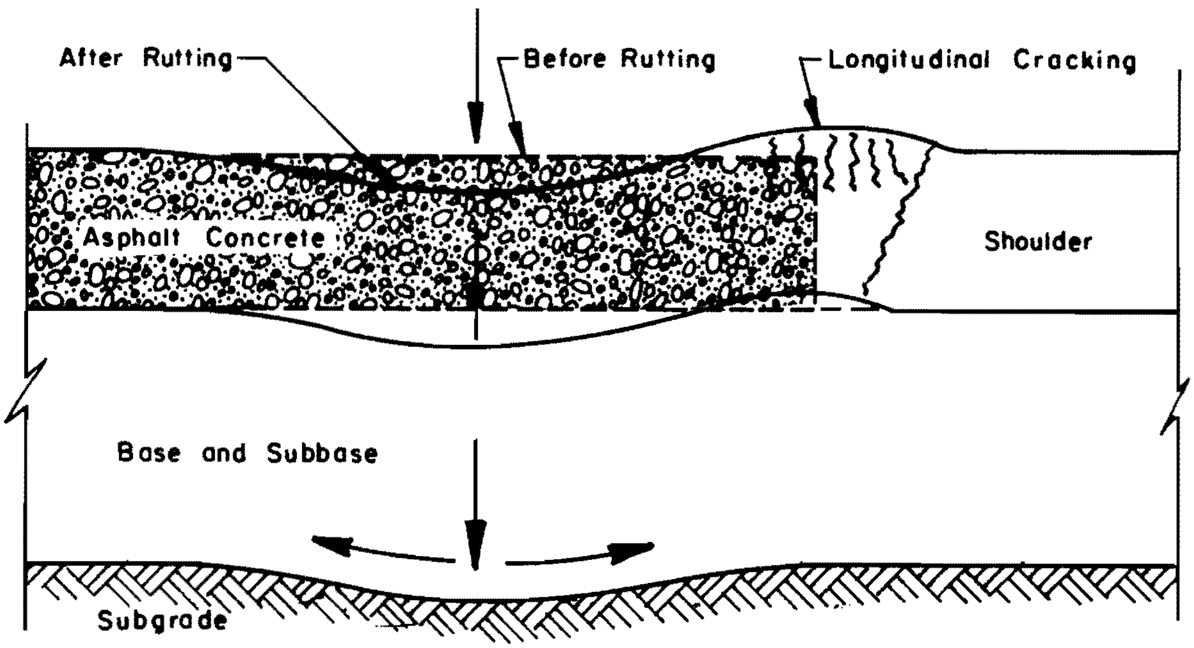


Fig 1. Typical rutting mechanism in outer wheel path at Brampton Test Road (Ref 43).

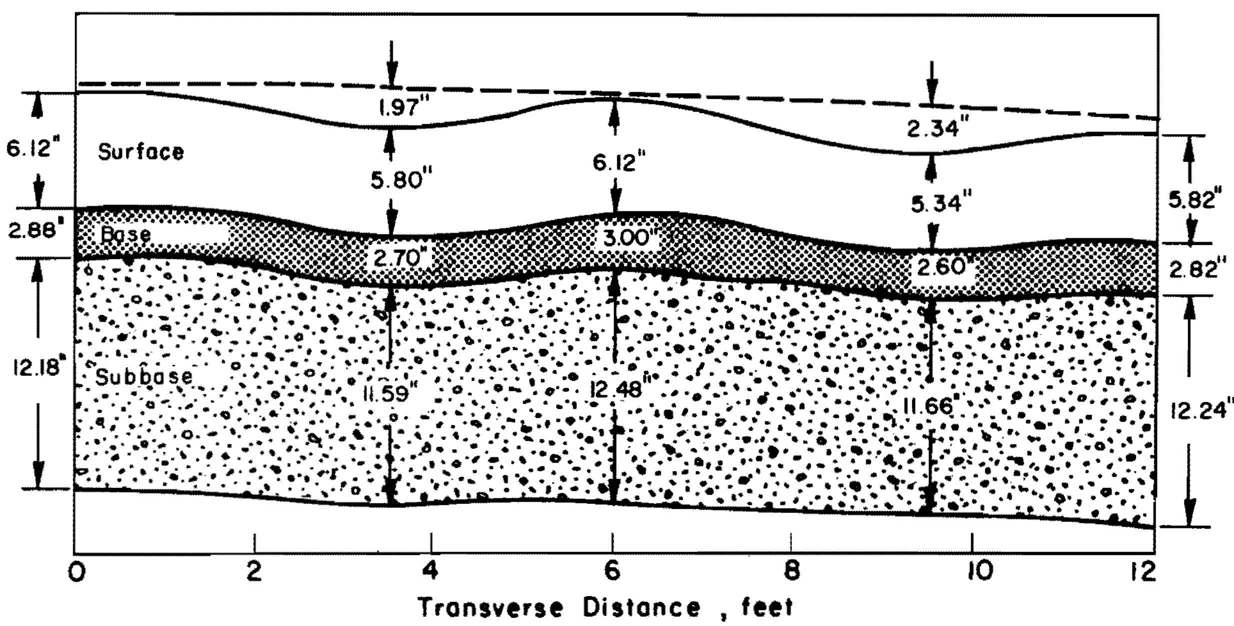


Fig 2. Typical transverse profile from 1959 AASHO trench study (Ref 21).

TABLE 1. RUT DEPTHS AT AASHO ROAD TEST - 1960 (Ref 21)

		Depth of Rut, inches				Rutting, percent			
Loop	Season	Surface	Base	Subbase	Subgrade*	Surface	Base	Subbase	Subgrade
3	Spring	0.20	0.04	0.40	0.06	29	6	57	8
	Summer	0.41	0.18	0.62	0.15	30	13	46	11
	Fall	0.35	0.02	0.53	0.13	34	2	51	13
4	Spring	0.33	0.06	0.81	0.03	27	5	66	2
	Summer	0.50	0.12	0.41	0.02	48	11	39	2
	Fall	0.40	0.10	0.15	0.15	50	12	19	19
5	Spring	0.49	0.01	0.71	0.12	37	1	53	9
	Summer	0.46	0.26	0.59	0.13	32	18	41	9
	Fall	0.39	0.12	0.61	0.20	30	9	46	15
6	Spring	0.05	0.33	0.45	0.15	5	34	46	15
	Summer	0.41	0.34	0.63	0.10	28	23	43	7
	Fall	0.44	0.38	0.44	0.13	32	27	32	9
				Grand Average		32	14	45	9

*Estimated from charts.

1 in. = 2.54 cm

TABLE 2. LAYER THICKNESS CHANGES DUE TO DENSIFICATION IN WHEEL PATHS OF AASHO ROAD TEST - 1960 (Ref 21)

	Change in Thickness Due to Densification, percent			
Material	Spring 1960	Summer 1960	Fall 1960	Average 1960
A/C Surfacing	18	18	24	20
Base	100	30	Not measured	—
Subbase	3	4	Not measured	4

32 percent of the total deformation occurred in the surface layer, 14 percent in the base, 45 percent in the subbase, and 9 percent in the subgrade.

Table 2 shows the effect of densification on total permanent deformation. It can be seen that densification was not the principal cause of permanent deformation at the AASHO Road Test. Goetz et al (Ref 14) studied asphalt concrete overlays in Indiana and found that permanent deformation failures were caused by progressive plastic flow of the material. Two cores from a badly deformed pavement were taken, the shorter, on the left hand side, was cored within the wheel path, and the other was taken between wheel paths (Fig 3). The rut depth is represented by the differences in height. Since the densities of the cores were essentially the same, this would indicate that the permanent deformation was in this case due to lateral distortion and not to densification. It has also been observed that the change in density of an asphalt concrete surface is relatively constant over the full width of the pavement irrespective of the amount of compaction (Refs 11 and 46). Thus, it can be concluded that permanent deformation is due primarily to lateral distortion on properly compacted materials even though some small amount of densification occurs over the full width of the pavement.

Morris et al (Ref 43) concluded from a study to evaluate permanent deformation in asphalt concrete pavements (Fig 4) that for all the pavement sections they examined:

(1) the rate and total permanent deformation in the upper compression zone is relatively minor,

(2) permanent deformation is almost entirely due to movements in the tension zone, and

(3) the rate of permanent deformation in the tensile zone increases rapidly with depth.

The findings also indicated that, for the asphalt mixture used in the Brampton Test Road, the total permanent deformation of the asphalt concrete was largely a function of the radial stresses in the tensile zone. It was recommended that the relative susceptibility to permanent deformation should be determined by testing the material in the tension mode.

Considerable caution, of course, has to be used in extending these findings to other areas, other materials, other sections, etc. For example, the findings may not be applicable to thin asphalt sections where the bound layer is in

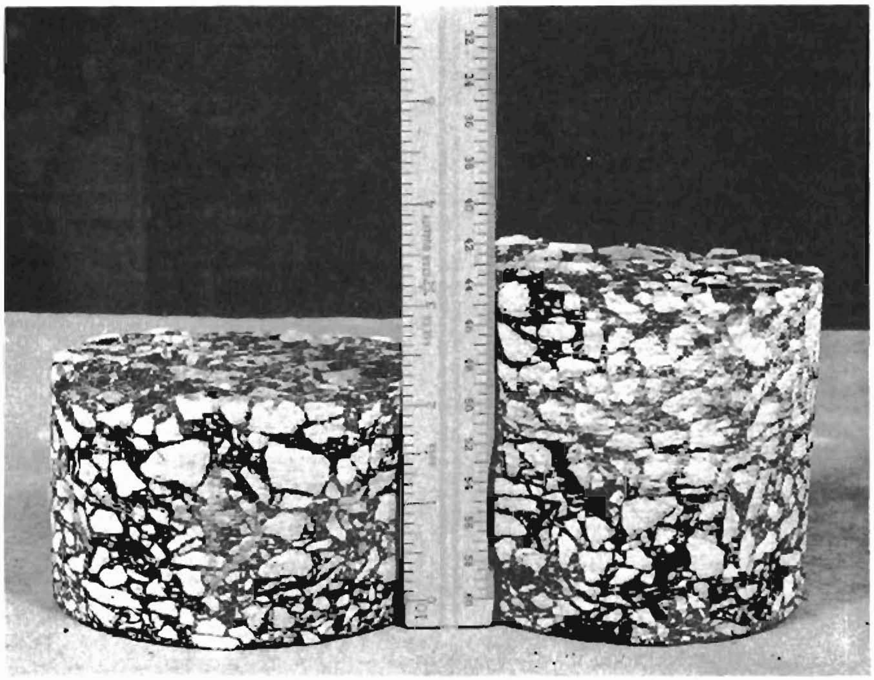


Fig 3. Asphalt concrete cores within and between wheel paths (Ref 14).

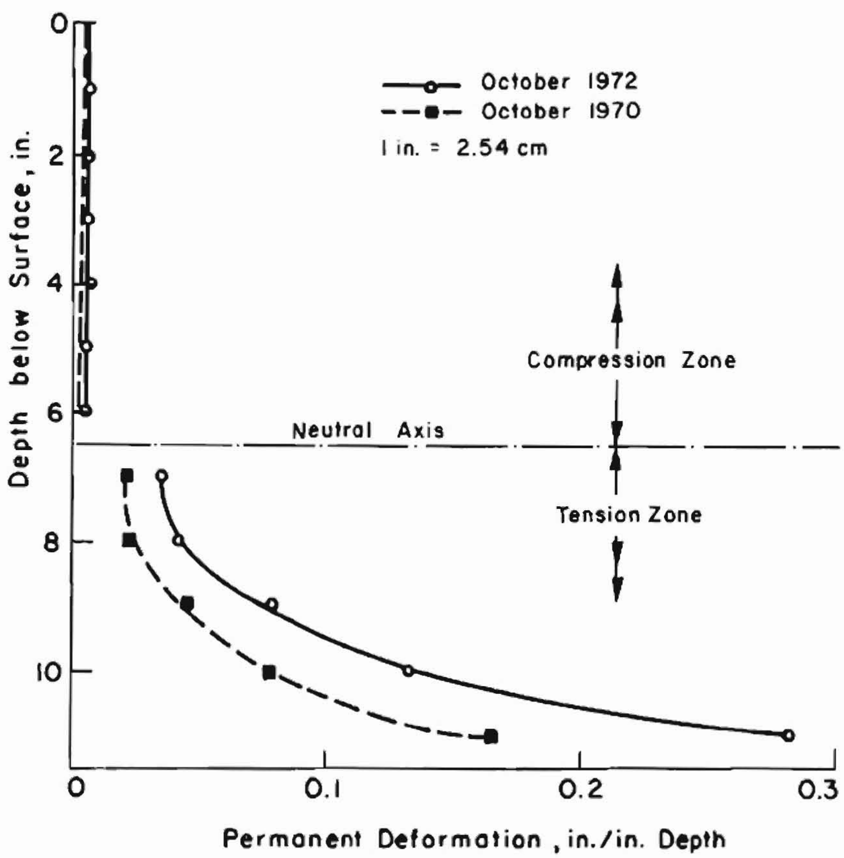


Fig 4. Variation of permanent deformation rate for typical asphalt concrete section (Ref 43).

compression or where the total pavement thickness is such that the major amount of permanent deformation will occur in the subgrade.

Figure 5 shows the behavior of a specimen subjected to a repeated stress. In general, a similar build-up of permanent deformation under repeated application of load is expected to occur in a pavement. In addition, permanent deformation may also occur after extensive fatigue cracking, i.e., as a secondary phenomenon. Nevertheless, permanent deformation, or rutting, which manifests itself as permanent longitudinal deformations along the wheel paths, normally is considered to be the cumulative result of deformations occurring under wheel paths in every layer of the pavement structure due to each application of a wheel load (Ref 10).

Design Approaches to Reduce Rutting, or Permanent Deformation

Four design concepts or approaches have been used for the permanent deformation problem:

(1) plastic or ultimate yield,
(2) limiting stress or strain criteria,
(3) cumulative deformation using numerical techniques, and
(4) empirical relationships.

Plastic or Ultimate Yield. Two of the most widely-used mixture design methods are the Hveem stabilometer and the Marshall method, which provide an empirical measure of plastic flow characteristics. Both methods are of interest and provide useful information, but neither is able to predict the magnitude of permanent deformation. However, it has been proposed that, if the R value from the Hveem stabilometer is at least 10 in the subgrade and ranges from five to seven in the asphalt layer, excessive permanent deformation will not be produced by traffic.

Limiting Stress or Strain Criteria. The concept of limiting stress or strain was initially developed by the Shell Oil Company during the 1960's. The basic hypothesis is that if the maximum compressive vertical strain or stress at the surface of the subgrade is less than a critical value then excessive rutting will not occur for a specified number of load applications to terminal serviceability of the pavement.

From studies conducted at the AASHO Road Test, it was found that there is a critical stress, or endurance limit, for the relationship between strain

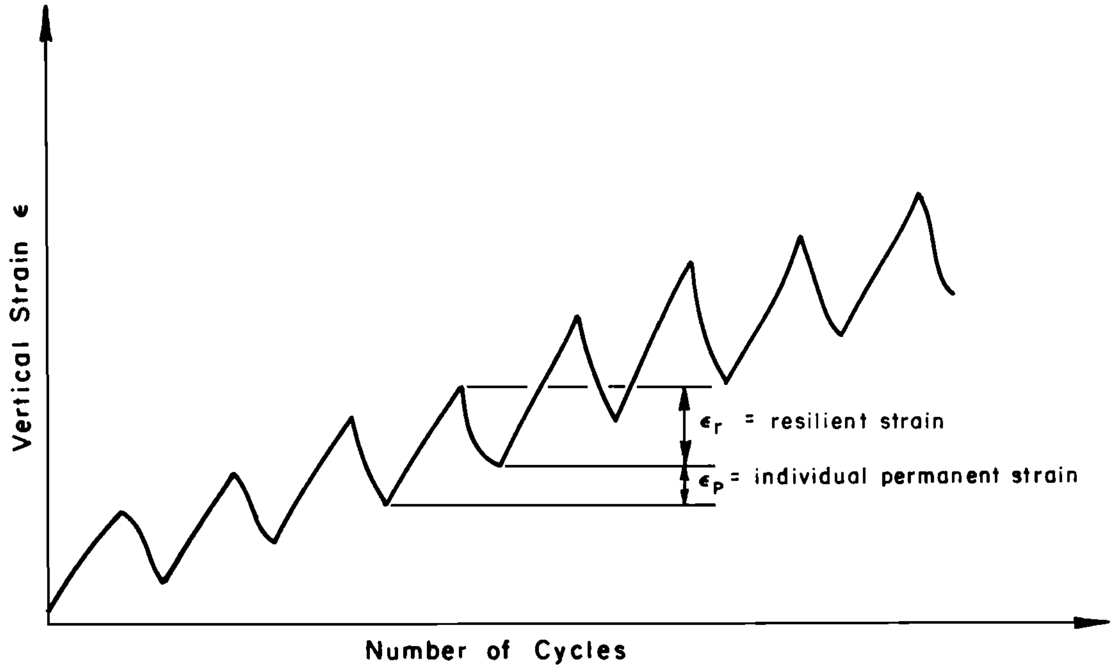


Fig 5. Typical behavior of mixtures subjected to repeated loads.

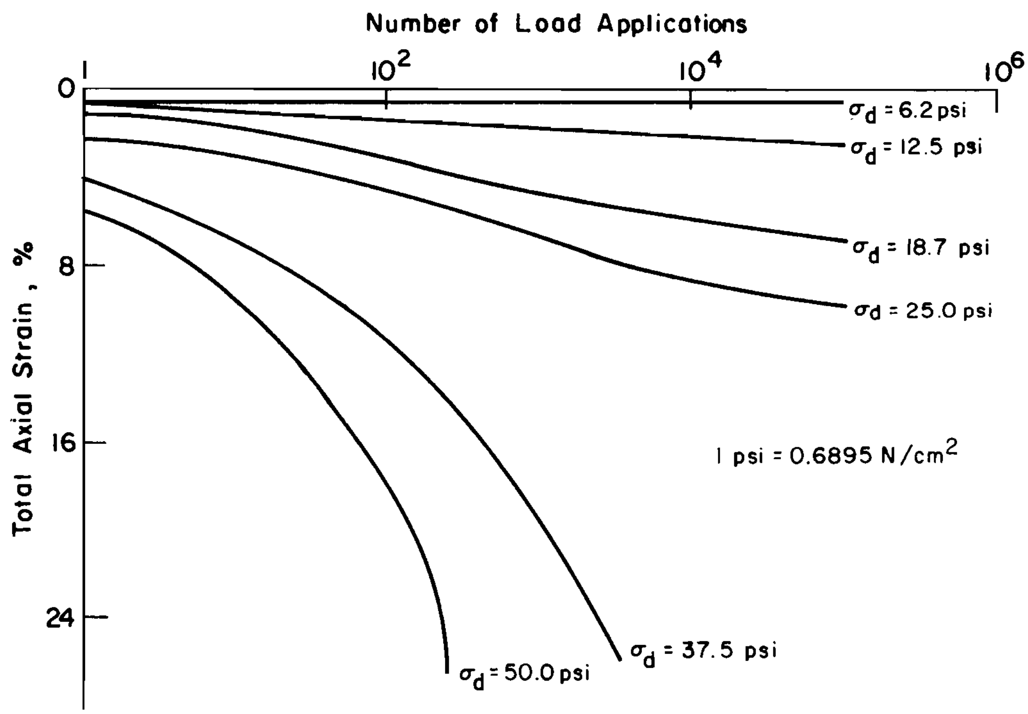


Fig 6. Typical relationships between axial deformations and the logarithm of load applications (Ref 53).

and the logarithm of the number of load repetitions, above which the slope increases until failure occurs. At stresses below this limit, the material exhibits a stable condition. Figure 6 illustrates the results of repeated triaxial compression tests conducted on the AASHO Road subgrade from which a critical stress of approximately 16.6 N/cm^2 (24 psi) was estimated (Ref 53).

Klomp and Dormon (Ref 31) and Heukelom and Klomp (Ref 20) suggested that if the strain at the top of the subgrade does not exceed 6.5×10^{-4}, excessive permanent deformation in the subgrade would not be expected for one million repetitions of an 8182-kg-axle (18-kip-axle) load to a terminal present serviceability index of 2.5.

Finn et al (Ref 13) found that more conservative values for the limiting subgrade strain should be used. In addition, Haas et al (Ref 43) calculated the vertical compressive strain on the subgrade of the Brampton Road Test using nonlinear elastic theory. They suggested values somewhat more conservative than those proposed by Klomp and Dormon.

The following limiting values are listed for the traffic applications to mid 1970 (approximately 0.6×10^6) for the Brampton Road Test (Ref 43):

Klomp and Dormon criteria	7.0×10^{-4}
Finn et al criteria	5.5×10^{-4}
Haas et al criteria	3.5×10^{-4}

The Shell concept of limiting strain or stress is a useful tool but it only precludes permanent deformation in the subgrade and does not predict what the magnitude would be in the pavement. Also, limiting the subgrade strain or stress may protect the subgrade from deformations but does not insure that rutting will not occur in the component layers of the pavement structure. Nevertheless, this method currently is being used for design of asphalt concrete pavements.

Cumulative Deformation. Two basic approaches are being used at the present time in an attempt to develop a permanent deformation predictive technique:

(1) the quasi-elastic approach and

(2) the linear viscoelastic approach.

The quasi-elastic approach assumes that a fundamental deformation law exists through which permanent strains can be predicted based upon the state of stress in the material.

Romain (Refs 51 and 52) suggested that the permanent vertical strain ε_p is a function of the maximum elastic stress σ_e and the number of load applications N, as shown by

$$\varepsilon_p = f(\sigma_e, N).$$

Heukelom and Klomp (Ref 20) and Klomp and Dormon (Ref 31) proposed a procedure based on the premise that strains above an elastic limit are plastic and suggested the following equation:

$$\Delta_p = \int_o^h (\varepsilon_v - \varepsilon_e) dh$$

where

Δ_p = total permanent deformation in the asphalt layer,
ε_v = total vertical strain on a typical element,
ε_e = elastic limit of the asphalt concrete, and
h = thickness of the asphalt layer.

For asphalt concrete, an arbitrary elastic strain limit of 5×10^{-4} was proposed (Ref 20).

The basic steps for calculating permanent deformation, by relating permanent strain to calculated elastic strains, are

(1) each pavement layer is divided into sublayers,

(2) the state of stress or strain in each sublayer is calculated through the use of elastic theory; nonlinear elastic material properties are analyzed either through the use of finite element techniques or by iterative elastic layered theory solutions;

(3) the permanent strain in each sublayer is calculated by either a deformation law or an empirical equation; and

(4) the amount of rutting is calculated as the sum of the permanent strain resulting from each traffic load times the thickness of each sublayer.

The quasi-elastic approach is a valuable tool, but it has some disadvantages, which are mainly that

(1) total strain is calculated on the basis of elastic theory;

(2) the elastic limit is assumed to be constant but in fact is a function of temperature, nature of loading, rate of loading, state of stress, and number of load repetitions for any given mixture;

(3) permanent deformation, by definition, is a function of the number of load applications and the quasi-elastic approach considers only a static system; and

(4) permanent deformation in the subgrade is ignored.

The linear viscoelastic approach has been used to describe the behavior of polymer materials. Pavement materials responses are time dependent due to the fact that they have a viscous as well as an elastic component. Therefore, a viscoelastic approach offers many advantages over elastic theory for the design or analysis of pavements. The viscoelastic theory offers a direct approach for the prediction of permanent deformation in that the constitutive relationships employed contain time dependent factors. In order to predict or estimate the manner in which deformation accumulates, the environment, loads, and materials characteristics must be described in suitable form. These are then incorporated in a linear viscoelastic model or layered system, such as that used in VESYS IIM, developed for the Federal Highway Administration (Refs 37, 38, and 53).

The main disadvantages of the linear viscoelastic approach are

(1) materials are assumed to behave linearly, which is not true, especially at high temperatures, at which materials tend to behave in a nonlinear manner; the assumption of linearity has been found to be true in some materials but only for low to medium temperatures (Refs 32 and 45);

(2) viscoelastic layered theory is relatively complex and has only been solved for a three layer system, although work has been initiated to expand the system to five layers;

(3) it is in the development stage; and

(4) material characterization is more complicated.

The linear viscoelastic method was recommended at the Texas Workshop (Ref 22) in 1970 and is currently under study by the Federal Highway Administration. A computer program, VESYS IIM was developed for the Federal Highway Administration in an attempt to use the linear viscoelastic theory on pavement design. This program contains a subroutine designed to predict rutting in asphalt pavement structures, and a sensitivity analysis of the output parameters involved in the subroutine has been conducted (Ref 50). The following is a description of the parameters used on this subroutine.

GNU and ALPHA functions were developed by Brademeyer et al (Ref 38) to describe the permanent deformation characteristics of asphalt mixtures and are used in the computer program VESYS IIM to predict rutting. The theory used is based on the assumption that from a laboratory repeated-load test a logarithmic relationship between repeated load and permanent strain can be obtained which is essentially linear over a range of load applications (Fig 7) and can be described by the equation

$$\varepsilon_a = IN^S \tag{1}$$

where

ε_a = accumulated permanent strain,

I = intercept with ε_a axis (arithmetic strain value, not log value),

N = number of load applications, and

S = slope of the straight line.

This assumes that the logarithmic relationship is essentially linear over a range of load applications.

The parameters GNU and ALPHA are defined as

GNU:

$$\mu = \frac{IS}{\varepsilon_r} \tag{2}$$

and

ALPHA:

$$\alpha = 1 - S \tag{3}$$

where

ε_r = resilient strain.

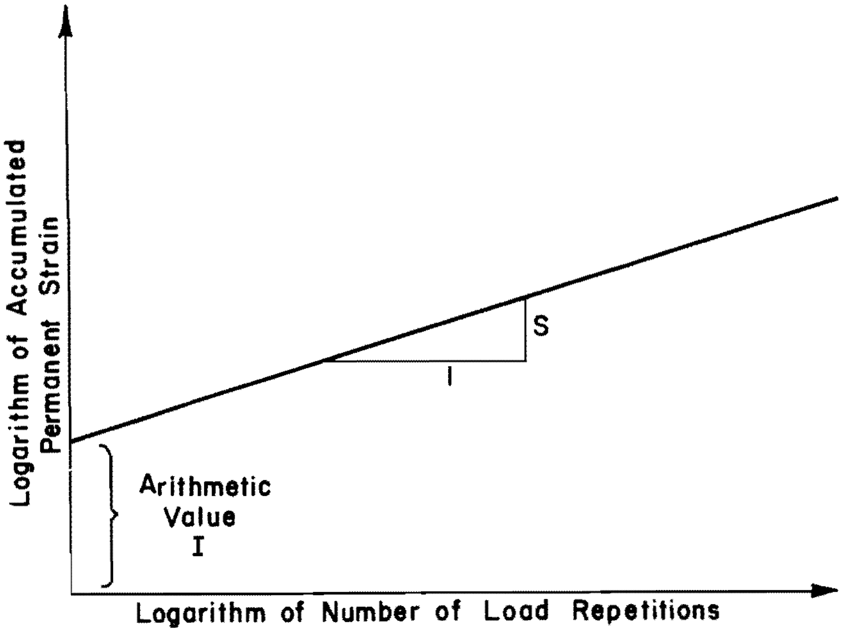


Fig 7. Assumed logarithmic relationship between permanent strain and number of load repetitions (Ref 38).

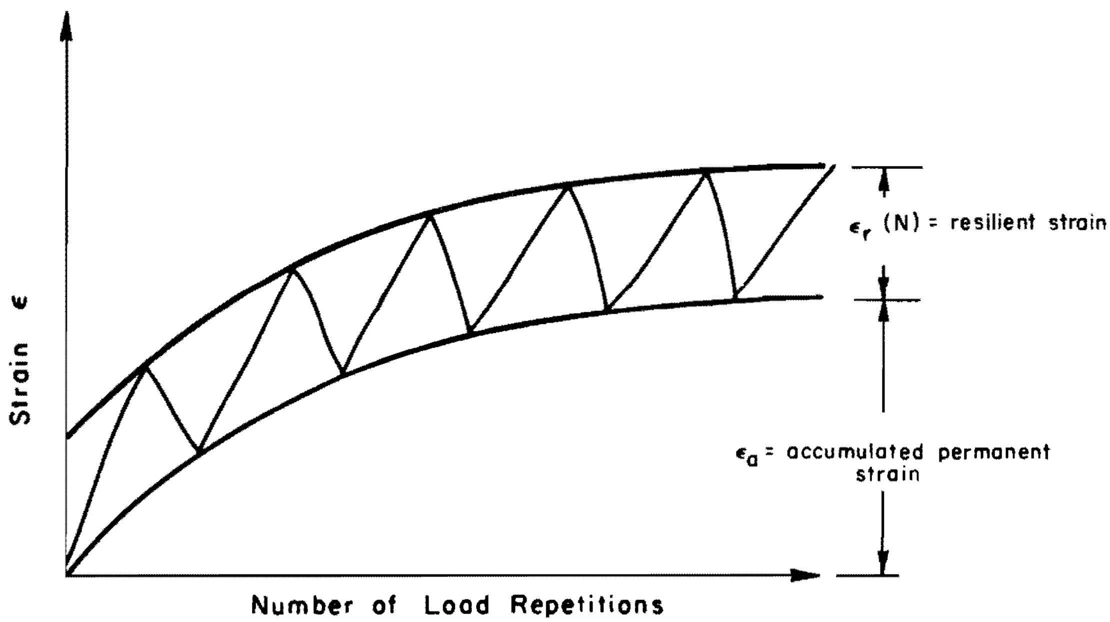


Fig 8. Typical relationship between strain and number of load repetitions (Ref 38).

The resilient strain is considered to become constant after a few load applications (Fig 8). The theory and development of GNU and ALPHA are contained in Refs 38 and 50.

Empirical Relationships. This approach assumes that an empirical relationship can be statistically formulated for estimating permanent strains based upon the calculated stress or strain state in the material.

Research for developing empirical relationships has been done by Monismith, Ogawa, and Freeme (Ref 40) for subgrade soils, Barksdale (Ref 3) and Dharmawardene (Ref 10) for granular materials, and Morris and Haas et al (Refs 43 and 44) and McLean and Monismith (Ref 35) for asphalt concrete.

(1) Monismith proposed the following equations for calculating permanent deformation in the subgrade:

$$\varepsilon_p = AN^b \tag{4}$$

and

$$\frac{\varepsilon_a}{\Delta\sigma_a} = \ell + m\,\varepsilon_a \tag{5}$$

where

ε_p = permanent strain,

ε_a = cumulative permanent strain at a specific number of stress applications,

N = number of stress repetitons,

$\Delta\sigma_a$ = repeated axial stress, and

A, b, ℓ, m = experimentally determined coefficients.

Only the elastic stress and the coefficients are required for calculating permanent deformation using these equations. The two equations may be used to bracket the amount of predicted permanent deformation.

(2) Barksdale proposed a hyperbolic stress-strain equation for relating permanent strain to the stress state in granular materials:

$$\varepsilon_p = \frac{\dfrac{(\sigma_1 - \sigma_3)}{K(\sigma_3)^N}}{1 - \dfrac{(\sigma_1 - \sigma_3)R_f\ (1 - \sin\phi)}{2(C\cos\phi + \sigma_3\sin\phi)}} \tag{6}$$

where

σ_1 = axial stress,

σ_3 = confining stress,

ε_p = plastic or permanent strain,

$K(\sigma_3)^N$ = relationship defining the initial tangent modulus as a function of the confining pressure (K and N are experimentally determined constants),

C = cohesion,

ϕ = angle of internal friction, and

R_f = constant relating compression strength to an asymptotic stress difference.

In order to use this equation, it is necessary to determine the cohesion, angle of internal friction, and R_f for the material being investigated.

(3) Haas et al proposed an equation in the following form for predicting permanent strains based on the stress state in asphalt concrete:

$$\varepsilon_p = f(\sigma_1, \sigma_3, T, N) \pm E \tag{7}$$

where

ε_p = permanent strain,

σ_1 = vertical stress,

σ_3 = confining stress,

T = temperature,

N = number of stress repetitions, and

E = estimate of error.

This procedure was developed for a certain range of conditions and, when applied to conditions out of this range, it requires analysis of asphalt concrete with a special temperature-controlled, dynamic, triaxial test which was developed at the University of Waterloo.

(4) McLean and Monismith developed the following relationship for permanent strains from repeated-load tests results on asphalt concrete:

$$\log \varepsilon_p = C_0 + C_1 \log N - C_2(\log N)^2 + C_3(\log N)^3 \tag{8}$$

where

ε_p = plastic strain,

N = number of load applications, and

C_0, C_1, C_2, and C_3 = coefficients reflecting the influences of stress state, time of loading, and temperature.

The following relationship was developed to obtain the coefficient C_0:

$$\varepsilon_{p1} = K_1(\sigma_D \cdot \varepsilon_e)^n \tag{9}$$

where

$\varepsilon_{p1} = 10^{C_0}$, permanent strain at first load repetition,

$\sigma_D = \sigma_A - \sigma_R$, stress difference in triaxial compression,

$_e$ = elastic strain, and

K_1 and n = experimentally determined coefficients.

MATERIAL CHARACTERIZATION TECHNIQUES

Most of the previous major work on material characterization for permanent deformation has involved the use of laboratory test tracks, triaxial testing, or creep testing in which the materials have been subject to static as well as repeated load conditions. In this section some of the material characterization techniques used until now for the permanent deformation subsystem are presented.

Laboratory Test Track

Many investigators have used this type of testing technique in an attempt to obtain a more realistic simulation of field conditions in the laboratory (Refs 8, 23, and 59).

Hofstra and Klomp (Ref 23) presented results from a circular laboratory test track in which the rutting of flexible pavements was studied at various temperatures under well-controlled conditions and with mixes chosen in such a way that rutting was expected to occur, e.g., the bitumen content was higher than would normally be used in practice.

The experiments were carried out on test sections which were part of asphalt pavements built up on a 0.7 m (2.3 ft) wide circular test track with an outside diameter of 3.25 m (10.7 ft). Rutting was caused by the repeated loading produced by a rolling wheel with a known load traveling at a known speed.

For tests at temperatures greater than room temperature, thermostatically controlled heaters were used, allowing the temperature to be varied from 20 to 60° C (68 to 140° F). This experiment showed that rutting increases progressively with increasing temperatures and that the viscous part of the deformation becomes more important at high temperatures.

It also was found that with an increasing number of wheel passages the permanent deformation caused by a single load decreases considerably as the asphalt mixture builds up resistance to flow during the process of deformation under repetitive loading (Fig 9).

Another important finding was that thick asphalt pavements produced a significant reduction in subgrade deformation (Table 3) and that the rutting in the asphalt layer did not increase when the layer thickness was increased from 10 to 20 cm (3.9 to 7.9 in.) (Fig 10).

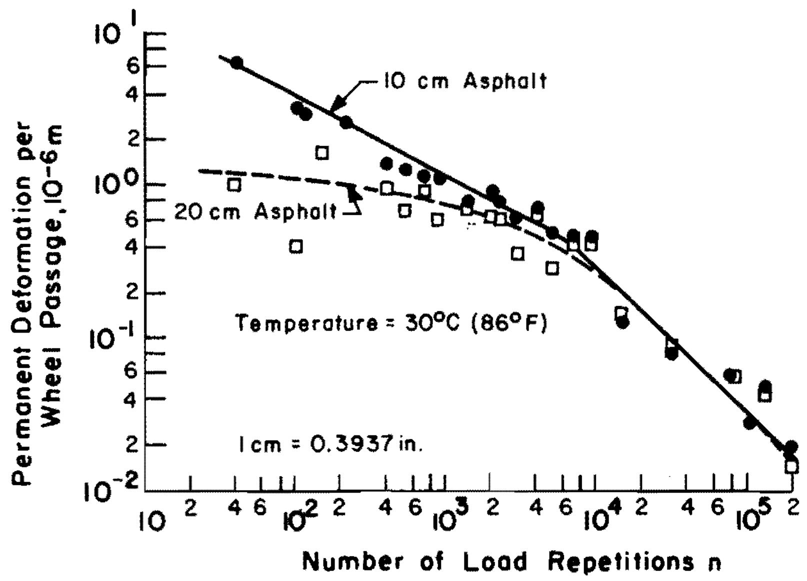


Fig 9. Permanent deformation per wheel passage as a function of the number of load repetitions (Ref 23).

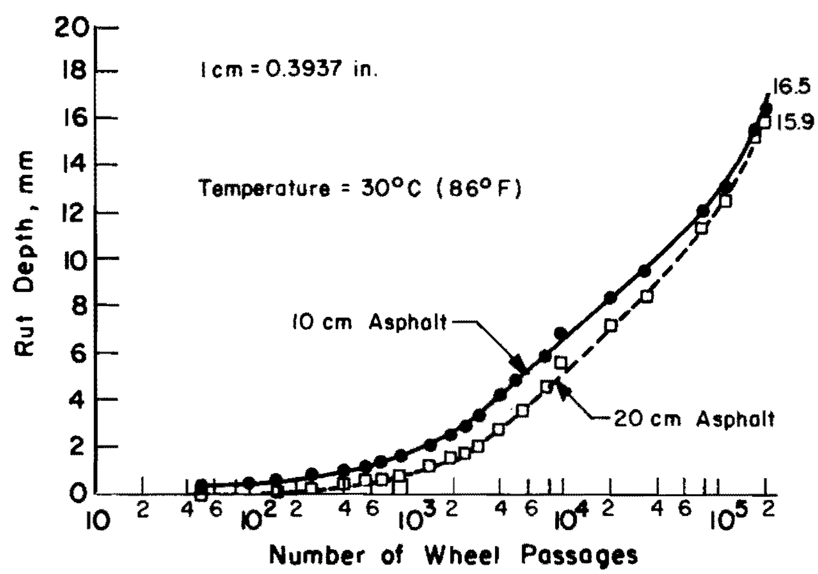


Fig 10. Rut depth in two asphalt sections as a function of the number of load repetitions (Ref 23).

TABLE 3. RUT DEPTH AND THICKNESS CHANGES IN ASPHALT LAYERS (Ref 23)

Asphalt Thickness, cm	Rut Depth, cm	Subgrade Deformation, cm	Change in Asphalt Thickness, cm	
			cm	percent
5	1.4	0.7	0.7	14
10	1.2	0.1	1.1	11
14.2	1.25	—	1.25	9

1 cm = 0.3937 in.

It should be noted that, in all these experiments, there were no temperature gradients through the depth of the layer. Therefore, the results cannot be directly compared with findings such as those of Morris where inservice temperature gradients were used in the analysis.

Triaxial Testing

Several repeated-load triaxial tests have been performed in order to characterize asphalt materials with respect to permanent deformation (Refs 3, 5, and 43). Most of them used compressive stress for both the axial and confining stresses; however, Haas et al used a compressive confining stress but subjected the specimen to repeated, axial tensile stresses (Ref 43).

Morris and Haas et al (Refs 43 and 44), in a study to develop a reliable method for predicting rut depths in asphalt concrete pavements, utilized a triaxial apparatus to simulate field conditions. The apparatus consisted of a high-pressure triaxial chamber with temperature control, independent control of vertical and horizontal stresses, and a variety of auxiliary measuring equipment and was capable of applying dynamic vertical compressive stresses and dynamic horizontal stresses in either tension or compression. Temperature conditions were controlled within a range of ± 0.3° C (± 0.5° F) for the material used in the Brampton Road Test. The amount of permanent strain ε_p in asphalt concrete was found to be dependent on vertical stress, horizontal stress, temperature, and number of load repetitions, i.e.,

$$\varepsilon_p = f(\sigma_1, \sigma_3, T, N) \pm E \qquad (7)$$

where

σ_1 = vertical stress,
σ_3 = horizontal stress,
T = temperature,
N = number of load repetitions, and
E = estimate of error.

On the basis of the results of the study, it was concluded that

(1) a technique capable of predicting rut depths in asphalt pavements under a wide range of conditions had been developed,

(2) the technique is based on experimental equipment and test procedures capable of simulating field conditions, and

(3) the models developed from the experimental results predict the rut depth of the full depth sections at the Brampton Road Test in Canada.

Figure 11 shows the permanent deformations predicted using this technique compared with actual values measured at the Brampton Road Test.

Creep Testing

Although several investigators have used this testing technique to study irrecoverable deformation characteristics, only a brief discussion of some of the work reported by Shell Oil is presented (Ref 59). From studies of asphalt mix stability properties, it was concluded that it is possible to calculate rut depths in a laboratory test track within a factor of 2 using a simple unconfined constant load creep test. As shown in Fig 12, the measured deformations were higher than the calculated values. Thus, a study was made to investigate the two main differences between the two test methods, i.e., unconfined versus confined tests and static versus dynamic tests.

Confined creep tests were conducted using parking tests under geometrical conditions equal to the conditions used in the rutting tests. The conditions differed only in that the rutting tests produced different deformation patterns in the longitudinal and transverse direction whereas in the parking test the pattern was essentially axisymmetric.

The parking test was carried out for 24 hours at ambient temperatures with a contact stress equal to that in the rutting test. The parking test results show the same systematic deviations from the rutting figures as the results obtained from the creep tests (Fig 13), which indicated that the differences were not due to the effect of confinement.

The effect of static versus dynamic tests was evaluated by conducting both static and repeated-load unconfined creep tests. The results indicated that permanent deformations were larger for the repeated-load tests, which may possibly be explained by the fact that the stiffness was greater for the static tests.

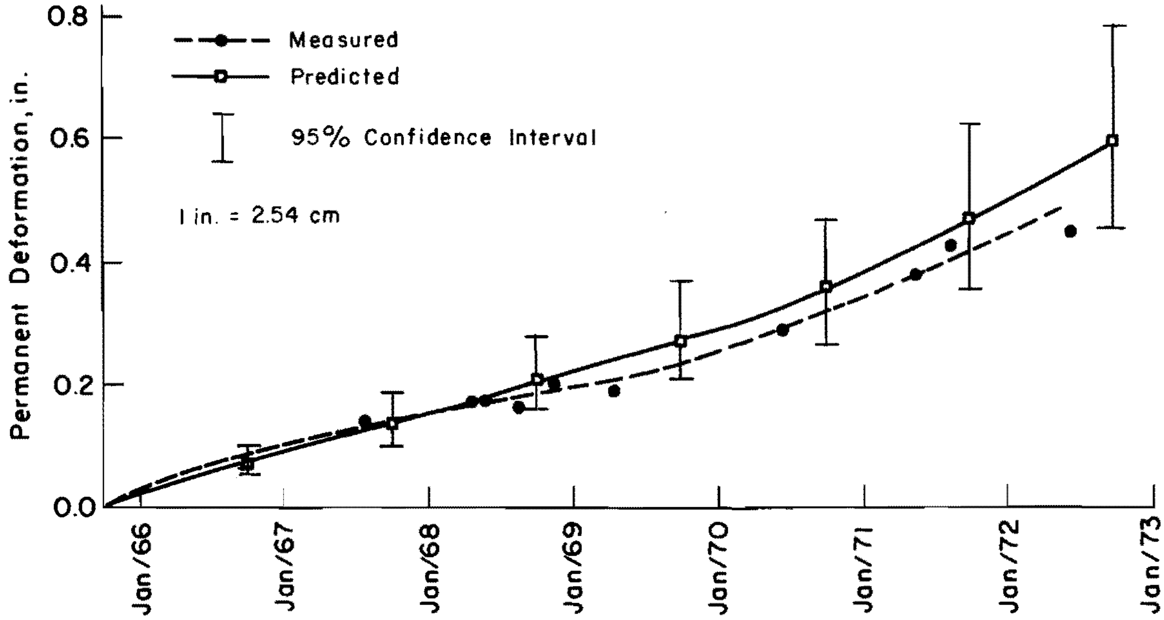


Fig 11. Comparison of measured and predicted permanent deformations at Brampton Road Test (Ref 43).

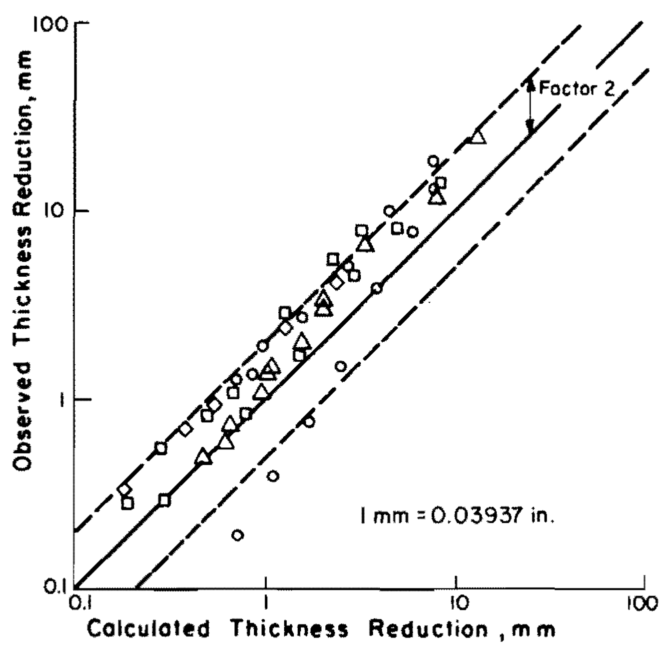


Fig 12. Observed thickness reduction of asphalt layer versus reduction calculated from creep test for various mixes (Ref 59).

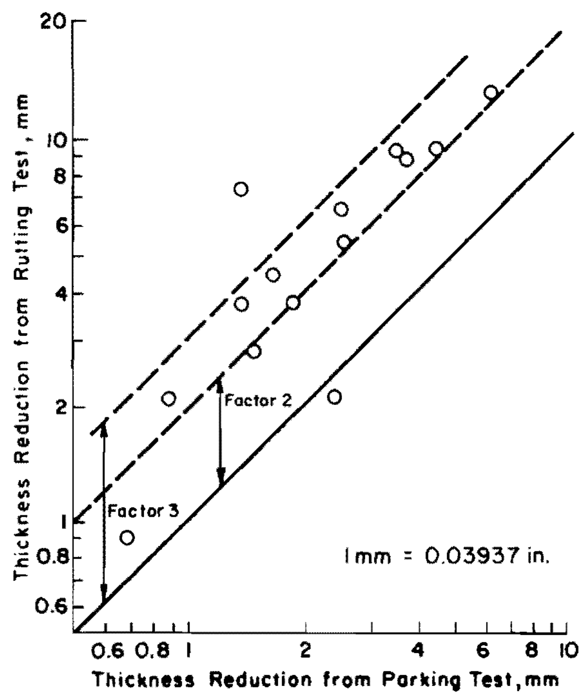


Fig 13. Thickness reductions of asphalt layer from a test track and a 24-hour parking test (Ref 59).

It was concluded that the assumption, based upon linear viscoelasticity, that permanent deformation in a dynamic test is only a function of the cumulative loading time or, at different temperatures, only a function of the viscous component of the stiffness of the binder, is incomplete. An extra term which includes the number of load applications must be added. It was also proposed that predicting rut depths on an actual road with a satisfactory degree of accuracy will be very complicated and that the main purpose of a laboratory test must be limited to the ranking of materials rather than the prediction of rut depths.

Repeated-Load Indirect Tensile Test

Until this time the repeated-load indirect tensile test has not been used to evaluate or characterize the permanent deformation characteristics of asphalt mixtures. Previous work, however, has shown that the test can be used to obtain the information needed for elastic analysis as well as for consideration of thermal and fatigue cracking, i.e., tensile strength, modulus of elasticity, Poisson's ratio, and the fatigue characteristics. Thus, if information on the permanent deformation characteristics can be obtained, all information required for elastic analysis and consideration of the three distress modes can be obtained from this one single test.

Primarily, the repeated-load indirect tensile test has been used by Kennedy et al at the Center for Highway Research, The University of Texas at Austin (Refs 9, 39, 42, 46, and 56). In addition, Schmidt (Ref 24) used a similar type of repeated-load indirect tensile test to determine elastic modulus but did not perform fatigue tests.

The indirect tensile test used by Kennedy et al applies repeated loads to the sides of a cylindrical specimen through 1.27-cm (0.5-in.) loading strips (Fig 14). These strips are used because the stress distributions are not altered significantly and because calculations of modulus of elasticity and Poisson's ratio are facilitated by maintaining a constant loading width rather than having a constantly changing loading width, which occurs with a flat loading strip (Refs 18 and 19). The center of the specimen is in a biaxial state of stress, as shown in Fig 14, and the resulting stresses are calculated as follows:

$$\sigma_T = \frac{2P}{\pi a h} \left(\sin 2\alpha - \frac{a}{2R}\right) \qquad (10)$$

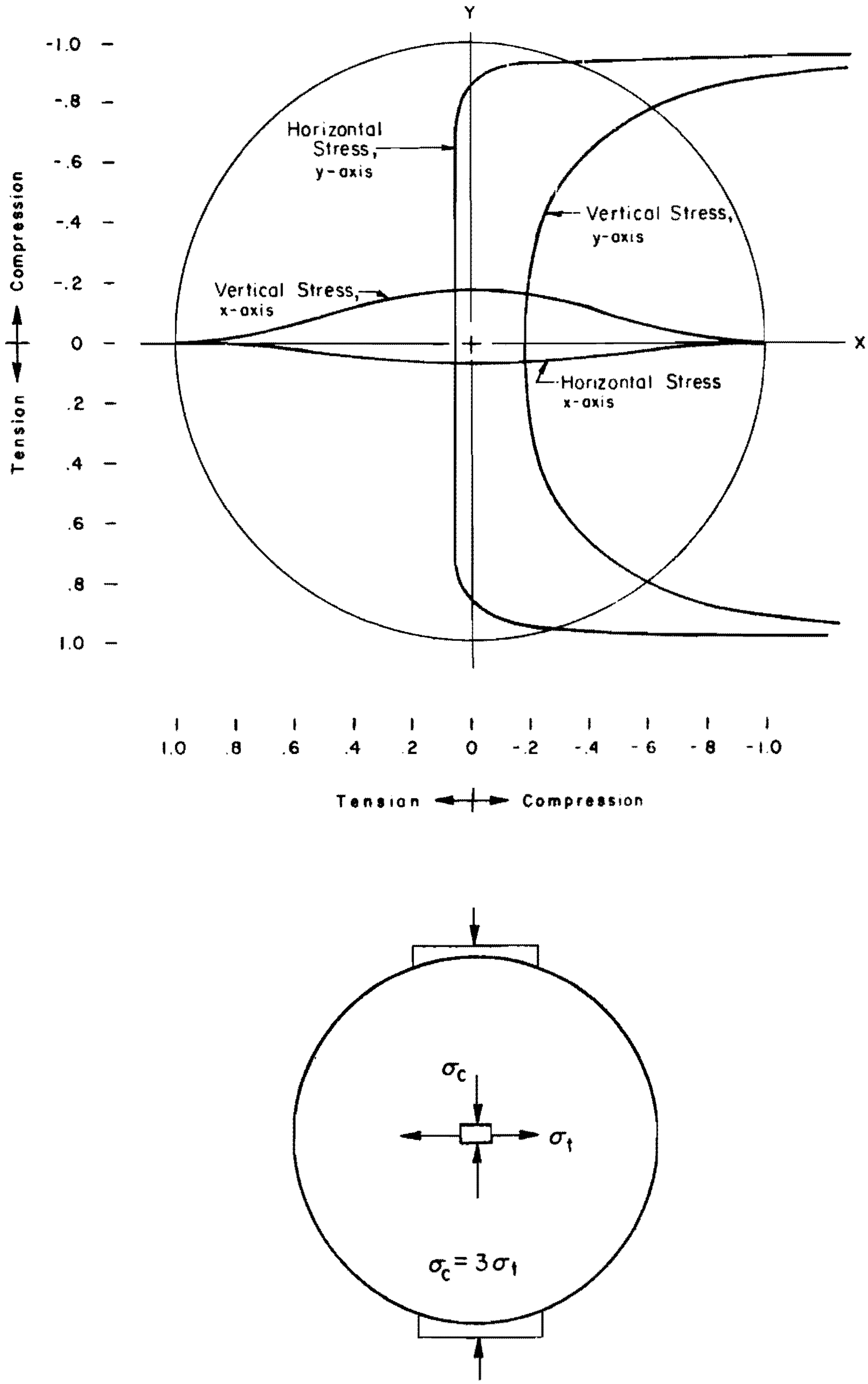


Fig 14. Relative stress distributions and element showing biaxial state of stress for the indirect tensile test.

and

$$\sigma_C = -\frac{6P}{\pi ah}\left(\sin 2\alpha - \frac{a}{2R}\right) \qquad (11)$$

where

σ_T = indirect tensile stress, in psi,

σ_C = indirect compressive stress, in psi,

P = total vertical load applied to specimen, in pounds,

a = width of loading strip, in inches,

h = height of specimen at beginning of test, in inches,

2α = angle at center of specimen subtended by width of loading strip, and

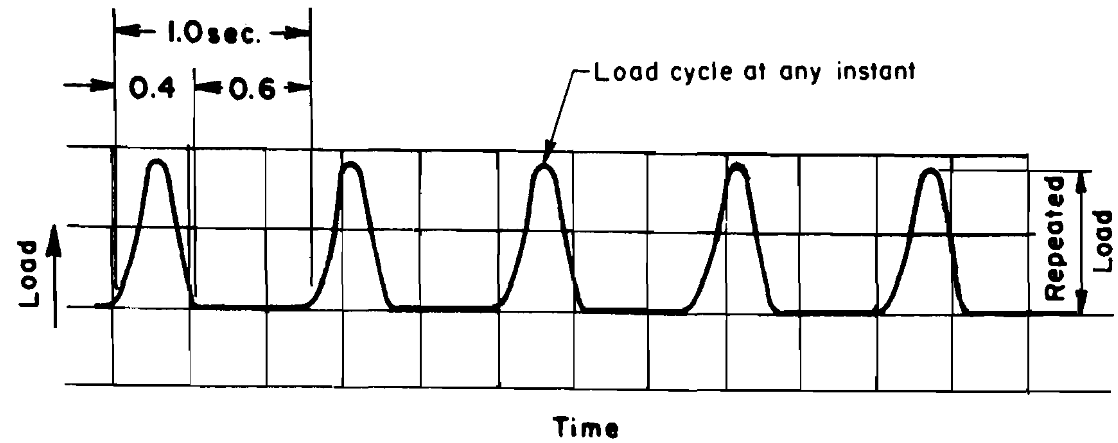
R = radius of specimen, in inches.

When P is maximum, σ_T equals the indirect tensile strength S_T.

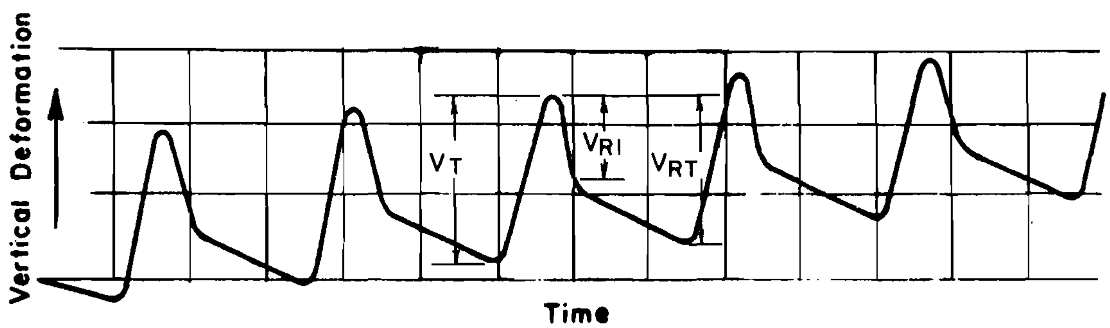
A haversine load pulse with and without a rest period has been used at a frequency of one cycle per second. Generally, a rest period of 0.6 second has been used with a load duration of 0.4 second. Typical load and deformation curves are shown in Figs 15 and 16. Permanent and creep deformations are allowed to occur, as shown in Fig 15. Fatigue failure of the specimen is assumed to have occurred when the specimen can no longer carry the applied load.

A resilient indirect tensile modulus of elasticity can be obtained by measuring the recoverable vertical deformations V_{RI} or V_{RT} and recoverable horizontal deformations H_{RI} or H_{RT} and assuming a linear relationship between load and deformation. Tensile strength is obtained from a static test in which a single load is applied to failure. In addition, this method also provides an estimate of permanent deformation resulting from the repeated loads. Since other needed material properties can be obtained, an effort should be made to investigate and evaluate the use of the test for obtaining such information.

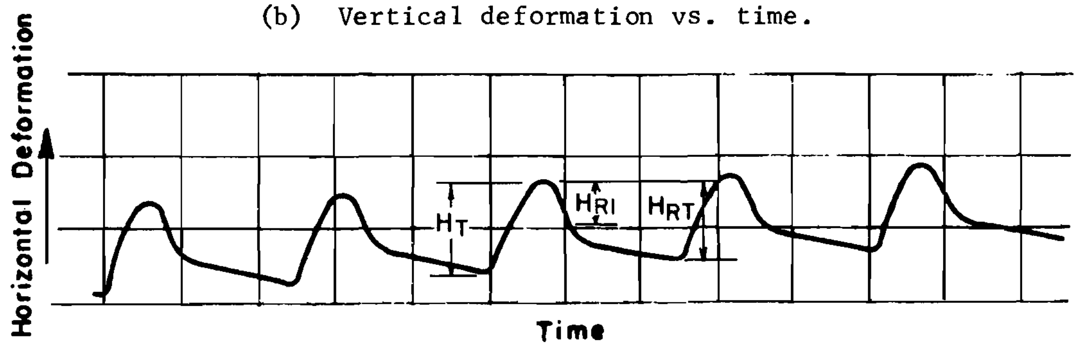
The indirect tensile test simulates the state of stress in the lower position of the asphalt layer, or tension zone, and appears to be a practical



(a) Load-time pulse.



(b) Vertical deformation vs. time.



(c) Horizontal deformation vs. time.

Fig 15. Typical load and deformation vs. time relationships for repeated-load indirect tensile test.

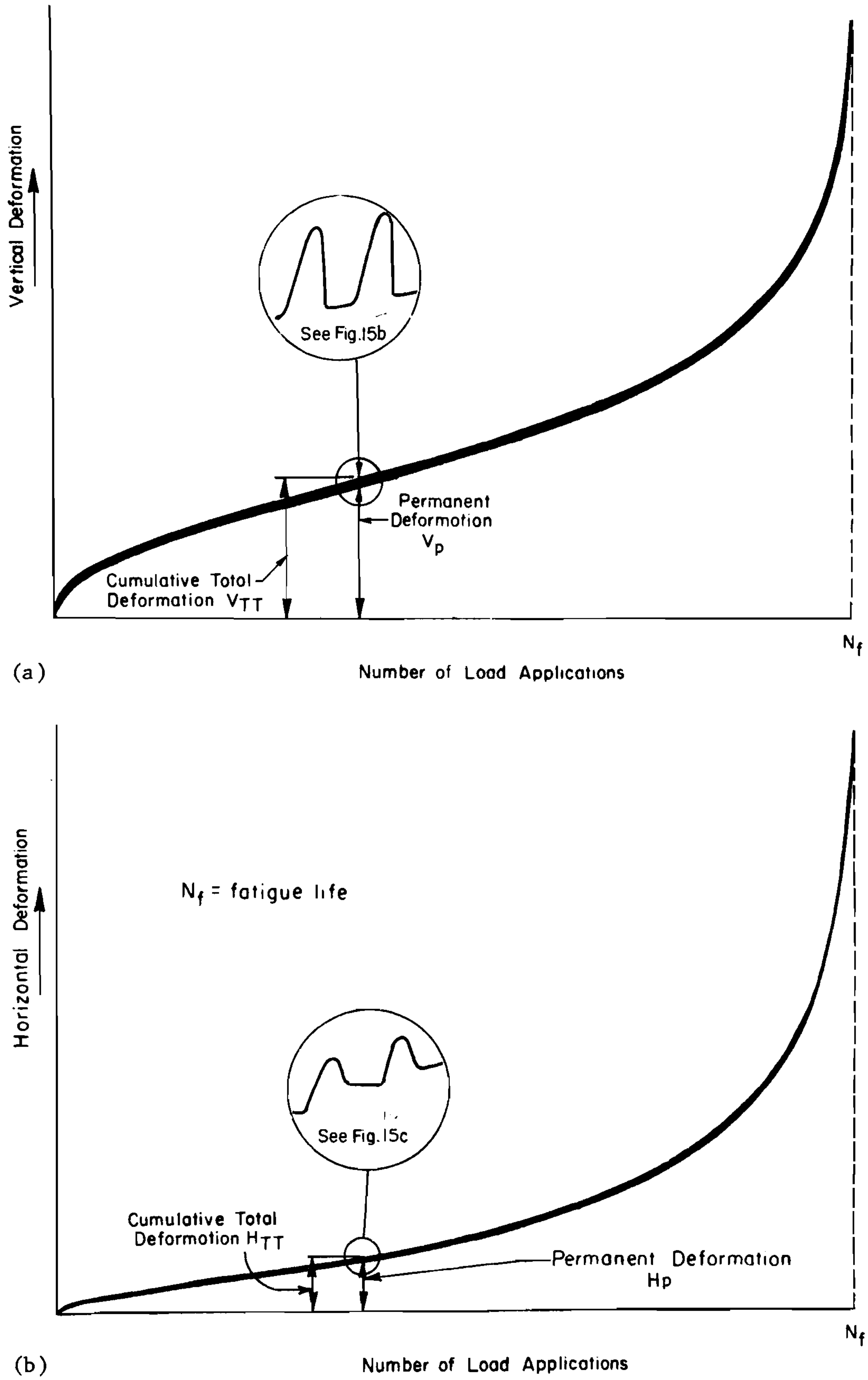


Fig 16. Relationships between number of load applications and vertical and horizontal deformations for the repeated-load indirect tensile test.

test method for characterization of asphalt materials. Some of the other advantages of this test are

(1) the test is relatively simple to conduct,

(2) cylindrical laboratory specimens or field cores can be tested easily,

(3) failure is not seriously affected by surface conditions,

(4) failure is initiated in a region of relatively uniform tensile stress,

(5) the coefficient of variation of test results is low compared to other test methods,

(6) the test can be used to test under repeated loads or a static load, i.e., a single load to failure,

(7) all cohesive materials can be tested, which allows materials to be compared, and

(8) fundamental engineering properties concerning tensile strength; modulus of elasticity and Poisson's ratio for both static and repeated loads; fatigue characteristics; and possibly permanent deformation characteristics of pavement materials can be obtained.

The only major disadvantage to the test is the fact that there is limited field experience with the test and the resulting information. In addition, the theory of the test is slightly more complex than for other test methods. However, the theory and equations for calculating properties have been developed and are available (Refs 18, 27, and 41).

CHAPTER 3. EXPERIMENTAL PROGRAM

The primary objective of this study was to evaluate the use of the repeated-load indirect tensile test as a means of characterizing asphalt materials for permanent deformation analysis.

In order to conduct the evaluation, permanent deformation data obtained from a previously conducted test program were used. This test program has been described in detail in a previous report (Ref 1). Consequently, only a summary of the basic materials, specimens, test equipment, experimental design, testing procedure, and the permanent deformation parameters analyzed is presented below.

MATERIALS

Two types of aggregate with contrasting properties were used in the test program: a relatively nonporous rounded gravel and an angular and relatively porous crushed limestone. These aggregates have been previously used in this research project and on various construction projects.

The gradation, as shown in Fig 17, was the same as the medium gradation previously used in earlier studies (Refs 41 and 42) and conformed with the Texas State Department of Highways and Public Transportation Standard Specifications for hot mix asphalt concrete pavement Class A, Type B (fine-graded base or leveling-up course) and Type C (coarse-graded surface course).

The asphalt was an AC-10 asphalt cement produced by Cosden Refinery; its properties are summarized in Table 4. Asphalt contents varied from 4 to 8 percent by weight of total mixture.

PREPARATION OF SPECIMENS

Aggregates were batched by dry weight to meet the specified gradation. The aggregates and the required quantity of asphalt cement were then heated to 135° C ± 3° C (275° F ± 5° F). Both materials were then mixed for approximately three minutes in an automatic Hobart mixer. After mixing, the mixtures

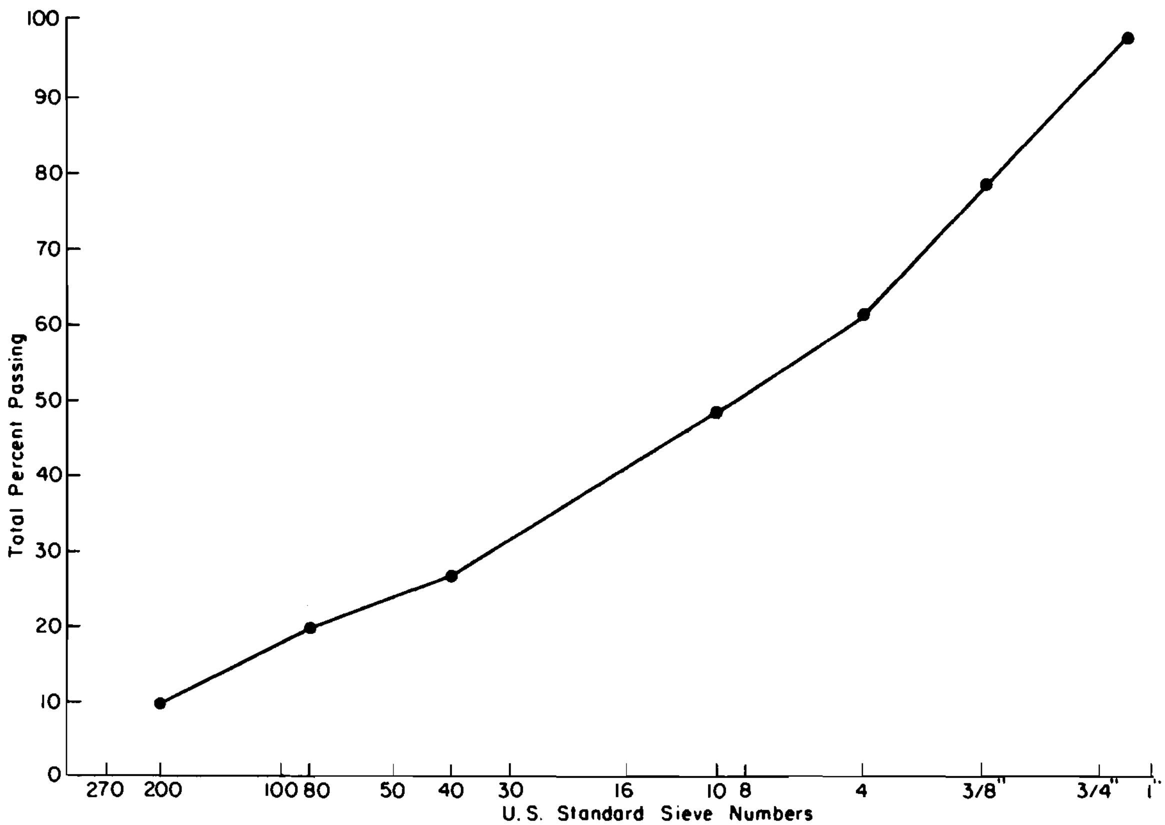


Fig 17. Aggregate gradation curve.

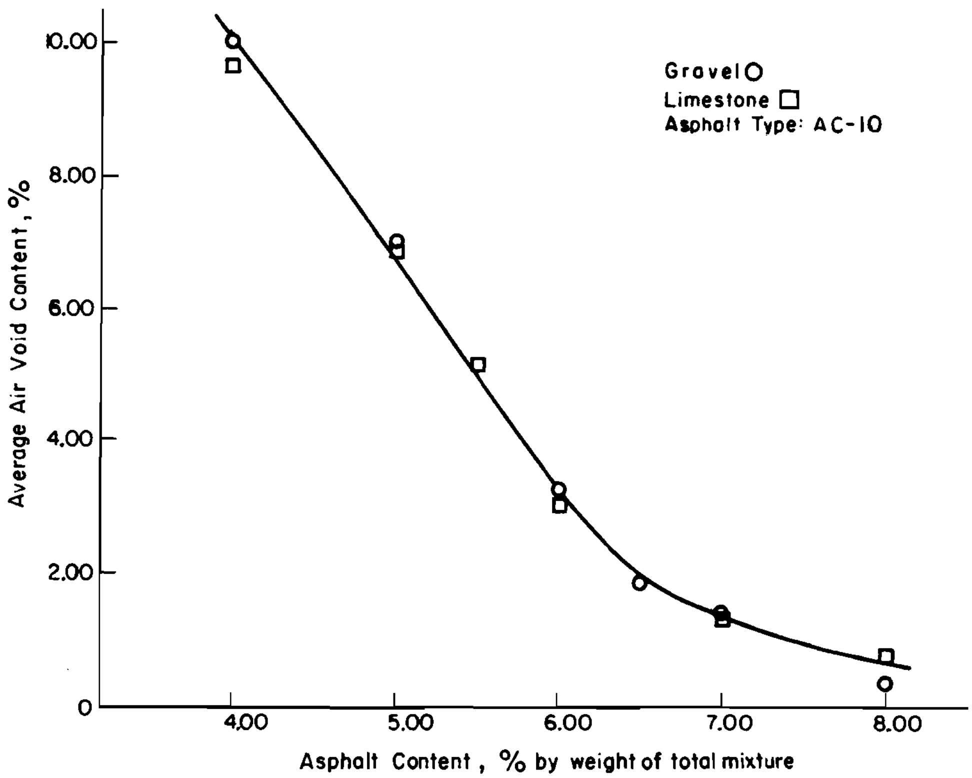


Fig 18. Relationship between asphalt content and average air void content.

TABLE 4. ASPHALT CEMENT PROPERTIES*

Item	Number
Water, percent	Nil
Viscosity at 275° F, stokes	2.45
Viscosity at 140° F, stokes	940
Solubility in CCl_4, percent	—
Flash point C.O.C., °F	585
Ductility at 77° F, 5 cm/min, cm	—
Penetration at 77° F, 100 g, 5 sec	88
Tests on residues from thin film oven test:	
Viscosity at 140° F, stokes	2052
Ductility at 77° F, 5 cm/min, cm	141+
Residual penetration at 77° F	52
Original specific gravity at 77° F	1.031

*Determined by the Texas State Department of Highways and Public Transportation.

$$°C = \frac{°F - 32}{1.8}$$

1 cm = 0.3937 in.

were compacted at 121° C ± 3° (250° F ± 5° F) using the Texas Gyratory Shear Compactor according to test method Tex-206-F, Part II (Ref 43). After compaction, the specimens to be tested at 24° C (75° F) were cured for two days at room temperature (24° C) before testing while those to be tested at 10° C (50° F) or 38° C (100° F) were cured for 24 hours at 24° C (75° F) and then transferred to temperature-controlled rooms at either 10° C (50° F) or 38° C (100° F) for an additional 24 hours before testing.

SPECIMEN CHARACTERISTICS

All specimens were approximately 10.2 cm (4 in.) in diameter by 5.1 cm (2 in.) high.

The percent air void was estimated using the bulk specific gravity of the aggregates, the bulk specific gravity of each specimen, and the bulk density of each specimen. These values are contained in Ref 1.

Maximum density of the limestone mixture was 2339 kg/m^3 (146 pcf) at the optimum asphalt content of 6.7 percent. The maximum density and optimum asphalt content for the gravel mixture were 2307 kg/m^3 (144 pcf) and 6.5 percent. The relationship between average air void content and asphalt content is illustrated in Fig 18.

TEST EQUIPMENT AND EXPERIMENT DESIGN

The test equipment consisted of an adjustable loading frame, a loading head, and an MTS closed-loop electrohydraulic loading system. The loading head was a commercially available die set with upper and lower platens constrained to remain parallel during testing (Fig 19). A curved, 1.27-cm (0.5-in.)-wide stainless steel loading strip was attached to both the upper and lower platens.

The resilient vertical and the permanent vertical deformations were measured by a DC linear variable differential transducer (Schaevitz Engineering Type 1000 DC-LVDT). The permanent horizontal deformations were measured by a special measuring device consisting of two cantilevered arms with strain gages attached (Fig 20), while two LVDT's (Trans-Tek Series 350), each with a working range of ± 0.127 cm (± 0.05 in.) and a mechanical travel of 0.36 cm (0.14 in.), were used to monitor the horizontal deformation of the specimen

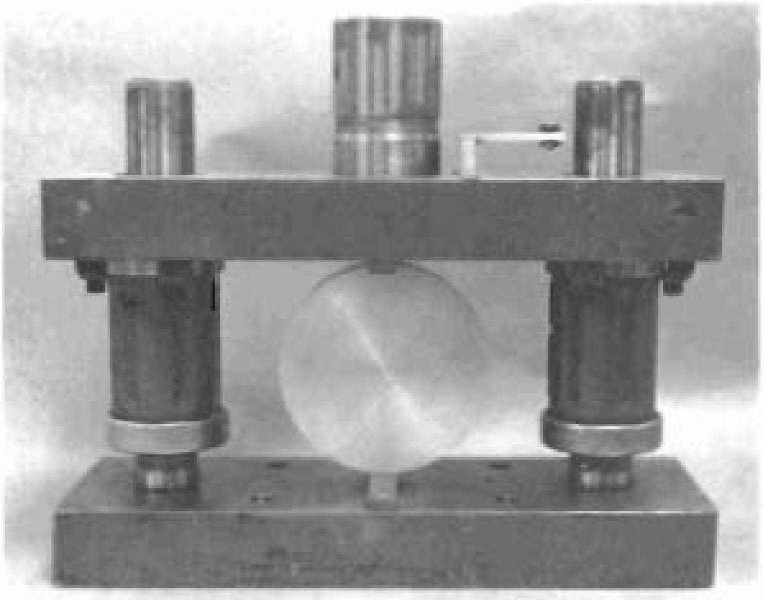


Fig 19. Loading head with rigid parallel platens.

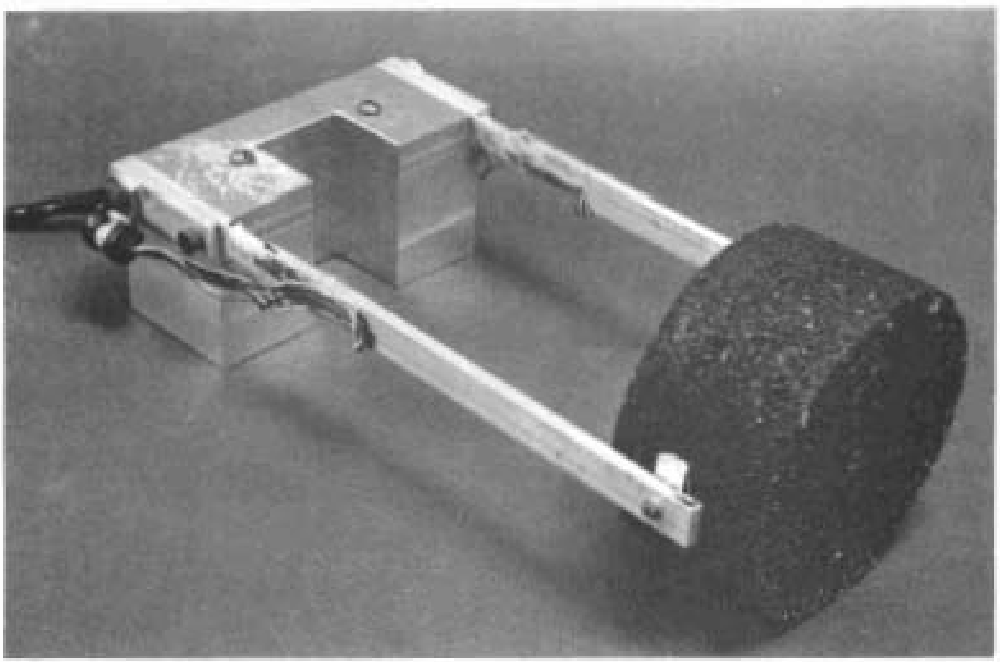


Fig 20. Lateral-strain measuring device.

which occurred during any given load cycle. For repeated-load tests, the horizontal and vertical deformations for selected cycles were recorded on a 2-channel strip chart with a Hewlett-Packard Recorder Model 7402A.

A typical horizontal and vertical deformation versus time pattern from an actual strip chart recording is illustrated in Fig 15 along with the corresponding load-time pulse. The cumulative horizontal and vertical deformations were initially recorded on a pair of X-Y plotters used for the static test, but later a data logging system was utilized. The deformations were indicated on a digital voltmeter and recorded on the system's paper-tape printer. Readings were automatically taken and recorded every 10, 100, or 1000 cycles, depending on the expected fatigue life of the specimen. Typical plots of horizontal and vertical cumulative total deformations versus number of load repetitions are shown in Fig 16.

Figure 21 shows a graphical representation of the number of specimens evaluated in terms of the experiment design utilized. The number of specimens tested for each cell or each combination of variables is indicated. The factors and levels considered in this study are shown in this same figure. In addition to aggregate type and asphalt content, the effects of stress level, testing temperature, and load duration were evaluated.

TESTING PROCEDURE

Prior to the test, all measuring devices were calibrated. The specimen was aligned in the loading head and the upper platen of the die set was brought into light contact with the specimen.

For the repeated-load tests, a preload of 89 N (20 lb) was applied and then the additional amount of load required to produce the prescribed stress level was applied at a frequency of one cycle per second (1 Hz). The majority of the tests involved a 0.4-second load duration and a 0.6-second rest period. To evaluate the effect of load duration, however, a limited number of additional tests were conducted at load durations and rest periods of 0.20 second and 0.80 second, respectively, and 0.05 second and 0.95 second, respectively. Tests at 10 and 38° C (50 and 100° F) were conducted in special temperature-controlled rooms.

Temperature, °C (°F)	Rest Period, seconds	Load Period, seconds	Stress Level, N/cm^2 (psi)	Limestone					Gravel				
Asphalt Content, percent				4	5	6	7	8	4	5	6	7	8
10 (50)	0.6	0.4	49.6 (72)			3					3		
			66.2 (96)			3					3		
			82.7 (120)			3					3		
24 (75)	0.6	0.4	11.0 (16)		3	5	6	2		3	4	6	1
			16.6 (24)	3	3	5	3	5	3	3	5	7	3
			22.1 (32)		3	5	4			3	5	5	
			27.6 (40)		3	5	3			3	5	3	
			33.1 (48)				1						
			38.6 (56)				1						
	0.8	0.2	16.6 (24)								2*		
	0.95	0.05	16.6 (24)								2*		
38 (100)	0.6	0.4	5.5 (8)			3					3		
			11.0 (16)			3					3		
			16.6 (24)			3					3		

Number of specimens indicated in each cell.

*Conducted to evaluate the effect of load duration.

Fig 21. Experiment design for repeated-load tests used to obtain permanent strains.

PERMANENT DEFORMATION PARAMETERS ANALYZED

The measured permanent deformations V_p and H_p (Fig 16) were analyzed using MODLAS 10, which calculates permanent strain values from the permanent deformations. The compressive strains in the vertical direction ε_{vp} can also be calculated using the following equations:

$$\varepsilon_{vp} = V_p \left[\frac{B_3 - \nu B_4}{B_1 - \nu B_2} \right] \tag{12}$$

and

$$\nu = \frac{\frac{V_p}{H_p}(A_1) + B_1}{\frac{V_p}{H_p}(A_2) + B_2} \tag{13}$$

where

V_p and H_p = the vertical and horizontal permanent deformations of the specimen (Fig 16, p 29),

ν = Poisson's ratio, and

A_1, A_2, B_1, B_2, B_3, and B_4 = constants which depend on the diameter of the specimen (Ref 15).

The VESYS IIM computer program utilizes two basic materials parameters in its permanent deformation subroutine to predict rutting. These two parameters, which are new in the engineering field, characterize the relationship between permanent accumulated deformation and number of load applications. These two parameters were calculated for the repeated-load indirect tensile test reuslts and analyzed. As discussed in Chapter 2, the theory used in the VESYS IIM computer program to represent permanent deformation characteristics of the materials involves the fitting of a straight line on the logarithmic relationship between permanent strains and the number of load applications (see Fig 7, p 15).

CHAPTER 4. ANALYSIS AND DISCUSSION

The permanent deformation information obtained from the repeated-load indirect tensile test was analyzed and evaluated indirectly in terms of the permanent deformation parameters in VESYS IIM, GNU, and ALPHA, and directly in terms of permanent strains. The actual evaluation involved

(1) an evaluation of GNU and ALPHA, which involved the following:

  (a) a comparison of GNU and ALPHA values from the repeated-load indirect tensile test with values which result in reasonable predictions of rutting,

  (b) an evaluation of permanent strain relationships for various test methods, and

  (c) a comparison and analysis of GNU and ALPHA values obtained from other test methods; and

(2) an evaluation of strains. This evaluation involved a comparison of permanent strain information from the repeated-load indirect tensile test with information obtained from other tests.

EVALUATION OF GNU AND ALPHA

As discussed in Chapter 2, two basic parameters, GNU and ALPHA, are used by the VESYS IIM program to predict rutting. These parameters relate to the intercept and slope of the relationship between the logarithm of permanent strain and the logarithm of the number of load applications (Fig 7, p 15) and are defined as

GNU:

$$\mu = \frac{IS}{\varepsilon_r} \qquad (2)$$

and

ALPHA:

$$\alpha = 1 - S \qquad (3)$$

where

I = arithmetic value of the intercept (not a logarithm) (Fig 7, p 15),

S = slope of the linear portion of the logarithmic relationship, and

ε_r = resilient strain.

Since VESYS IIM and its permanent deformation parameters are relatively new to the engineering profession, very few tests have been conducted for the purpose of obtaining values of GNU and ALPHA. Rauhut et al (Ref 50) conducted a literature search to obtain information from long-term repeated-load tests and conducted a limited number of tests in order to obtain information required for a sensitivity analysis of VESYS IIM. These data are utilized in this study as a source of information for comparison.

Evaluation of GNU and ALPHA Values from VESYS IIM

Rauhut et al (Ref 50) established a range of GNU and ALPHA values which when used as an input to VESYS IIM will result in reasonable predictions of rut depths for asphalt pavements. Using ALPHA values of 0.6, 0.75, and 0.9 and GNU values of 0.2, 0.8, and 1.5, along with other combinations of input variables, estimates were made of rutting, slope variance, present serviceability index, and remaining service life after a period of five years. Values of GNU and ALPHA were then estimated for rut depths of 5.1 to 10.2 mm (0.2 to 0.4 in.), present serviceability indexes of 2.75 to 3.75, and expected additional life of 5 to 10 years. These values are shown in Fig 22 by the shaded band, the limits of which represent poor and good performances.

Rauhut et al (Ref 50) concluded that only values of GNU and ALPHA falling near or within the shaded band in Fig 22 could be considered to be typical of asphalt concretes used in practice and that while mixtures represented by combinations of GNU and ALPHA substantially outside the band are not necessarily impossible, such mixtures and values should not generally be expected when modern mixture and pavement thickness design procedures are applied. Thus, ALPHA values ranging from 0.68 to 0.93 and GNU values ranging from 0.2 to 1.5 were considered to be realistic (Ref 50).

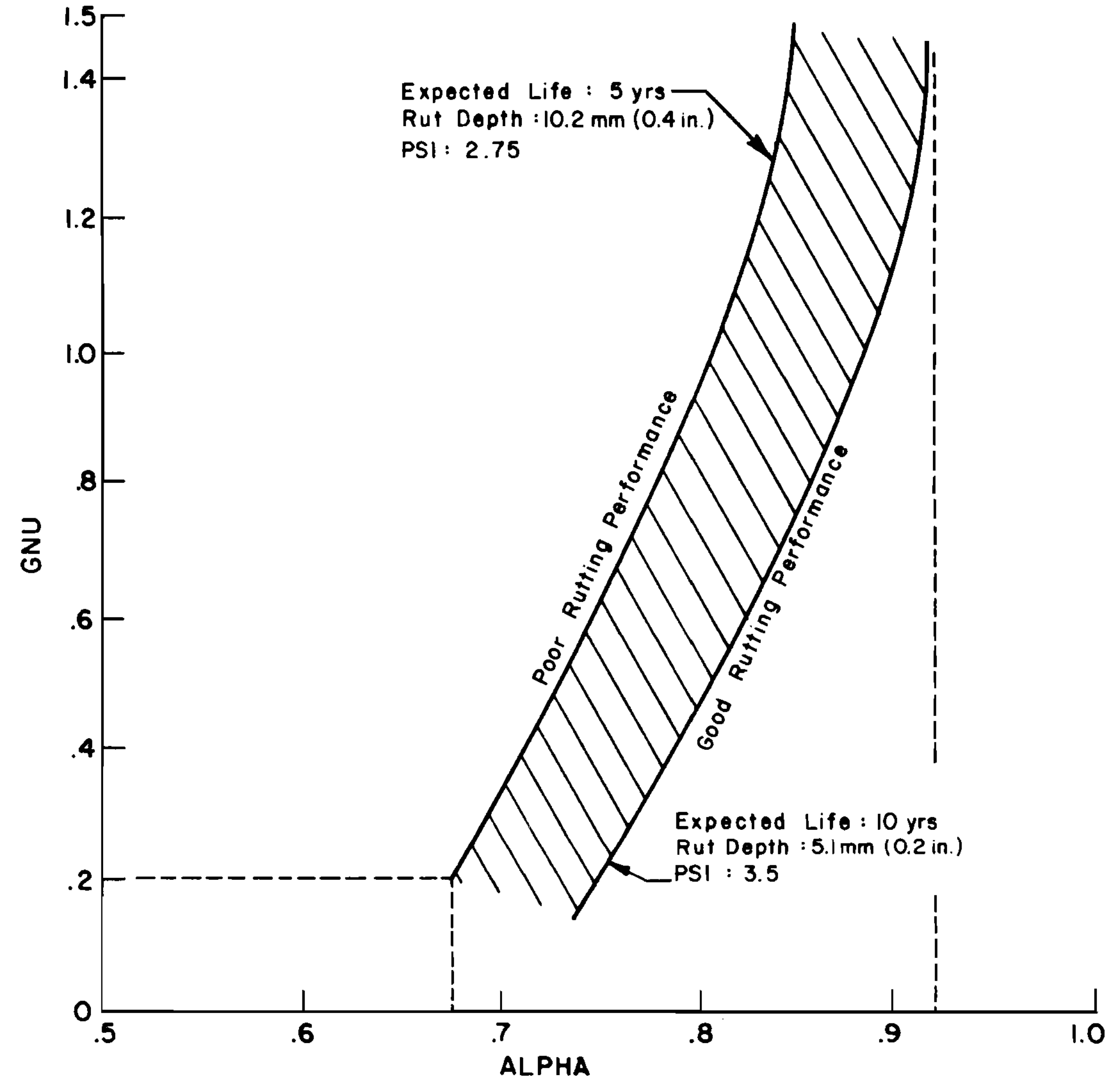


Fig 22. Range of practical GNU and ALPHA values for asphalt concrete (Ref 50).

Figure 23 illustrates typical arithmetic relationships between the number of load applications and both the permanent compressive and tensile strains for the repeated-load indirect tensile test. As shown, the compressive strains generally are slightly larger than the tensile strains. Thus, GNU and ALPHA values can be obtained for either the compressive or tensile strain relationships.

A typical logarithmic relationship between permanent tensile and compressive strains and the number of load applications for the indirect tensile test is shown in Fig 24. The linear portion of these relationships was found to generally occur during the first 10 percent of the loads required to cause failure. In terms of the arithmetic relationships (Fig 23), this portion represents the conditioning zone with the linear stable portion occurring between about 10 and 80 percent of the loads required to cause failure.

Thus, a preliminary analysis was conducted. Four sets of GNU and ALPHA values were calculated. Values characterizing the first 10 percent of the compressive and tensile strain relationships for mixtures with 6 percent asphalt and subjected to a stress of 11 N/cm^2 (16 psi) are shown in Fig 25, and values for the region between 10 and 80 percent are shown in Fig 26. The band of acceptable values for VESYS IIM (Ref 50), which is shown in Fig 22, is repeated in Figs 25 and 26. The GNU and ALPHA values for the relationships between 10 and 80 percent fell outside the range of acceptable values for VESYS IIM. Thus, neither the compressive nor the tensile values were acceptable although it would appear that the compressive values were slightly better. The values obtained for the initial 10 percent of the relationships (Fig 25) were found to be much more realistic. The compressive-strain values for the gravel mixtures fell within the acceptable band while the ALPHA values for the limestone mixtures were low, causing the points to fall to the left of the acceptable band. The values obtained from the tensile values were scattered over a range of ALPHAS. Thus, the ALPHA and GNU values for the initial 10 percent of the compressive strain relationships were found to be slightly better. In addition, since in a pavement the permanent compressive strains in the vertical direction produce rutting, especially when horizontal tensile strains are present, primary emphasis will be placed on the evaluation of the permanent compressive strains. This is also more convenient since the compressive vertical strains are larger and therefore easier to measure.

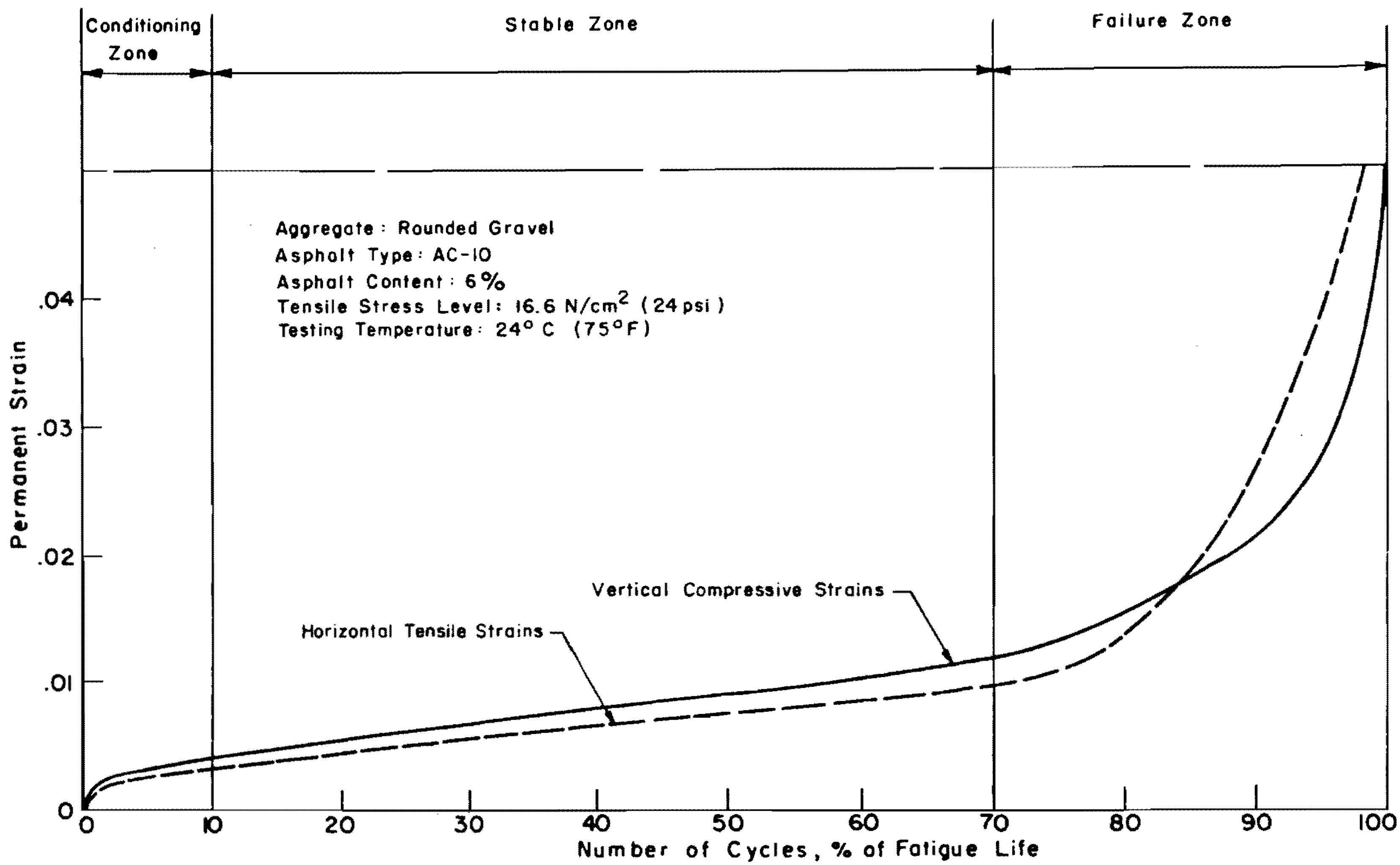


Fig 23. Typical relationships between number of loads and permanent tensile and compressive strains for the repeated-load indirect tensile test.

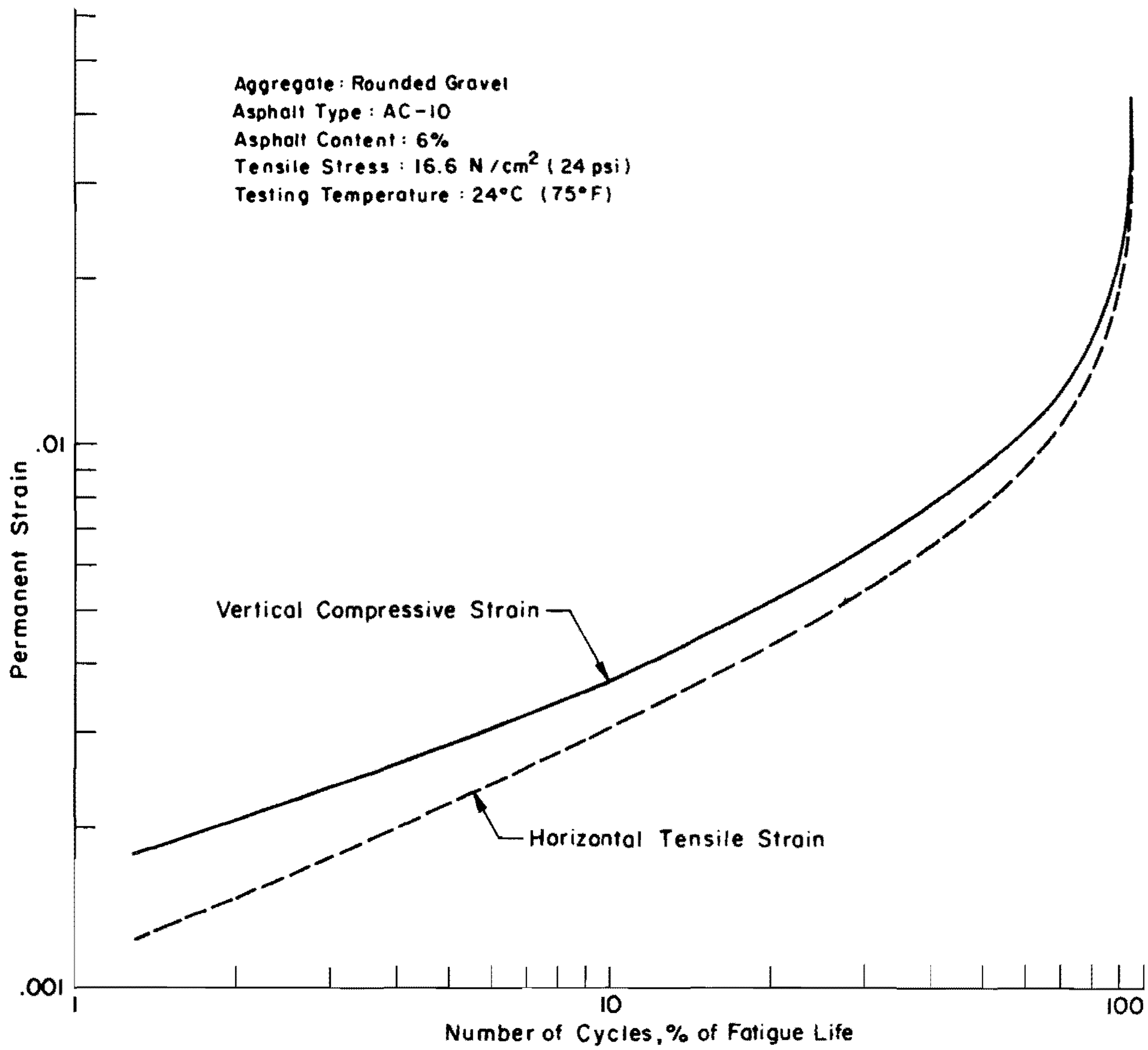


Fig 24. Typical logarithmic relationships between permanent strains and number of load repetitions for the repeated-load indirect tensile test results.

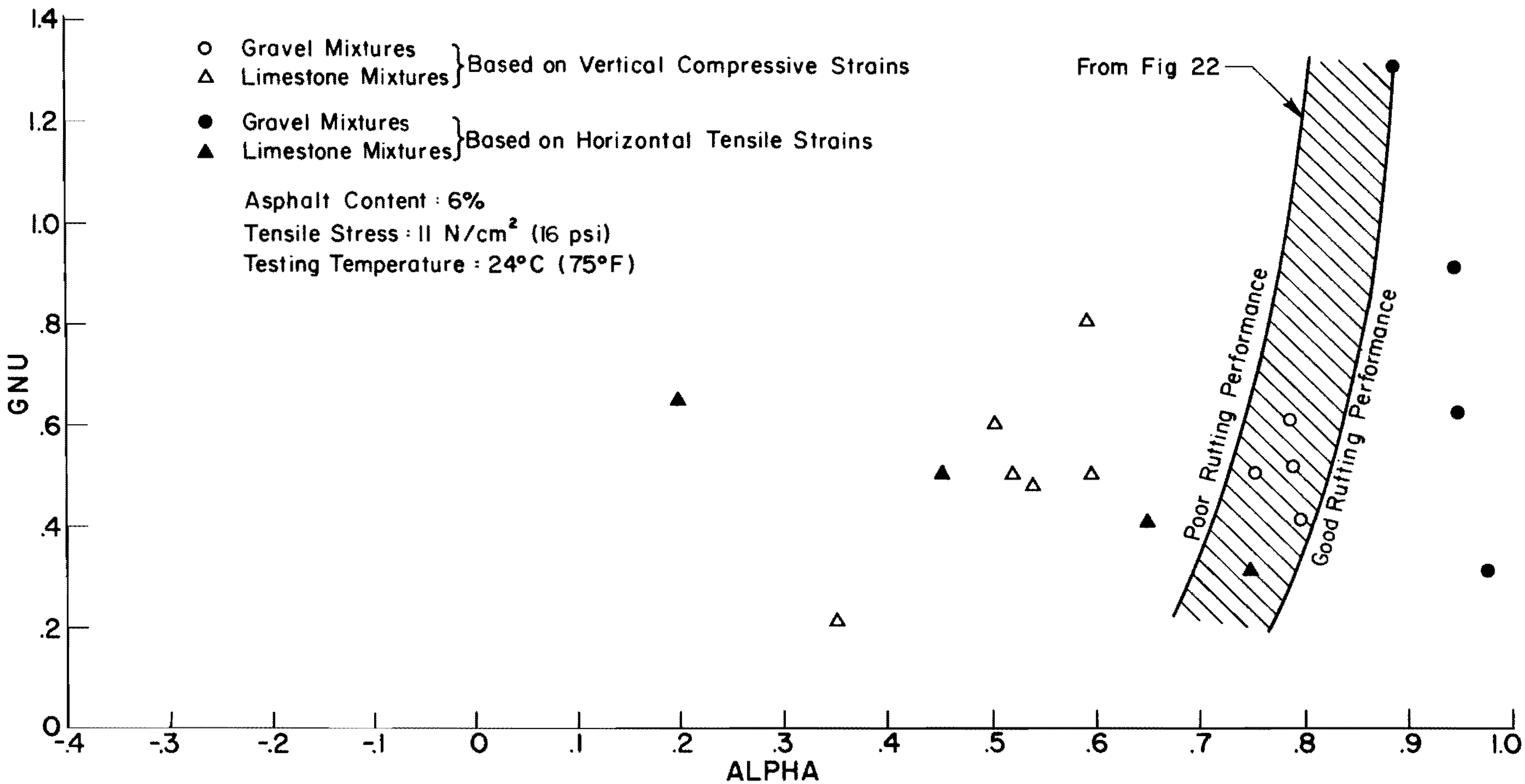


Fig 25. GNU and ALPHA values obtained from the initial 10 percent of the permanent strain relationship.

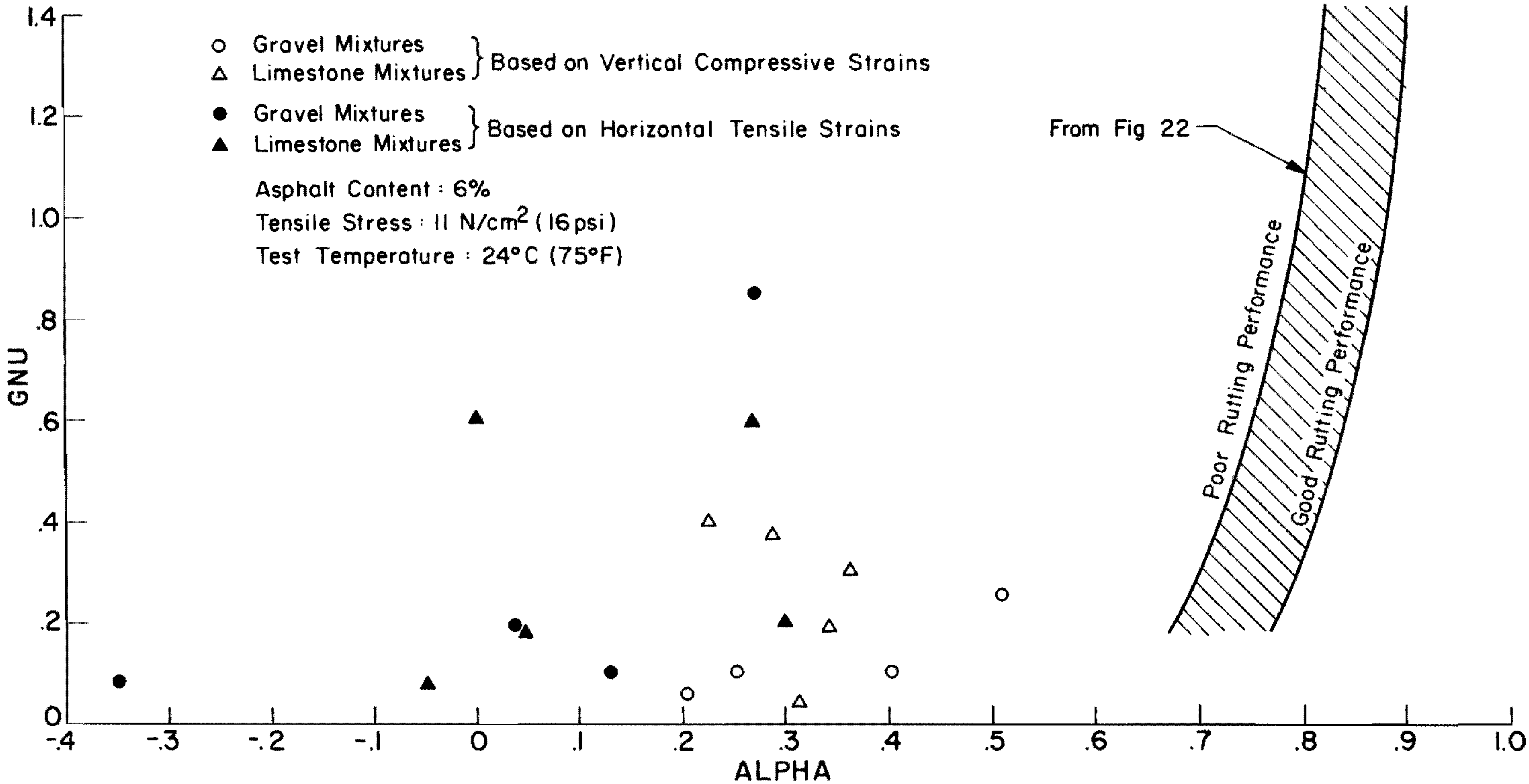


Fig 26. GNU and ALPHA values obtained from the 10 to 80 percent region of the permanent strain relationship.

Evaluation of Permanent Strain Relationships

A primary concern of the concept of ALPHA and GNU is the nature and shape of the permanent strain relationships. To obtain workable values of GNU and ALPHA for VESYS IIM, it is necessary to characterize the first 10 percent of the permanent strain relationship, which does not represent the life of the mixture. In addition, Rauhut et al (Ref 50) apparently found that for triaxial compression tests the logarithmic relationship between permanent strain and load cycles was not linear and that it was necessary to fit the linear relationship through the last two points for which data were available (Fig 27) to obtain reasonable values of GNU and ALPHA. Using the same approach for the repeated-load indirect tensile test resulted in small values of ALPHA which Rauhut et al (Ref 50) attributed to the repeated-load indirect tensile test and the high deviator stresses which were causing failure. A preliminary evaluation of the relationships obtained by Haas et al for triaxial stresses with an axial tensile stress indicated that these relationships were similar to those obtained for the repeated-load indirect tensile test (Fig 28).

Thus, it was felt that the relationships between permanent strain and number of load applications should be evaluated in more detail since

(1) the logarithmic relationships for the various tests are not linear, as assumed in the development of GNU and ALPHA,

(2) the nature and shape of the relationships are different, and

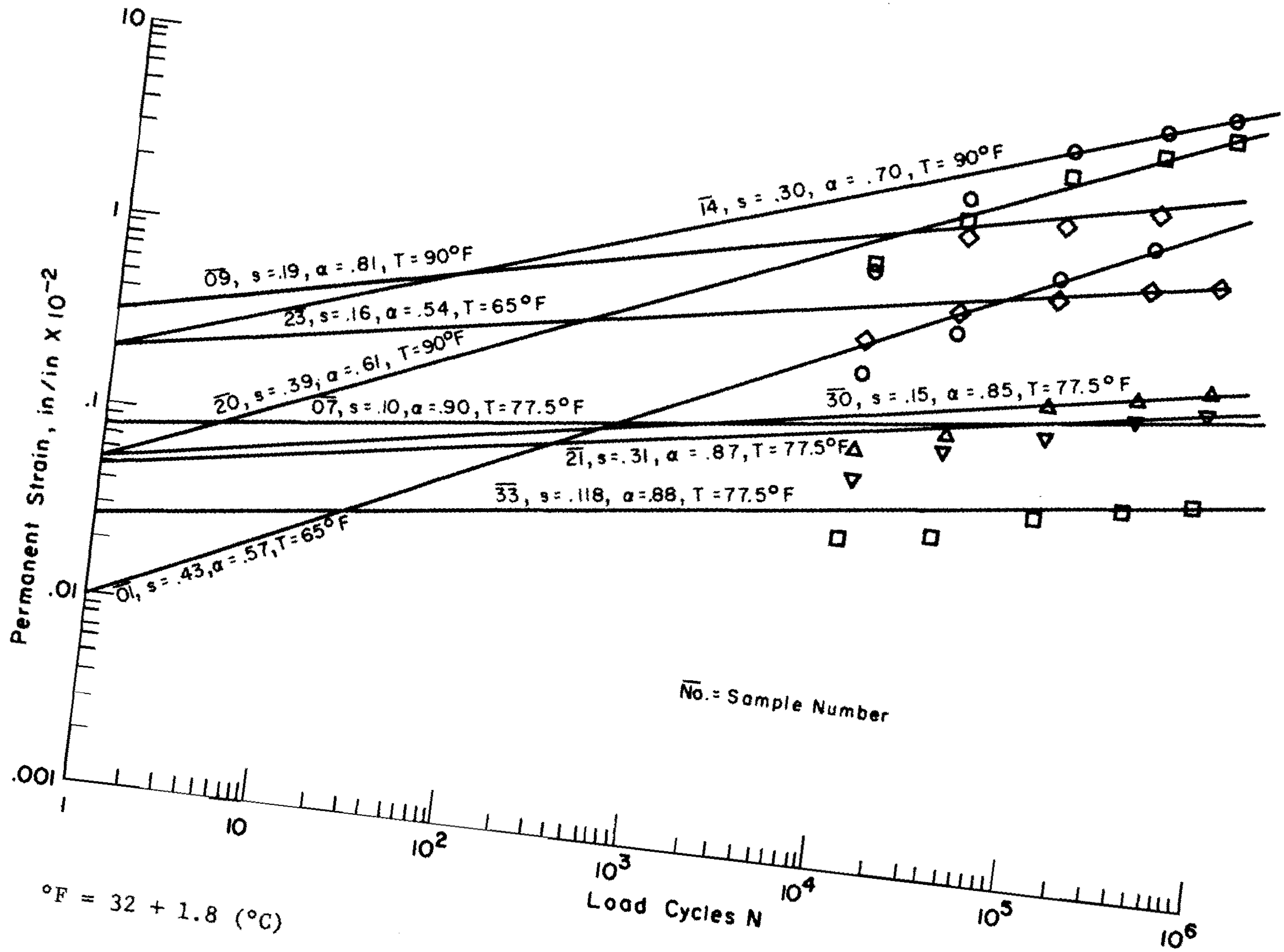
(3) the methods of analysis required to obtain realistic values are different.

Essentially two different modes of testing have been used to obtain values of GNU and ALPHA, compressive tests and tensile tests. The compressive tests reproduce the zone above the neutral axis of the asphalt layer in which the vertical and horizontal stresses are compressive; the tensile tests simulate the zone below the neutral axis in which the vertical stresses are compressive and the horizontal stresses are tensile. Three basic types of tests have been used:

(1) triaxial compressive tests,

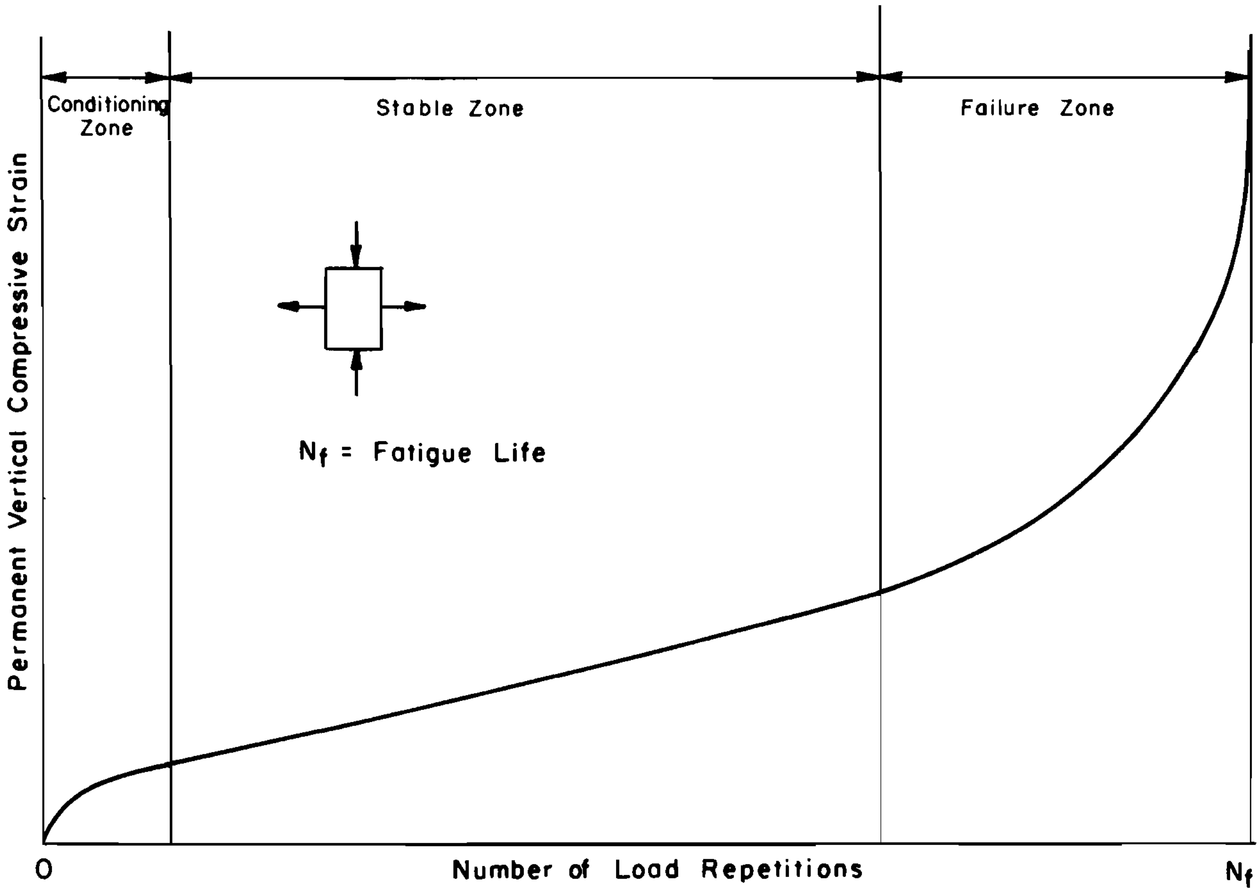
(2) triaxial tests with compressive confining stresses and tensile axial stresses, and

(3) indirect tensile tests which involve horizontal tensile stresses and compressive vertical stresses.

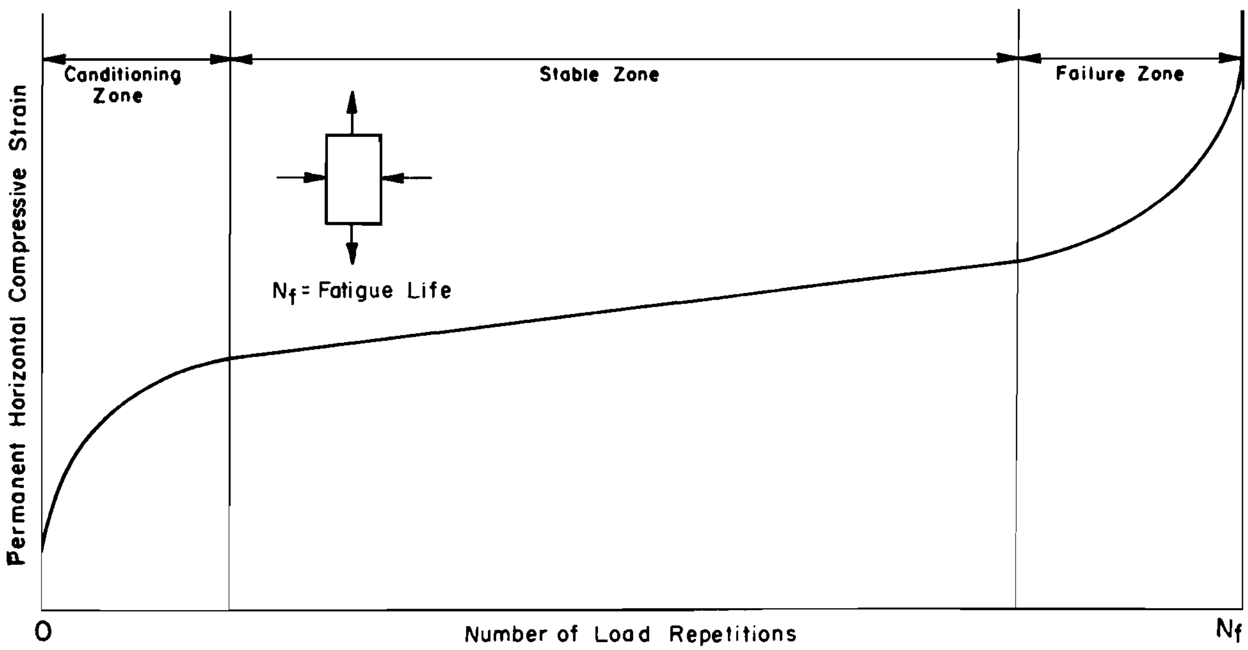


°F = 32 + 1.8 (°C)

Fig 27. Plots of permanent strain versus load cycles for Brampton asphaltic concrete base (Ref 50).



(a) Repeated-load indirect tensile test.



(b) Triaxial test with a tensile stress.

Fig 28. Permanent strain relationships for tests involving tensile stresses.

As previously mentioned, a comparison of the latter two types, both of which involve tensile stresses, indicates that the permanent compressive strain relationships are similar (Fig 28) but are different from the relationships for the triaxial compressive test.

Typical permanent strain relationships for compressive and tensile tests are shown in Fig 29. For compressive tests the semilogarithmic relationship appears to have 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 36 and 43). Thus, the permanent compressive strain relationships and behavior for tests with tensile strains are apparently different from the behavior for tests with all compressive stresses.

Since the behavior differs for tensile and compressive tests and is different from the relationship used to develop the theory, it is mandatory that the effect of the differences be evaluated.

The parameter ALPHA is difficult to define and determine for both tensile and compressive tests since a linear logarithmic relationship is assumed and ALPHA is equal to $1 - S$, where S equals the slope.

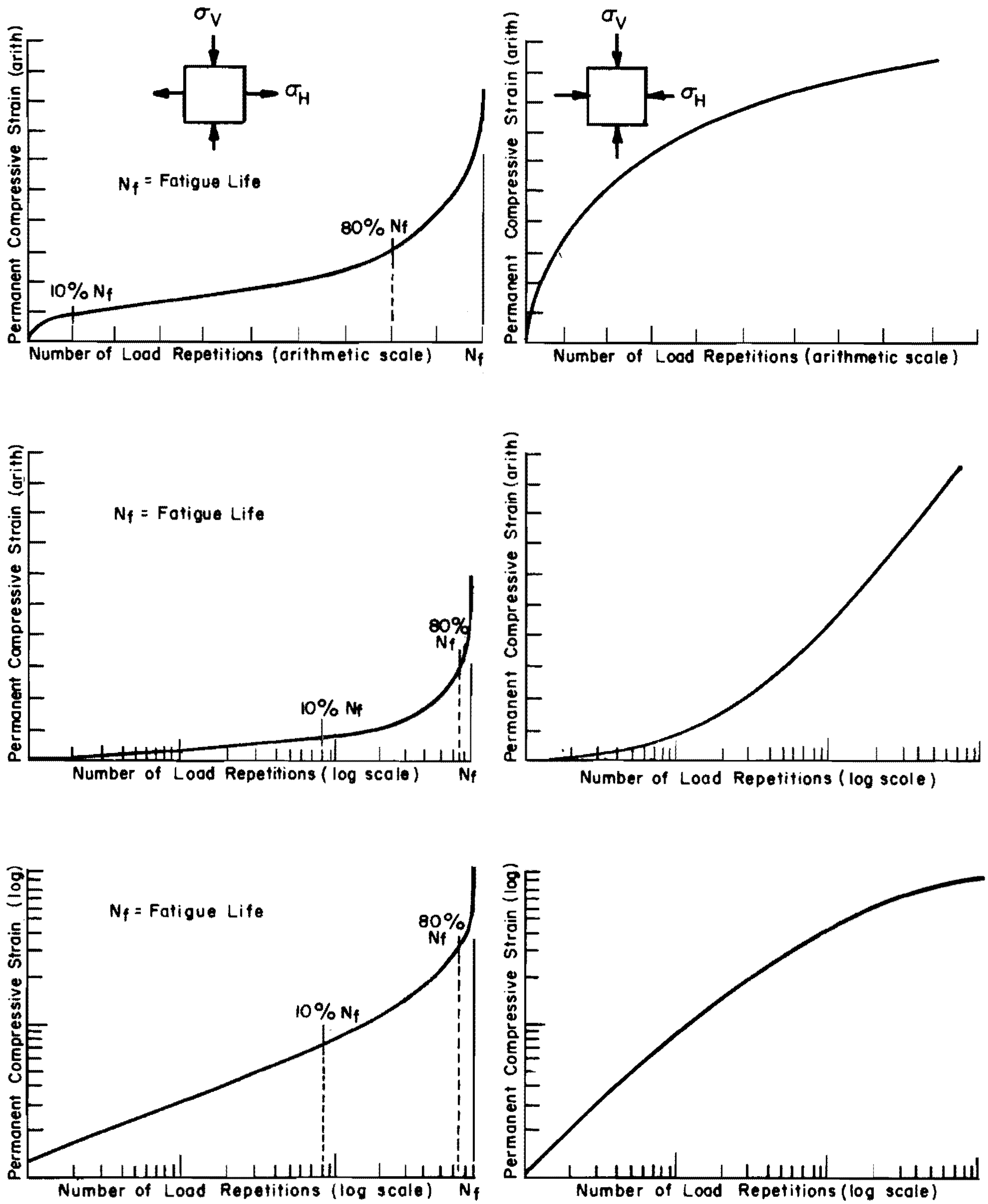
For the repeated-load indirect tensile test and triaxial tests involving tensile stress, the logarithmic relationship is essentially linear during the initial load applications. Subsequently, however, the slope increases with increased load applications; thus, the value of ALPHA approaches a value of zero prior to actual failure. This occurs because the arithmetic relationship is linear, which means the logarithmic relationship takes the form

$$\log \varepsilon_p = \log (mN + b) \tag{14}$$

where

m = the slope of the arithmetic relationship and

b = the intercept of the arithmetic relationship.



(a) Tensile test. (b) Compressive test.

Fig 29. Typical arithmetic and logarithmic permanent strain relationships for tensile and compressive tests.

For an intercept value b of zero,

$$\log \varepsilon_p = \log m + 1.0 \log N. \tag{15}$$

Thus, for intercept values of zero, the slope will be equal to 1.0. At low values of N the value of b will be more important and will cause the slope to be less than 1; however, as N continues to increase, b will become relatively small and the slope will approach a value of 1.0. Therefore, for tests involving tension, the approximate region between 10 and 80 percent of the fatigue life will be characterized by an ALPHA which is small and approaches zero. It should be noted that this is due to the fact that the arithmetic relationship is linear, which causes the logarithmic relationship to have a slope of 1.0.

On the other hand, for triaxial tests involving compressive stresses, the arithmetic and logarithmic relationships are nonlinear, although the logarithmic relationship appears to become more linear with an increased number of loads. Nevertheless, the slope of the logarithmic relationship tends to decrease with increased number of loads such that ALPHA tends to increase and approach a value of 1.0.

Thus, ALPHA is dependent on the type of test and the portion of the permanent strain relationship which is characterized. It is assumed that the original concept was developed for dynamic compression tests and that the concept of ALPHA will be improved as additional information is developed, especially for tests involving tensile stresses, which simulate the lower portion of the pavement in which the major amount of rutting can occur (Ref 43).

The GNU parameter is more difficult to evalute since it is a function of the slope of the logarithmic relationship, the arithmetic value of the intercept of the logarithmic relationship, and the inverse of the resilient strain and, therefore, has no real physical meaning. According to Rauhut et al (Ref 50), GNU for asphalt mixtures is quite variable and may be as high as 2.0. Nevertheless, GNU is highly dependent on the slope, which is directly involved as an input and which influences the actual value of the intercept value I .

Based on work reported by Rauhut et al (Ref 50) and work summarized in this report, it is concluded that in order to obtain workable values of GNU and ALPHA the permanent deformation relationships for triaxial compressive tests must be characterized at a relatively large number of load applications, while tests involving tensile stresses must be characterized in the initial portion of the permanent strain relationship in order to obtain reasonable values. Thus, it is recommended that the concept of ALPHA and GNU be re-evaluated in order to improve their ability to characterize the permanent strain characteristics of asphalt mixtures for use in VESYS IIM.

Comparison of GNU and ALPHA Values from Different Test Methods

The GNU and ALPHA values obtained from different test methods (Ref 50) were compared with the values obtained from the repeated-load indirect tensile test in terms of stress difference, or deviator stress, and testing temperature. Most of the values obtained from the literature were for mixtures tested under triaxial compressive stresses. Some values, however, were obtained for mixtures tested under a state of stress similar to the one used in the repeated-load indirect tensile test, in which the zone below the neutral axis is simulated. Since the data for the other test methods were presumably for mixtures at or near an optimum asphalt content, only GNU and ALPHA values from repeated-load indirect tensile tests on optimum mixtures were included in the comparison. For the reasons previously discussed, the values for the compressive tests were obtained at a relatively high number of load applications while the values for the tensile tests were obtained from the initial 10 percent of the relationship between permanent strain and the number of cycles to failure.

Figure 30 compares ALPHA values for different tests and illustrates the relationship between ALPHA and stress difference for the different types of tests and testing temperatures. The range of ALPHA values was 0.37 to 0.90 with values for the repeated-load indirect tensile test in the range of 0.03 to 0.80; however, the majority of the values are well within the range of values produced by the other tests. In addition, it appears that ALPHA tends to decrease with increased stress difference.

The relationship between GNU and stress difference for different test methods and testing temperatures is shown in Fig 31. The range of values for all tests except the indirect tensile test was 0.12 to 4.80. Values for the indirect tensile test were in the range of 0.02 to 2.40, with most of the values in the range of 0.1 to 1.0. Rauhut et al (Ref 50) proposed that values greater than 1.80 should not be considered since these values would occur only at low stress differences. If this is true, then the range of GNU values for

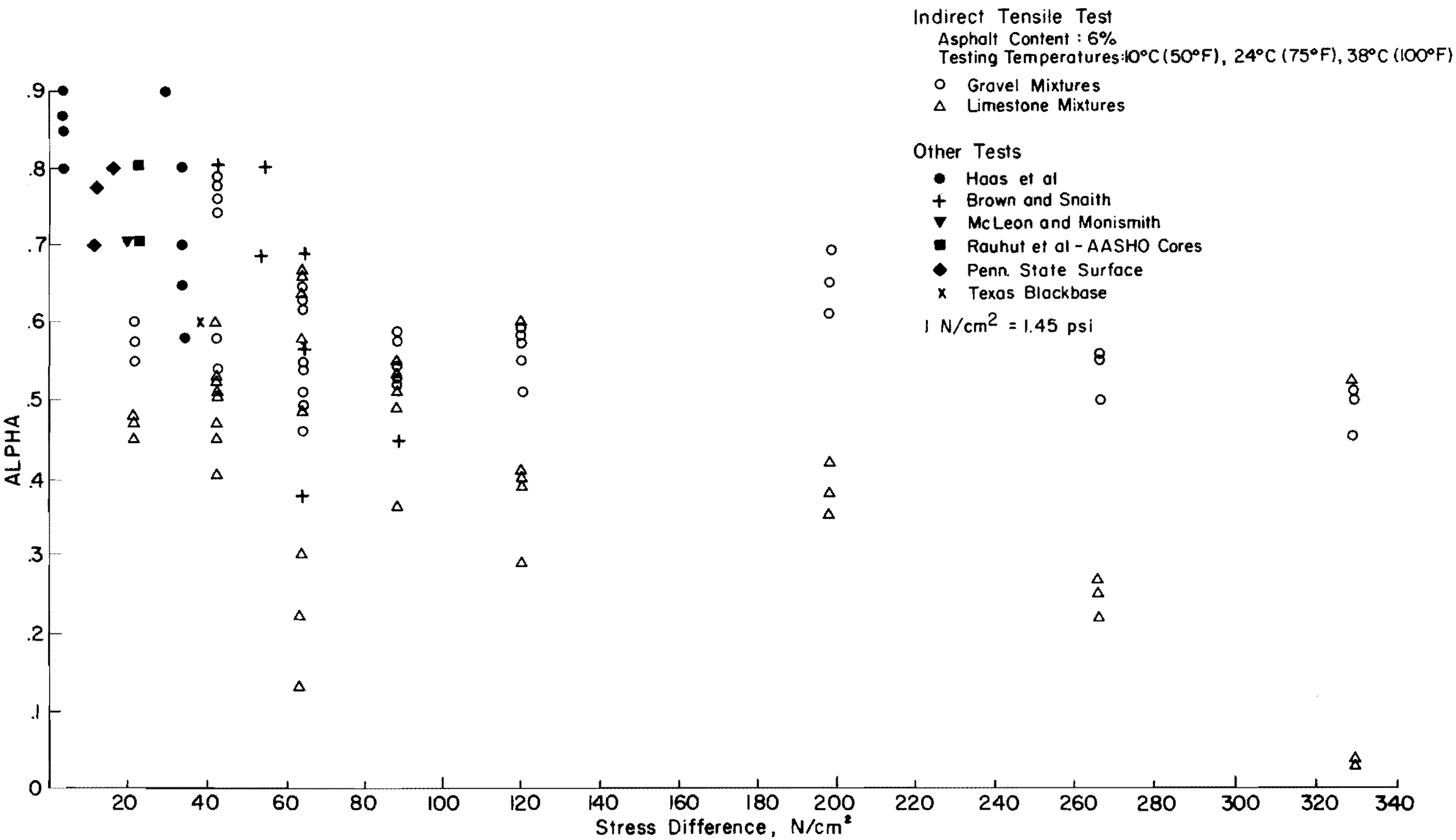


Fig 30. Relationship between ALPHA and stress difference for different test methods.

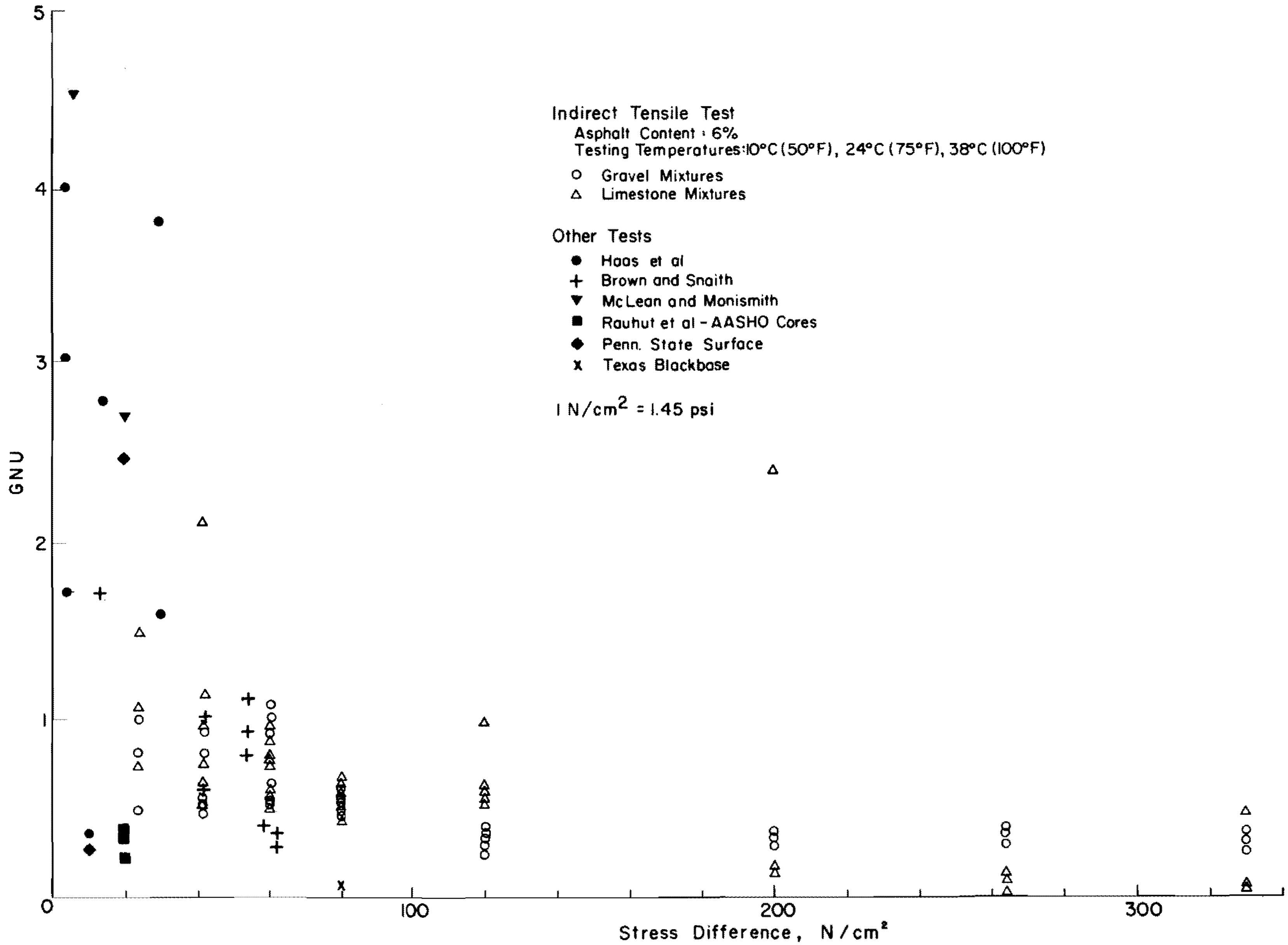


Fig 31. Relationship between GNU and stress difference for various test methods.

the other tests would be from 0.12 to 1.80, which makes repeated-load indirect tensile test values compare even more favorably. It also appears that stress difference has very little effect on the magnitude of GNU.

The interrelationship between GNU and ALPHA was also analyzed. Rauhut et al (Ref 50) plotted all data available for ALPHA and GNU at the time of their analysis, as shown in Fig 32, in which the region defined by A, B, C, D, and E corresponded to GNU and ALPHA values tested under stress differences between 13.8 and 62.1 N/cm^2 (20 and 90 psi). They concluded that the data fell into three distinct groups, depending on stress difference, and that the indirect tensile test values fell into a high stress difference region. Unfortunately, these values were the only values in this region and, therefore, it is difficult to conclude that stress level is the reason for the observed difference. An analysis of values obtained in this study does not, however, substantiate the observation that the values can be grouped according to stress difference since values obtained by the indirect tensile test do not fall into any particular region.

EVALUATION OF PERMANENT STRAINS

The second phase of the evaluation of the repeated-load indirect tensile test was a comparison of the permanent strains obtained using this testing technique with the permanent strains obtained in other experiments using other testing techniques. Values of permanent compressive strains obtained from specimens containing different asphalt contents and aggregates and tested under the different stress levels and temperatures were

(1) used to develop regression equations for permanent strains of laboratory specimens and

(2) compared with results obtained by Haas et al using the triaxial test with an axial tensile stress.

Predictive Equations for Permanent Strains

A multiple regression analysis, using STEP-01, was conducted for the permanent strains obtained from the repeated-load indirect tensile test. A regression equation was developed for permanent strains as a function of temperature, stress level, asphalt content, aggregate, air voids, and number of load applications. Preliminary equations were obtained by expressing the number of load repetitions in cycles; however, it was found that the equation

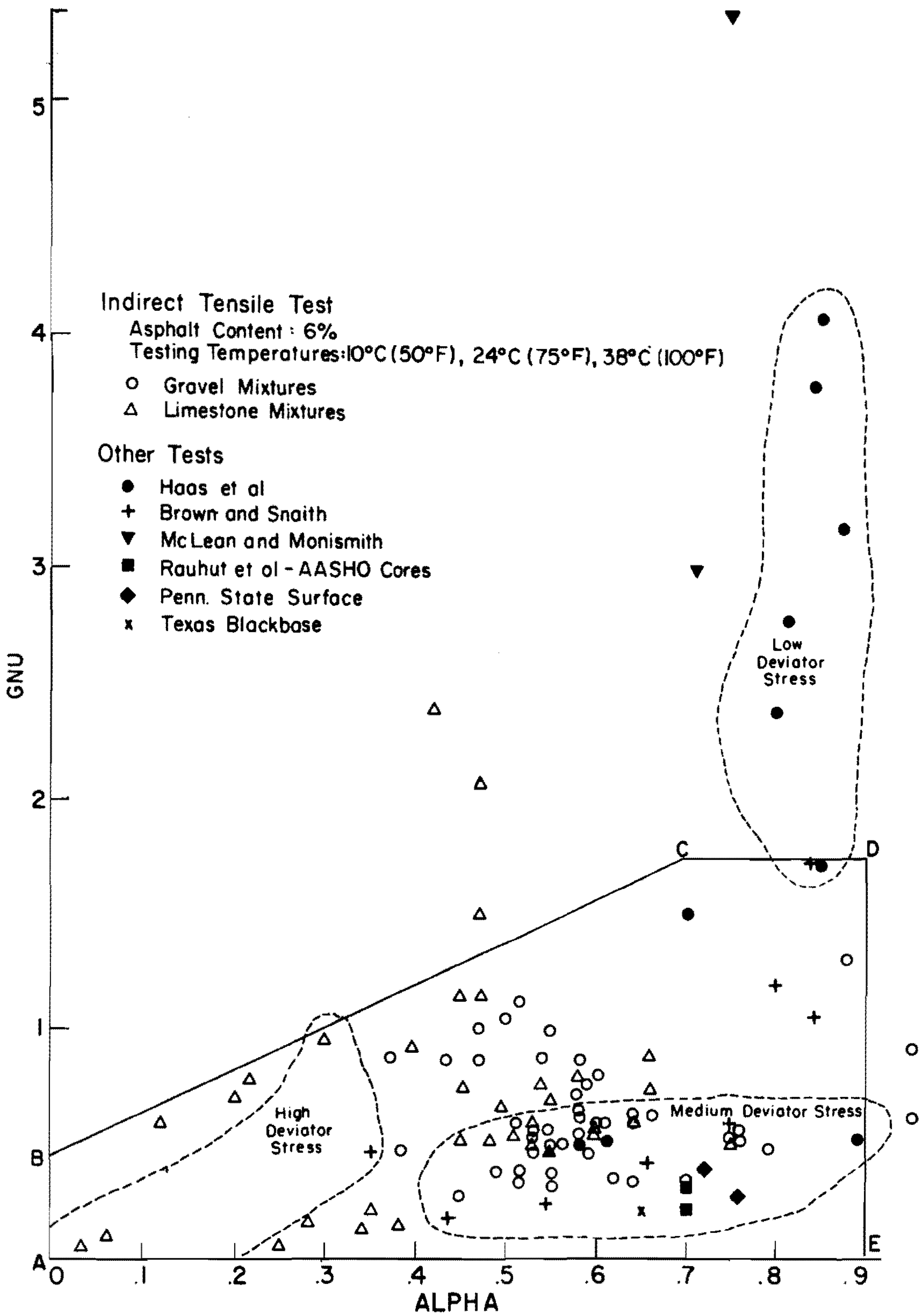


Fig 32. Relationship between GNU and ALPHA for different test methods (Ref 50).

could be simplified and improved by expressing the number of load repetitions as a percentage of fatigue life, percent N_f . The resulting equation, however, was still relatively complex and unwieldy.

Because of this complexity, it was desirable to further simplify the equation. Meyer (Ref 36) assumed that the deformation which occurs during the conditioning phase is a function of testing and is relatively small. Therefore, this portion of the permanent deformation was eliminated. In support of this assumption, Morris and Haas et al (Refs 43 and 44) characterized the slope of the arithmetic permanent compressive strain relationship and successfully predicted rutting for the Brampton Road Test.

Thus, the slope of the arithmetic, permanent compressive relationship from the repeated-load indirect tensile test was estimated to be between 30 and 50 percent of the fatigue life using the regression equation. The resulting equation is

$$y = \frac{-0.10656 + 0.01283AC + 0.001911G + 0.000353T}{N_f} \tag{16}$$

where

y = permanent compressive strain per load application,
AC = asphalt content, percent of total weight of mixture,
G = type of aggregate (10 for gravel, 20 for limestone),
T = temperature, °F*, and
N_f = fatigue life = number of cycles to failure.

Figure 33 illustrates the relationship between the predicted permanent strains per load application and the measured values for the data from which the equation was developed. As shown, the predicted values are essentially the same as the measured values.

The major disadvantage of the equation is the need to have an estimate of fatigue life. However, this is not overly serious since tests to determine fatigue life can be conducted more readily than permanent strain tests, which require deformation measurements. In addition, it may be possible to estimate

* °F = 32 + 1.8(°C).

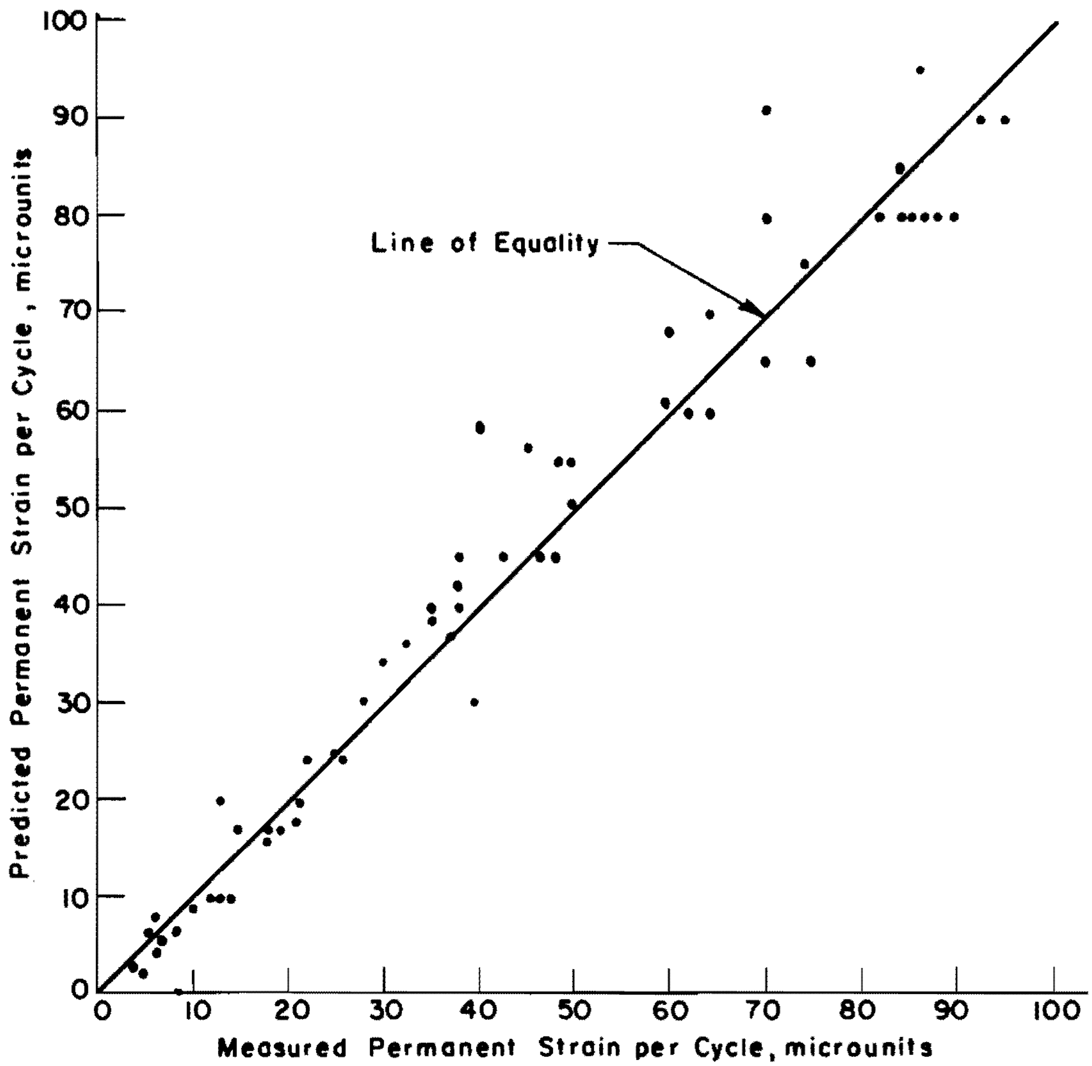


Fig 33. Relationship between measured and predicted permanent strains.

fatigue life by some suitable method, such as equations previously reported in Refs 1 and 6.

Evaluation

The measured and predicted permanent strain results, i.e., the permanent strain per load application, obtained from the repeated-load indirect tensile test were compared with the results obtained by Meyer (36) and Morris and Haas et al (Refs 43 and 44) using triaxial stress conditions similar to the stress conditions of the indirect tensile test.

Unfortunately, permanent strain data with estimates of fatigue life are not readily available for tests other than the repeated-load indirect tensile test. Thus, it was not possible to evaluate the prediction equation directly. Therefore, the first attempt at evaluation utilized the equation developed by Haas et al to estimate permanent strains for the indirect tensile test.

The regression equation developed by Meyer (Ref 36) is

$$\ell n\ y = -0.1305 + 0.8404\ \sigma_a + 0.3261\ \sigma_r + 0.3963\ T + 0.2830\ AV + 0.2217\ \sigma_r \cdot AV \tag{17}$$

where

- y = permanent radial compressive strain per 100,000 load repetitions, percent,
- σ_a = axial tensile stress (-1 for 20 psi and +1 for 40 psi),
- σ_r = radial compressive stress (-1 for 15 psi and +1 for 35 psi),
- T = temperature (-1 for 16° C and +1 for 21° C), and
- AV = air voids (-1 for 2.5 percent and +1 for 10 percent).

This equation was used to estimate the permanent strains for the repeated-load indirect tensile test specimens. Since the conditions were different, including different load frequencies, coded input values were obtained by linear extrapolation and interpolation. Tables 5 and 6 summarize the results.

The measured indirect tensile test values were much larger than the predicted values. Since the load duration used in the indirect tensile test

TABLE 5. CODED VALUES FOR THE INDIRECT TENSILE TEST FOR THE PREDICTIVE EQUATION DEVELOPED BY MEYER (Ref 36)

Tensile Stress σ_a	Code	Compressive Stress σ_r	Code	Temperature	Code
11 N/cm^2 (16 psi)	-1.4	-27.8 N/cm^2 (-48 psi)	2.3	24° C (75° F)	2.2
16.6 N/cm^2 (24 psi)	-0.6	-49.7 N/cm^2 (-72 psi)	4.7	24° C (75° F)	2.2
22.1 N/cm^2 (32 psi)	0.2	-66.2 N/cm^2 (-96 psi)	7.1	24° C (75° F)	2.2
27.6 N/cm^2 (40 psi)	1.0	-82.8 N/cm^2 (-120 psi)	9.5	24° C (75° F)	2.2
33.1 N/cm^2 (48 psi)	1.8	-99.3 N/cm^2 (-144 psi)	11.9	24° C (75° F)	2.2
38.6 N/cm^2 (56 psi)	2.6	-115.9 N/cm^2 (-168 psi)	14.3	24° C (75° F)	2.2

TABLE 6. EXTRAPOLATED AND INTERPOLATED CODED VALUES FOR MEAN VALUES OF AIR VOID CONTENTS FROM INDIRECT TENSILE TEST SPECIMENS AT 24° C (75° F)

	Aggregate									
	Limestone					Gravel				
σ_a \\ % AC-10	4	5	6	7	8	4	5	6	7	8
11 N/cm^2 (16 psi)	0.82	0.16	-0.79	-1.29	-1.46	0.94	0.18	-0.82	-1.25	-0.52
16.6 N/cm^2 (24 psi)	0.91	0.17	-0.84	-1.26	-1.38	0.96	0.15	-0.83	-1.30	-1.58
22.1 N/cm^2 (32 psi)	0.92	0.14	-0.82	-1.29	-1.45	1.07	0.14	-0.92	-1.28	-1.50
27.6 N/cm^2 (40 psi)	0.92	0.19	-0.81	-1.29	-1.48	0.99	0.26	-0.76	-1.32	-1.21
33.1 N/cm^2 (48 psi)	—	—	—	-1.33	—	—	—	—	—	—
38.6 N/cm^2 (56 psi)	—	—	—	-1.40	—	—	—	—	—	—

was much larger than that assumed by Eq 7, it was felt that the effect of load duration, or frequency, should be evaluated.

Previous work on this project (Ref 6) developed the following equation, which related load pulse to fatigue life:

$$\log \hat{N}_f = 13.2424 - 3.4190 \log SD - 0.07899T + 0.9226(PCA) - 0.04795(PCA^2) - 0.02616(AP) + 0.0003621T(AP) - 1.4325(TD + TR) \quad (18)$$

where

$\hat{N}_f$ = estimated fatigue life,

SD = stress difference = applied stress for uniaxial tests,

T = testing temperature, °F,

PCA = percent asphalt cement,

AP = penetration of asphalt cement,

TD = duration of tensile stress, seconds, and

TR = rest period after a tensile stress, seconds.

This equation was used to obtain an estimate of fatigue for a load duration of 0.04 second and a rest period of 0.21 second, which were the values used by Haas. This estimated fatigue life was then used in Eq 16 to obtain a new estimate of permanent strain per cycle, which was then compared to the values predicted by Haas et al using Eq 17. As shown in Fig 34, the indirect tensile test values predicted by the two equations are much closer in magnitude. Thus, it appears that a large portion of the earlier differences can be attributed to the load duration.

As a final check, a small experimental program was conducted involving four specimens which were tested at two different load durations. Two specimens were tested at a load duration of 0.2 second with a rest period of 0.8 second, and two specimens were tested at a load duration of 0.05 second with a rest period of 0.95 second. The specimens were composed of a gravel mixture at the optimum asphalt content of 6 percent and were tested under a repeated tensile stress of 16.6 N/cm^2 (24 psi) at 24° C (75° F), as shown in Fig 21.

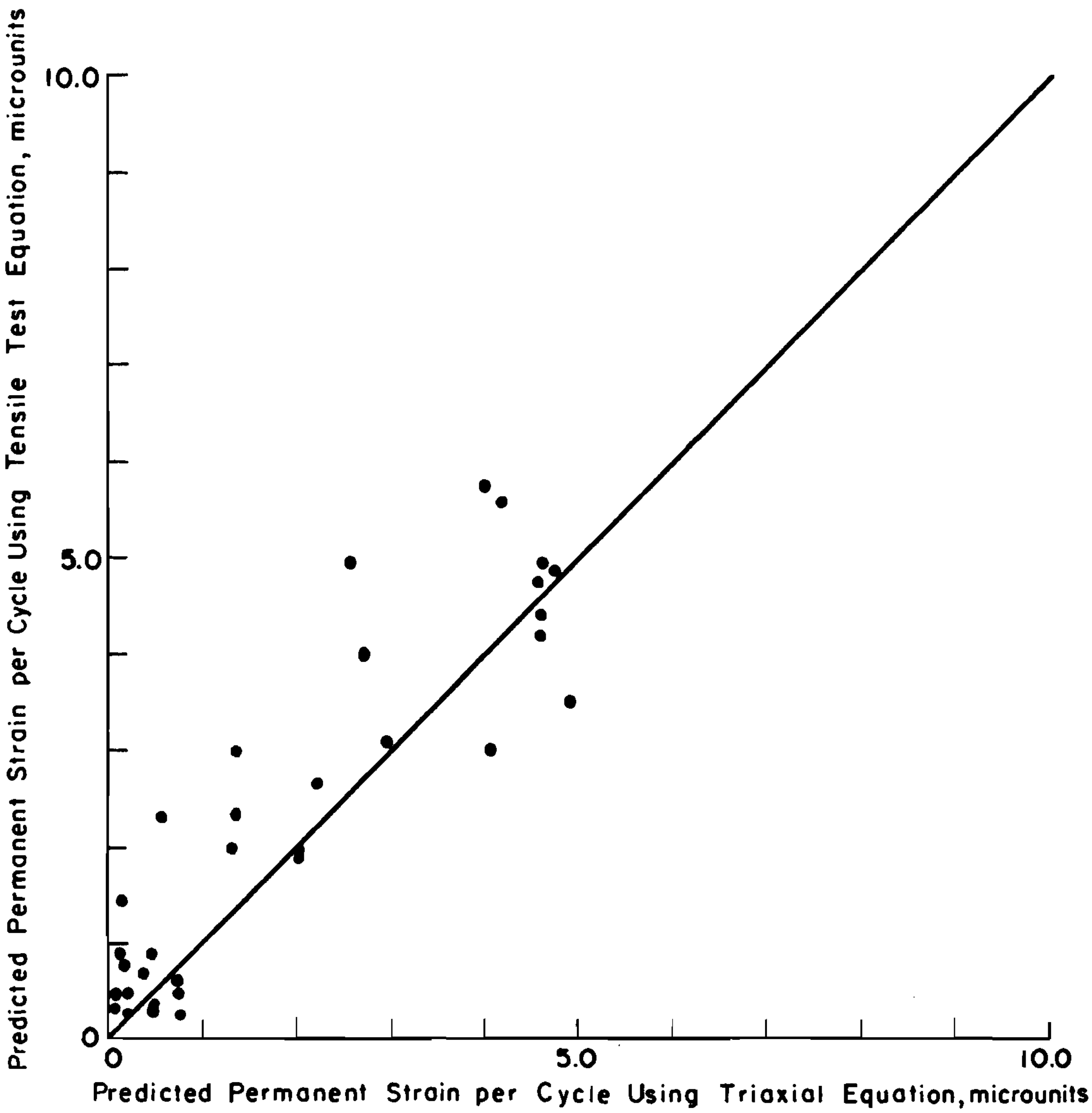


Fig 34. Relationship between predicted permanent compressive strains.

The results are summarized in Table 7 and are shown in Fig 35. As shown in Fig 35, both the permanent strain and fatigue life are significantly affected by load duration.

Using the fatigue lives in Table 7, the indirect tensile test equation (Eq 16) was used to predict the rate of permanent strain for the specimens tested at various load durations. The relationship between the predicted and measured strain rates is shown in Fig 36.

In addition, the triaxial equation developed by Haas et al (Eq 17) was used to predict the permanent strain rate for an indirect tensile test for a load duration of 0.04 second, which was estimated from Fig 35. The measured and predicted relationships are shown in Fig 37.

Based on the above analysis, it appears that the equation developed by Haas et al can be used to estimate permanent strains not only for the Brampton Road Test but also for the laboratory values obtained using the repeated-load indirect tensile test. Consequently, it appears that the repeated-load indirect tensile test provides reasonable estimates of permanent strain. However, it is evident that for most higher-speed highway situations the load duration must be shortened in order to simulate field conditions. This change should also improve the predictive capability for fatigue behavior.

TABLE 7. EFFECT OF LOAD DURATION ON PERMANENT STRAIN PER CYCLE OF LOAD

Specimen	Load Duration, sec.	Rest Period, sec.	Permanent Strain Per Cycle, microunits	Fatigue Life, cycles
1 G	0.05	0.95	0.16	31,778
2 G			0.11	—
3 G	0.20	0.80	4.0	3,175
4 G			3.6	3,780
405 G	0.40	0.60	10.8	1,217
546 G			9.8	1,594

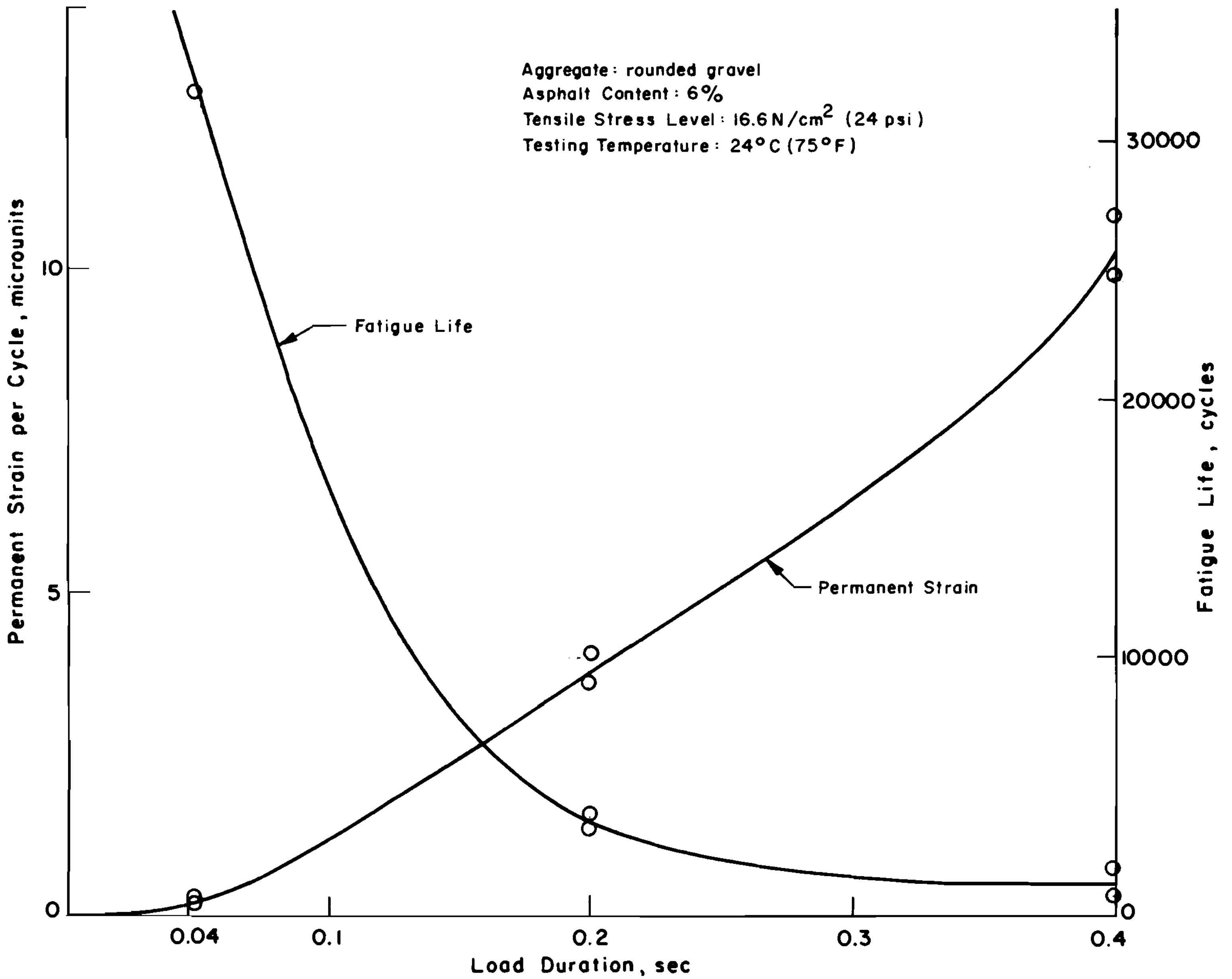


Fig 35. Relationship between load duration and both permanent strain and fatigue life.

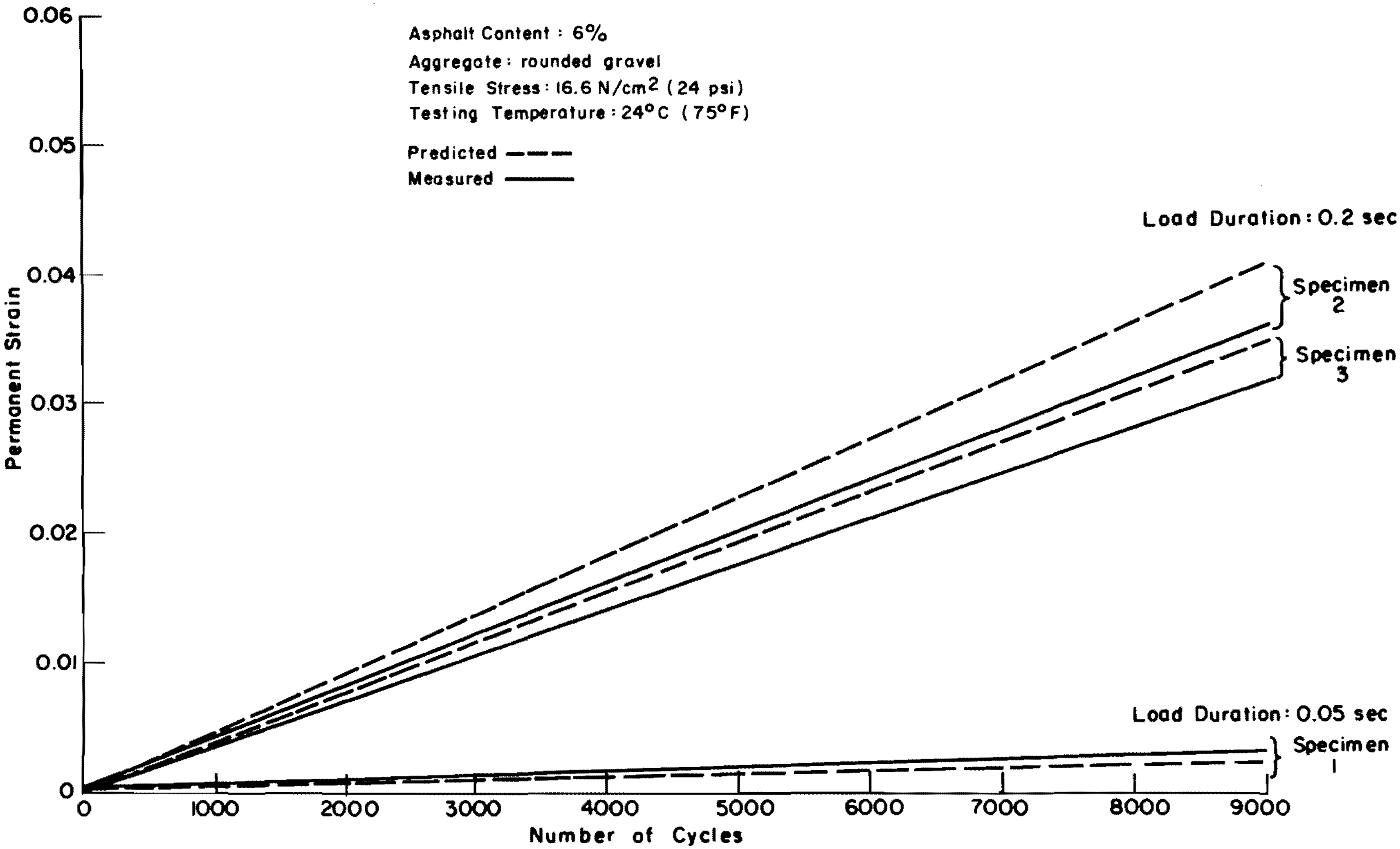


Fig 36. Comparison between predicted and measured values from the repeated-load indirect tensile test.

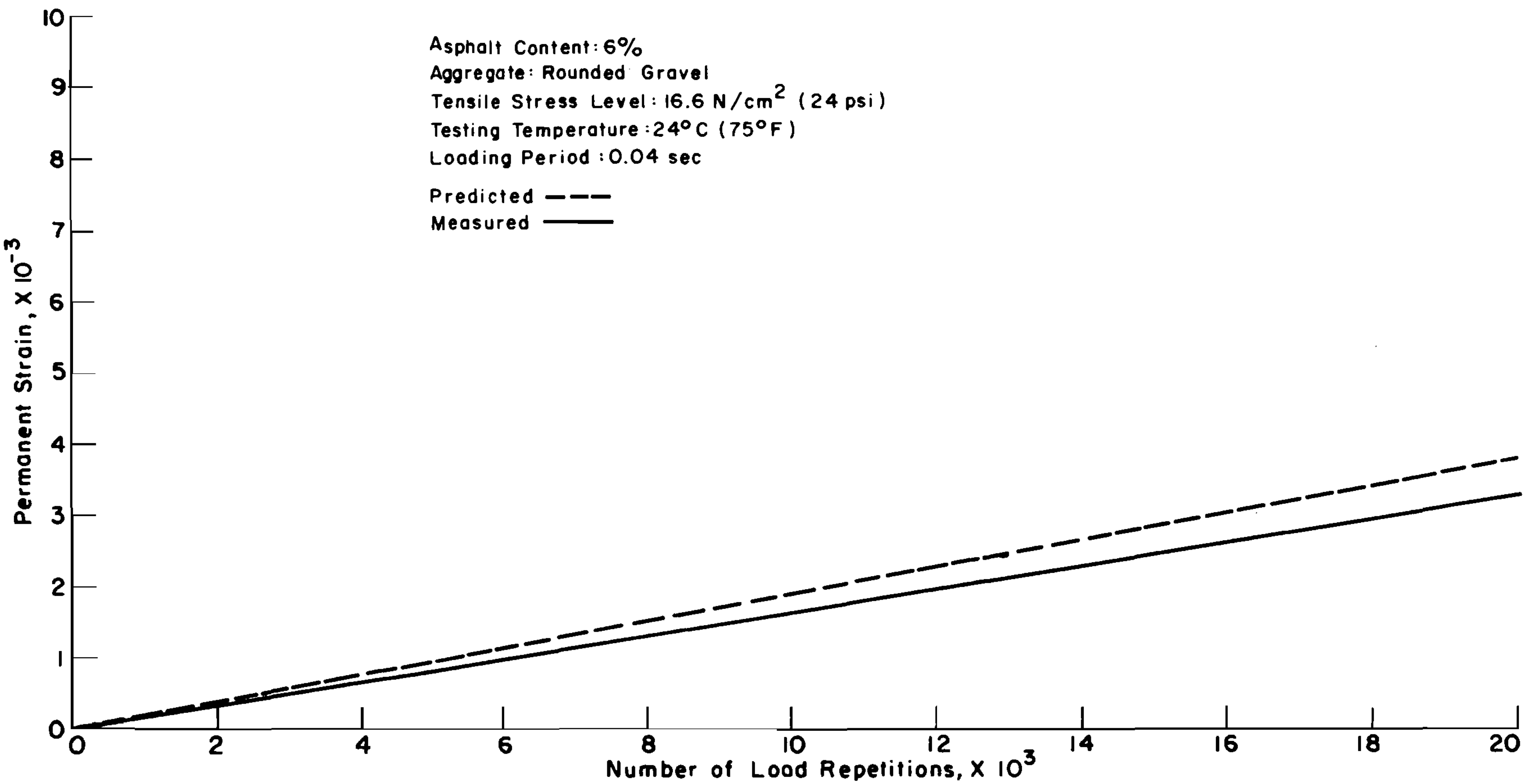


Fig 37. Comparison of predicted permanent strain per cycle by triaxial equation with measured values from the indirect tensile test.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report presents the findings of a preliminary study of the repeated-load indirect tensile test as a means of characterizing asphalt materials for permanent deformation analysis.

Laboratory-prepared specimens of two asphalt mixtures containing either gravel or limestone aggregates and various percentages of asphalt cement (AC-10) were subjected to repeated indirect tensile stresses. Permanent strain measurements were recorded and evaluated by comparing them with permanent strain information from other test methods. The strains were also evaluated by obtaining the parameters GNU and ALPHA and comparing them with GNU and ALPHA values obtained from other test methods and with values that work in the Federal Highway Administration's VESYS IIM design system.

Based on the results of this preliminary analysis, the following conclusions and recommendations have been made.

CONCLUSIONS

(1) The repeated-load indirect tensile test can be used to estimate the permanent deformation characteristics of asphalt materials.

(2) Realistic values of ALPHA and GNU, permanent deformation properties used in VESYS IIM, can be obtained. The analysis, however, suggests that the two properties are dependent on whether the stresses are compressive or tensile and are dependent on which portion of the permanent strain versus load cycles relationship is used.

(3) The permanent compressive strain relationships for the indirect tensile test and for the triaxial tests with an axial tensile stress are similar, but both are different from the permanent compressive strain relationships for triaxial compression tests.

   (a) The logarithmic relationship for the tensile test is linear for the first 10 percent of the load and then begins to increase with the slope approaching a value of 1.0 prior to failure.

   (b) The strain, on a logarithmic basis, in a triaxial compression test increases, but at a decreasing rate until the slope approaches zero after a large number of load cycles.

(4) ALPHA values must be estimated for the first 10 percent of the relationship for the tensile test and at a larger number of load applications for the compressive test in order to be realistic for use in VESYS IIM.

(5) ALPHA values for the repeated-load indirect tensile test were generally in the range of 0.3 to 0.8; GNU values were generally in the range of 0.2 to 1.0. These values compare favorably with values reported for other test methods.

(6) Predictive equations developed by Haas which successfully predicted rutting at the Brampton Road Test were able to predict the permanent compressive strains obtained using the repeated-load indirect tensile test. These predictions required a correction for load duration which was different for the two test programs.

RECOMMENDATIONS

(1) The repeated-load indirect tensile test should be used to estimate rutting for an actual pavement or test section in order to verify and improve, if required, the testing method.

(2) The means for characterizing GNU and ALPHA should be carefully examined for possible improvements, regardless of the potential test methods that can be used, since the values derived are dependent largely on interpretation. Such improvements should serve to enhance the prediction and analysis capabilities of VESYS IIM.

(3) Additional experimental work should be conducted to improve the predictive capability of the repeated-load indirect tensile test. It is not anticipated, however, that additional work will be conducted as a part of this project.

(4) The load duration in the indirect tensile test should probably be decreased and the frequency increased to more closely simulate field loading conditions. This will also decrease the testing time required.

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