TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-93-1177-1F		

4. Title and Subtitle RESILIENT MODULUS OF ASPHALT CONCRETE	5. Report Date November 1991; revised April 1992
	6. Performing Organization Code
7. Author(s) D.N. Little, W.W. Crockford, V.K.R. Gaddam	8. Performing Organization Report No. Research Report 1177-1F
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, TX 77843-3135	10. Work Unit No.
	11. Contract or Grant No. Study No. 2/3-10-8-89/0-1177
12. Sponsoring Agency Name and Address Texas Department of Transportation Division of Transportation Planning P.O. Box 5051 Austin, TX 78763	13. Type of Report and Period Covered Final: March 1989 - August 1991
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportion and the U.S. Department of Transportation, Federal Highway Administration.
Research Study Title: Development of Routine Resilient Modulus Testing for Use with the New AASHTO Pavement Design Guide

16. Abstract

The 1986 AASHTO Guide for Design of Pavement Structures incorporates the resilient modulus of pavements into the procedure. This parameter is analogous to one of the two constants used for linear elastic models of material behavior. Mechanistic models that incorporate parameters such as the modulus are being explored in current major research efforts that may replace the AASHTO Guide in the future.

At present, the Texas Department of Transportation does not routinely perform resilient modulus tests. Several approaches to measurement of the modulus of asphalt concrete have been developed in this study to provide the Department with the capability to perform this test in support of both design activities and corroboration of nondestructive field testing. Techniques were developed that can be modified easily to incorporate new research findings and procedures oriented toward mechanistic design methods.

17. Key Words	18. Distribution Statement
Resilient Modulus, Asphalt Concrete	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	152	

RESILIENT MODULUS OF ASPHALT CONCRETE

by

Dallas N. Little
William W. Crockford
Venkata Krishna Reddy Gaddam

Research Report 1177-1F

Development of Routine Resilient Modulus (M_R) Testing for Asphalt Bound Materials

Conducted for

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

by the

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas 77843-3135

November 1991; revised April 1992

SUMMARY

The 1986 AASHTO Guide for Design of Pavement Structures incorporates the resilient modulus of the pavements into the procedure. This parameter is analogous to one of the two constants used for linear elastic models of material behavior. Mechanistic models that incorporate parameters such as the modulus are being explored in current major research efforts that may replace the AASHTO Guide in the future.

At present, the Texas Department of Transportation does not routinely perform resilient modulus tests. Several approaches to measurement of the modulus of asphalt concrete have been developed in this study to provide the Department with the capability to perform this test in support of both design activities and corroboration of nondestructive field testing. A production testing technique was attempted, as well as techniques that can be modified easily to incorporate new research findings and procedures oriented toward mechanistic design methods.

Two test configurations were selected for development. The uniaxial compression test with sinusoidal loading can be used with a wide range of materials and stress conditions. A procedure was developed that can be used for relatively short field cores. The diametral indirect tension test can be conducted very quickly on short (two inches) specimens of dense graded asphalt concrete. In both test configurations, the capability to measure Poisson's ratio in addition to the resilient modulus has been provided.

IMPLEMENTATION

Test methodology developed in this study will provide expedient and flexible testing to quantify moduli for asphalt concrete surface courses and other asphalt bound materials. These moduli can be used together with nondestructive back-calculation techniques in pavement design and maintenance and will provide materials data necessary as input to the 1986 AASHTO Guide.

The benefits are that Texas Department of Transportation personnel would be able to use the new AASHTO Pavement Design Guide to its fullest extent, thus improving the methodology used in the design of Texas Highways. In addition, the results of this study can be utilized in future refinements of mechanistic pavement design procedures with minor modifications.

A proposed test procedure is presented in Appendix B of the report. The testing equipment has been delivered to the Department for evaluation and implementation.

CREDITS AND DISCLAIMERS

This report has been prepared in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

Some of the devices described in Appendix D were first conceived or reduced to practice during the course of this contract and may be patentable under the patent laws of the United States of America or a foreign country.

The engineer in charge of the study was Dallas N. Little, Jr., PhD, PE 40392.

METRIC CONVERSION CHART

METRIC (SI*) CONVERSION FACTORS

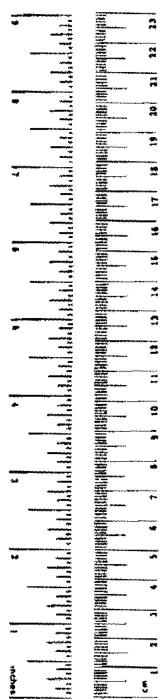
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

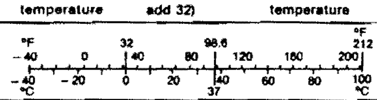
Symbol	When You Know	Multiply By	To Find	Symbol
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The 'resilient modulus' of asphalt concrete is a single number that is used to describe material behavior and to predict pavement performance in many pavement design procedures. It is analogous to Young's modulus in the small strain theory of elasticity, which is one of two parameters needed to fully characterize a linear elastic, rate-independent material. The second parameter is Poisson's ratio.

Several techniques exist for determining resilient modulus. The most common methods are dynamic laboratory tests and nondestructive field tests (NDT). Both laboratory and field tests have limitations that include instrumentation problems, deviation of the actual procedure from the theory upon which the procedure is based, and wave propagation anomalies.

A rapid and consistent laboratory testing method should address these problems and should complement the field testing and evaluation program in pavement design and evaluation. New devices for laboratory testing were developed during this project to address the laboratory needs of the AASHTO Guide and to corroborate NDT results. They are intended for use primarily in the determination of the resilient modulus, but provisions for measurement of Poisson's ratio have been made as well.

This area of research is undergoing considerable change at the present time with the SHRP and AAMAS programs in the final stages of development. The developments in this project have been directed toward short term implementation and production, while maintaining long term flexibility to cope with new research findings.

II. BACKGROUND

An understanding of stress-strain behavior of the materials in a pavement structure is required for the prediction of stresses, strains, and deflections occurring under vehicle wheel loads. A portion of this behavior is expressed in terms of a quantity known as the resilient modulus of the material. This material property is used to characterize roadbed soil and asphalt bound materials for flexible and composite (asphalt concrete overlay on portland cement concrete slab) pavements in the *AASHTO Pavement Design Guide* (*AASHTO 1986*). Since a wide range of 'modulus' numbers exist in engineering, the next section is devoted to clarification of the modulus numbers and other terminology as used in this report.

A. Terminology

Chord modulus

The slope of a line between any two points on a stress-strain curve.

Complex Modulus

A complex number that defines the relationship between uniaxial stress and strain for a linear viscoelastic material (*Witczak 1989*). The complex modulus, E* incorporates both real and imaginary parts or :

$$E^* = E' + iE'' \tag{1}$$

where

$$E' = \frac{\sigma_0}{\epsilon_0} \cos\phi \equiv \text{Storage Modulus} \tag{2}$$

$$E'' = \frac{\sigma_0}{\epsilon_0} \sin\phi \equiv \text{Loss Modulus} \tag{3}$$

and σ = stress, ϵ = strain, and ϕ = phase angle between stress and strain.

Constitutive Model

Mathematical relationship between stress and strain.

Dilatant material

A material that exhibits a change in volume when subjected only to simple shear stress. Microcracking or very high Poisson's ratios and nonlinear stress-strain curves are often associated with this type of material.

Dynamic Modulus

The magnitude of the complex modulus that defines the elastic properties of a linear viscoelastic material subjected to a sinusoidal loading, $|E^*|$.

Linear Material

A material whose stress to strain ratio is independent of the loading stress applied.

Nonlinear material

A material whose stress-strain response is not linear.

Plastic behavior

Material behavior in which some or all of the strain can not be recovered after unloading.

Pulsed Loading

This loading is similar to the sinusoidal loading with introduction of a rest period after each load application as shown.

Resilient Modulus

The resilient modulus M_R is a dynamic test response defined as the ratio of the repeated axial deviator stress σ_d to the recoverable axial strain ϵ_a in a test involving uniaxial loading (*Yoder & Witczak 1975*). This is mathematically represented by the following equation.

$$E_{ra} = \frac{\sigma_d}{\epsilon_a} \tag{4}$$

For uniaxial loading, this interpretation is essentially equivalent to the dynamic modulus. For the indirect tension case, the resilent modulus is the value obtained from the solution of the generalized Hooke's law for the loading and geometry used in the testing. In this case, the modulus is dependent on Poisson's ratio, ν, and the deflection, as shown below.

$$M_R = P(\nu + 0.732)/t\delta \tag{5}$$

Secant modulus

The slope of a line between the origin and any other point on a stress-strain curve.

Sinusoidal Loading

Load application from one stress level to another along a path that can be described by a simple sine function.

Tangent modulus

The slope of a line tangent to the stress-strain curve at any point.

Viscoelastic material

A material whose stress-strain response is nonlinear due to time dependent factors (*e.g.* viscous fluid flow).

B. Overview of Existing Testing Methods

The resilient modulus can be used directly in the design of flexible pavements. The AASHTO Pavement Design Guide suggests the use of the resilient modulus to characterize the materials in various pavement layers to estimate the values of the layer coefficients. Direct laboratory test procedures used to determine this property include, but are not limited to: (a) Direct Tension, (b) Beam Flexure, (c) Indirect Tension, (d) Triaxial Compression. Among the moduli resulting from these various test procedures are: (1) elastic or Young's, (2) shear, (3) bulk, (4) complex, (5) dynamic, (6) resilient, (7) double-punch, (8) flexural, (9) creep and (10) Shell nomograph moduli. Much research has focused upon simplification and refinement of the diametral and triaxial resilient modulus testing devices for use in material characterization (*Brickman 1989*). These two types of devices are used in this research as well.

Each modulus and test procedure has different assumptions and limitations, and the real dilemma is how to determine which modulus to use in characterizing asphalt concrete structural pavement layers in various modes of pavement behavior (*e.g.* flexural, compressive, tensile). For example, layered elastic modeling of flexible pavements is widely used as a pavement design tool and as a pavement analysis tool. However, the results of multilayered elastic analyses are highly sensitive to the modulus used to characterize the asphalt concrete. Since the value of these moduli vary greatly even when evaluating the same material, the results of the multilayered design or analysis will also vary greatly depending on which modulus was used for characterization (*Mamlouk & Sarofin 1988*).

Indirect Tension Devices

The indirect tension method of testing pavement cores has been in use for some time. It has been used for both strength testing and resilient modulus testing of bound materials. Both types of test are basically the same geometry, and only the shape of the loading function is different.

Baladi (*1990*) designed an indirect tensile appartus that is capable of measuring deformations in three directions (along the vertical diameter, the horizontal direction, and the along thickness of the material of the specimen).

Schmidt (*1972*) developed a practical method for measuring resilient modulus of asphalt-treated mixtures. This method is rapid and economical. During the course of the test, dynamic load and total horizontal deformation are recorded. The resilient modulus is calculated using the following equation:

$$M_R = P(\nu + 0.273)/t\delta \qquad (6)$$

A range of values for Poisson's ratio were assumed based on Sayegh's (*1967*) sonic experiments.

Maupin (*1972*) related results of indirect tensile tests to asphalt fatigue. The diametral device adopted by Maupin has a transducer to measure strain over a 1-in gauge length. The maximum tensile strain is at the center of the specimen.

Hudson & Kennedy (*1968*) have summarized the advantages and disadvantages of several methods and used the indirect tensile test to characterize the strength of stabilized materials. Results of this test were utilized to evaluate the effects of such factors as composition and width of the loading strip, testing temperature, and loading rate on the parameters of strength, vertical failure deformation, and a modulus based on load and vertical deformation for asphalt stabilized materials. It was recommended by Hudson & Kennedy that the test be conducted utilizing a 1.0 in. wide stainless steel loading strip, loading rate of 2 in/min, and a test temperature of 77°F.

Predictive Models

The predictive equation for $|E|$ developed by Witczak (*1989*) is based upon measured laboratory tests following the ASTM D3497 procedure for dynamic modulus. The equation is based upon over 20 years of cumulative laboratory test studies.

The method developed by the Shell Oil Company to determine the modulus of an asphalt mix is based upon over 20 years of laboratory work. Nomographic solutions are used to obtain the properties of the bitumen. Several equations are used to convert these properties to the stiffness of the asphalt mix. The bitumen properties are dependent on origin, hardness, temperature susceptibility, temperature at the load condition, duration of load and rate of loading (*Huekelom 1966*, *Van der Poel 1965*).

Nondestructive Methods

Several nondestructive techniques are used in evaluating pavement systems. The method developed by Heisley *et al.* (*1982*) evaluates the moduli of the various materials in existing pavement systems, but seems to be best suited for measurements of the properties of the surface layer. Elastic waves are generated by steady-state vibrations or transient impulses, and they propagate through individual layers and/or the entire pavement structure. Frequency and phase content of the surface waves generated by the source are collected with spectral analysis equipment. Moduli and thicknesses are calculated from the velocities of the surface waves.

The Benkelman beam is one of the simpler nondestructive methods. A truck having an 18-kip load on the rear axle with dual tires (70-80 psi tire pressure) is normally used to load the pavement when using this device. Other vehicles with known wheel loads can be used for the test. In this method, rebound deflections of the pavements are measured when the truck moves away from the testing point.

The Road Rater is an electro-hydraulic vibrator capable of generating harmonic loads up to 8 kips (peak to peak) at driving frequencies between 6 and 60 Hz. A static preload of 5 kips is applied through 12-in circular loading plate while a vibrator is set at the testing point. The desired peak-to-peak load is then generated at a preselected driving frequency, and peak-to-peak deflections are recorded with velocity transducers (geophones).

The FWD (Falling-Weight Deflectometer) operates on impulse-loading principle. There are on the order of four types of FWD's presently in use (*Bentsen et al. 1989*). Each FWD operates under the same basic loading principle and uses similar data collection techniques. A weight is raised mechanically and dropped on a set of rubber cushions, and the force is transmitted to the pavement through a steel plate. The resulting pavement movement is monitored with either velocity transducers or seismometers. The load pulse generally has a time period on the order of 20-100 milliseconds, depending on load level and the design of the device.

C. Material Behavior

The resilient modulus is a property that is similar in concept to the modulus of elasticity. Along with Poisson's ratio, it defines a portion of an elastic stress-strain relationship. However, results of many different types of tests indicate that the behavior of asphalt mixtures is influenced by factors such as temperature and other environmental conditions, loading frequency, mix properties, applied load and triaxial stress state, specimen type, and type of test. The reason for the dependency on the various factors is that asphalt concrete often exhibits a combination of elastic, time dependent, and plastic behavior in response to loading at in-service temperatures. The temperature and/or loading frequency controls the balance of what percentage of the response is elastic, what percentage is time dependent, and what percentage is plastic. The temperature and/or frequency also controls what portion of the failure mode can be described as brittle cracking and what portion of the failure can be attributed to higher degrees of ductile behavior. This can be illustrated schematically as in Figure 1 (*Lytton 1991 unpublished*).

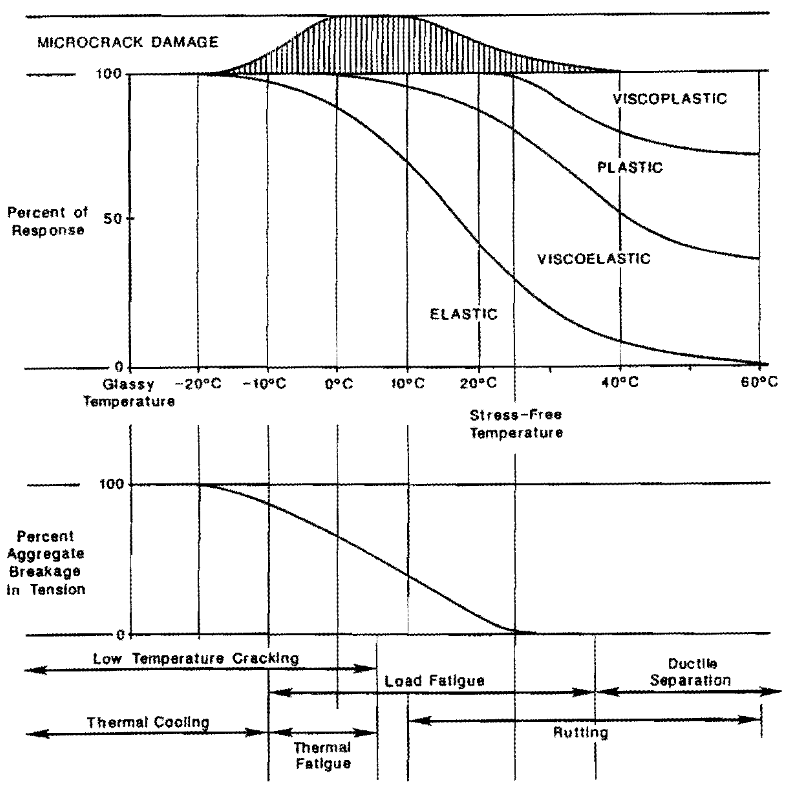


Figure 1. Components of asphalt concrete material response as a function of temperature/frequency (*after Lytton, unpublished*).

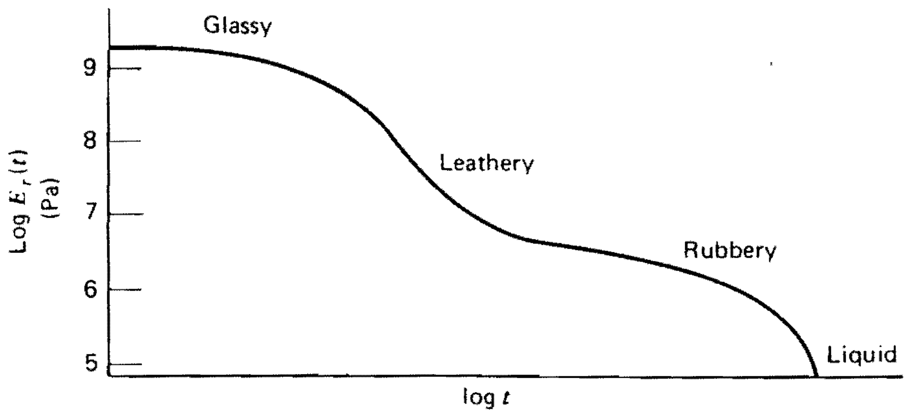
Temperature

Asphalts can be classed as thermoplastic materials because they gradually liquefy when heated and become solid again on cooling. Their behavior is dependent on temperature. In this respect, asphalts are quite similar to many polymers. The thermoplastic property of the asphalt binder has a significant influence on the resilient modulus of asphaltic mixtures (*Schmidt 1974*). The dependency of the storage modulus on temperature for a polymer as compared to the resilient modulus of an asphalt material can be illustrated schematically as shown in Figure 2. The curve drawn for asphalt in part (b) of this figure corresponds roughly to the region labeled 'leathery' on the schematic for a polymer in part (a) of the figure. As the temperature decreases, the asphalt curve just begins to level off on the left side of Figure 2(b) which corresponds to the 'glassy' region at short loading times (or cold temperatures) in part (a), and there appears to be a very slight change toward the 'rubbery' shelf as the temperature increases in part (b) of the figure. Other studies at TTI have indicated that the rubbery shelf may be very small or nonexistent for most asphalt mixtures on the hot side and that the transition from the leathery region to the glassy region is not very well defined on the cold side.

The temperature effect extends to Poisson's ratio as can be seen in Figure 3. The theoretical limit of Poisson's ratio is 0.5. At temperatures above approximately 90°F, the figure indicates that Poisson's ratios greater than the theoretical limit are observed. This can be interpreted to be an indication of dilation and indicates that aggregate particle interaction becomes an important factor as the viscosity of the asphalt decreases with increasing temperature.

Component and Mix Properties

Physical and chemical properties of asphalt, aggregate, and composite mixture have a vital influence on the dynamic response of asphalt concrete. The grade of asphalt is critical to the dynamic behavior of asphalt treated mixtures (*Roque et al. 1987*). Asphalt consistency is related to the type of asphalt. Consistency is a qualitative term used to describe viscosity or degree of fluidity (Penetration) at any particular temperature (TAI 1989). The high viscosity (low penetration) asphalts are called 'hard' asphalts because the material is relatively stiff (high modulus).



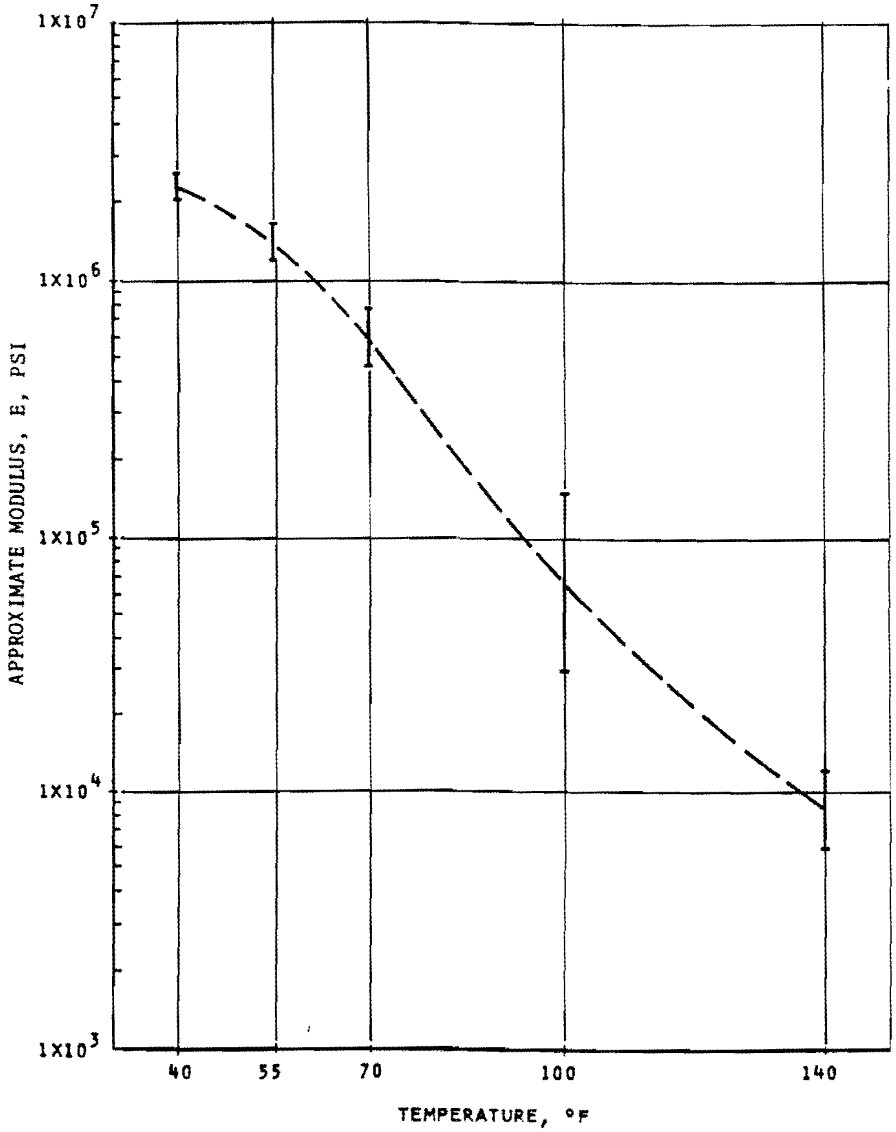


Figure 2. Schematic of modulus versus temperature: (upper) polymer (*Hertzberg 1983*), (lower) asphalt (*Nair et al. 1972*)

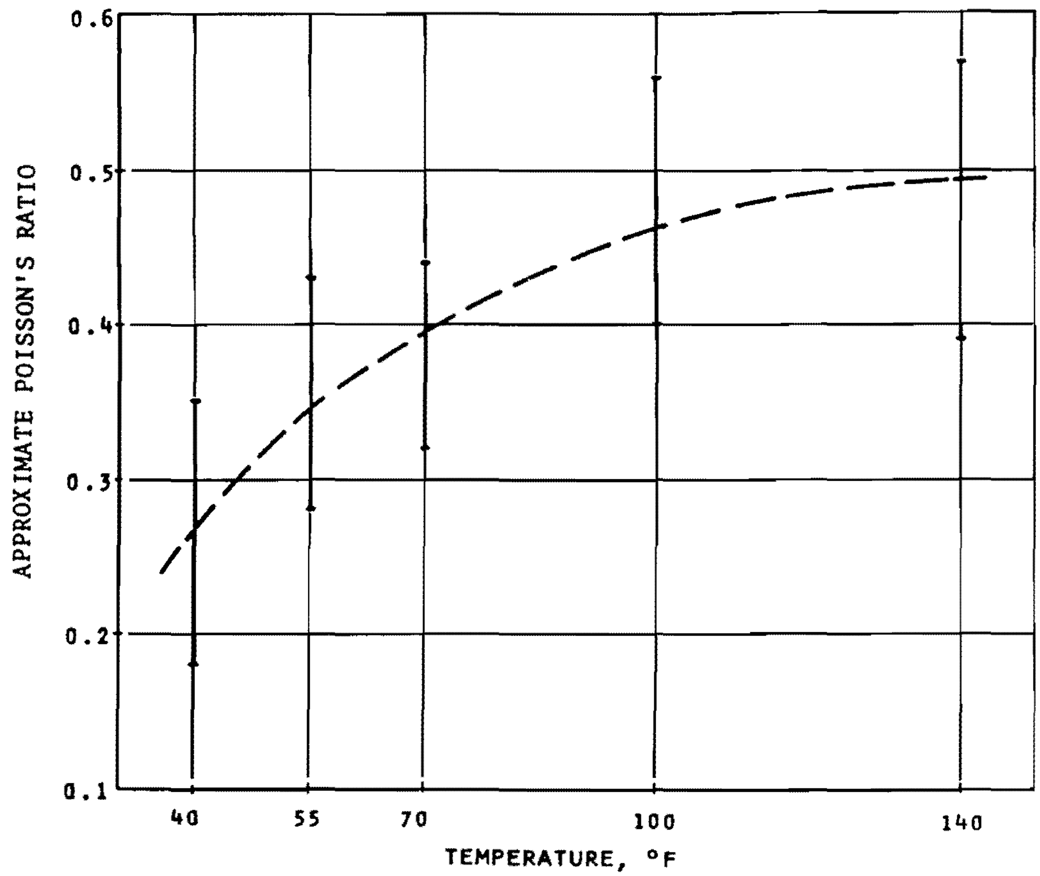


Figure 3. Variation of Poisson's ratio with temperature for an asphalt concrete (*Nair et al. 1972*)

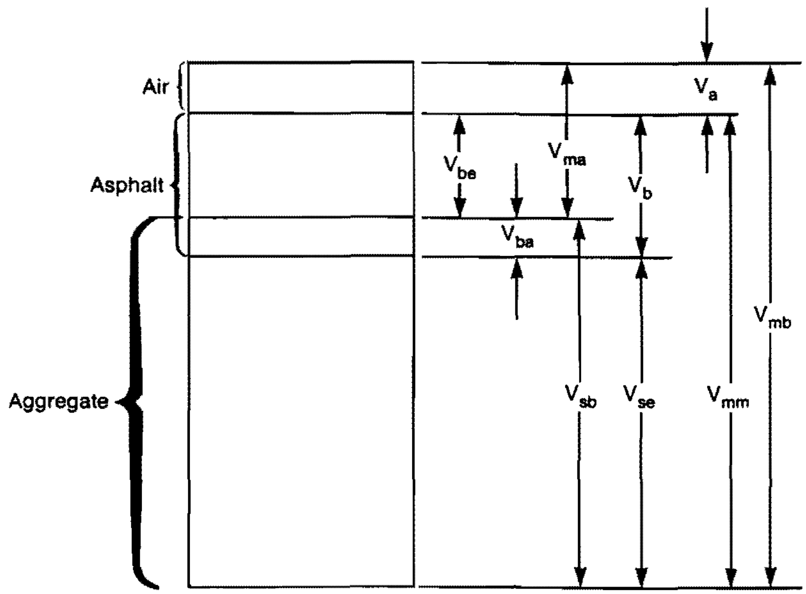
When asphalt cement is exposed to air in thin films at elevated temperatures (*e.g.* during mixing with the aggregate), the asphalt tends to harden. Field measurements show higher viscosity values due to increased state of hardness. This effect is due to chemical and mechanical processes (e.g. oxidative hardening that occurs during mixing, laydown, and upon exposure to environmental conditions (*Bell et al. 1990, Goode & Owings 1961*)).

The gradation of the aggregate has a significant influence on the mix properties (*Gemayel & Mamlouk 1988, Ishai & Gelber 1982*). The type of aggregate (macro texture, crushed versus rounded, geologic source) often has a slightly less pronounced effect when compared to gradation. However, surface texture and particle angularity are often extremely important as well.

Other important mix property parameters are amount of asphalt and air voids. Amount of asphalt is expressed by weight or volume percentages. Generally as the asphalt content increases, the modulus of the mix decreases (taking other parameters into account). The percent asphalt and air voids in a mix are inversely related (*Gemayel & Mamlouk 1988*). As the percentage of asphalt content increases, the percentage of air voids decreases. During the process of mixing and compacting, a portion of asphalt is aborbed by the mineral aggregates. This absorption is less influential than the properties at the asphalt-aggregate interface and the asphalt film on the physical response of the mix. Illustrated in Figure 4 is a schematic of the relationship between percent air voids and percent asphalt content.

Applied Load

One of the most important factors affecting the modulus of the asphalt treated materials is duration of applied dynamic load. It is observed that, at constant mix conditions (temperature, confining pressure and magnitude of load), the modulus of the mix decreases with the increase of the duration of applied dynamic load. This characteristic of the asphalt treated mixtures makes it necessary to estimate the loading time applied by vehicles to be simulated in the laboratory. Alternatively, a complete frequency spectrum characterization may be undertaken. To see why the load duration makes such a difference, Figure 5 should be consulted. Part (a) of the figure shows a square pulse stress application. The strain response to this loading for a typical polymer or asphalt concrete is shown in part (b) of the figure in which *E* indicates the elastic part of the response, *P* is the plastic part of the response, and *V* indicates a time dependent ('visco-') effect. Finally, part (c) of Figure 5 illustrates the two most common waveforms used in resilient modulus testing. The waveforms shown in part (c) of the figure will not induce a response like that illustrated in part (b) of the figure; instead, they will induce a response similar to that shown later in the report (see Figure 14).



V_{ma} = Volume of voids in mineral aggregate and effective asphalt
V_{mb} = Volume of compacted specimen
V_{mm} = Voidless volume of paving mix
V_a = Volume of air voids
V_b = Volume of asphalt
V_{ba} = Volume of absorbed asphalt
V_{be} = Volume of effective asphalt
V_{sb} = Volume of aggregate (by bulk specific gravity)
V_{se} = Volume of aggregate (by effective specific gravity)
W_b = Weight of asphalt
W_s = Weight of aggregate
γ_w = Unit weight of water 1.0 g/cm^3 (62.4 lb/ft^3)
G_{mb} = Bulk specific gravity of compacted paving mixture sample

Figure 4. Schematic of phase relationships for asphalt concrete (*TAI 1990*).

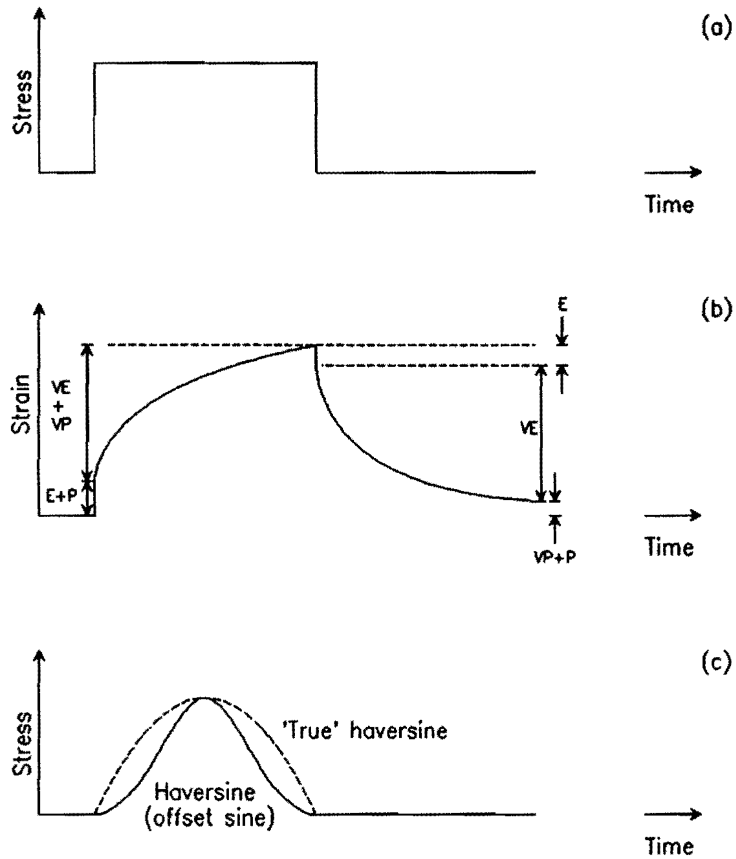


Figure 5. Time dependent material response: (a) Step function loading, (b) response to step function loading, (c) haversine type loading normally used in resilient modulus testing.

The type of truck (vehicle) affects the load duration as well as the rest period between loadings. Wheel spacing affects the relaxation time in the application of pulsed loading. There is a stress overlap between wheel loads on dual wheel and tandem axle truck configurations.

Specimen Type

The geometry of the specimen and the mode of compaction can have a significant impact on the dynamic response of the asphalt materials . Often, there are differences associated with the method of compaction (impact, rolling wheel, kneading compactor and Texas gyratory) used in the laboratory and specimens cored from field sites (*Consuegra et al. 1989*).

The specimen geometry governs the analysis procedure. The dimensions associated with each geometry are governed by the maximum size of the aggregate. Normal practice in the laboratory is to limit the maximum size of the aggregates to 1 inch for a 4 inch diameter specimen. This 4:1 ratio is used to try to avoid adverse effects from the mold during the compaction process (i.e. hindrance of effective densification) and to avoid altering the true failure mechanism during testing. The 4:1 ratio is somewhat smaller than that normally used in geotechnical circles, but the asphalt mix is usually stiffer than soils, and the size distribution is also important in the decision. In fact, if the smallest dimension is used to specify the size ratio, the ratio becomes 2:1 for the indirect tension test.

Test Type

The most popular techniques in practice are direct compression and indirect tension. Results from the previous research show that moduli obtained from direct compression and direct tension are equal if the stress level is sufficiently low. These tests are generally conducted on 4 inch diameter by 8 inch tall specimens. However, many pavements are not 8 inches thick, and those that are at least that thick are almost never homogeneous through the thickness. One solution to this problem is to test short cores using a 'brush platen' type loading surface as described in Appendix B of this report. Another successful approach is to take a large diameter core from the pavement and then core the specimen again, along the diameter this time.

In some instances, confining pressure is applied during the test to develop relationships that cover a wide range of stress states on Mohr's diagram as illustrated schematically in Figure 6. These relationships are then used to refine the constitutive models in mathematical pavement design and evaluation computer programs.

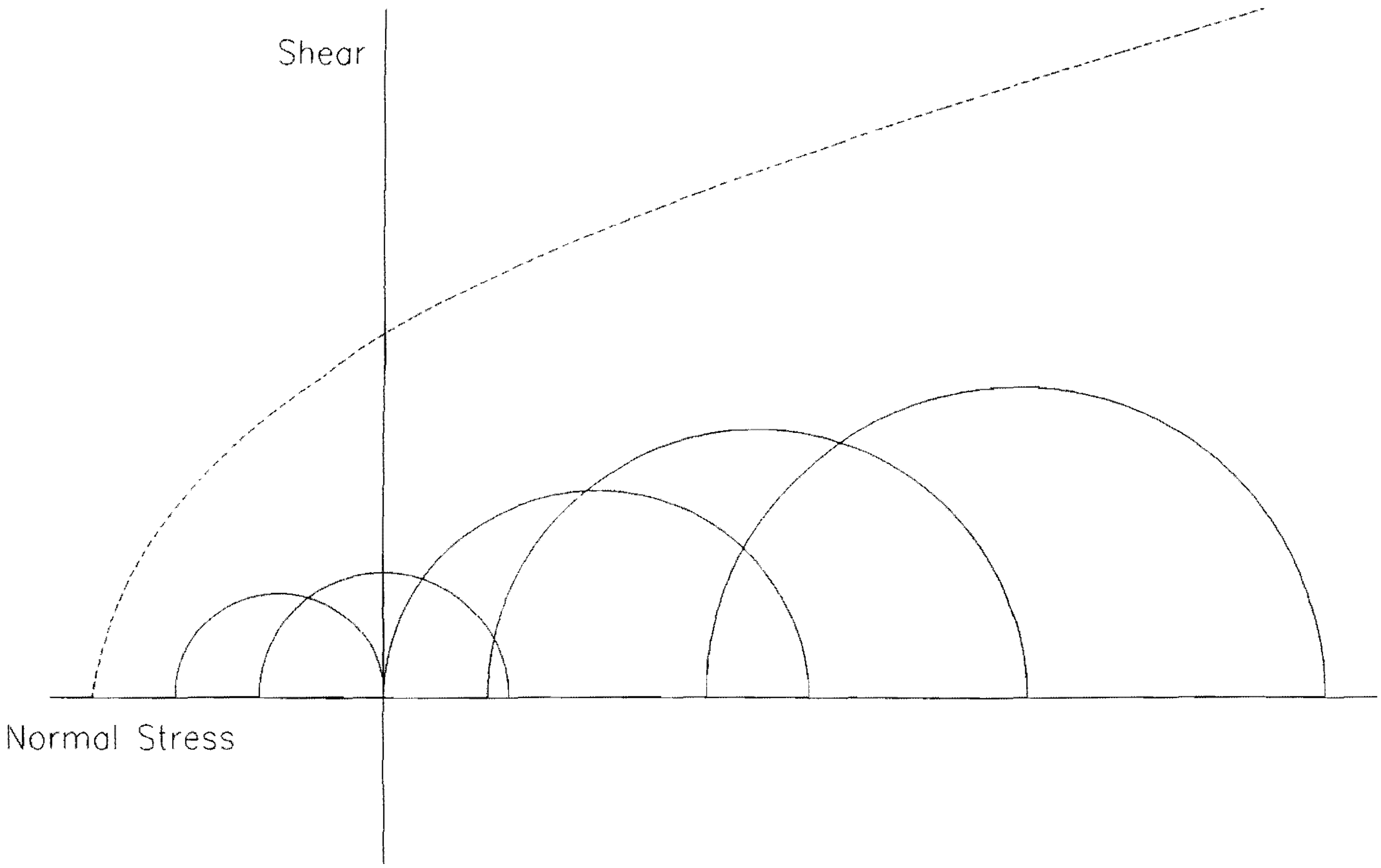


Figure 6. Schematic of possible stress states to be applied in the laboratory to refine asphalt concrete constitutive models.

Beam fatigue studies have shown a nonlinear effect at higher tensile stress levels. The degree of nonlinearity is high when compared to that of direct compressive testing techniques. Beams are relatively easy to produce in the laboratory, but are somewhat more difficult and expensive than cores removed from an in-service pavement. Therefore, the indirect tensile test has become popular due its simplicity. Ironically, the diametral (indirect tension) test has simultaneously garnered popularity and notoriety (*ODOT 1989*). Most of the notoriety is centered around repeatability and failure of the test procedure to adequately simulate the theory upon which it is based. Because of these concerns, the test results are sometimes labeled as 'test' properties rather than 'material' properties. Often, the traditional approach of using 3 specimens for statistical analysis is considered to be inadequate.

D. AAMAS

The Asphalt Aggregate Mixture Analysis System (AAMAS) is a system developed to measure engineering properties of mixtures and then to judge the potential of these mixtures to function in pavement layers based on the best available and appropriate failure criteria for each test mode simulated. Figure 7 shows a conceptual flow chart of the different steps that are required for AAMAS.

Four distress mechanisms were selected for incorporation in AAMAS. These are rutting, fatigue cracking, low temperature cracking and moisture damage. Secondary considerations are given to disintegration such as raveling and loss of skid resistance.

Five tests were selected as tools for mixture evaluation in AAMAS because they measure the mixture properties required by the structural models. These tests are the diametral resilient modulus test, indirect tensile strength test, gyratory shear strength test and the indirect tensile and uniaxial compression creep tests.

Figure 8 shows the mixture design procedure in flow chart form, and Figure 9 shows the AAMAS procedure in flow chart form, identifying the four sections of the AAMAS anaysis. Table 1 summarizes the approximate time requirement for the laboratory compaction, conditioning and testing of asphaltic concrete mixtures.

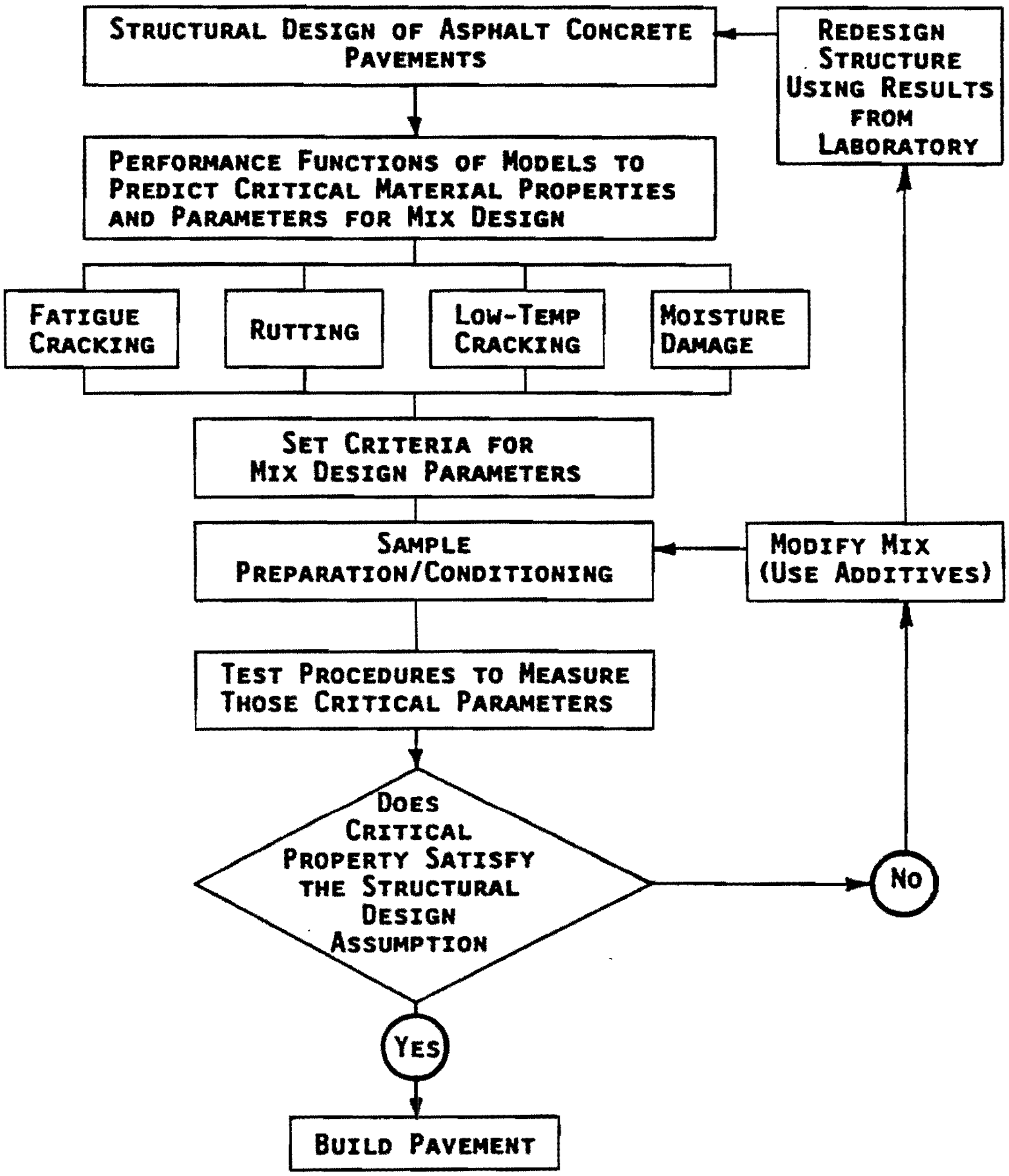


Figure 7. Conceptual flow chart illustrating the AAMAS procedure.

Table 1. Summary of the approximate time required for the laboratory compaction, conditioning, and testing of asphalt concrete mixtures using AAMAS (*Von Quintus et al. 1991*).

Laboratory Steps	Time in Days										
	1	2	3	4	5	6	7	8	9	10	11
1. Prepare & Mix Materials											
2. Initial Heat Conditioning of Loose Mix	12	12									
3. Specimen Compaction - Unconditioned	9										
Moisture Conditioned	3										
Temperature Conditioned		6									
Traffic Densified		6									
4. Measure Air Voids & Sort Into Subsets			24								
5. Moisture Condition Samples			3								
6. Heat Conditioning			6								
7. Traffic Densification				6							
8. Test Unconditioned Specimens			3 @ 41F	3 @ 77F	3 @ 104F						
9. Test Heat Conditioned Specimens											6 @ 104F
10. Test Moisture Conditioned Specimens						3 @ 77F					
11. Test Traffic Densified Specified						6 @ 104F					

(Numbers in blocks represent the number of specimens and /or test temperature. The total time frame to complete the entire AAMAS process is less than 2 weeks. The times shown above are in relation to the time needed to run the Marshall and Hveem mix design methods.)

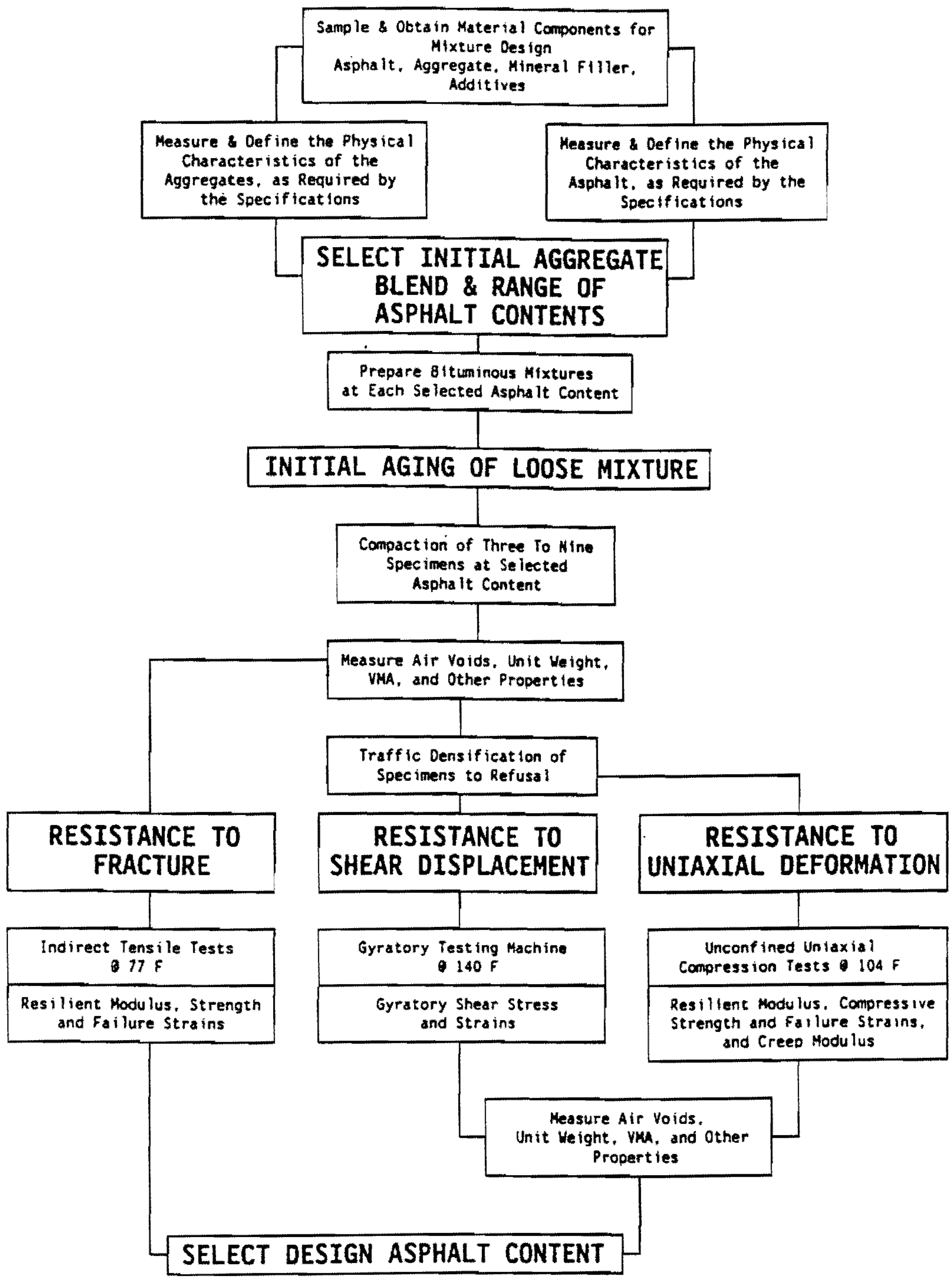


Figure 8. Flow chart for the design of dense-graded asphalt concrete mixtures (*Von Quintus et al. 1991*).

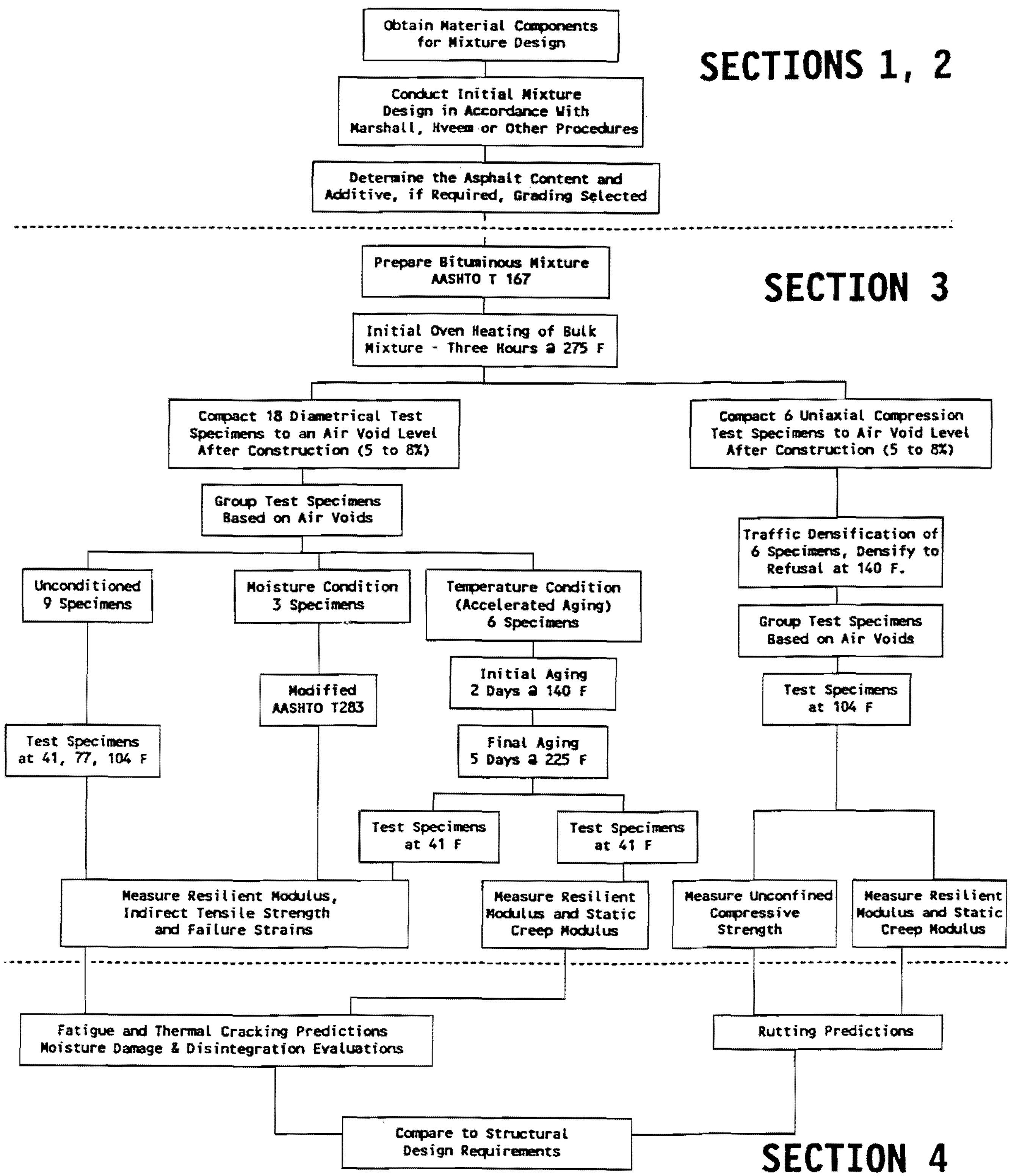


Figure 9. Flow chart for the AAMAS procedure (*Von Quintus et al. 1991*).

Since this report is concerned with the development of a resilient modulus test procedure and accompanying equipment to reliably measure resilient moduli of densely graded asphalt concrete mixtures, the resilient modulus testing phase of AAMAS is of concern only. Therefore, the role of resilient modulus testing in AAMAS and the pertinent findings from resilient modulus evaluation during the AAMAS procedural development at Brent Rauhut Engineering and Texas A&M University will be discussed here.

Role of Resilient Modulus Testing in AAMAS

AAMAS is divided into two broad segments: mixture design and mixture evaluation. In the mixture design segment of testing, the role of the resilient modulus test is to provide an approximation of the AASHTO structural layer coefficient and to provide an approximation of the fatigue charactersitics of the mixture.

The AASHTO 1986 *Guide for the Design of Pavement Structures* provides a relationship between resilient modulus and structural layer coefficient of the asphalt concrete to be used as the surface course and the structural layer coefficient. This relationship is shown in Figure 10.

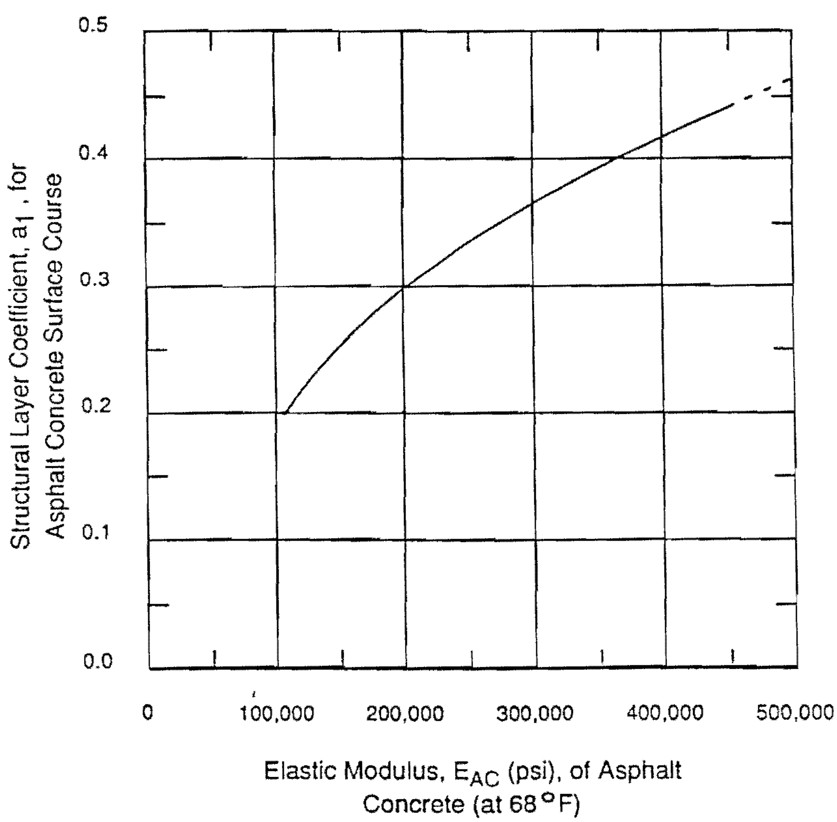


Figure 10. Chart for estimating structural layer coefficient of dense graded asphalt concrete based on the elastic (resilient) modulus (*Von Quintus et al. 1991*).

Ironically, this relationship was developed based on the uniaxial resilient modulus (*Van Til et al., 1972*), but the 1986 Design Guide requires the diametral resilient modulus (ASTM D 4123). These two approaches are similar to Method C and Method B, respectively, of the proposed test procedure in Appendix B of this report. Since the Guide requires the indirect test approach for input to Figure 10, Method B would be the corresponding procedure. Appendix C contains more discussion on this topic. An acceptable mixture design in this phase of AAMAS is based on the asphalt content, or mixture components in general, that produce the minimum acceptable AASHTO structural layer coefficient.

In the mixture design phase of AAMAS, the total diametral resilient modulus is used in conjunction with the strain at failure in the indirect tensile test to predict fatigue potential. Figure 11 is used to plot the relationship between indirect tensile total resilient modulus and indirect tensile strain at failure for each asphalt concrete mixture design. Those asphalt contents that fall above the minimum design relationship are assumed to meet the minimum fatigue cracking criteria.

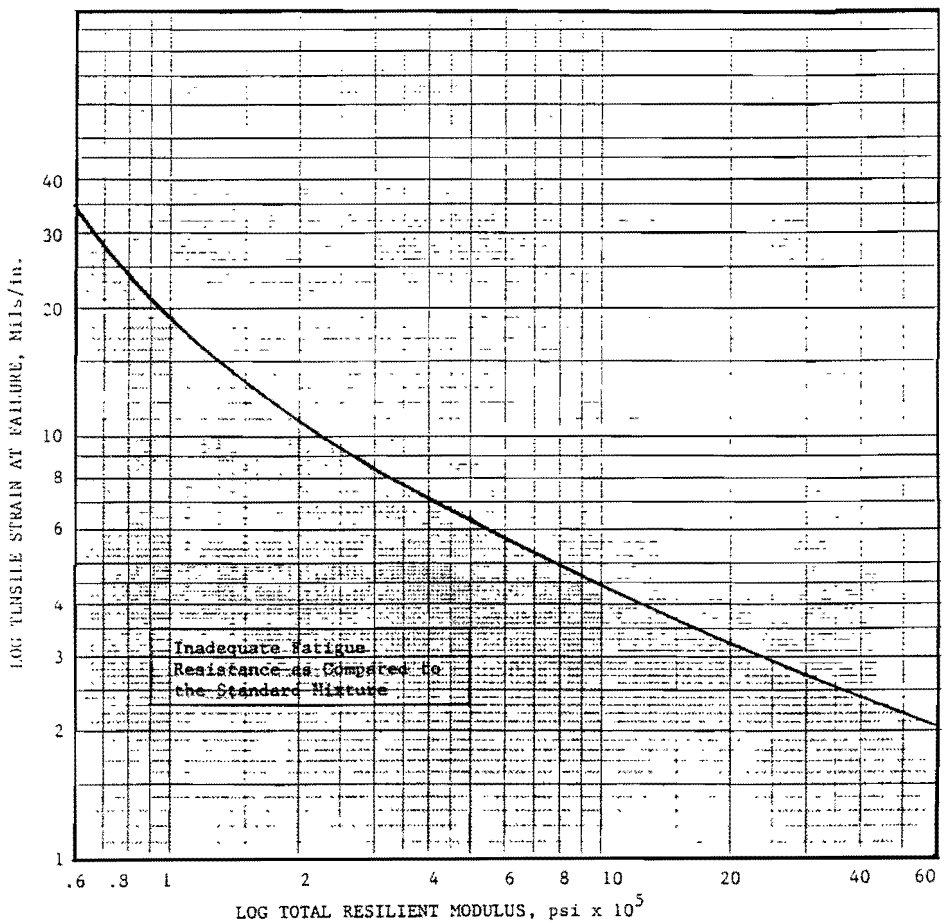


Figure 11. Minimum tensile failure strains required for the mix as a function of resilient modulus (*Von Quintus et al. 1991*).

In the mixture analysis phase of AAMAS, diametral resilient modulus testing is used to predict mixture performance acceptability based on unconditioned specimens, moisture conditioned specimens, and temperature conditioned specimens.

Unconditioned specimens are tested at 41, 77 and 104°F in accordance with ASTM D 4123. The specimens are preconditioned by applying a repeated 'haversine' load to the specimen without impact using a loading frequency of 1 Hz for a minimum period sufficient to obtain uniform deformation readout (less than two percent deviation). A preconditioning time of of 25 to 45 seconds is sufficient in most cases.

The fixed load to be used in the diametral repeated load resilient modulus test for each test temperature can be selected by using elastic layer theory to calculate the tensile stress and strain at the bottom of the asphalt concrete layer. For those conditions where the asphalt concrete layer is in compression (*i.e.* asphalt concrete overlays), the fixed load applied to the specimen should be of a sufficient magnitude to result in a horizontal deformation greater than 0.0001 inches. In most cases, the load established by these criteria will induce a tensile stress in the specimen in the range of 5 to 20 percent of the indirect tensile strength.

Following preconditioning, the total resilient modulus is measured in accordance with ASTM D 4123 along two orthogonal axes at a loading frequency of 1 Hz. The lower value of resilient modulus is to be used. After the resilient modulus of the unconditioned specimens is determined at each temperature, the indirect tensile strength is measured at a loading rate of 2 inches per minute. The values of resilient modulus and indirect tensile strength are used in Figure 11 to determine the fatigue cracking potential (or acceptability) of the mixtures evaluated.

Resilient modulus testing is used following moisture and temperature conditioning. The primary purpose of resilient modulus testing following moisture conditioning is to identify the critical axis for testing in order to determine the indirect tensile strength which, in turn, is used to determine the tensile strength ratio. Testing following temperature conditioning in the resilient modulus mode is used primarily to identify the low temperature cracking and fatigue cracking potential of mixtures at the low test temperature of 41°F.

Performance Evaluation Schemes in the Mixture Analysis Phase of AAMAS

Four performance evaluation schemes are included in the mixture analysis phase of AAMAS which employ the diametral resilient modulus test. The procedural schemes include: the fatigue evaluation (Figure 11), the resilient modulus versus temperature accepability analysis (Figure 12), the weighted average structural layer coefficient analysis (Figure 13) and the thermal fracture analysis.

The flexural fatigue anlysis is essentially the same as that discussed in the mixture design section (Figure 8). Figure 12 is used to ascertain if the relationship between the diametral resilient modulus and temperature is within the band deemed to be acceptable. If the modulus is above the upper limit of this band, then the mixture is too stiff and fatigue and/or thermal cracking may be a problem. If the mixture is too soft and the resilient modulus versus temperature relationship plots below the lower limit, then the mix is deemed too soft and hence does not adequately protect the underlying layers or may be succeptable to deformation.

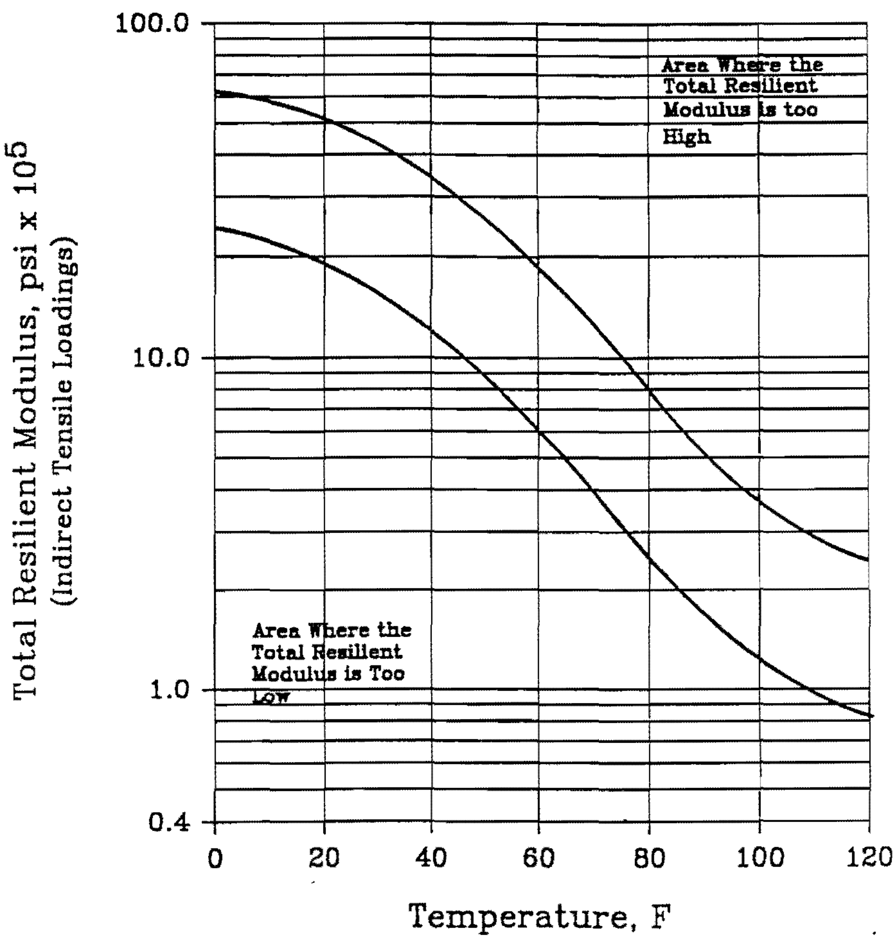


Figure 12. Chart for total resilient modulus versus temperature using indirect tensile loading conditions (*Von Quintus et al. 1991*).

Figure 13 is used to calculate the weighted annual structural layer coefficient. One technique that can be used to evaluate the environmental effects on the structural design is to consider seasonal fatigue damage. From the annual damage, an equivalent asphaltic concrete resilient modulus can be calculated by the following equation:

$$E_{RE} = \Sigma(E_{Rt}(i) \times FF(i))/\Sigma FF \tag{7}$$

where E_{RE} is the equivalent resilient modulus based on a fatigue damage approach, E_{Rt} is the total resilient modulus as measured in accordance with ASTM D 4123 at the pavement temperature for season i and FF is the fatigue factor obtained from Figure 13.

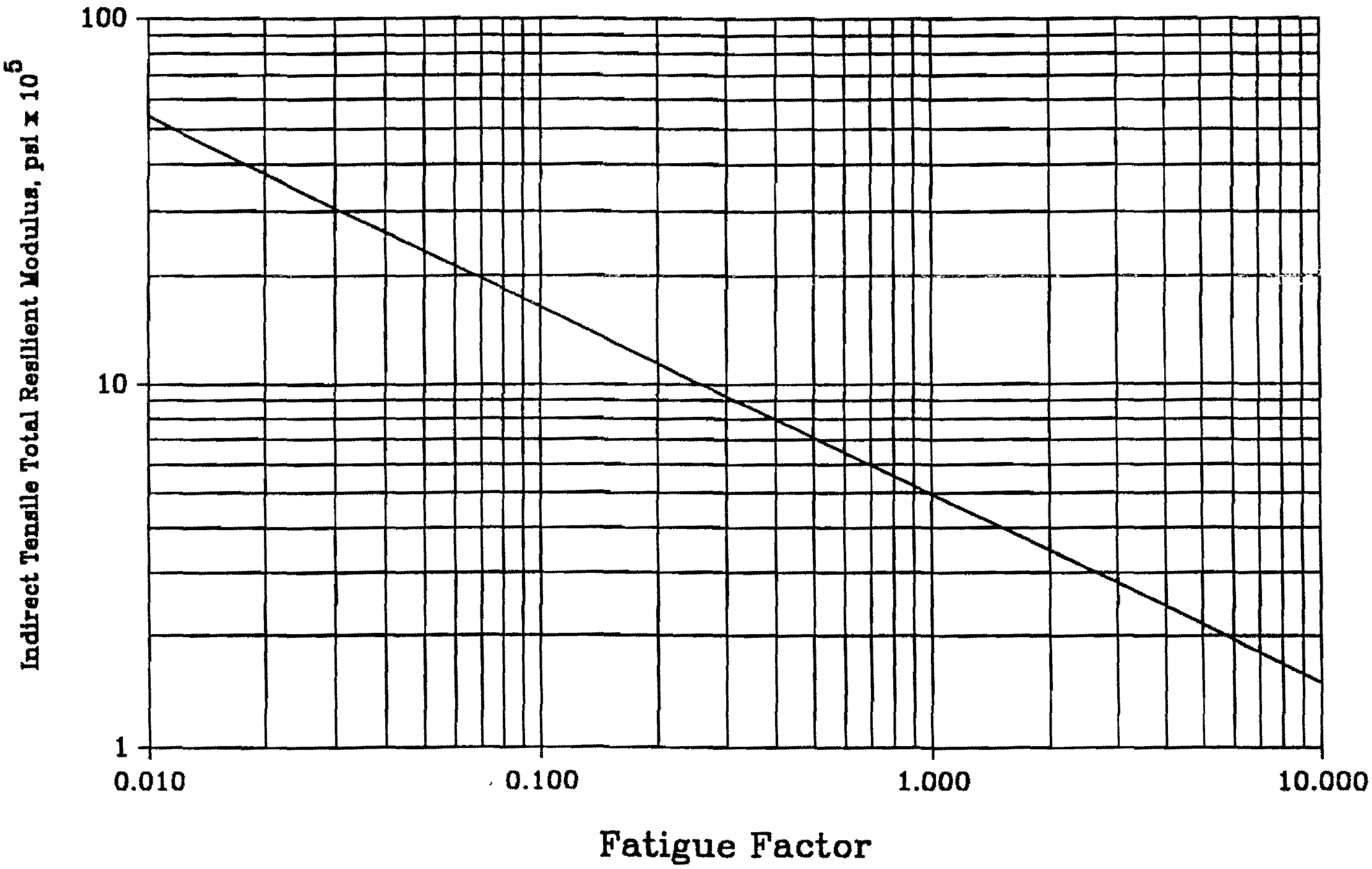


Figure 13. Estimation of the fatigue factor to determine an equivalent annual resilient modulus (*Von Quintus et al. 1991*)

Equation 7 includes only the damage associated with fatigue cracking and ignores any damage caused by permanent deformation and disintegration. Through the use of the fatigue factor, the equation allows seasonal and environmental effects to be used in estimating the AASHTO structual layer coefficient.

The step-by-step procedure that can be used to ensure that the asphaltic concrete mixture meets or exceeds the layer coefficient assumed during structural design is as follows:

* Obtain the seasonal average pavement temperature (for each season).

* Determine the total resilient modulus at each seasonal temperature.

* Obtain the fatigue factor for each seasonal resilient modulus from Figure 13.

* Calculate the equivalent resilient modulus using equation 7.

This equivalent resilient modulus should equal or exceed the modulus value used to estimate the AASHTO structural layer coefficient used for design.

The tendency of a mixture to fracture due to thermal fluctuations in the AAMAS process is evaluated by means of the following relationship:

$$\Delta T = \left[\frac{E_{ct}(T_i)}{E_0}\right]^{\frac{1}{n_t}} \frac{t_r^{n_c}}{\alpha_A E_0(T_i)} \tag{8}$$

where T is the critical change in temperature at which cracking occurs, $E_{ct}(T_i)$ is the indirect tensile creep modulus measured at temperature T_i, E_o is a regression constant, t_r is the relaxation time, α_A is the thermal coefficient of volume change, $E_0(T_i)$ is the intercept of the indirect tensile creep curve at temperature T_i, n_c is the slope of the indirect tensile creep relationship and n_t is the slope of the relationship between indirect tensile strength and total resilient modulus of the mixture at temperatures of 41, 77 and 104°F (unconditioned). Therefore, the indirect tensile resilient modulus (ASTM D 4123) is of significant importance as the relationship presented in equation 8 is quite sensitive to the slope of the relationship between resilient modulus and indirect tensile strength of the mixture at the three test temperatures.

Testing Procedures in AAMAS for Diametral Resilient Modulus

The general testing procedure in AAMAS for samples tested for resilient modulus in the indirect tensile mode is discussed in the following paragraphs.

Place the test specimen in the loading apparatus, position as stated in Test Method ASTM D 4123, adjust and balance the electronic measuring system, as necessary.

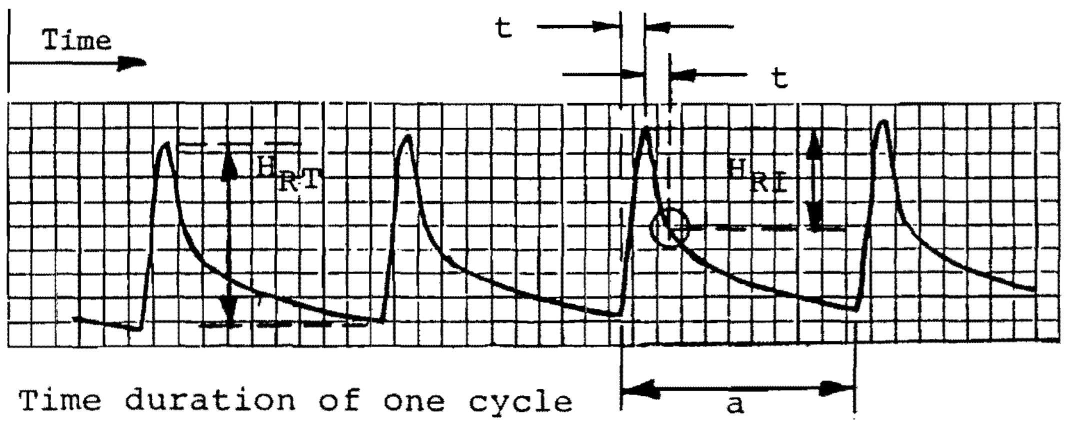
Precondition the specimen by applying a repeated haversine (or other suitable wave form) to the specimen without impact, using a loading frequency of 1 cps (0.1-sec load duration and 0.9-sec rest period) for a minimum period sufficient to obtain uniform deformation readout (less than 2 percent deviation). In most cases, a preconditioning time of 25 to 45 sec is sufficient (25 to 45 loading cycles). The fixed load applied to the specimen is that which will result in a horizontal deformation greater than 0.0001 in. (0.00254 mm). Normally, the load established by this criterion will induce a tensile stress in the range of 5 to 20 percent of the indirect tensile strength.

After preconditioning, measure the total and instantaneous resilient deformations for the next three loading cycles along each of two previously marked orthogonal axes. A loading frequency of 1 cps (0.1-sec load duration and 0.9-sec rest period) shall be used. The total resilient modulus is the parameter used for mixture design. The instantaneous resilient modulus is used for information purposes only. The total resilient horizontal deformation shall be measured in accordance with ASTM D 4123. The instantaneous resilient horizontal deformation shall be measured at the time defined as twice the time interval from load application (or horizontal movement) to peak horizontal movement (see Figure 14).

For each specimen tested, calculate the total resilient modulus, E_{RT}, for the last 3 cycles after preconditioning. The instantaneous resilient modulus can be calculated for information purposes, if needed.

$$E_{Rt} = \frac{P}{hH_R} (A_3 + A_4\nu_R) \quad (9)$$

where P is applied load or repeated load, lb; H_R is total or instantaneous resilient deformation, whichever applies, measured along the horizontal axis, in.; h is height of specimen, in.; ν_R is resilient Poisson's ratio (assumed to be 0.35 for a test temperature of 77°F); A3 equals 0.2692 for 4-inch diameter specimens, and 0.2714 for 6-inch specimens; A_4 equals 0.9974 for 4-in. diameter specimens, and 0.9988 for 6-in. (15 cm) specimens (*Von Quintus et al 1991*).



a = Time duration of one cycle
H_{RT} = Total Recovery of Specimen
H_{RI} = Instantaneous Recovery of Specimen
t = Time duration from initial specimen response from load application to the peak of deformation

Figure 14. Typical deformation (horizontal or vertical) versus time relationship for repeated-load indirect tensile using a 'haversine' wave form with a rest period.

A general description of the apparatus required for resilient modulus testing in accordance with the AAMAS guidelines is discussed in the following paragraphs.

Any loading machine capable of providing a repetitive sinusoidal or square type compression load of fixed cycle and duration can be used. Typically, a cam and switch or timer control of solenoid valves operating a pneumatic air piston, or a closed-loop electrohydraulic system is used. Pneumatic systems are the simplest, while closed-loop electrohydraulic systems allow more versatility (variable wave forms, higher loads, and higher frequency response). Generally, a haversine wave form is characteristic of closed-looped electrohydraulic equipment, while rectangular wave forms are used with pneumatically operated loading equipment. Both wave forms can be used for the resilient modulus test. The two waveforms will give similar results if the load level and duration of loading are sufficiently small and the duration of the rest period is sufficiently long that the effects of time dependent and plastic behavior do not overshadow the approximation of the elastic response in the analysis. It is often the case that a pneumatic system that is being commanded to deliver a square wave will actually deliver something between a square wave and a sine wave anyway (at the loading frequencies typically used for resilient modulus testing). A loading frequency of 1 cycle per second has been found to be satisfactory for most applications. With a pneumatic loading system, a square wave form with a load duration of 0.1 second and a rest period of 0.9 seconds is recommended.

The resilient modulus, creep modulus and indirect tensile strength tests require deformation transducers with a sufficient range to cover the cumulative deformation during the test and also a high resolution for the smallest resilient strains to be measured. The linear variable differential transformer (LVDT) is generally considered to be the most suitable deformation transducer for the test. Table 2 provides the required accuracy of the axial deformation measurement device.

LVDT Clamps are used to hold the LVDTs in place during indirect tensile testing. There are different sample holding devices that can be used in the test program. One such device is described in ASTM D 4123, and another in Federal Highway Administration Report No. FHWA/RD-88/118. Either of these devices can be used provided that the specimen has smooth surfaces, and is centered under the axial load (i.e., no load eccentricity). For uniaxial compression loading, LVDT clamps are not required if a friction reducing material is placed between the specimen and top and bottom platens. Thin teflon tape can be used as a friction reducing material.

The axial load measuring device is an electronic load cell. The load may be measured by placing the load cell between the specimen cap and the loading piston. The total load capacity of the load transducer (load cell) should be of the proper order of magnitude with respect to the maximum total loads to be applied to the test specimen. Generally, its capacity should be no greater than five times to the total maximum load applied to the test specimen to ensure that the necessary measurement accuracy is achieved. The minimum performance characteristics of the load cell are presented in Table 2. The axial load-measuring device shall be capable of measuring the axial load to an accuracy within 1 percent of the applied axial load.

Specimen behavior is evaluated from continuous time records of applied load and specimen deformation. Commonly, these parameters are recorded on a multichannel strip-chart recorder. Analog to digital data acquisition systems may be used provided that data can be converted later into a convenient form for data analysis and interpretation. Fast recording system response is essential if accurate specimen performance is to be monitored. It is recommended that the response characteristics in Table 2 be satisfied.

For analog strip-chart recording equipment, the load and deformation recorder trace must be of sufficient amplitude and time resolution to enable accurate data reduction. Resolution of each variable should be better than 2 percent of the maximum value being measured. To take advantage of recorder accuracy and for subsequent data analysis, 2 to 4 cycles per inch of recording paper is acceptable. The clarity of the trace with respect to the background should provide sufficient contrast and minimum trace width, so that the minimum resolution of 2 percent of the maximum value of the recorded parameter is maintained, and the trace should be included in the reports.

For uniaxial compression testing, the number of recording channels can be reduced by wiring the leads from the LVDTs so that only the average or total signal from a pair is recorded. For indirect tensile loadings, the signal from each LVDT shall be recorded separately. This permits observation of individual LVDT readings, rather than an average or total signal, to determine if significant differences are being recorded between the two LVDTs. If the differences between LVDTs is large, the specimen shall be repositioned.

Table 2. Data acquisition - minimum response characteristics for resilient modulus tests (*Von Quintus et al. 1991*).

Analog Records Recording Speeds: 0.5 to 50 cm/sec (0.2 to 20 in./sec) System Accuracy (include linearity and hysteresis); 0.5%[1] Frequency Response: 100Hz		
Measurement Transducers	Load Cell	Displacement[2]
Minimum Sensitivity, mv/v	2	0.2 mv/0.25 mm/v (AC LVDT) (5mv/0.025 mm/v) (DC LVDT)
Nonlinearity, % Full Scale	+0.25	+0.25
Hysteresis, % Full Scale	+0.25	+0.0
Repeatability, % Full Scale	+0.10	+0.01
Thermal Effects on Zero Shift or sensitivity, % of Full Scale /F(c)	+0.005 (+0.025)	--
Maximum Deflection at Full Rated Value in Inches (mm)	0.005 (0.125)	

[1] System frequency response, sensitivity, and linearity are functions of the electronic system interfacing, the performance of the signal conditioning system used, and other factors. It is, therefore, a necessity to check and calibrate the above parameters as a total system and not on a component basis.

[2] LVDTs, unlike strain gauges, cannot be supplied with meaningful calibration data. System sensitivity is a function of excitation frequency, cable loading, amplifier phase characteristics, and other factors. It is necessary to calibrate each LVDT-cable-instrument system after installation, using a known input standard.

Resilient Modulus as the AASHTO Design Parameter

In the 1986 AASHTO Pavement Design Guide, the resilient modulus at 68°F is used to estimate the AASHTO layer coefficient for pavement thickness design. The chart used to approximate the structural layer coefficient in the 1986 Design Guide was actually based on the resilient modulus determined on cylindrical samples tested in compression in accordance with ASTM D 3497. However, the 1986 Design Guide allows for the determination of resilient modulus in either the compressive or diametral (ASTM D 4123) mode. This is unusual, since there can be substantial differences between moduli measured in the compressive and diametral directions (especially if loading is carried past the level at which strains are truly recoverable). Figure 15 shows the differences that can occur between these two test procedures.

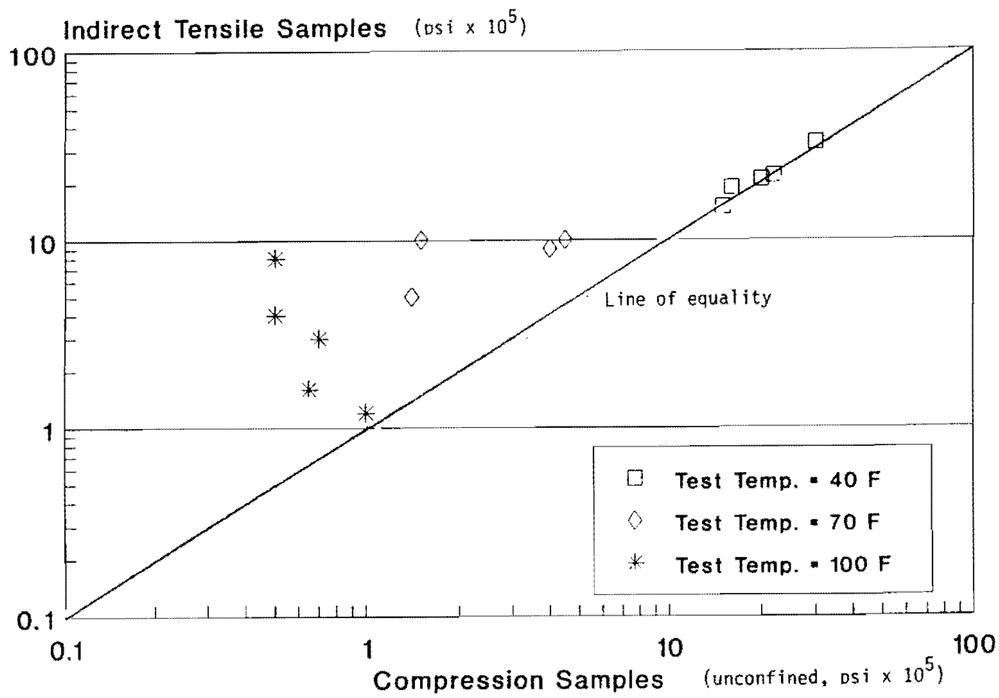


Figure 15. Comparison of test results between unconfined compression and indirect tensile tests (*Von Quintus et al. 1991*).

In addition to the type of test, other factors significantly affect resilient modulus. These include testing device, sample size and recovery time.

In the laboratory verification and testing phase of the AAMAS study sponsored by the National Cooperative Highway Research Program, three different holding or testing devices were used to measure resilient modulus: the Retsina device, Baladi's indirect tensile holder (*Baladi 1987*) and the holder used and referred by Kennedy et al. (*1975*).

Figures 16 and 17 compare resilient modulus values measured from all three devices. Even though resilient moduli were measured on the same specimens and along identical axes with identical load levels, considerable differences were obtained when comparing the devices. Standard deviations and coefficients of variations for the resilient moduli measured on the same specimens for each device are summarized in Table 3. A careful study of the test results indicates that the mixtures with larger coarse aggregate gave the largest coefficients of variation.

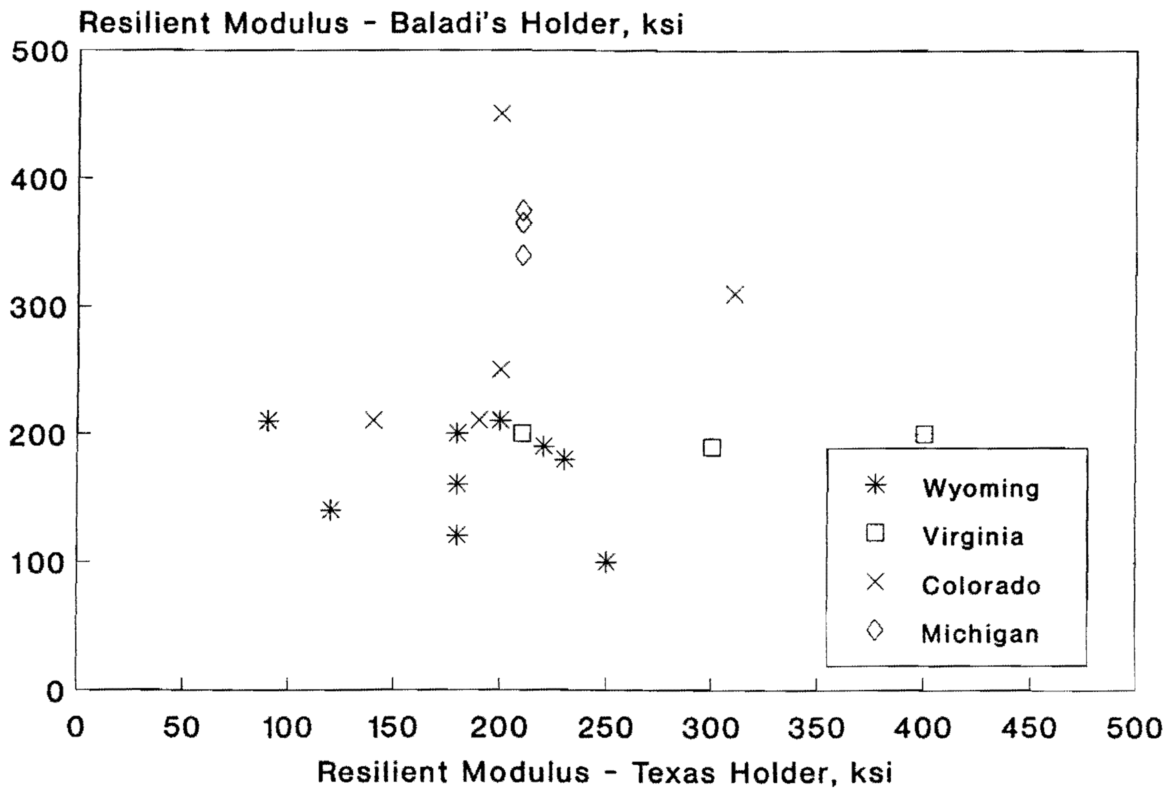


Figure 16. Comparison of resilient modulus measured on cores using different specimen holding devices and test equipment (Texas versus Baladi, after *Von Quintus et al. 1991*)

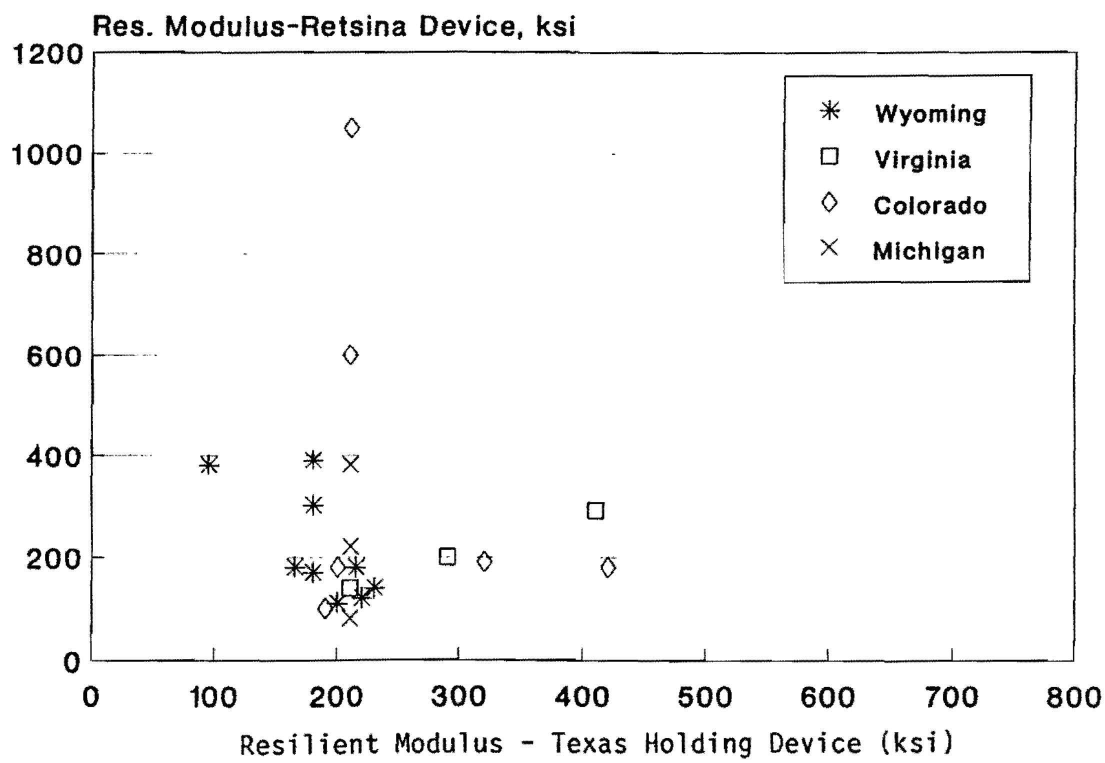


Figure 17. Comparison of resilient moduli measured on cores using different specimen holding devices and test equipment (Texas versus Retsina, after *Von Quintus 1991*)

Table 3. Summary of resilient modulus variations measured using different testing/holding devices (*Von Quintus et al. 1991*)

Mixture	Average Value	Testing Device		
		Standard	Baladi	Retsina
CO-0009	Std. Deviation	107	224	220
	Coefficient of Variation, %	40	37	48
MI-0021	Std. Deviation	1	14	73
	Coefficient of Variation, %	0.3	4.0	23
VA-0621	Std. Deviation	103	1	72
	Coefficient of Variation, %	33	0.6	37
WY-0080	Std. Deviation	39	25	114
	Coefficient of Variation, %	20	14	58

Figure 18 provides an illustration of the coefficients of variation for resilient moduli measured on cores using the different holding devices and test equipment.

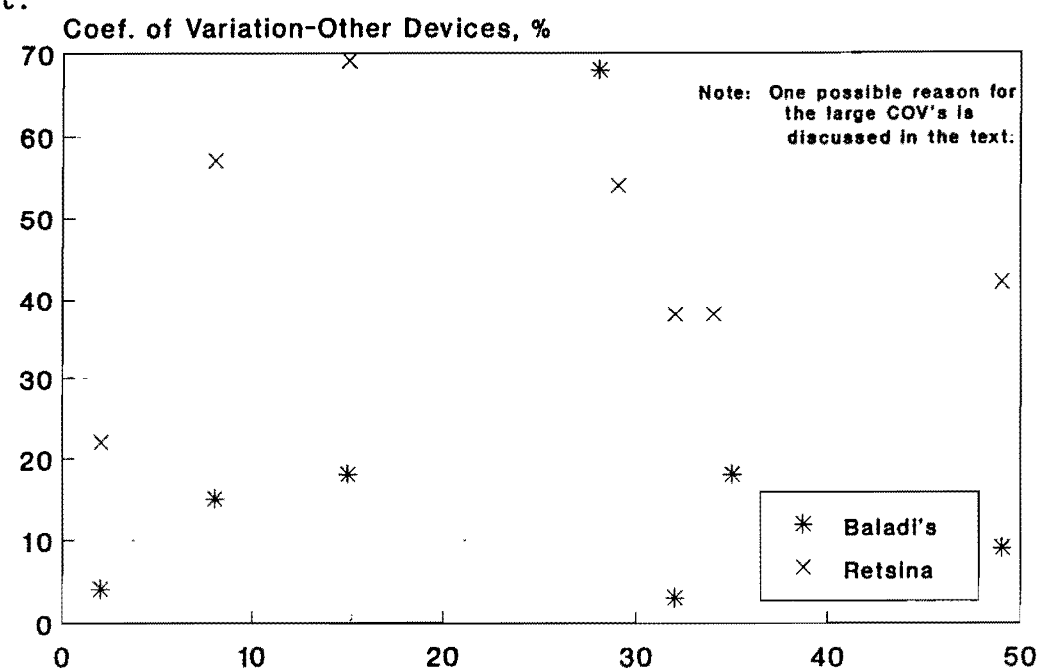


Figure 18. Comparison of coefficient of variation for resilient moduli measured on cores using different specimen holding devices and test equipment (*Von Quintus et al. 1991*)

A separate study on the effects of nominal size of the aggregate within the sample was completed in the AAMAS laboratory study. The study determined the existence of a significant effect of the ratio of nominal aggregate size to specimen size on the value of resilient modulus measured. As the sample size to aggregate diameter ratio increases, the resilient modulus decreases substantially. In addition, as the sample diameter decreased in relation to aggregate size, the variation in test results increased.

In the ASTM D 4123 test procedure, two equations are presented for the calculation of the resilient modulus. One value relates to the instantaneous resilient modulus and the other to the total value of the resilient modulus. Complete load-deformation time traces were recorded during repeated resilient modulus testing; both of these values were calculated for selected samples. Table 4 summarizes the differences between resilient moduli obtained from each equation. As shown, larger differences occurred at 104°F; and smaller differences were found at 41°F because of the difference in creep and recovery properties between these two temperatures. The total resilient modulus was selected in the AAMAS guide. The variability of resilient modulus testing is considerable. Table 5 summarizes the resilient modulus testing of five sets of field cores tested in the AAMAS laboratory study.

Table 4. Summary of the difference between the instantaneous and total resilient modulus at different test temperatures (*Von Quintus 1991*).

Mixture	Modulus Ratio*, E_{Rt}/E_{RI}			E_{rp}**, ksi	Modulus Ratio E_{Rp}**/E_{RI}
	41F	77F	104F		
CO-0009	.88	.71	.67	255	.44
MI-0021	.82	.65	.58	216	.67
TX-0021	.90	.81	.60	173	.27
VA-0621	.88	.78	.58	137	.27
WY-0080	.92	.82	.65	234	.35

* Modulus Ratio = E_{Rt}/E_{RI}
E_{RI} = Instantaneous Resilient Modulus, as defined by ASTM D 4123
E_{Rt} = Total Resilient Modulus, as defined by ASTM D 4123

** E_{Rp} = Total Resilient Modulus at a Test Temperature of 77F, as Defined by ASTM D 4123, but Measured After the Permanent Deformation Testing

Table 5. Summary of indirect tensile test results for the field cores recovered immediately after construction (*Von Quintus et al. 1991*).

State/ Project	Temperature °F	Test Section	Air Voids %	Indirect Tensile Strength, psi		Resilient Modulus, ksi		Strain at Failure Mils/in.	
				Mean	Cov	Mean	Cov	Mean	Cov
Colorado CO-0009	41	1-VB	7.56	361	1.8	1625	6.4	1.30	20.0
		2-PB	8.41	295	0.5	1991	66.8	1.80	23.4
	77	1-VD	8.30	90	10.2	583	11.2	15.40	15.7
		2-PB	8.67	88	4.7	460	14.9	13.17	2.2
	104	1-VB	7.92	30	23.6	329	31.3	16.38	47.2
		2-PB	9.63	27	37.5			15.40	13.9
Michigan MI-0021	41	1-VB	3.42	347	8.1	1473	29.0	6.40	12.8
		2-PB	4.17	382	5.5	2379	8.9	4.51	24.0
	77	1-VB	3.87	84	7.0	420	11.1	15.17	16.6
		2-PB	4.15	90	8.9	456	9.2	14.56	18.9
	104	1-VB	3.50	23	9.2	161	10.8	18.89	39.8
		2-PB	4.25	34	20.8	168	16.8	13.70	9.6
Texas TX-0021	41	1-SB	9.27	316	5.6	4480	43.7	1.21	24.8
		2-VB	9.58	291	14.9	1189	21.4	1.31	16.3
	77	1-SB	9.15	119	3.7	1287	11.0	9.01	12.0
		2-VB	10.88	106	29.6	709	29.1	11.23	30.5
	104	1-SB	9.16	33	3.5	242	1.5	11.01	5.5
		2-VB	10.50	32	17.3	267	19.8	16.12	19.0
Virginia VA-0621	41	1-VB	6.91	424	11.3	3449	17.4	2.38	82.1
		2-SB	7.25	407	11.9	1509	26.7	3.35	41.7
	77	1-VB	5.57	224	7.3	925	22.9	6.96	5.2
		2-SB	7.68	184	5.5	504	28.4	11.51	27.2
	104	1-VB	5.75	99	6.6	252	39.3	3.45	17.3
		2-SB	7.29	70	31.3	246	39.9	10.75	22.9
Wyoming WY-0080	41	1-VB	6.06	398	27.0	2062	74.2	0.95	15.7
		2-PB	8.07	446	11.6	1877	36.1	1.04	70.7
	77	1-VB	6.03	143	3.7	707	28.0	6.40	28.3
		2-PB	9.84	103	9.3	197	11.2	5.29	14.2
	104	1-VB	6.61	56	21.5	204	24.9	10.14	3.6
		2-PB	9.12	42	2.4	260	24.1	10.92	33.1

Relation of Resilient Modulus to Pavement Performance

The familiar and widely used AASHTO performance equation is based on the concept of serviceability. In this performance equation, the influence of the structural pavement layers on overall performance is defined by the structural number term. The structural number (SN) is defined as the sum of the products of the structural layer coefficient and the thickness of the corresponding layer:

$$SN = \Sigma(a_i/D_i)$$

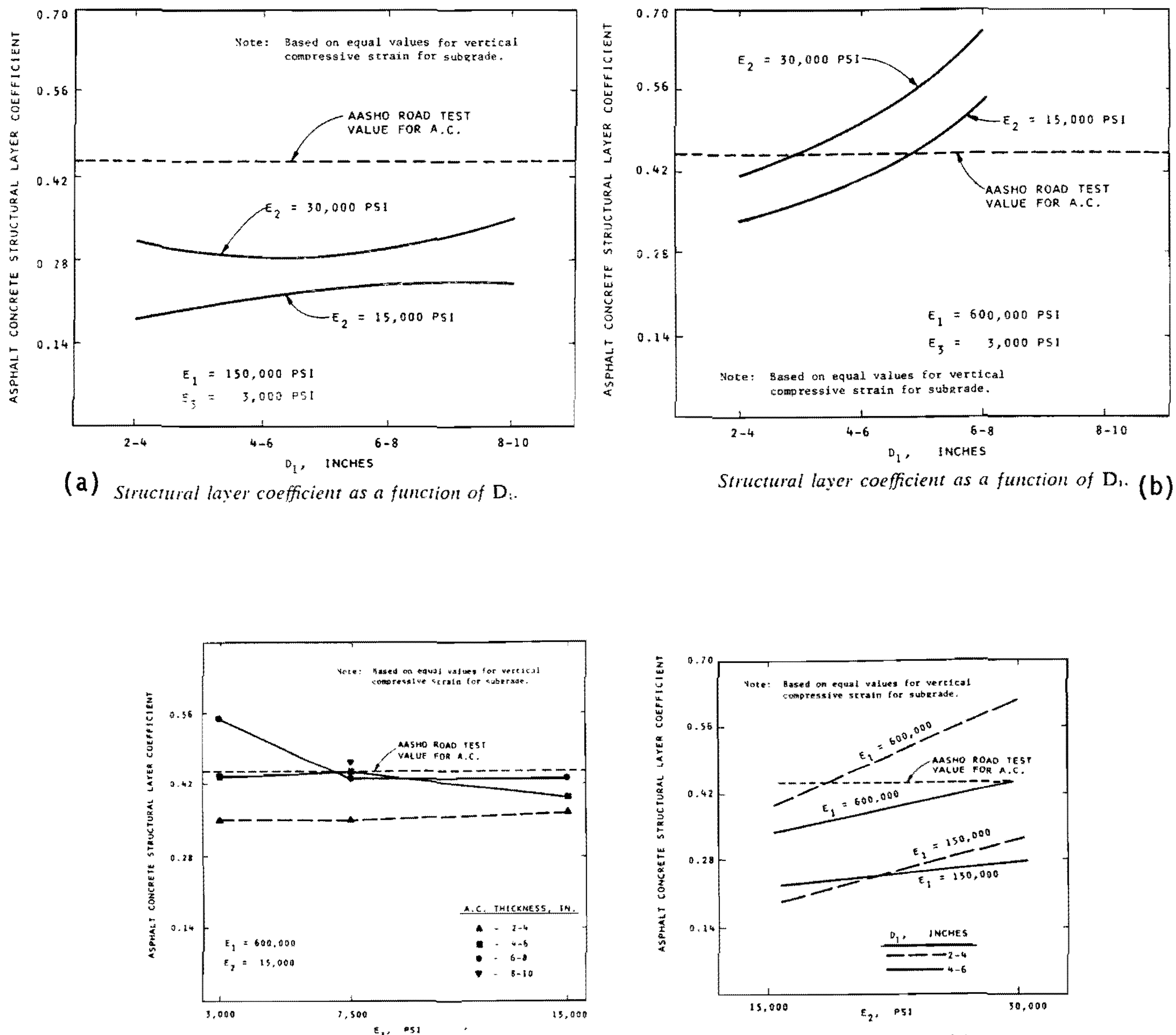
where a_i is the structual layer coefficient of layer i, and D_i is the thickness of layer i. National Cooperative Highway Research (NCHRP) report 128 (*1972*) discusses the variability of the layer coefficients derived from various layers and in different climatic periods of the AASHTO Road Test.

The structual layer coefficient is not a material property or even an engineering property of the pavement layer in question. Instead it is a regression constant that is selected by statistical regression techniques to reduce the variability between the preformance equation and actual data. Consequently one would expect the layer coefficient to be highly sensitive to the pavement structure and the pavement environmental conditions, especially temperature.

The influence of thickness of the asphalt concrete surface (D_i) and the subgrade modulus (E_3) is presented in Figure 19. This sensitivity analysis was performed by Van Til et al. (*1972*).

The results of the Van Til et al. study (*1972*) clearly demonstrate that the layer coefficients are not constant and that it would be difficult, if not impossible, to develop a sliding scale for layer coefficients which appropriately consider the many important influencing factors. The findings of Van Til et al. (*1972*) have been further developed by Little and Epps (*1980*). Until a more realistic and interactive method can be developed, a simple sliding scale concept for prediction of the structural layer coefficient, a_i, must be used.

The sliding scale for determination of a_i from the NCHRP 128 study uses resilient modulus as the determining factor for the selection of the structural layer coefficient. This was accomplished by using layered elastic analysis techniques and modeling the various pavement cross sections at the Road Test. Pavement subgrade deflections measured at the Road Test were found to relate well with deterioration in serviceability. By calculating the subgrade deflection using layered elastic theory in the computer modelled sections, it was possible to develop a link between the resilient modulus of the asphalt concrete surface and the contribution of the surface layer to the serviceability of the pavement. Figure 10 is the chart used to calculate the design a_1 from the diametral resilient modulus determined at 68°F. This chart was developed from the evaluation of the effect of the modulus of the asphalt concrete surface on pavement serviceability accomplished in NCHRP report 128.



(a) *Structural layer coefficient as a function of* D_1.

(b) *Structural layer coefficient as a function of* D_1.

(c) *Asphaltic concrete structural layer coefficient as a function of subgrade modulus* (E_3) *and asphaltic concrete surfacing thickness.*

(d) *Asphaltic concrete structural layer coefficient as a function of base modulus* (E_2), *surface course modulus* (E_1), *and surface course thickness* (D_1) *when* E_3 *=3,000 psi.*

Figure 19. Thickness and modular influence on structural layer coefficient (*Van Til et al. 1972*).

III. APPARATUS DEVELOPMENT

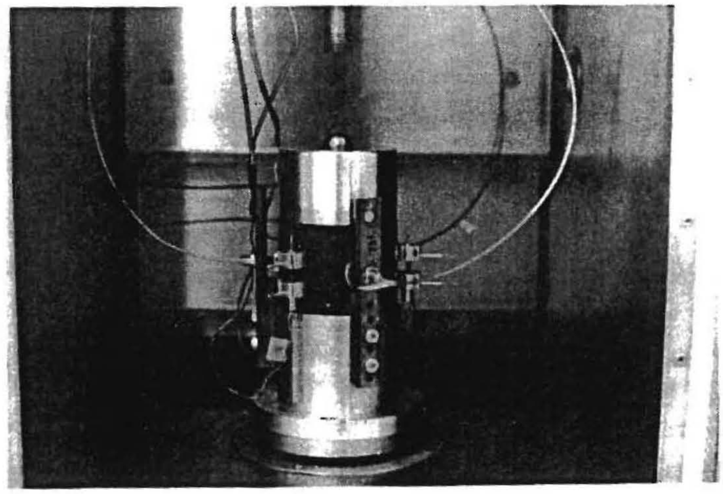
Three new devices were designed and fabricated during the course of this study. Machine drawings for the critical components of the devices can be found in Appendix D. The use of the three devices is described in Part II of the suggested test procedure presented in Appendix B. Two of the devices that were developed are indirect tension test devices and the remaining device is for axial loading. The primary objectives in the design of the axial loading device were to obtain more complete instrumentation coverage of the specimen, provide instrumentation for measurement of Poisson's ratio/dilation, and suggest some approaches for solving the problem of axial loading of short pavement cores. This device is not necessary for routine Department use unless Method C of the the suggested test procedure found in Appendix B is to be used. Cases in which Method C might be particularly useful include elevated temperature testing, investigation of effects of confining pressure at elevated temperature, and detailed investigation of the various components of time dependent behavior. The goals of the development of the diametral resilient modulus apparatus were to overcome problems associated with mounting sensors and specimen alignment with respect to the loading axis. A capability for measurement of Poisson's ratio was desired while maintaining the maximum speed and simplicity possible. Overall, the common goal of the development of the devices and test procedures was to provide the Department of Transportation with laboratory test procedures that can be used in conjunction with the 1986 AASHTO Guide and nondestructive testing to improve design and evaluation. Although the devices provide the necessary capability for current design procedures and NDT evaluation procedures, they should also maintain their utility for the foreseeable future as new design and evaluation tools are developed.

A. Axial Loading Apparatus

The axial loading apparatus is a simple modification of existing equipment. The emphasis in the development was put on on-sample measurements. This approach was required because remotely mounted sensors are usually inadequate if the specimen translates (tilts or slides horizontally) during loading or if there is considerable slack in the loading system. Specimens cored from an in-service pavement will almost always have ends that are not parallel. These ends are very difficult to saw parallel, so capping compounds must be used. This technique is acceptable for length to diameter ratios greater than two, but the practice restricts the movement of the ends on shorter cores. For this reason, short cores are not capped, and load application almost always results in some specimen translation.

To ensure that a reasonable average of vertical displacements is available, three vertical Linear Variable Differential Transformers (LVDTs) are glued to the surface of the specimen using small mounting fixtures. A simple positioning jig is used to make sure the fixtures are placed every 120° around the diameter and at a specified gauge length (usually 2-4 inches for an 8 inch tall specimen, 1.5 inches for a 3 inch specimen). To ensure that a reasonable integrated picture of the radial strain is available, a circumference measurement device is positioned around the specimen at mid-height between the vertical sensor gauge points. Both the non-contact, externally mounted sensor system and the circumferential measurement device are illustrated in Figure 20. The non-contact system shown in Figure 20 illustrates a radial displacement sensor every 120° around the specimen. If specimen translation (tilting or sliding) is anticipated, the sensor configuration should be changed to a 180° spacing in order to simplify the cancellation of the translational effects in the data analysis procedure.

The axial configuration can be used with confining pressure to extend the range of stress states that can be applied. For relatively low confining pressures and fast cycle times, a membrane is not used. For slower rates and higher confinement, the specimen should be placed in an impermeable membrane. Generally, the specimen in this test configuration is loaded with a sine wave frequency spectrum to obtain the 'dynamic' modulus. As will be shown later in the report, the results from loading at a frequency equal to that applied in the indirect tensile configuration will generate results that are not statistically different from one procedure to the other.



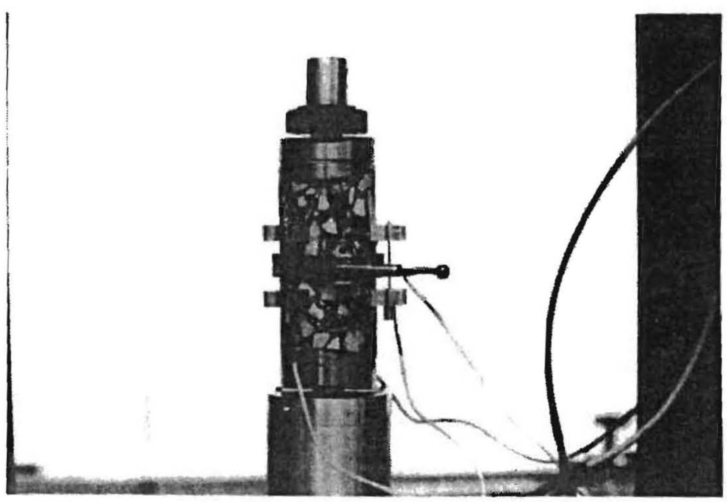


Figure 20. Axial measurement devices: (top) contact vertical LVDTs and remotely mounted noncontact radial transducers, (lower) contact sensors all directions.

B. Indirect Tension (Diametral) Devices

Two devices were developed. The first device allows the measurement of Poisson's ratio. The second device was developed for speed only, does not include a capability for measuring Poisson's ratio, and does not function properly at this time. Both devices use a universal loading head that incorporates a removable loading strip. The loading head is illustrated in Figure 21.

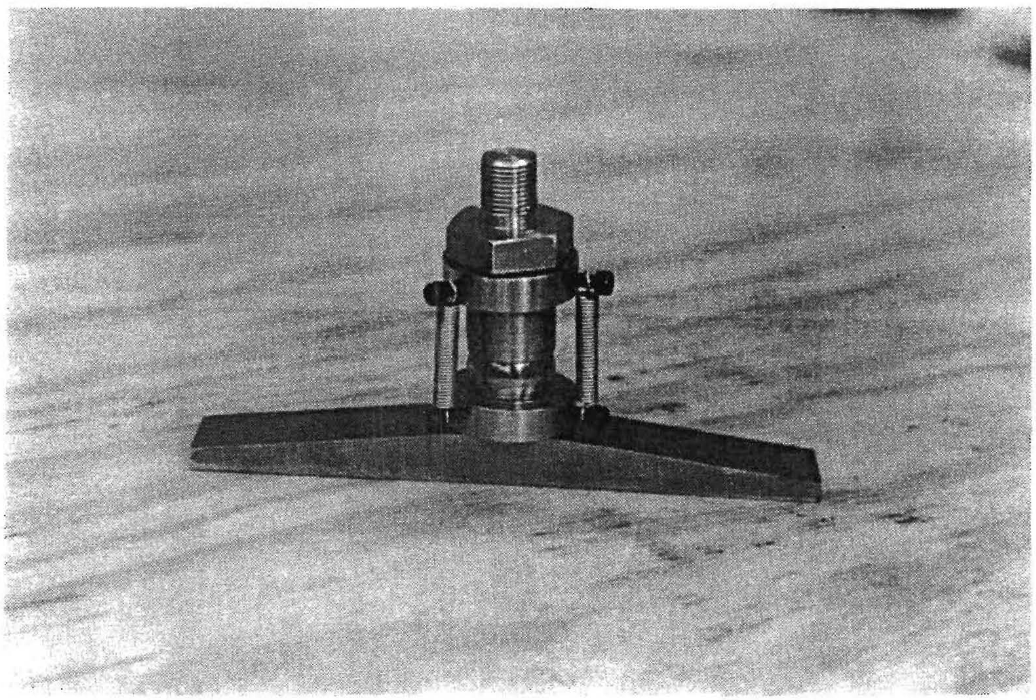


Figure 21. Universal loading head for diametral test.

Generalized Indirect Tension Device

The measurement of Poisson's ratio in the diametral test has been met with mixed reviews. Many of the reviews are not complimentary. The reason for this is that, unless the applied load levels are very small and/or the temperatures very low, a plastic zone develops in the vicinity of the loading strip where it contacts the specimen. The development of this plastic zone can cause erroneous vertical deformation readings. This is especially true if the loading strips are not aligned with each other along the diameter of the specimen.

In the new device, the loading strips are glued to the specimen in an alignment frame as shown in Figure 22. This frame insures that the strips are located on the diameter and that the specimen will be loaded through the center. The glue stiffness should be reasonably well matched to the specimen stiffness. A hot glue appears to work reasonably well for this application as long as the testing is conducted at a sufficiently low temperature and the glue film thickness is kept to a minimum. The device allows for control of both vertical and horizontal alignment of the diametral resilient modulus specimen. After the strips have been glued to the specimen, the assembly is as shown in Figure 23.

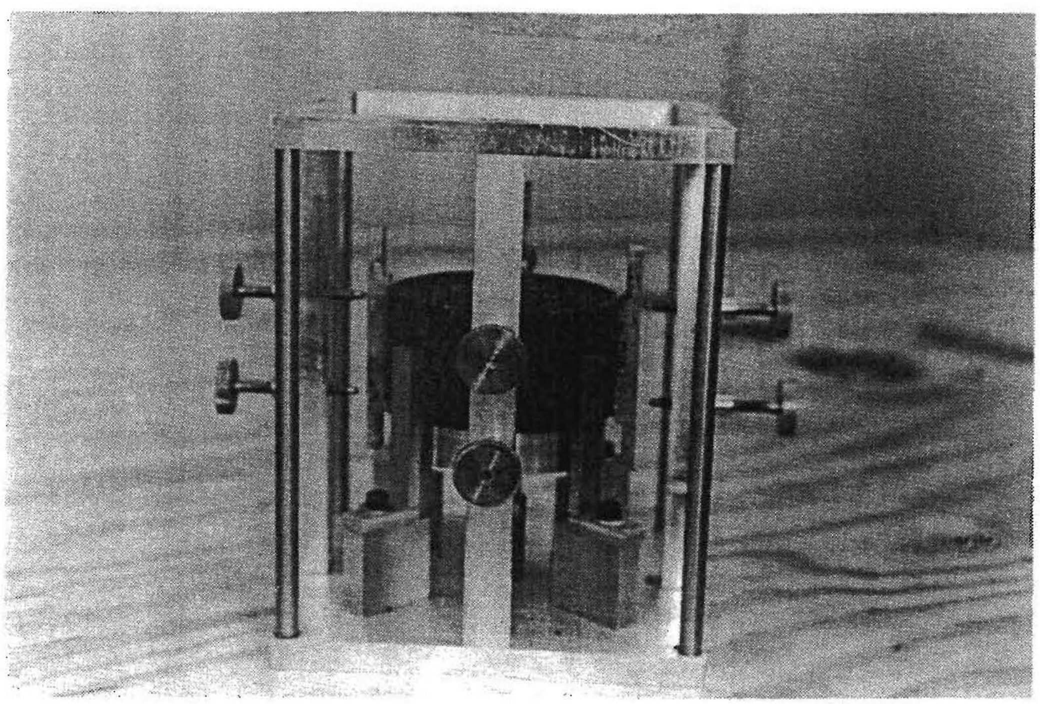


Figure 22. Gluing fixture for diametral loading strips.

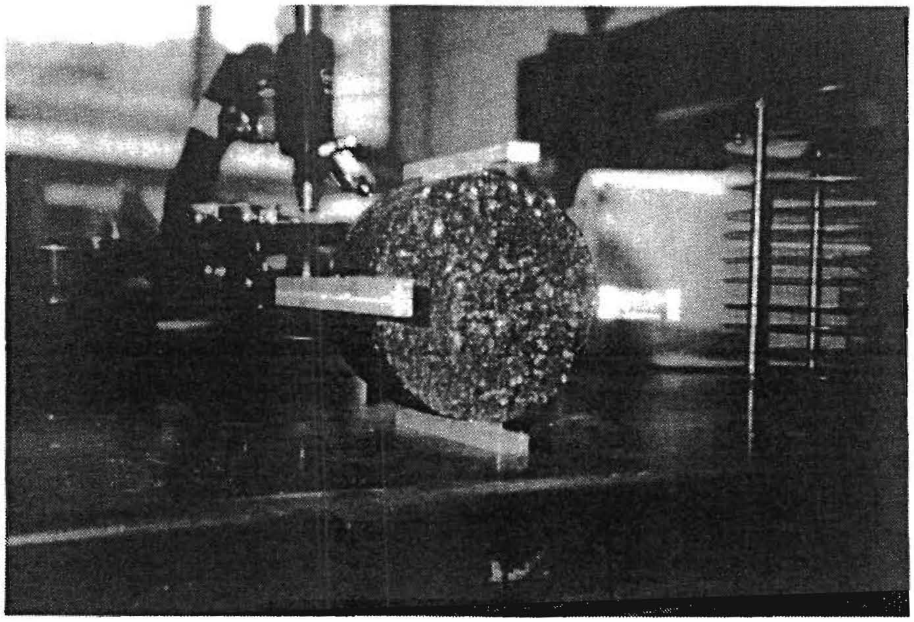


Figure 23. Specimen with loading/gauging strips mounted.

The dual purpose loading/gauging strips have been designed to accomodate four spring loaded sensors. The four loading strips are positioned perpendicular to the face of the specimen and 90° apart from each other. Two sensors are positioned on each side of the specimen such that they can measure both vertical and horizontal displacements. The surface of the strip glued to the specimen is machined to the nominal specimen radius.

Schlumberger/Sangamo AGZ0.5 spring loaded gauging transducers have been used to measure the horizontal and vertical displacements. Selected features of these spring loaded sensors include:

a. a linear stroke of 0.5 mm;

b. an acceptable temperature range of -40°C to 100°C;

c. AC powered and perform very well when there is vibration or wide temperature variations; and

d. accurate linear movement of the shaft assured by a linear bearing and antirotation guide.

Two important properties of these 'gage head' type LVDTs must be recognized. The first is that the standard spring may be too strong for this application at high temperature if the hot glue begins to soften. The standard spring can be removed quite easily and replaced with a weaker spring if desired. The second property is that the core of the LVDT is not free to move completely through the body of the device. Therefore the vertical LVDTs should be carefully set and monitored throughout the test so that they are not damaged by a compressive load. External signal conditioning for these LVDTs is provided by a CAH series carrier card. The original cards contained some inferior chips which were replaced after results from a portion of the testing revealed inconsistent and significant noise problems.

Rapid Diametral Testing Device

The Texas Department of Transportation reviewed the generalized indirect tension testing device and determined that a method having a shorter setup time was needed. Several devices were studied to determine their acceptability. The disadvantages of existing devices were that many of the devices had large sensor support structures mounted on the specimen or mounted on a rigid base that did not move with the specimen as it moved under loading. Some of the devices have a yoke that is held to the specimen by four screws. This concept was extended to the design of the accelerated testing device. Instead of using screws to hold an instrumentation support structure; spring loaded, grooved, linear bearing shafts were used to mount a yoke system to the specimen. The pressure points were then used as the gauge points for displacement measurements. The difference between the approaches is shown in Figure 24. The spring pressure should be adjusted if necessary as a function of the temperature to make up for the changing stiffness of the specimen. Since the horizontal displacement measurement is not taken across the full diameter, an integration must be performed to determine the formula for the horizontal strain. This derivation is carried out in Appendix A. The reader can easily demonstrate that the formula reduces to the more familiar form when the gauge length is made equal to the diameter and substituted into the final equation.

The yoke system was designed to be light, yet stiff. The weight of the yokes acts through the contact points parallel to the gravity vector. The springs are removed from the LVDTs in this application. The entire system comprises a specimen centering and loading strip aligning device, and the yoke system. In Figures 25 through 29, the components of this device are illustrated. Unfortunately, this system does not function properly and yields smaller strains than expected probably because of the slack in the yoke bearings, the LVDT bearings, or bulging of the specimen.

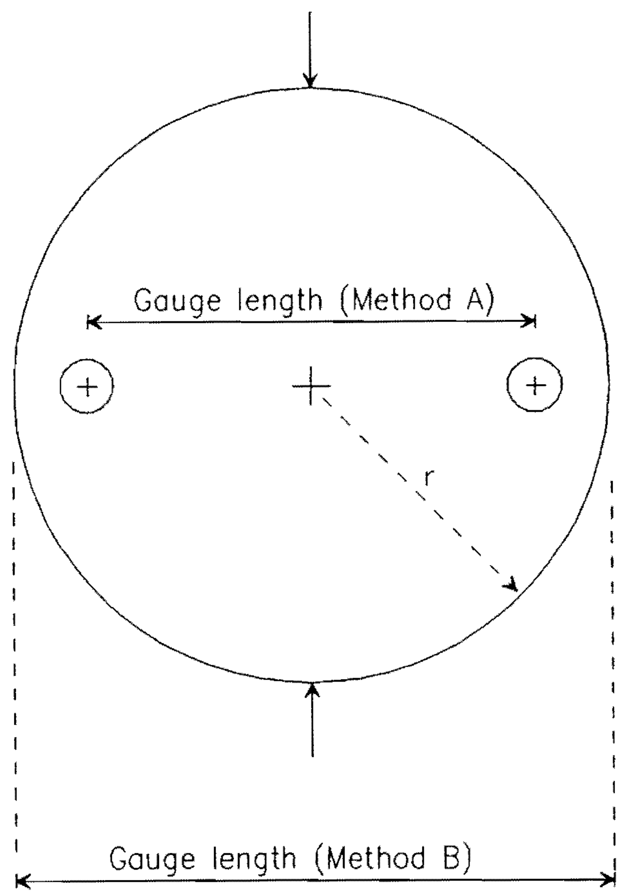


Figure 24. Comparison of horizontal deflection measurements in the diametral test.

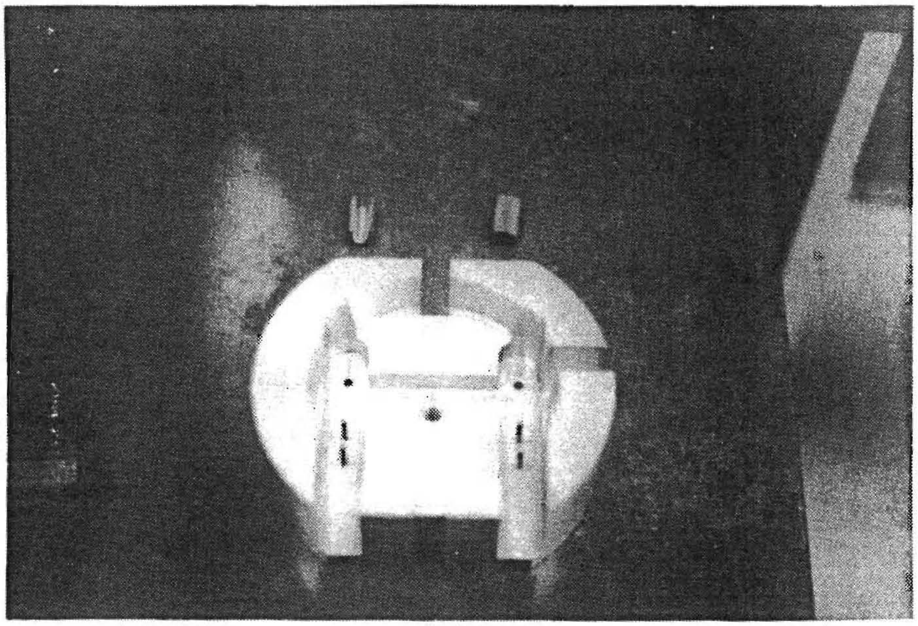


Figure 25. Specimen centering and loading strip alignment device.

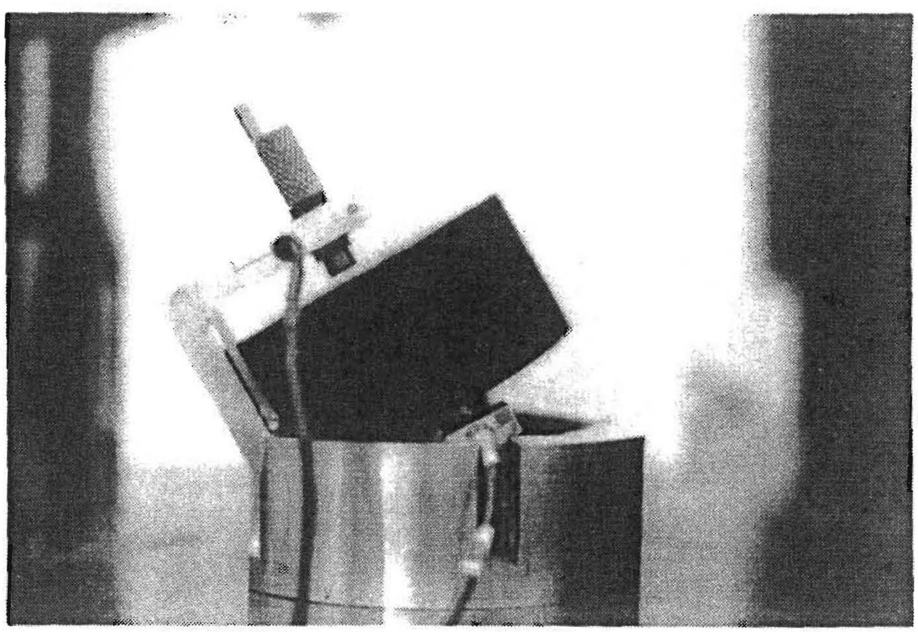


Figure 26. Installing specimen in yoke/centering device assembly.

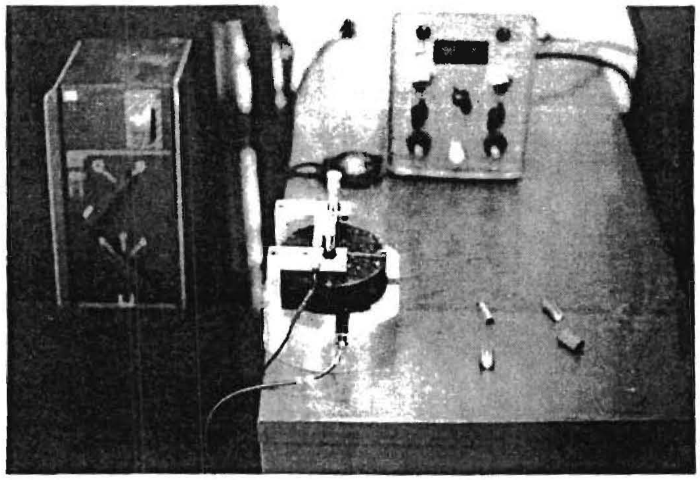


Figure 27. Centering device with yokes and specimen in place.

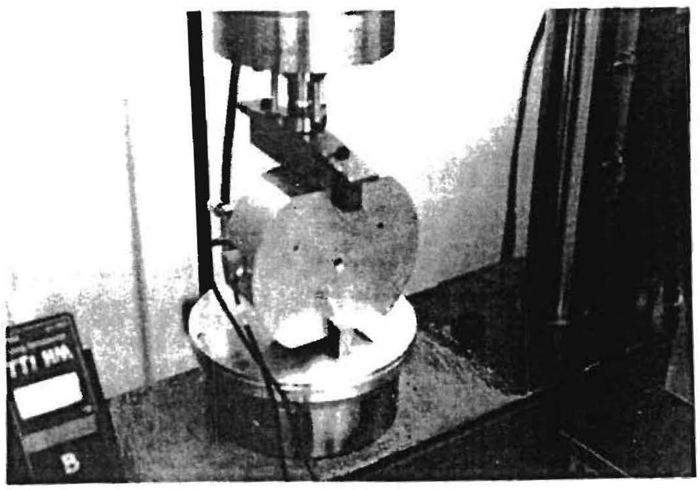


Figure 28. Complete assembly of previous figure in testing machine with static seating load applied.

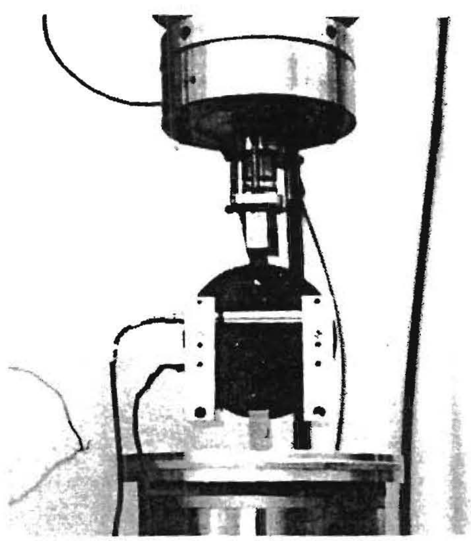


Figure 29. Centering device removed and specimen and yoke assembly ready for testing.

IV. EMPIRICAL STUDY

As the testing devices were being developed, a small test program was conducted to evaluate the equipment. In the initial test series, only the axial loading device with noncontact radial measurement transducers and the generalized indirect tension apparatus were used. Over 30 tests were conducted in the initial series. After development of the accelerated indirect tension device, over 650 additional tests were conducted to compare and refine all three devices and to develop a test procedure for the Department.

A. Experiment Design

An analysis was undertaken to evaluate the ability of the new diametral resilient modulus testing device to measure the various asphalt mixtures. The sensitivity analysis was based on a partial factorial analysis of mixture and procedural variables including the following.

(1) Asphalt Grade: Two asphalt types were used.

(2) Aggregate Type: Limestone.

(3) Aggregate Gradation: Type D and Type C

(4) Percent Passing the No. 200 Sieve Size: Percentage ranging from 0 to 8 were considered.

(5) Frequency of Loading or Time of Duration of Loading: Frequencies from 1 to 16 Hz were considered.

(6) Temperatures considered: 0 to 140°F

In the first series of tests, Type C and D mixtures were used. An AC-10 and an AC-20 asphalt were used in the mix. A crushed limestone (CLS) aggregate was used. Tests were conducted at 77 and 104°F.

In the second series, only the type C mix was used. An AC-10 from two different sources, and an AC-20 from two different sources were used in the mix. A crushed limestone and a crushed, rounded river gravel (chert, RL) were used for aggregate. Tests in this series were conducted at 50, 77, and 104°F at four different load levels. The factor level combinations are listed in Table 6. In addition to the mixtures listed in the table, four cores were obtained from an in-service pavement. These cores were taken at the northbound off-ramp from Mopac to Highway 183 in Austin. The cores were relatively short and were approximately 3.75 inches in diameter.

Table 6. Summary of levels of aggregate and asphalt factors.

ASPHALT	AGGREGATE
AAM-1 AC20	CLS
Texaco AC20	CLS
Witco AC10	CLS
Shamrock AC10	CLS
Shamrock AC10	RL

B. Materials and Methods

The mixtures were designed in accordance with SDHPT Bulletin C-14 and Test Method Tex-204-F to conform with the requirements therein. This procedure provides a means to determine the proper proportions of approved aggregates and asphalt which, when combined, will produce a mixture that will satisfy the specification requirements. In this method, the mix is designed both by weight and by volume. If the determined values for the design by weight vary by 0.300 or more, the mix design is done by the volumetric method (Test Method Tex-204-F, Part II).

The design should produce an acceptable mixture at optimum density. Acceptability is determined by the following laboratory density and stability requirements.

Density		**Percent**	**Stability, Percent**
Min	Max	Optimum	Not less than 35 unless
95	99	97	otherwise specified

Paving mixtures consist of a mixture of coarse aggregate, fine aggregate and asphalt materials. Mineral filler, and/or additive may also be required. When properly proportioned, the aggregate gradation will conform to the limitations for master grading given in Tables 7 and 8 for the type specified. The gradation is determined in accordance with Test Method Tex-204-F (Dry Sieve Analysis) and shall be based on aggregate only. The percentage or quantity of asphaltic material shall conform to the limitations shown for the paving type specified. Texas gyratory compaction was used for diametral test specimens and kneading compaction was used for taller specimens.

Table 7. Gradation requirements for Type 'C' coarse graded surface course.

Type "C" (Coarse Graded Surface Course):	Percent Aggregate by Weight or Volume
Passing 7/8" sieve	100
Passing 5/8" sieve	95 to 100
Passing 5/8" sieve, retained on 3/8" sieve	16 to 42
Passing 3/8" sieve, retained on No.4 sieve	11 to 37
Passign No.4 sieve, retained on No.10 sieve	11 to 32
Total retained on No.10 sieve	54 to 74
Passing No.10 sieve, retained on No.40 sieve	6 to 32
Passing No.40 sieve, retained on No.80 sieve	4 to 27
Passing No.80 sieve, retained on No.200 sieve	3 to 27
Passing No. 200 sieve	1 to 8

The asphaltic material shall form from 3.5 to 7 percent of the mixture by weight or from 8 to 16 percent of the mixture by volume, unless otherwise specified.

The AAM-1 asphalt used in the experiment had viscosities of 1992 poises and 569 cSt at 140 and 275°F, respectively. After thin film oven testing, the viscosities at the two temperatures were 3947 poises and 744 cSt. The original asphalt penetration at 77°F was 64. The ring and ball softening occurred at 125°F. Asphaltenes made up 3.9 percent of the material.

The RL aggregate had a bulk specific gravity of 2.59. It had a flakiness index of 14.4 percent and an L.A. Abrasion value of 20.2 percent.

Table 8. Gradation requirements for Type 'D' fine graded surface course.

Type "D" (Fine Graded Surface Course)	**Percent Aggregate by Weight or Volume**
Passing 1/2" sieve	100
Passing 3/8" sieve	85 to 100
Passing 3/8" sieve, retained on No.4 sieve	21 to 53
Passing No.4 sieve, retained on No.10 sieve	11 to 32
Total retained on No.10 sieve	54 to 74
Passing No.10 sieve, retained on No.40 sieve	6 to 32
Passing No.40 sieve, retained on No.80 sieve	4 to 27
Passing No.80 sieve, retained on No.200 sieve	3 to 27
Passing No.200 sieve	1 to 8

The asphaltic material shall form from 4 to 8 percent of the mixture by weight or from 9 to 19 percent of the mixture by volume, unless otherwise specified.

To determine an appropriate aggregate grading Cooper *et al.* (1985) have formulated the following relationship:

$$P = \frac{(100 - F)\ (d^n - 0.075^n)}{(D^n - 0.075^n)} + F \qquad \textbf{(10)}$$

where P = Percentage passing a sieve of size d (mm)

D = Maximum aggregate size (mm)

F = Percentage passing a 0.075 mm sieve

In this study, the gradation used in laboratory specimen preparation was obtained by setting F equal to a value between 0 and 8 percent and setting D to the maximum size specified for the mix type. Minor adjustments of the value of F in the vicinity of 5 percent were made to produce a smooth gradation curve that fell within the specified band for the mix type.

General Procedure for Axial Tests

The resilient modulus of most of the materials in flexible pavements can be determined by a repeated load triaxial compression test. The term triaxial is interpreted loosely in this terminology since it is actually an axisymmetric problem and not a true three dimensional one. The 'unconfined' compression test is a triaxial test in which the confining pressure is simply the ambient atmospheric pressure (approximately 14.7 psi). The specimen size used for dense graded asphalt mixtures is normally 4 inches in diameter by 8 inches high.

Triaxial tests often employ monotonically applied stresses to failure in order to characterize the strength of the material. The inherent stability of a material can be represented by the general (linear) Coulomb equation:

$$s = c + \sigma \tan \phi \qquad (11)$$

The use of the Coulomb equation to represent internal stability is predicated on the assumption that material behavior is a function of shearing resistance due to internal friction. It is further assumed that cohesion and internal friction may be combined in a single expression for shearing stress. A nonlinear interpretation of the Coulomb equation presented above is illustrated by the dashed line in Figure 6.

The resilient modulus of a material is determined using a cyclic application of stresses that are usually well below those attained in monotonic failure tests. The cyclic stress states can be illustrated by the Mohr's circles in Figure 6 which are well below the failure envelope. In a triaxial resilient modulus test, the specimen is subjected to a repeated axial stress, σ_d ($=\sigma_1 - \sigma_3$) and, if desired, a confining pressure, σ_c ($=\sigma_3$). In Figure 6, the first circle on the right side of the origin (compression) is usually interpreted to be the unconfined compression case (atmospheric pressure is usually considered to be the zero reference point). Other confining pressures would give circles farther toward the right in the figure.

The recoverable axial strain , ϵ_a, is determined by measuring the recoverable deformations across a known length ('gauge length') on the specimen. The resilient modulus is calculated from the following equation:

$$M_R = \frac{\sigma_d}{\epsilon_a} \tag{12}$$

With the application of the first deviator stress in a resilient modulus test, there is an immediate deformation that can be followed by a plastic deformation. When the load is removed, there is a partial recovery or rebound. Similar deformations occur with the application of successive loads; but the *rate* of accumulation of total deformation since the start of the test generally decreases with additional load applications (depending on load level, specimen integrity, and temperature), tends toward a constant value (preferably as close to zero rate of accumulation as possible), and then increases again as failure conditions are approached. The resilient deformation should remain approximately constant over the period of loading. The results of tests conducted during this study indicate that measurements taken in the range of 45-50 cycles will be in the stable region of the deformation curve where the rate of change of the total deformation is small. The test procedure in Appendix B recommends 50 cycles for the test.

The repeated axial (deviator) stress is calculated from the following equation:

$$\sigma_d = \frac{P}{A} \tag{13}$$

where, P = repeated load
A = cross-sectional area

The axial strain is calculated using the output of displacement transducers according to the following equation:

$$\epsilon_a = \frac{\delta}{L_g} \tag{14}$$

where δ = axial deformation
L_g = original gauge length

Poisson's ratio is calculated from the measurement of radial as well as axial deformations of the specimen which are then converted to strains. The following equation is used to calculate Poisson's ratio from the strains:

$$\nu = \frac{\epsilon_r}{\epsilon_a} \tag{15}$$

where ϵ_r is radial strain and ϵ_a is the axial strain.

The resilient moduli obtained in a repeated load triaxial test are expressed by the equation of the form

$$M_R = K\,\theta^c \tag{16}$$

where K and c = experimental constants

θ = bulk stress

General Procedure for Diametral Indirect Tension Tests

The resilient modulus of asphalt-treated materials can also be determined by means of the diametral resilient modulus (M_R) device. This test is generally used because of the simplicity of the equipment and because it is possible to test asphalt specimens similar in size to those used for the widely known Marshall and Hveem tests.

To determine the resilient modulus of an asphalt concrete specimen, horizontal deformations are measured with displacement transducers such as linear variable differential transformers (LVDT). These LVDT's are mounted on the specimen. If Poisson's ratio is to be determined, an additional set of LVDTs must be mounted so as to measure deformation in the vertical direction. It is preferable that the vertical measurement be taken over a gauge length that is shorter than the diameter. However, the practice has usually been to take the measurement between the loading strips (*i.e.* with a gauge length equal to the specimen diameter) because of the logistical problems involved in any other approach. The material properties of the test specimen (*i.e.*, resilient modulus and Poisson's ratio) are calculated with the following equation

$$M_R = \left(\frac{P}{Ht}\right)(\nu + 0.27) \tag{17}$$

where M_R = resilient modulus

P = repeated load

H = total recoverable horizontal deformation

t = thickness of the specimen

ν = Poisson's ratio

The tensile strain at the center of the specimen is given by

$$\epsilon_t = [\frac{0.16 + 0.48\nu}{0.27 + \nu}] H \quad (18)$$

where ϵ_t = tensile strain at the center (microstrain, μ)

ν = Poisson's ratio calculated from vertical and horizontal deformations

and

$$\nu = \frac{-3.50 -0.27 (V/H)}{0.063 + (V/H)} \quad (19)$$

where V = total recoverable vertical deflection

The theoretical distribution of stresses in a disk of idealized elastic material subjected to a concentrated (line) load is shown in Figure 30. This is the theory upon which the diametral indirect tension test is based. The obvious objection to the finite width strip used in the test procedure is that the two halves of a failed specimen can support a load if the load is applied with a finite width strip, but a line load can not be supported once failure occurs. Of course, there is the practical argument against the line load because the stress concentration is very high at the contact point, which can cause a wide array of problems when the material being tested is a thermoplastic, nonhomogeneous composite instead of a perfectly homogeneous, elastic solid.

The equations presented in Figure 30 can be manipulated to derive the formula for the modulus to be used with test measurement input.

Horizontal diametral:

$$\sigma_x = \frac{2P}{\pi td} \left[\frac{(d^2 - 4x^2)}{(d^2 + 4x^2)} \right]^2 \quad (20)$$

$$\sigma_y = -\frac{2P}{\pi t d}\left[\frac{4d^4}{(d^2 + 4x^2)^2} - 1\right] \tag{21}$$

$$\tau_{xy} = 0 \tag{22}$$

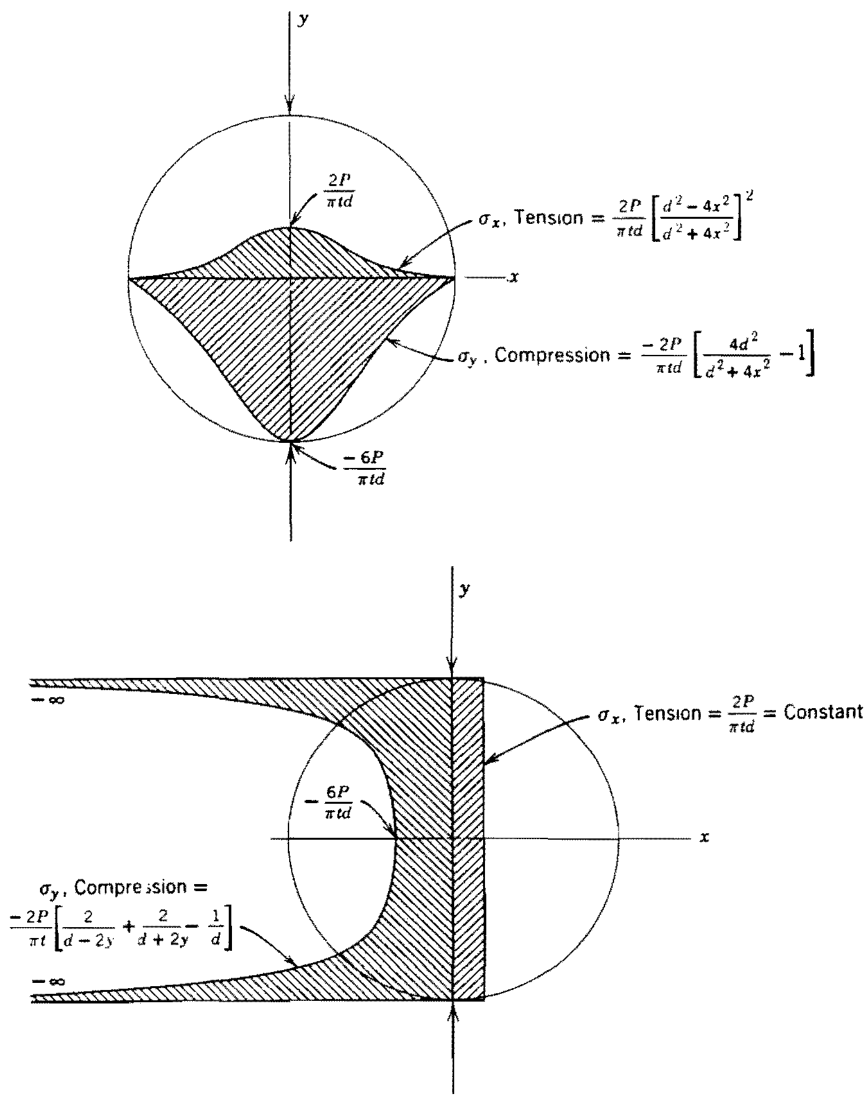


Figure 30. Theoretical stress distribution used for the diametral indirect tension test for M_r (*Frocht 1957, Yoder & Witczak 1975*).

Vertical diametral:

$$\sigma_x = \frac{2P}{\pi t d} = Constant \tag{23}$$

$$\sigma_y = -\frac{2P}{\pi t}\left[\frac{2}{(d-2y)} + \frac{2}{(d+2y)} - \frac{1}{d}\right] \tag{24}$$

$$\tau_{xy} = 0 \tag{25}$$

where P = total applied load (lb)
t = specimen thickness (in)
d = specimen diameter (in.)
x,y = coordinate values from center of specimen

The above equations are presented by Frocht (*1957*) for an idealized elastic solid. Assuming that plane stress conditions are applicable ($\sigma_z = 0$) the resultant strain ϵ_x is given by

$$\epsilon_x = \frac{2P}{E\pi t d}\left[\frac{4d^4\nu - 16d^2x^2}{(d^2 + 4x^2)^2} + (1-\nu)\right] \tag{26}$$

The deformation across the full distance of the horizontal diameter (at y = 0) may be found by integrating the last equation above between x = - d/2 and x = d/2. This results in the horizontal deformation being equal to:

$$\delta_h = \frac{P}{tE}\left[\frac{4}{\pi} + \nu - 1\right] \qquad (27)$$

Hence, for an applied dynamic load of P in which the resulting horizontal dynamic deformation is measured, the modulus or M_R value is:

$$M_R = \frac{P(\nu + 0.2734)}{t\delta_h} \qquad (28)$$

A more general solution for the modulus as a function of the gauge length along the diameter (for applications in which the gauge length is less than the diameter) is given in Appendix A. For a configuration in which a 4-inch diameter specimen is used and a 3-inch gauge length is used, the solution for the modulus is as shown below.

$$M_R = \frac{P(0.36 + 1.27\nu)}{t\delta} \qquad (29)$$

When no vertical measurements are taken, a value of Poisson's ratio at 77°F for asphaltic material is $\nu = 0.35$ is often used as input to these equations. At other temperatures, values are sometimes taken from Figure 3. When more instrumentation is available and a volume change can be measured, an approximate relationship for the Poisson's ratio can be used. This method is illustrated in the equation below in which ϵ_a is the strain along the axis parallel to the load vector.

$$\nu \approx \frac{1}{2}\left[1 - \frac{1}{\epsilon_a}\frac{\Delta V}{V}\right] \qquad (30)$$

where ΔV = change in volume,

V = original volume.

For diametral specimens, the ASTM test procedure D4123 uses the following equation to calculate Poisson's ratio:

$$\nu_{RT} = 3.59 \frac{\Delta H_T}{\Delta V_T} - 0.27 \tag{31}$$

where ΔH_T = total recoverable horizontal deformation,
ΔV_T = total recoverable vertical deformation.

C. Test Results

The ASTM D4123 equation has been used to compute Poisson's ratio from the results of the diametral resilient modulus tests conducted during this study. Resilient modulus was calculated as shown in Appendices A and B as appropriate for the test procedure being conducted. Summaries of the data from the tests are given in Appendix C. Table 9 shows the codes used to identify the different devices.

Table 9. Device codes.

Code	Device/Sensors	Testing Machine
0	Retsina	Pneumatic
1	Retsina	Hydraulic
2	Accelerated IDT method/LVDTs	Hydraulic
3	Generalized IDT/2 horizontal LVDTs only	Hydraulic
4	Generalized IDT/both horizontal & vertical	Hydraulic
5	Axial: lab mix, 4 LVDTs	Hydraulic
6	Axial: field core, 4 LVDTs	Hydraulic

Comparison of Diametral Devices

A series of tests was conducted to evaluate the differences between various diametral devices. The commercially produced Retsina device was used as the reference. The approach was to conduct tests with each device on a given set of specimens. Twenty limestone aggregate test specimens were compacted in the gyratory compactor with three different asphalts (total of 60 specimens). Ten companion 4-inch diameter by 8-inch tall specimens were compacted with a kneading compactor (total of 30 specimens). An additional 10 gyratory specimens and 5 kneading specimens were compacted using the RL aggregate. Load levels ranged from a 1 pound seating load with a 10 pound cyclic load to a 15 pound seating load and a 200 pound cyclic load.

Poisson's ratios calculated from the early portion of the testing program were larger for AC-10 mixtures than for AC-20 mixtures having the same type aggregate and gradation. This trend was expected because of the lower viscosity of the AC-10 binder.

Since none of the other diametral devices could measure Poisson's ratio, no comparisons among devices can be made. However, comparisons can be made with respect to resilient modulus computation. The first comparison to be made is to compare the results of tests using a pneumatic actuator with the results of tests conducted using an hydraulic actuator. These tests have device codes of 0 and 1. Since the transducers used in the Retsina device (device code 0) were sufficiently portable to move from one loading system to another, a direct comparison could be made between the pneumatic and the hydraulic loading system. An analysis of variance showed that no statistically significant difference was found between the two types of load actuators using the materials and load levels applied in this portion of the study. This conclusion is documented in Table 10.

Table 10. Analysis of variance for pneumatic versus hydraulic loading systems.

One-Way Analysis of Variance

Data: M_R

Level codes: Loading Method (pneumatic versus hydraulic

Means plot: Conf. Int. Confidence level: 95 Range test: Bonferroni

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1.7269E0010	1	1.7269E0010	.575	.4567
Within groups	1.0474E0013	349	3.0012E0010		
Total (corrected)	1.0492E0013	350			

The data for all tests at various temperatures for all the mixtures were combined to perform an ANOVA (analysis of variance) for the overall experiment, the results of which are presented in Table 11. Contributing to the variability were the following factors: (a) the load level was not taken into account, (b) the use of more than one untrained technician was not taken into account, (c) the experiment was unbalanced with unequal cell sizes.

Air voids and temperature were used as covariates in the analysis. For qualitative discussion purposes, a covariate may be considered to be similar to a pre-existing condition or an independent regression variable. In the upper portion of Table 11, the overall results of the ANOVA are presented. At the 10 percent significance level ('sig. level' less than 0.1000), the main effects (device type and mixture) are significant variables, and the temperature covariate is significant. For this experiment and this ANOVA model, the air void content was not significant (*i.e.* the modulus was not sensitive to air voids *in the range of air voids tested*).

In the middle and lower portions of Table 11, a test was performed concerning the differences among means. Consider the middle portion of Table 11. The first column (level) lists the device codes included in the analysis (from Table 9). The second column (count) is the number of tests in the level. The third column is the 'least squares' mean (LS mean) which is a mean for the level that would be expected for a balanced design with the covariates held at their mean value. Considering the mean and variance, a test called Tukey's studentized range test was conducted to identify differences among the testing devices. A formal test is necessary because simply taking the mean (average) of the moduli for each level will result in different mean values in most cases, but there is no proof that the differences are real and statistically sound unless the variances are considered. In the fourth column (homogeneous groups), the results of this test are presented. The levels associated with the 'X's that are in the same column and that overlap are not statistically different. Using this logic, it can be seen that levels 3 and 4 are not statistically different while levels 1 and 2 are significantly different. The accelerated device gives moduli that are approximately 2.35 times the values obtained with the Retsina device. It is assumed that the accelerated device is incorrect and that the deflections are not being measured accurately (*i.e.* deflections are too small) with this device. This could be caused by roughness in the LVDT bearings (least likely), slipping of the contact points, or slack in the linear bearings in the yoke assembly (most likely). It is also possible that correction factors for specimen bulging must be developed. These factors were found to be important by *Roque & Buttlar* (*1992*) with their device which is similar to the accelerated device (device code 2 of Table 9), except that their device uses a much shorter gauge length, and the device that holds the LVDT is actually glued to the specimen, which is a more time consuming process.

Tukey's test also found a difference in mixture types as shown in the lower portion of Table 11. The difference was found between an AC-10 and an AC 20. The same aggregate and gradation were used in these two mixes, so it can be concluded that the diametral test is sensitive to asphalt type.

Table 11. ANOVA for IDT devices and mixtures.

Analysis of Variance for Modulus - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
COVARIATES					
Air voids	4.1215E0012	1	4.1215E0012	1.361	.2440
Temperature	7.4287E0014	1	7.4287E0014	245.268	.0000
MAIN EFFECTS					
Device	7.7545E0013	3	2.5848E0013	8.534	.0000
Mixture	3.2200E0013	5	6.4400E0012	2.126	.0612
RESIDUAL	1.4023E0015	463	3.0288E0012		
TOTAL (CORRECTED)	2.5704E0015	473			

All F-ratios are based on the residual mean square error.

Multiple range analysis for Modulus by Device

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups	
1	193	677446.1	X	Retsina + hydraulic
3	30	844371.8	XX	Generalized IDT + hydraulic
4	9	864674.4	XX	Generalized IDT + hydraulic
2	242	1595251.2	X	Accelerated IDT + hydraulic

Multiple range analysis for Modulus by Mix type

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups	
S4	55	340122.9	X	Shamrock AC-10 + CLS
RL	42	954201.0	XX	Shamrock AC-10 + RL
S3	123	1092195.6	XX	Witco AC-10 + CLS
S2	82	1125543.0	XX	Texaco AC-20 + CLS
S1	166	1207830.7	X	AAM-1 AC-20 + CLS
MO	6	1252722.1	XX	Mopac field cores

Comparison of Axial versus Diametral Resilient Moduli

In the diametral test, the specimen is loaded and unloaded within 0.1 seconds, and then a rest period of 0.9 seconds is allowed prior to the succeeding load pulse. In the axial test, the load is cycled continuously. Because of the complex time dependent nature of the strain response of this material, it is not certain that the axial loading test can produce the same results as the diametral test. The period of the loading pulse is expected to be the most important factor. In an effort to determine which loading frequency in the axial test simulates the conditions in the diametral test (and to demonstrate frequency dependence), the following study was undertaken.

Specimens of lab mix and field mix were tested using the axial loading test. After the completion of the test, the center 2 inches was cut from each specimen and tested in the diametral device. This procedure made it absolutely certain that any differences detected by the analysis of data from the two test procedures would be due to differences in the test procedures and not due to extraneous factors such as variations in the air voids and particle distribution in the test specimens.

In Figures 31 and 32, the dependency of the materials on frequency is illustrated. The Mopac specimens were taken in 1991 in an area near that tested by Roesset et al. (*1990*) using spectral analysis of surface waves (SASW) approximately one to two years earlier. In that study, the researchers found the modulus to be approximately 1.94×10^6 psi at a frequency of approximately 15 kHz at 88°F. Cyclic torsional tests by those researchers indicated modulus values in the range of 521 ksi at 10 Hz down to 278 ksi at 1Hz. The results of the current study are shown in Figure 31 and indicate that the material tested in this study are slightly higher than the SASW results. This can be verified by substituting the appropriate frequency in the simplified regression equation shown in Figure 31, $E=460{,}146\ f^{0.270806}$ (where f is frequency in Hz and E is modulus in psi). For example, at 10 Hz, the predicted modulus in Figure 31 is 858,424 psi. However, this is quite a reasonable agreement in the results, given that the pavement was only 4 days old when the SASW measurements were taken, but had been exposed to over a year of traffic and aging prior to the axial laboratory testing in this study. The Mopac specimens used in this study were approximately 3.75 inches in diameter and had been trimmed to a height near 4 inches. Laboratory specimens of a type C mix were tested in a similar fashion as the Mopac specimens. The results of these tests are shown in Figure 32.

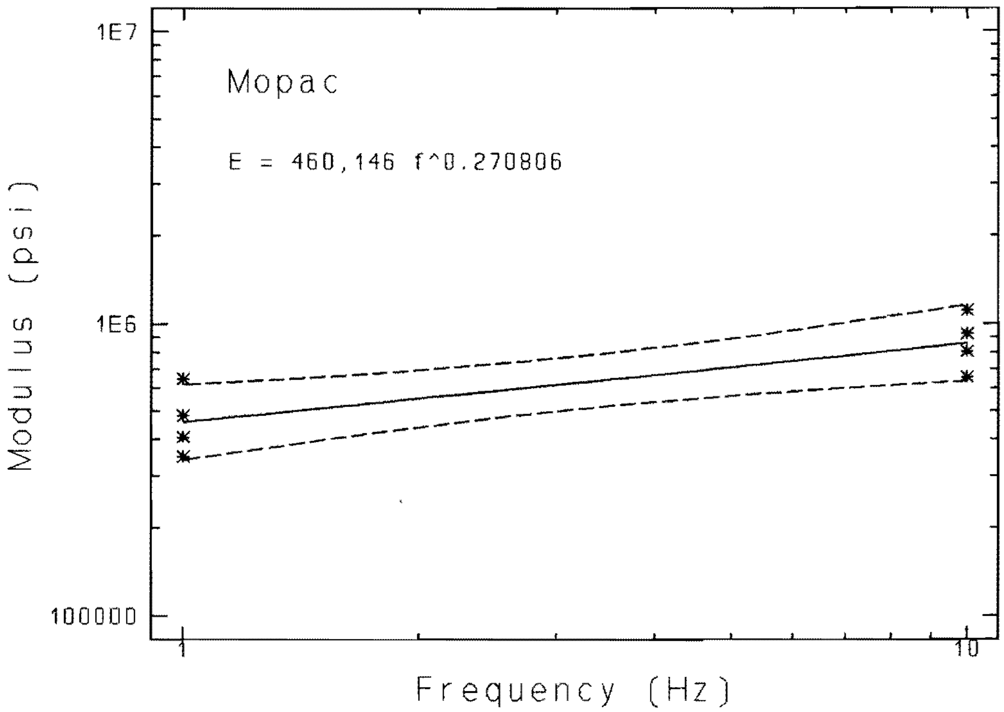


Figure 31. Frequency dependence on field cores (Mopac, 77°F).

After the field and laboratory specimens were cut down and tested in the diametral device, the data was analyzed to determine if results from tests with the axial device could be interchanged with diametral test results. The 'mix type' variable defines the response as being the result of a test on either a Mopac specimen or a laboratory mix. The 'frequency' variable identifies the frequency as 1 or 10 Hz from the axial test, or the 0.1 second load pulse with 0.9 second rest used in the indirect tension test (IDT). The analysis of variance (ANOVA) table indicates that all treatments are significant and the least significant difference (LSD) analysis indicates that the response at the 1 Hz frequency in the axial test is significantly different from the 10 Hz response in the same test and that the mix types are significantly different. The more important result is that the LSD procedure indicates that there does not appear to be a significant difference between the 10 Hz axial test results and the diametral resilient modulus test results. A means plot with 95 percent confidence intervals to accompany the ANOVA in Table 12 is presented in Figure 33.

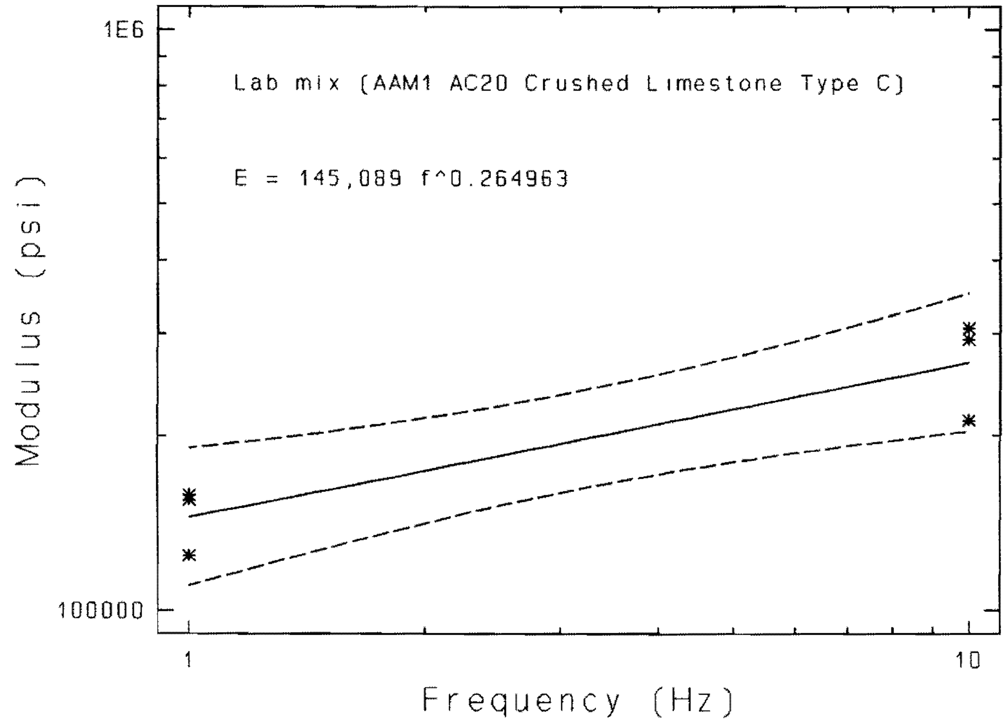


Figure 32. Frequency dependence (Crushed limestone, AAM-1 AC20, Type C, 77°F)

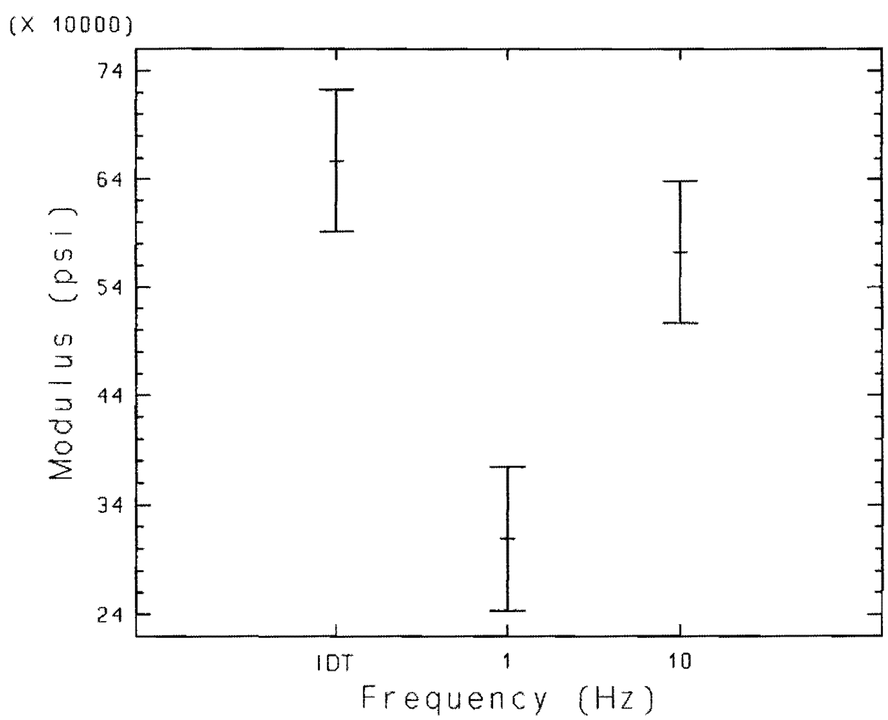


Figure 33. Comparison of axial resilient (dynamic) modulus with diametral resilient modulus means with 95 percent confidence intervals.

Table 12. Analysis of variance for axial and diametral tests.

Analysis of Variance for M_R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
Frequency	4.5132E0011	2	2.2566E0011	17.275	.0001
Mix type	5.5680E0011	1	5.5680E0011	42.625	.0000
INTERACTIONS					
f x mix	2.5676E0011	2	1.2838E0011	9.828	.0019
RESIDUAL	1.9594E0011	15	1.3063E0010		
TOTAL (CORRECTED)	1.4531E0012	20			

All F-ratios are based on the residual mean square error.

Multiple range analysis for M_R by frequency

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	7	309329.29	X
10	7	572428.96	X
IDT	7	657234.25	X

contrast	difference	+/- limits	
IDT - 1	347905.	131597.	*
IDT - 10	84805.3	131597.	
1 - 10	-263100.	131597.	*

* denotes a statistically significant difference.

Multiple range analysis for M_R by Mix type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
Lab	9	348477.67	X
Mopac	12	677517.33	X

contrast	difference	+/- limits	
Lab - Mopac	-329040.	107448.	*

* denotes a statistically significant difference.

In general, the summarized data shown in Appendix C indicates the expected trend with respect to identifying differences in mixtures and temperature conditions. Poisson's ratio appears to be larger for the AC-10 mixtures than for the AC-20 mixtures with the same type of aggregate, and the resilent modulus values indicate the reversed trend. Increasing the test temperature always increases Poisson's ratio and decreases the resilient modulus.

The data sets for the 77°F tests for selected mixtures were analyzed to provide some indication of how many specimens would be recommended for replicate testing as a function of the allowable error. The equation used to define the allowable error is given by the equation

$$n = (2\sigma_o/e)^2$$

where n = number of specimens recommended

σ_o = estimate of the standard deviation

e = maximum allowable sampling error.

The result of this computation is illustrated in the following Figure 34. The most gain appears to be between 10 and 25 specimens. There seems to be little reason to test more than 25 specimens of a given mix. In its present stage of development, the accelerated testing device requires more specimens to achieve a given error rate than the more conventional devices.

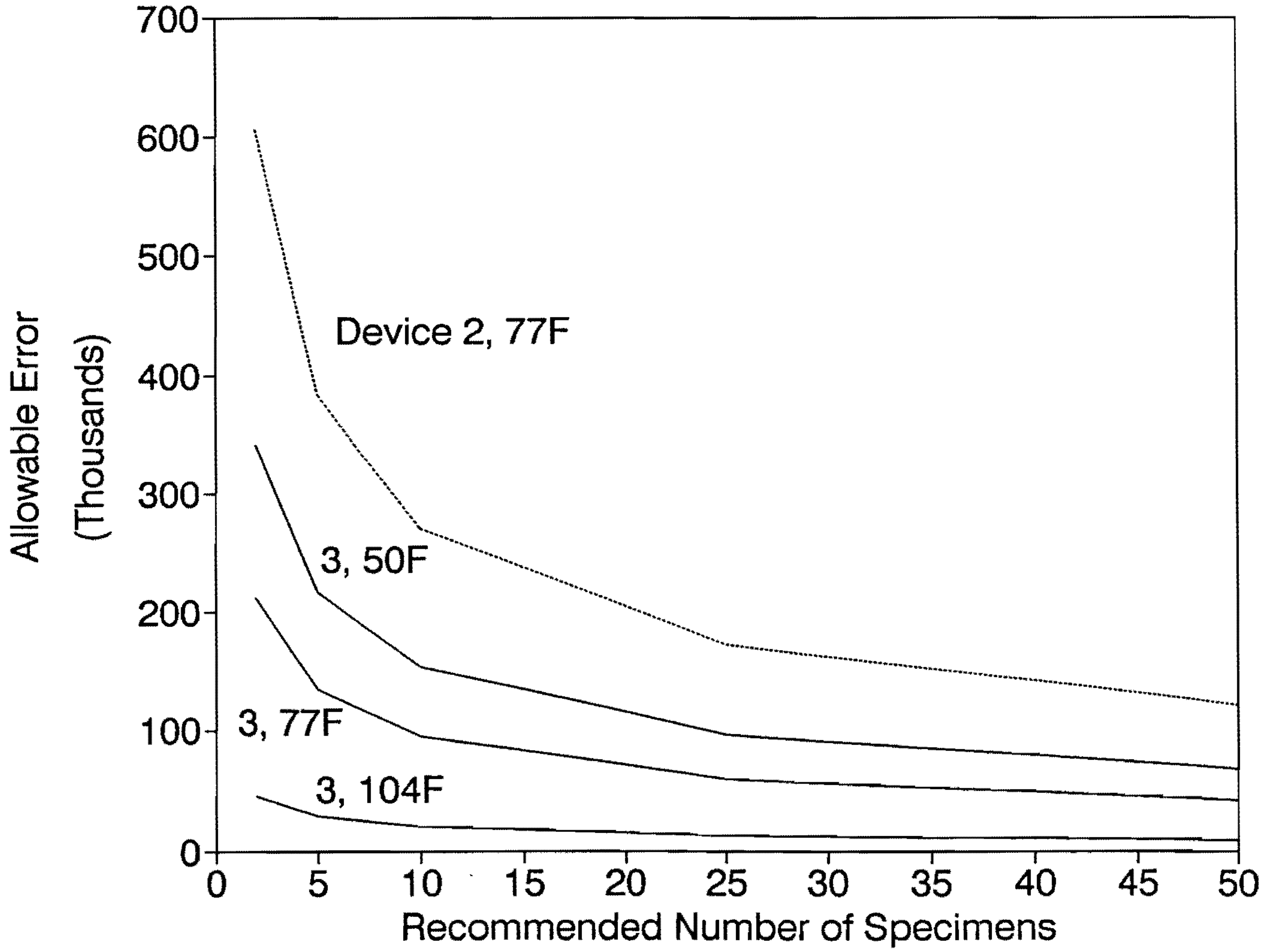


Figure 34. Relationship between sample size and error tolerance (Type C, CLS, AAM-1 AC-20).

V. CONCLUSIONS

(1) A procedure was developed for the measurement of both resilient modulus and Poisson's ratio. The draft recommended procedure is presented in Appendix B of the report. During the course of the procedural development, new hardware was developed and tested for both axially loaded and diametrally loaded specimens. The new devices can be used to cover a wide range of testing conditions. Two different diametral devices were constructed, one of which is capable of measuring Poisson's ratio in addition to the resilient modulus, and the other of which allows very rapid testing to be accomplished for high volume testing requirements. Although the rapid testing device meets the objective of maximizing the speed of testing quite well, its development was initiated too late in the project for its deficiencies (*i.e.* the measured strains are apparently less than the actual specimen strains) to be corrected prior to the end of the project. The time estimates for testing with these devices are listed in items 2 through 4 below. The estimates assume that all the necessary components and the specimen are at the desired temperature before starting the instrumentation mounting process.

(2) The minimum time required for specimen preparation and testing in the diametral test that incorporates both horizontal and vertical measurements is approximately 9-10 minutes.

(3) The minimum time required for specimen preparation and testing in the diametral test that incorporates only horizontal measurements with spring-loaded contact points is approximately 2-4 minutes.

(4) The minimum time required for specimen preparation and testing in the the fully instrumented unconfined axial test is appoximately 20-40 minutes, depending on the drying time of the adhesives used. The confined test setup and take down would require an additional time period (*e.g.* 30 minutes).

(5) The test procedure is capable of distinguishing among important mix variables.

(6) Axial testing at a continuous frequency of 10 Hz corresponds well to the diametral test. This frequency corresponds to the frequency of the load pulse portion of the diametral wave form. The result also compares favorably with extrapolations (to corresponding temperatures and frequencies) of SASW test results.

(7) The qualitative features of the expected temperature and frequency dependent response to loading was observed with the new equipment.

(8) No statistically significant difference was observed between loading with a pneumatic actuator and loading with an hydraulic actuator.

(9) Commercially available LVDTs and signal conditioning equipment can provide the required sensitivity for resilient modulus testing. However, the equipment should be checked using an oscilloscope to verify that the individual unit to be used has an adequately small noise level and that any relatively large noise signals do not appear at frequencies to be used in the test.

(10) The materials tested apparently dilated slightly, especially at the higher temperatures and load levels.

(11) Tests to corroborate nondestructive field testing results should be conducted at the temperature (and as close to the frequency as possible) that was used in the field test.

(12) A significant desirable drop in the error rate can be obtained with as few as 5 specimens of a given mix. Up to 25 specimens of a given mix may be required to reach an optimum practical error rate. Fewer specimens may be tested if the consequent error rate is acceptable to the engineer. The number can also be reduced by using extraordinary care in the control of mixture properties such as gradation and air voids, and in the control of specimen testing temperature. The number of specimens needed is also a function of the testing device, temperature, and mix homogeneity.

VI. RECOMMENDATIONS

(1) The testing devices were delivered to the Department in November 1991. The devices should be used in conjunction with the test procedure given in Appendix B. The procedure should be reviewed by the Department and revised as necessary to keep pace with AAMAS methodology and emerging SHRP testing and design and evaluation procedures.

(2) The clamping apparatus on the accelerated testing device should be evaluated for possible improvement. Decreasing the weight of the instrumentation yoke would be a small improvement. A more important improvement would be to replace the Thomson super ball bushing bearings (Delrin cage) with instrument quality or adjustable diameter linear bearings that are more rigid, and to place the LVDT on the clamping shafts closer to the specimen. This would help to correct the apparent underestimation of strains. The use of standard LVDTs with a separate core and body could also be evaluated to replace the gauging type LVDTs currently being used. If specimen bulging occurs, the gauging type LVDTs could restrict movement since their core shaft is guided by a precision bearing that does not allow any misalignment that would be associated with specimen bulging. The standard LVDT can tolerate a small degree of misalignment. Until these deficiencies can be corrected, Method A of Part II of the test procedure in Appendix B should not be used.

(3) Consideration should be given to using the concept of the yoke system on the accelerated device for a vertical measurement application. If this technique could be perfected, the resulting vertical measurement could be designed with a sufficiently short gauge length. Then St. Venant's principle could be used to virtually eliminate the concerns about localized plastic deformations in the vicinity of the loading strips causing erroneous measurement of Poisson's ratio. However, the short gauge length may require a correction factor for specimen bulging and measurements may be affected by aggregate size.

VII. ACKNOWLEDGEMENT

Mr. S.G. Phillips designed most of the equipment for the generalized indirect tension device and performed much of the electronic troubleshooting. Mr. Crockford designed the accelerated test apparatus and a portion of the generalized indirect tension device. Machine work was done by Mr. Bill Ray and his staff. The signal conditioning system was built by Mr. Carl Fredericksen.

VIII. REFERENCES

AASHTO Guide for Design of Pavement Structures. American Association of State Highway and Tranportation Officials, Washington, D. C., 1986.

Annual Book of ASTM Standards. Road and Paving Materials, Traveled Surface Characteristics, Vol. 04.03, American Society for Testing and Materials, Philadelphia, 1988, pp. 406-407.

Baladi, G. Y., Harichandran, R. and Defoe, J. H. "The Indirect Test - A New Apparatus." Interim Report prepared for the Federal Highway Administration, Michigan State University, 1987.

Baladi, G. Y. "Integrated Material and Structural Design Method for Flexible Pavements, Volume 3 - Laboratory Design Guide." Report No. FHWA/RD-88/118, Federal Highway Administration, 1988.

Baladi, G.Y., and M. B. Snyder. *Highway Pavements*, Vol II, Prepared for U.S. Dept. of Transportation, Publication No. FHWA-HI-90-027, May 1990, pp. 6-141.

Bell, C.A., Y. Abwahab, and M. E. Cristi. "Laboratory Aging of Asphalt-aggregate Mixtures," ASCE, Boston Society of Civil Engineers, Boston, 1990, pp. 254-262.

Bentsen, R.A., S. Nazarian, and J.A. Harrison. Reliability Testing of Seven Nondestructive Pavement Testing Devices, *Nondestructive Testing of Pavements and Backcalculating Moduli*, ASTM STP 1026, 1989, pp. 41-58

Brickman, A.M. "An Overview of Resilient Modulus Test Systems," Proceedings, Workshop on Resilient Modulus Testing, Corvallis, Oregon, 1989.

Consuegra, A., D. N. Little, H. Von Quintus, and J. Burati. "Comparative Evaluation of Laboratory Compaction Devices Based on their Ability to Produce Mixtures with Engineering Properties Similar to those Produced in the Field," Transportation Research Record 1228, Transportation Research Board, National Research Council, Washington, D. C., 1989, pp. 80-87.

Cooper, K.E., S. F. Brown, and G. R. Pooley, "The Design of Aggregate Gradings for Asphalt Basecourses," Proc., Association of Asphalt Paving Technologists, San Antonio, Texas, 1985.

Elliott, R.P. and S. I. Thornton. "Resilient Modulus and AASHTO Pavement Design," Transportation Research Record 1196, Transportation Research Board, National Research Council, Washington, D.C., 1988.

Frocht, M.M., *Photoelasticity*, Vol. 2, John Wiley and Sons, New York, 1957.

Gemayel, C.A., and M. S. Mamlouk. "Characterization of Hot-mixed Open-Graded Asphalt Mixtures," Transportation Research Record 1171, Transportation Research Board, National Research Council, Washington, D. C., 1988, pp. 184-192.

Goode, J.F., and E. P. Owings. "A Laboratory - Field Study of Hot Asphalt Concrete Wearing Course Mixtures," *Public Roads*, Vol. 31, No. 11. Bureau of Public Roads, Washington, D. C., 1961.

Ishai, I., and H. Gelber. "Effect of Geometric Irregularity of Aggregates on the Properties and Behavior of Bituminous Concrete, Asphalt Paving Technology," Proc., AAPT, Vol. 51, University of Minnesota, Minneapolis, 1982, pp. 494-521.

Hadley, W. O., W. R. Hudson, and T. W. Kennedy, "Evaluation and Prediction of the Tensile Properties of Asphalt-Treated Materials," Highway Research Board Annual Meeting, Washington, D.C., 1971.

Heisey, J.S., K. H. Stokoe II, and A. H. Meyer. "Moduli of Pavement Systems from Spectral Analysis of Surface Waves," Transportation Research Record 852, Transportation Research Board, National Research Council, Washington, D. C., 1982, pp. 22-31.

Hertzberg, R.W., *Deformation and Fracture Mechanics of Engineering Materials*, J. Wiley & Sons, N.Y.

Huekelom, W. "Observations on the Rheology and Fracture of Bitumens and Asphalt Mixes," Shell Bitumen Reprint No. 19, Shell Laboratorium-Koninklijke, 1966.

Kennedy, T.W. and W. R. Hudson. "Application of the Indirect Tensile Test to Stabilized Materials," Highway Research Board Annual Meeting, Washington, D.C., 1968.

Kennedy, T. W., G. Gonzaliz, and J.N. Anagnos. "Evaluation of the Resilient Elastic Characteristics of Asphalt Mixtures Using the Indirect Tensile Test." Research Report 183-6, Center for Transportation Research, The University of Texas at Austin, 1975.

Little, D. N. and J.A. Epps. "Evaluation of Certain Structural Characteristics of Recycled Pavement Materials." Proceedings of the Association of Asphalt Paving Technologists, Vol.49, 1980.

Mamlouk, M.S., and R. T. Sarofin. "Modulus of Asphalt Mixtures - An Unresolved Dilemma," Transportation Research Record 1171, Transportation Research Board, National Research Council, Washington, D. C., 1988.

Maupin, G.W., Jr. "Results of Indirect Tensile Tests Related to Asphalt Fatigue," Highway Research Record 404, Highway Research Board, National Research Council, Washington, D. C., 1972, pp. 1-7.

Nair, K., W.S. Smith, and C-Y Chang. *Characterization of Asphalt Concrete and Cement-treated Granular Base Course*, Final Report, contract FH-11-7319, FHWA, 1972.

ODOT. *Proceedings of the Workshop on Resilient Modulus Testing - State of the Practice*, March 28-30, 1989, Corvallis, Oregon, Oregon DOT.

Roesset, J.M., D-W. Chang, K.H. Stokoe, and M. Aouad. "Modulus and Thickness of the Pavement Surface Layer from SASW Tests," Paper presented at the 1990 annual meeting of the Transportation Research Board.

Roque, R. and W.G. Buttlar. "The Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties Using the Indirect Tensile Mode," Draft submitted to the Association of Asphalt Paving Technologists for the 1992 Annual Meeting, Charleston, South Carolina.

Roque, R., M. Tia, and B. E. Ruth. "Asphalt Rheology to Define the Properties of Asphalt Concrete Mixtures and the Performance of Pavements," *Special Technical Publication 941*, ASTM, Philadelphia, 1987, pp. 3-27.

Sayegh, G. *Proceedings, 2nd International Conference on Structural Design of Pavements*, 1967, p. 743.

Schmidt, R.J. "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes," Highway Research Record 404, Highway Research Board, National Research Council, Washington, D. C., 1972, pp. 22-29.

Schmidt, R. J. "Effect of Temperature, Freeze-Thaw, And Various Moisture conditions on the resilient modulus of Asphalt-treated Mixes," Transportation Research Record 515, Transportation Research Board, National Research Council, Washington, D. C., 1974, pp. 27-39.

The Asphalt Institute Handbook, Manual Series No. 4, Asphalt Institute, College Park, Maryland, 1989, pp. 33.

Van der Poel, C. "A General System Describing the Visco-elastic Properites of Bitumens and Its Relation to Routine Test Data," Strasse und Antobahn, Vol. 35, 1965.

Van Til, C. J., B.F. McCullough, B.A. Vallerga, and R.G. Hicks. *Evaluation of AASHO Interim Guides for Design of Pavement Structures*, NCHRP report 128, 1972.

Von Quintus, H. L., J.A. Scherocman, C.S. Hughes and T.W. Kennedy. *Asphalt-Aggregate Mixture Analysis System (AAMAS)*, NCHRP report 338.

Witczak, M.W. *The Universal Airport Pavement Design System*, University of Maryland Technical Report, College Park, Maryland, 1989.

Yoder, E.J. and M. W. Witczak. *Principles of Pavement Design*, John Wiley & Sons, Inc., New York, 1975.

APPENDIX A

DERIVATION OF DIAMETRAL RESILIENT MODULUS EQUATION

$$\sigma_x = \frac{2\rho}{\pi d t} \left[\frac{(d^2 - 4x^2)^2}{(d^2 + 4x^2)^2}\right]$$

$$\sigma_y = \frac{2P}{\pi d t} \left[1 - \frac{4d^4}{(d^2 + 4x^2)^2}\right]$$

$$\epsilon_x = \frac{1}{E} [\sigma_x - \nu\sigma_y]$$

$$\int_x \epsilon_x \, dx = \int_{x_1}^{x_2} \frac{\delta}{d} \, dx = \frac{\delta}{d} (x_2 - x_1)$$

$$= \frac{2P}{E\pi d t} \int_{x_1}^{x_2} \left[\frac{4\ d^4\nu - 16d^2x^2}{(d^2 + 4x^2)^2} + (1 - \nu)\right] dx$$

Let $x_2 = Ld$, $x_1 = -Ld$, $0 \le L \le 0.5$

where

$$L = \frac{\left(\frac{\text{Gage length}}{2}\right)}{\text{Diameter}}$$

$$\Rightarrow E = \frac{P}{\delta t \pi}\left[\frac{[2L - Tan^{-1}(2L) + Tan^{-1}(-2L)](1-\nu)}{L} + \frac{4(1+\nu)}{(1+4L^2)}\right]$$

Case 1: Let $L = \frac{1}{2}$

$$\Rightarrow E = \frac{P}{\delta t}\left[\frac{4}{\pi} + \nu - 1\right]$$

Case 2: Let $L = \frac{(3/2)}{4} = \frac{3}{8}$

$$\Rightarrow E = \frac{P}{\delta t}\left[\frac{\left(\frac{3}{4} - Tan^{-1}\left(\frac{3}{4}\right) + Tan^{-1}\left(-\frac{3}{4}\right)\right)(1-\nu)}{\left(\frac{3\pi}{8}\right)} + \frac{4(1+\nu)}{\pi\left(1 + 4\left(\frac{9}{64}\right)\right)}\right]$$

APPENDIX B
TEST PROCEDURE

Test Method Tex-2XX-F
November 1991

Texas Department of Transportation
Materials and Tests Division

RESILIENT MODULUS OF ASPHALT CONCRETE

Scope

This procedure is used for characterization of the elastic properties of asphalt concrete materials. The three part procedure provides methods suitable for the characterization of a wide range of mix types. Parts I and II are mandatory. Part III is optional. In Part II, three methods are provided, only one of which is necessary to perform. The choice of which method to use rests with the laboratory engineer. Method A is a rapid test useful for high production output. Method B allows computation of Poisson's ratio in an indirect tension test. Method C allows computation of Poisson's ratio in a direct compression test and can be used to control applied stress paths to a limited degree. The preferred test temperature for the indirect testing is in the 40-60°F range because the assumptions made in the development of the equations for computation of modulus rapidly lose credibility above these temperatures for many asphalt concretes. However, most of the testing in this procedure is performed at a temperature of 77±2°F primarily because (a) the temperature is easily controlled within the specified tolerance by a standard room thermostat, and this feature implies the availability of large storage areas for specimens, and (b) this temperature is closer to the average pavement temperature for much of the year in a large portion of the state. However, it is necessary to conduct testing at other temperatures which require environmental chambers (*e.g.* refrigerators and ovens) in cases involving corroboration of field testing and in cases requiring a full temperature sensitivity characterization. Part III of the test procedure describes the full temperature sensitivity characterization.

This standard may involve hazardous materials, operations, and equipment.

This procedure does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

Related Documents

Tex-226-F	Indirect Tensile Strength Test
ASTM D2493	Viscosity-Temperature Chart for Asphalts
ASTM D3497	Dynamic Modulus of Asphalt Mixtures
ASTM D4123	Indirect Tension Test for Resilient Modulus of Bituminous Mixtures
Research Report 1177	Routine Resilient Modulus Testing

Definitions

Chord modulus-the slope of a line between any two points on a stress-strain curve.

Complex modulus-a complex number that defines the relationship between stress and strain for a linear viscoelastic material, E*. The *Storage Modulus* and the *Loss Modulus* are components of the complex modulus.

Dilatant material-a material that exhibits a change in volume when subjected only to simple shear stress. Microcracking or very high Poisson's ratios and nonlinear stress-strain curves are often associated with this type of material.

Dynamic modulus-the magnitude of the complex modulus that defines the elastic properties of a linear viscoelastic material subjected to a sinusoidal loading, |E*|.

Linear material-a material whose stress to strain ratio is independent of the loading stress applied.

Nonlinear material-a material whose stress-strain response is not linear.

Plastic behavior-material behavior in which some or all of the strain can not be recovered after unloading.

Resilient modulus-ratio of the recovered stress to the recovered strain in a repeated load test. For the purposes of this test procedure, the recovered strain is the maximum difference in strain during the time period between the maximum load in the cycle and the start of the following loading cycle.

Secant modulus-the slope of a line between the origin and any other point on a stress-strain curve.

Tangent modulus-the slope of a line tangent to the stress-strain curve at any point.

Viscoelastic material-a material whose stress-strain response is nonlinear due to time dependent factors (*e.g.* viscous fluid flow).

PART I
STRENGTH TESTING

Apparatus

1. Loading press capable of applying a compressive load at a controlled deformation rate of 2 inches per minute.

2. Even though the theory upon which the strength equation is based assumes a line load, finite width loading strips are used to apply the load. Loading strips consisting of 1/2-inch by 1/2-inch square steel bars which have one surface (surface in contact with specimen) machined to the curvature of the specimen should be used when testing 4-inch diameter specimens. When testing 6-inch diameter specimens, a 3/4-inch width loading strip should be used.

Test Record Forms

See Figure B.1.

Preparation of Test Specimen

1. Prepare laboratory-molded specimens in accordance with Test Method Tex-206-F. The specimens should have a height of at least 2 in. (51 mm) and a minimum diameter of 4 in. (102 mm) for aggregate up to 1 in. (25 mm) maximum size, and a height of at least 3 in. (76 mm) and a minimum diameter of 6 in (152 mm) for aggregate up to 1.5 in. (38 mm) maximum size.

2. If field cores are being used, trim the cores so that the thickness is 1.875-2.000 inches and so that the core is a right circular cylinder with parallel ends. If the core shows evidence of core bit "wobble" greater than 0.075 inch, if the core has been damaged during shipping, or if the core has been taken at an angle so severe that it can not be corrected by trimming, discard the core without testing. Cores should conform to the height and diameter requirements specified for laboratory specimens.

Procedure

1. Determine the height and diameter of the test specimen.

2. Place the test specimen in the constant temperature apparatus long enough to insure a consistent temperature of 77 ± 2°F throughout the test specimen.

3. Align the specimen and loading strips in accordance with Part II, Method A or Method B of this procedure.

4. Slowly move the actuator so as to apply approximately 10 pounds load on the specimen while maintaining proper loading strip alignment and

parallelism. (The 10 pound load can be adjusted upward or downward slightly depending on the material strength).

5. Apply the load at a controlled deformation rate of 2 inches per minute and determine the total vertical load at failure of the specimen. Optionally, the specimen may be instrumented as in Part II, Method B of this procedure for acquisition of data that enables computation of Poisson's ratio and strain energy density.

Calculations

Calculations of tensile strength:

$$S_T = \frac{2P}{\pi d h}$$

Where:

S_T	=	Indirect tensile strength, in psi
P	=	Total applied vertical load at failure (lbs)
d	=	Specimen diameter (inches)
h	=	Height of specimen, in inches

INDIRECT TENSILE STRENGTH TEST

Lab. No.____________________ Date ________________

Specimen Number			
Specimen Diameter (4" if no entry)			
Specimen Height			
Total Vertical Load (Lbs.)			
Indirect Tensile Strength (psi)			
Average Value			

Remarks: ____

$$S_T = \frac{2P}{\pi d h}$$

Where:

S_T = Indirect tensile strength, in psi
P = Total applied vertical load at failure (lbs)
d = Specimen diameter (inches)
h = Height of specimen, in inches

Figure B.1. Test record form.

PART II
RECOVERABLE RESPONSE

Introduction

Asphalt concrete often exhibits a combination of elastic, time dependent, and plastic behavior in response to loading at in-service temperatures. For this reason, Part II of the test procedure allows engineering judgement to be used in the selection of loading frequencies and environmental conditions (*e.g.* temperatures, moisture conditions) at which the test will be conducted. Frequencies and temperatures specified in this Part are to be used in the event that no engineering considerations indicate a need for additional temperatures and frequencies.

METHOD A: ACCELERATED TEST

(Note: See Recommendation number 2, Part VI of this report)

Summary of Method

The repeated-load indirect tension test for determining resilient modulus of bituminous mixtures is conducted by applying compressive loads with an offset sine wave (commonly, but incorrectly termed a 'haversine') followed by a rest period that has a long duration in relation to the duration of the sinusoidal pulse. The load is applied vertically in the vertical diametral plane of a cylindrical specimen of asphalt concrete (Figure A.2). The resulting horizontal deformation of the specimen is measured and, with an assumed Poisson's ratio, is used to calculate a modulus based on the recovery portion of the stress-strain curve.

The total resilient modulus is calculated using the total recoverable deformation which includes both the instantaneous recoverable and the time-dependent continuing recoverable deformation during the unloading and rest-period portion of one cycle. (The instantaneous value obtained from calculations using only the recoverable deformation from the peak load to the start of the rest period is not used in this procedure.)

Apparatus

Testing Machine - The testing machine must have the capability of applying a load pulse over a range of frequencies, load durations, and load levels. As a minimum, the machine must be able to apply a load sufficient to break the specimen and must be able to apply 50 cycles of a 0.1 second duration offset sine pulse with a 0.9 second rest period between each pulse.

Temperature-Control System - The temperature-control system should be capable of maintaining a temperature of 77±2°F.

Measurement and Recording System - The measurement and recording system should include sensors for measuring and recording horizontal deformation. The minimum acceptable system should be capable of measuring horizontal deformations in the range of 0.00001 in (0.00025 mm) of deformation. The linear variable differential transformers (LVDT's) and their associated signal conditioning system must meet this resolution requirement. Loads should be measured with a minimum precision of 1 percent of the maximum load.

Data Acquisition - The measuring or recording devices should be independent of frequency for tests conducted up to 10.0 Hz. Digital data acquisition systems must have a sampling rate of at least 100 Hz.

Loading Strips - Use loading strips as specified in Part I of this procedure. For specimens with rough textures, a thin hard rubber membrane attached to the loading strip can reduce stress concentration effects, but should be used only when vertical deformations are not measured.

Alignment Fixture - Use the alignment fixture illustrated in Figure B.2. Machine drawings for the fixture are presented in Research Report 1177.

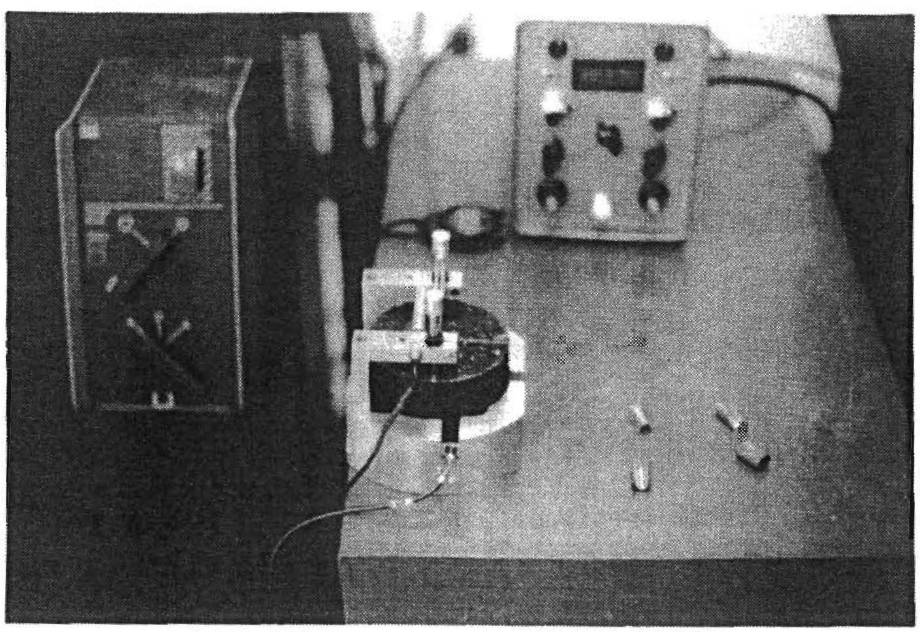


Figure B.2. Accelerated test fixture (Method A).

Procedure

1. Prepare specimens as noted in Part I of this procedure.

2. Place the test specimens in a controlled-temperature environment at 77°F for at least 24 hours prior to testing.

3. Place a specimen into the alignment fixture and adjust and balance the electronic measuring system as necessary.

4. Place the fixture and specimen in the testing machine as a unit by aligning the slot in the fixture with the bottom loading strip. Bring the upper strip into contact with the specimen by moving the testing machine actuator. Put a static load of 10-20 pounds (but not more than 20% of the average failure load applied to similar mixes as determined in Part I of this procedure) on the specimen. Maintain the static load on the specimen, and gently remove the alignment fixture without disturbing the displacement measuring transducers.

5. Recheck the transducers. If the voltage is out of range or if it is likely that it will go out of range during the testing, remove the specimen and return to step 3 above.

6. Adjust the static load to 15 pounds (or 20% of the average failure load for the mix, whichever is less), and begin the cyclic test. The waveform to be applied is a sine wave with an amplitude of 40% of the average failure load of the mix found in Part I of this procedure applied over a period of 0.1 second followed by a rest period (*i.e.* unload to the static load level) of 0.9 second. A total of 50 cycles of loading is to be applied to each specimen.

7. Each test should be completed within 5 min from the time the specimens are removed from the temperature-control cabinet if the specimen temperature is different from the temperature of its environment during the test.

8. As a minimum, load and deflection data must be acquired for cycles 42 through 49 of the test.

9. Remove the specimen from the testing apparatus and remove the displacement measurement assembly from the specimen. If the specimen is to be discarded, conduct the test specified in Part I of this procedure prior to disposing of the specimen. If the specimen is to be retained for future testing, store it in an appropriate environment.

Calculations

Calculate the elastic modulus, E, in pounds-force per square inch (or megapascals) as shown below. Assume Poisson's ratio is 0.35 unless other sources of information indicate otherwise.

where:

$$E = \frac{P}{\delta t \pi}\left[\frac{[2L - \tan^{-1}(2L) + \tan^{-1}(-2L)]}{L}(1 - \nu) + \frac{4(1 + \nu)}{(1 + 4L^2)}\right]$$

E = Modulus

P = Vertical load

t = Specimen thickness (height)

δ = Horizontal deflection

ν = Poisson's ratio

L = (Gauge length/2)/specimen diameter

For a 3.0 inch gauge length and a 4.0 inch specimen diameter, the previous equation reduces to:

$$E = \frac{P}{\delta t}(0.359+1.271\nu)$$

If the temperature is greater than 40°F, Poisson's ratio may be estimated with the following equation (Note: this equation is based on a steeper slope than that presented by *Nair et al.* and predicts a value of 0.38 for Poisson's ratio at T=77°F). Use a Poisson's ratio of 0.15 for temperatures below 40°F. Until such time as dilation can be adequately described by theory, use a Poisson's ratio of 0.499 for temperatures above 112°F.

$$\nu = 0.312031 \ln T - 0.97432$$

METHOD B: GENERALIZED INDIRECT TENSION TEST

Summary of Method

The repeated-load indirect tension test for determining resilient modulus of bituminous mixtures is conducted by applying compressive loads with an offset sine wave (commonly, but incorrectly termed a 'haversine') followed by a rest period that has a long duration in relation to the duration of the sinusoidal pulse. The load is applied vertically in the vertical diametral plane of a cylindrical specimen of asphalt concrete (Figure B.3). The resulting horizontal and vertical deformations of the specimen are measured and subsequently used to calculate a modulus and Poisson's ratio based on the recovery portion of the stress-strain curve.

The total resilient modulus and Poisson's ratio are calculated using the total recoverable deformation, which includes both the instantaneous recoverable and the time-dependent, continuing recoverable deformation during the unloading and rest-period portion of one cycle. (The instantaneous value obtained from calculations using only the recoverable deformation from the peak load to the start of the rest period is not used in this procedure.)

Apparatus

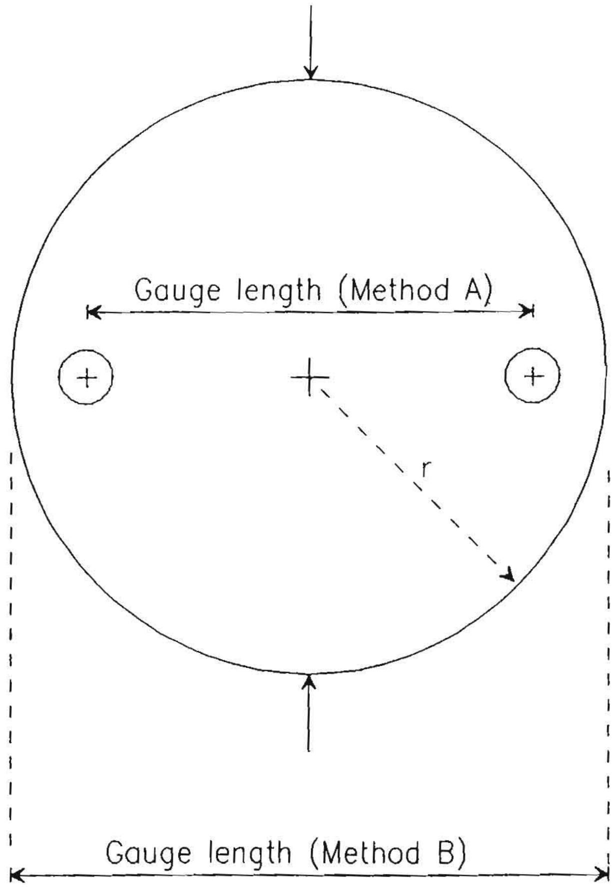
Testing Machine - The testing machine must have the capability of applying a load pulse over a range of frequencies, load durations, and load levels. As a minimum, the machine must be able to apply a load sufficient to break the specimen and must be able to apply 50 cycles of a 0.1 second duration offset sine pulse with a 0.9 second rest period between each pulse.

Temperature-Control System - The temperature-control system should be capable of maintaining a temperature of 77±2°F.

Measurement and Recording System - The measurement and recording system should include sensors for measuring and recording horizontal deformation. The minimum acceptable system should be capable of measuring horizontal deformations in the range of 0.00001 in (0.00025 mm) of deformation. The linear variable differential transformers (LVDT's) and their associated signal conditioning system must meet this resolution requirement. Loads should be measured with a minimum precision of 1 percent of the maximum load.

Data Acquisition - The measuring or recording devices should be independent of frequency for tests conducted up to 10.0 Hz. Digital data acquisition systems must have a sampling rate of at least 100 Hz.

Loading Strips and Specimen Alignment - Specimen alignment is automatically provided by the loading strips. The loading strips are aligned with a gluing jig and glued in place with hot glue. Epoxy or other adhesives may be substituted as desired. Hot glue should not be used for tests conducted at temperatures above its softening point. Machine drawings for the fixture are presented in Research Report 1177.



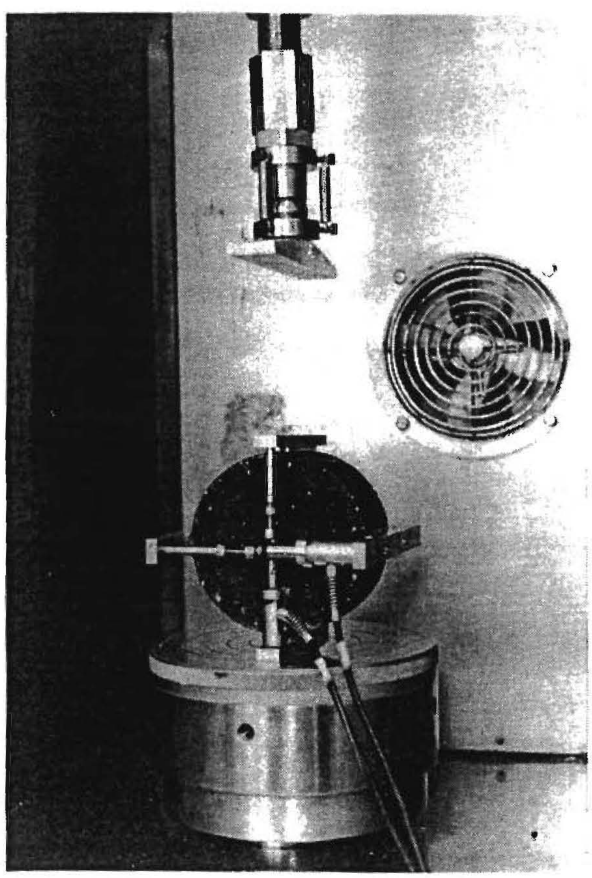


Figure B.3. Generalized indirect tension test fixture (Method B).

Procedure

1. Prepare specimens as noted in Part I of this procedure.

2. Place the test specimens in a controlled-temperature environment at 77°F for at least 24 hours prior to testing.

3. Place the loading strips in a 140°F or hotter oven. Turn on the hot glue gun.

4. Place a specimen into the load strip alignment fixture, and glue each loading strip in place.

5. Install, adjust and balance the electronic measuring system as necessary.

6. Place the instrumented specimen in the testing machine as a unit. Manually align the specimen with the central axis of the actuator. Move the testing machine actuator to put a static load of 10-20 pounds (but not more than 20% of the average failure load applied to similar mixes as determined in Part I of this procedure) on the specimen.

7. Recheck the transducers. If the voltage is out of range or if it is likely that it will go out of range during the testing, remove the specimen and return to step 5 above.

8. Adjust the static load to 15 pounds (or 20% of the average failure load for the mix, whichever is less) and begin the cyclic test. The waveform to be applied is a sine wave with an amplitude of 40% of the average failure load of the mix found in Part I of this procedure applied over a period of 0.1 second followed by a rest period (*i.e.* unload to the static load level) of 0.9 second. A total of 50 cycles of loading is to be applied to each specimen.

9. Each test should be completed within 10 min. from the time the specimens are removed from the temperature-control cabinet if the specimen temperature is different from the temperature of its environment during the test.

10. As a minimum, load and deflection data must be acquired for cycles 42 through 49 of the test.

11. Test each specimen for resilient modulus twice: Following the first test, rotate the specimen 90°, and repeat the test starting at Step 5.

12. Remove the specimen from the testing apparatus, and remove the displacement measurement assembly from the specimen. If the specimen is to be discarded, conduct the test specified in Part I of this procedure prior to disposing of the specimen (Note: If gauge head type transducers are being used, remove the vertical sensors before performing the strength test). If the specimen is to be retained for future testing, remove the sensors from the loading strips, and store the specimen in an appropriate environment.

Calculations

Calculate Poisson's ratio and the elastic modulus as shown below. If Poisson's ratio is measured to be greater than 0.5, use 0.499 in the calculation of the modulus and make a note of the change in the report.

$$E_{RT} = \frac{P(\nu_{RT} + 0.27)}{t \Delta H_T}$$

$$\nu_{RT} = \frac{3.59 \Delta H_T}{\Delta V_T - 0.27}$$

where:

E_{RT} = total resilient modulus of elasticity, psi,

ν_{RT} = Poisson's ratio

P = repeated load, lbf,

t = thickness of specimen, in,

ΔH_T = total recoverable horizontal deformation, in, and

ΔV_t = total recoverable vertical deformation, in.

METHOD C: GENERALIZED AXIAL COMPRESSION TEST

Summary of Method

A sinusoidal axial compressive stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency. The resulting recoverable axial strain response of the specimen is measured and used to calculate resilient modulus.

Apparatus

Testing Machine - The testing machine must have the capability of applying a load pulse over a range of frequencies, load durations, and load levels. As a minimum, the machine must be able to apply a load sufficient to break the specimen and must be able to apply multiple cycles of an offset sine wave at frequencies of 0.1 to 20 Hz with or without a rest period.

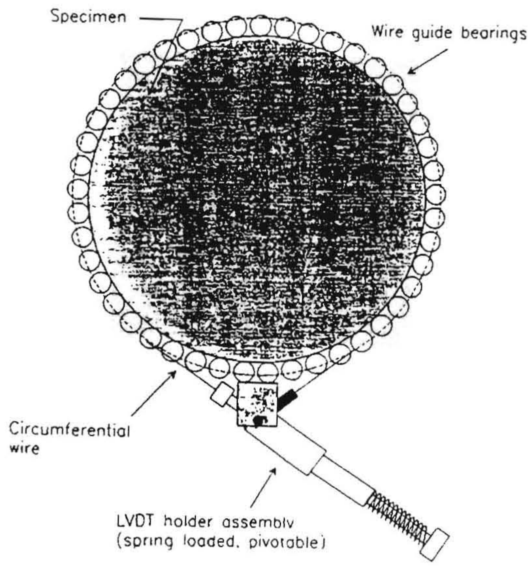
Temperature-Control System - The temperature-control system should be capable of maintaining a temperature of 77±2°F.

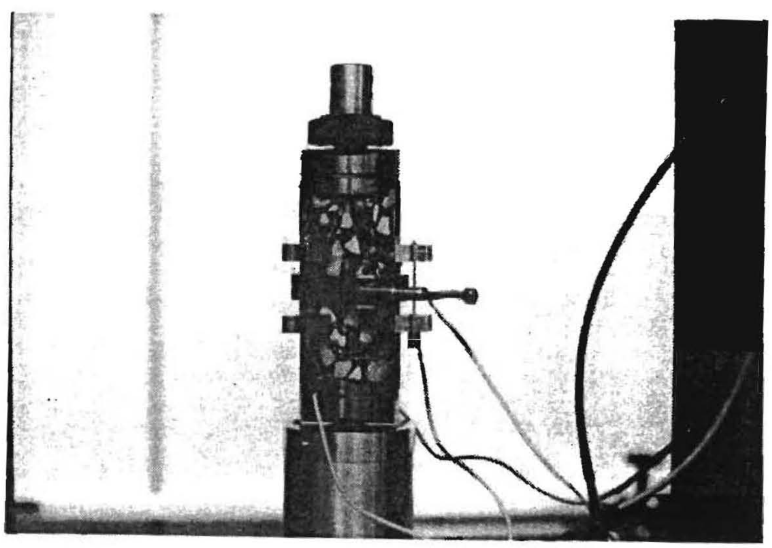
Measurement and Recording System - The measurement and recording system should include sensors for measuring and recording horizontal deformation. The system should be capable of measuring horizontal deformations in the range of 0.00001 in (0.00025 mm) of deformation. The linear variable differential transformers (LVDT's) and their associated signal conditioning system must meet this resolution requirement. Loads should be measured with a minimum precision of 1 percent of the maximum load.

Data Acquisition - The measuring or recording devices should be independent of frequency for tests conducted up to 20.0 Hz. Digital data acquisition systems must have a sampling rate of at least 100 Hz.
Apparatus

Loading Platens - The steel loading platens should incorporate a spherical seat so that imperfect specimens can be tested. Two rubber sheets with a lubricant such as silicone grease should be prepared and placed between the ends of the specimen and the loading platens.

Instrumentation - Two to three vertical LVDTs and one circumferential LVDT (or two radial non-contact transducers or contact LVDTs if necessary) should be mounted on the specimen. A schematic of the circumferential measurement device and photographs of specimens instrumented for testing are shown in Figure B.4.





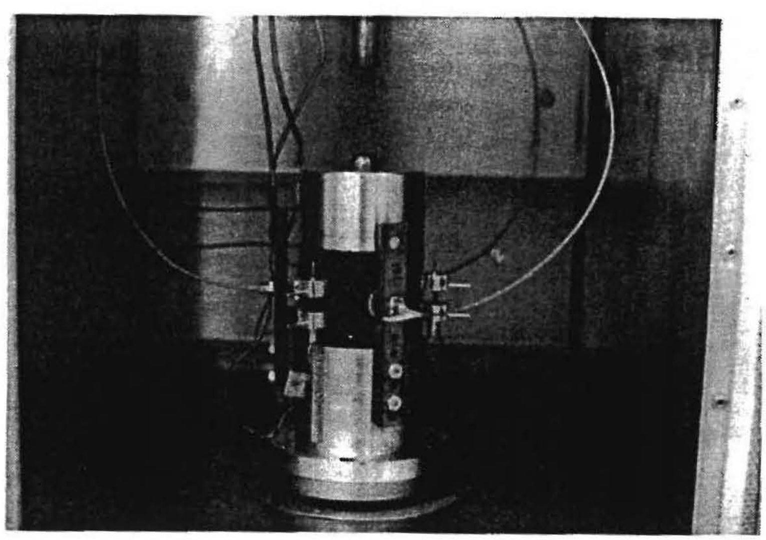


Figure B.4. Axial testing apparatus (Method C): (top) schematic of circumference measurement device, (center) instrumented specimen with circumference measurement device, (bottom) instrumented specimen with non-contact transducers.

Laboratory Molded Specimens - In general, laboratory molded specimens will not be prepared for this test since the Department does not currently mold tall asphalt specimens. However, some gyratory compaction machines can be pushed to their limits to prepare 3 inch tall specimens which can be used in this test procedure. Alternatively, large specimens can be compacted in the large gyratory (soils) press, and a smaller diameter core can be taken from the large specimen. Preferably, the specimens should have a height-to-diameter ratio of 2 to 1, a minimum diameter of 4 in. (101.6 mm) and a diameter four or more times the maximum nominal size of aggregate particles. However, a 4 inch diameter, 3 inch tall specimen geometry will be allowed for this procedure as the minimum acceptable size.

Pavement Cores - A minimum of six cores from an in-service pavement is required for testing. If possible, obtain cores having a minimum height-to-diameter ratio of 2 to 1 and with diameters not less than two times the maximum nominal size of an aggregate particle. Select cores to provide a representative sample of the pavement section being studied. If the core shows evidence of core bit "wobble" greater than 0.075 inch, if the core has been damaged during shipping, or if the core has been taken at an angle so severe that it can not be corrected by trimming, discard the core without testing. Do not cap the cores. Trim the ends to parallel (within ±0.030 inches of a plane parallel to a flat surface used as a height measurement reference taken at the ends of the diameter). Cores should conform to the height and diameter requirements specified for laboratory specimens.

Procedure

1. Prepare specimens as noted in Part I of this procedure.

2. Glue the LVDT mounting hardware to the specimen. (If a membrane is being used for triaxial testing, the membrane must be glued to the specimen at the contact point, and the LVDT mounts must be glued to the membrane at the contact point so that positive contact with the specimen is maintained).

3. Place the test specimens in a controlled-temperature environment at 77°F for at least 24 hours prior to testing.

4. Install the LVDTs, and adjust and balance the electronic measuring system as necessary.

5. Place the instrumented specimen in the testing machine as a unit. Move the testing machine actuator to put a static load of 10-20 pounds (but not more than 20% of the average failure load applied to similar mixes as determined in Part I of this procedure) on the specimen. (If confining pressure is to be applied, the pressure vessel must be secured and the desired pressure applied).

6. Recheck the transducers. If the voltage is out of range or if it is likely that it will go out of range during the testing, remove the specimen and return to step 4 above.

7. Adjust the static load to 15 pounds (or 20% of the average failure load for the mix, whichever is less) and begin the cyclic test. The waveform to

be applied is a sine wave with an amplitude of 40% of the average failure load of the mix found in Part I of this procedure applied at 10 Hz for 1 minute.

8. Each test should be completed within 10 min from the time the specimens are removed from the temperature-control cabinet if the specimen temperature is different from the temperature of its environment during the test.

9. As a minimum, load and deflection data must be acquired for the last 5 cycles of the test.

10. If desired, conduct a monotonic load compressive strength test (to failure) after the completion of the cyclic test using a loading rate of 2 inches per minute. Use caution to avoid damage to the transducers if the strength test is performed. Remove the specimen from the testing apparatus and remove the displacement measurement assembly from the specimen.

Calculations

Measure the average amplitude of the load and the recoverable strains over the last 5 loading cycles. Calculate dynamic modulus, |E*|; as follows:

$$\text{Dynamic modulus} = \sigma_a/\epsilon_a$$

where:

σ_a = axial loading stress, psi, (= load/specimen cross sectional area) and
ϵ_a = recoverable axial strain, in/in (= displacement/gage length)

and compute Poisson's ratio, ν, as follows:

$$\nu = -\epsilon_r/\epsilon_a$$

where:

ϵ_r is the radial strain (sign is opposite that of the axial strain).

If the circumferential measurement device is used, additional factors enter into the computation of the radial strain. Assuming that the difference between a circular line segment and the path of the wire between two bracelet inserts is negligible, and that the included angle between the tangent points of the wire/bracelet contacts remains constant during testing, the following formula can be used for computation of the radial engineering strain:

$$\epsilon_r = \frac{\delta}{2r(\pi-\theta+\tan\theta)}$$

where ϵ_r = radial strain, r = radius to the center of the wire resting in a bracelet insert groove, δ = LVDT displacement, and θ = one half of the total included angle defined by the two tangent points of the wire and the central axis of the specimen.

PART III
FULL TEMPERATURE SENSITIVITY CHARACTERIZATION

In order to fully characterize asphalt concrete materials, a modulus-temperature and/or modulus-frequency relationship should be developed. In general (*i.e.* for thermorheologically simple materials), cold temperature performance can be predicted from high frequency tests and vice versa. In general, the range of temperatures for a full characterization that would cover pavement conditions in almost all of the climatic regions of the country is 0-60°C. A range of loading frequencies between 0.01 and 20 Hz will cover the simulation of many traffic situations.

The use of a single specimen for multiple tests (*i.e.* at different temperatures and frequencies) is permitted in this procedure. However, the order of testing is important in this case. Testing should begin with the lowest temperature, shortest load duration, and smallest load. Subsequent testing on the same specimen should be for conditions producing progressively lower moduli. Bring the specimens to the specified temperature before each test.

Part II, Method A or B may be used from 50°F (10°C) up to 104°F (40°C). At high temperature, specialized adhesives for the loading/gauging strips may be required for Method B. Below 10°C, Method B is recommended. Method A can be used, but a stronger spring may be necessary to keep the gauge points from sliding on the specimen surface. Method C can be used for all temperatures (within the temperature limits of the measurement transducers as specified by the manufacturer).

Choice of Testing Frequencies

Six frequencies of load duration are suggested for use in a full frequency characterization. In order of application, they are: 20 Hz for 50 cycles, 10 Hz for 50 cycles, 5 Hz for 50 cycles, 1 Hz for 50 cycles, 0.1 Hz for 10 cycles, and 0.01 Hz for 5 cycles. The procedures in Part II must be adjusted in terms of duration of the cyclic loading (Method C) or number of cycles (Methods A and B) so that the test can be completed in a reasonable period of time while maintaining a sufficient number of cycles to obtain stable readings. The rest period used in Methods A and B can be deleted if desired for this test, but a note should be made to that effect in the report.

Choice of Testing Temperatures

Testing at six temperatures should be accomplished for full temperature characterization. An arbitrary choice of temperatures that covers the desired range of response for most materials is: 0, 4, 10, 25, 40, 50 and 60°C. Alternatively, a more objective method for temperature selection may be desired. This method is based on the viscosity of the asphalt.

Obtain the viscosity of the asphalt used in the mixture by testing in accordance with AASHTO T201 and AASHTO T202. Perform the appropriate tests at temperatures of 40, 60, and 135°C. Obtain the specific gravity of the asphalt in accordance with AASHTO T228. Convert kinematic viscosities to absolute viscosities according to the following formula:

absolute viscosity in poises = (kinematic viscosity in stokes)(specific gravity)

where 1 Stoke = 100 cSt.

After converting all viscosities to units of poise, plot the data on the viscosity-temperature chart in Figure B.5 and draw a smooth line through the points. The chart coordinates are the logarithm of the logarithm of viscosity in centipoise as the ordinate and logarithm of absolute temperature in degrees Rankine (degrees Fahrenheit +459.7) as the abscissa. However, viscosity in poises and the temperature in degrees Fahrenheit are shown in the chart for convenience. Some asphalts have viscosity-temperature relationships too complex to be represented by only three points. In this case determine the viscosity at sufficient temperatures to produce a curve adequate for the purpose intended.

Once the viscosity-temperature relationship has been established, the temperatures for resilient modulus testing can be determined. It is suggested that modulus testing be conducted at temperatures corresponding to at least three of the following viscosities of the asphalt binder: 5×10^9, 1×10^9, 1×10^8, 2×10^7, 2×10^6, 1×10^5, 2×10^4, and 4×10^3. Alternatively, tests may be conducted at three temperatures that cover the range of temperatures expected at the site of interest. These test results can then be used to generate a plot of the relationship between resilient modulus and temperature similar to that illustrated in Figure C.1 in Appendix C of Report 1177.

VISCOSITY - TEMPERATURE CHART

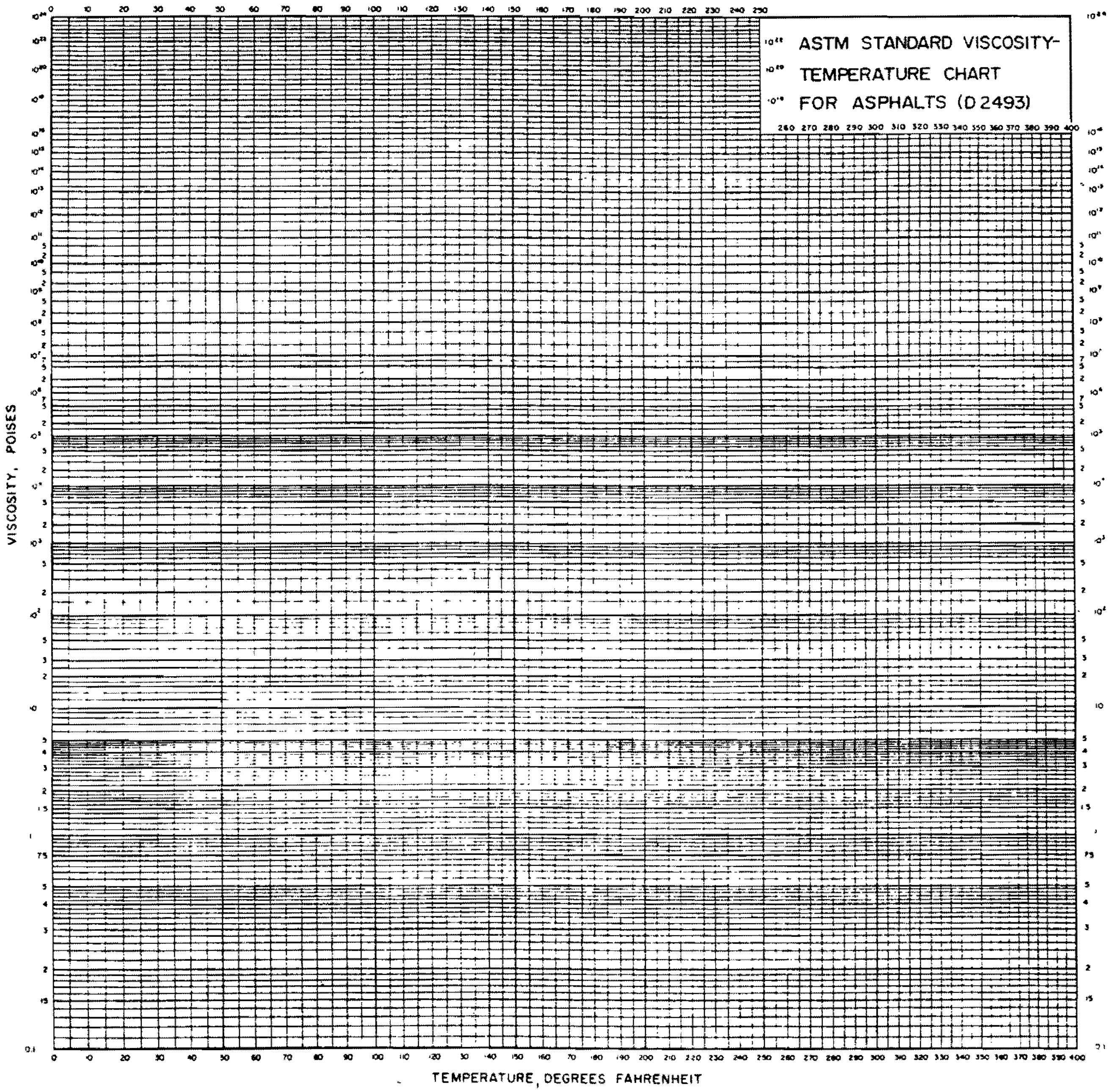


Figure B.5. Viscosity-Temperature Chart (*from ASTM D2493*).

APPENDIX C

USE OF TEST RESULTS

INTRODUCTION

This Appendix illustrates the usage of the resilient modulus in quality control, analysis and design. In order to obtain the full benefit of the design and analysis problems, the user must obtain a copy of the 1986 AASHTO Guide for the Design of Pavement Structures, the TFPS computer program, and Research Reports 455-1 and 455-2 to accompany the TFPS program. This Appendix is not meant to duplicate or take precedence over those documents or the TFPS computer program. The examples given in this Appendix are hypothetical in nature. However, test results from the research conducted during this research study are used in the illustrations. The examples include the design of the surface course thickness on a new flexible pavement using the 1986 AASHTO Guide for the Design of Pavement Structures, an overlay design using the TFPS computer program, and a brief suggestion of how to use the test results in quality control. The examples are not intended to suggest least cost, or optimal structure solutions. They only serve to illustrate the use of the modulus test results.

PAVEMENT DESIGN AND ANALYSIS - 1986 AASHTO GUIDE

The first problem to be discussed is the solution of a design problem in which everything is given except for the thickness of the asphalt concrete surface layer. The situation is one of new construction. Volume I of the 1986 AASHTO Guide is divided into four parts designated with Roman numerals (*e.g.* I-IV). Volume 2 consists of several Appendices designated with two letters (*e.g.* AA, BB, *etc.*) In the discussion below, references to Volume I include the appropriate Roman numeral and the paragraph, Table, or Figure number. References to Volume 2 begin with the appropriate Appendix letters.

The following parameters are *given*:

General		Materials
ΔPSI=4.2-2.7=1.5	(II-2.2.1)	Granular Base: D_2=10 inches
Standard Deviation, S_o=0.44	(I-4.3)	E_{BS}=25,000 psi
Reliability, R=80%	(II-Table 2.2)	No Subbase
Total 18kip ESALs=10,000,000		Subgrade: M_R=10,000 psi

Assume that the drainage is good and that the pavement structure is exposed to moisture levels approaching saturation from 1-5% of the time. This results in a quality of drainage factor, m_2, of about 1.20 (II-Table 2.4). (Note: research study 1173 set forth guidelines for computing M_R from Texas triaxial test results, presented further details on drainage, and developed computer program subroutines to solve the nomograph equation in II-Figure 3.1 of the Guide) Using II-Figure 2.6, the layer coefficient of the base course, a_2, is approximately 0.12.

Find: the required thickness of an asphalt concrete surface course to meet the design requirements of the given conditions using mix S1 from the study (AAM1, AC20, crushed limestone, Type C).

For flexible pavements, the structural number (SN) equation is used in thickness design. For this problem with two layers, the equation has two terms on the right hand side:

$$SN = a_1D_1 + a_2D_2m_2$$

where 'a' is a layer coefficient, 'D' is the layer thickness, and 'm' is the drainage factor (II-2.4.1). Using the table of known information, it is seen that all of the second layer parameters have been given. The solution is D_1. Therefore, SN and a_1 remain to be found. Refer back to Figure 10 in the body of this report. This is the same figure as II-Figure 2.5 in the AASHTO Guide. If it can be assumed that the figure is based on the 10 Hz response from the uniaxial test, Figure 33 of the body of this report indicates that either the IDT type test results or the uniaxial test results may be used in II-Figure 2.5. For this problem, the IDT type test results (device code 3 of Table 9 in the body of this report) will be used. However, note that II-Figure 2.5 requires the modulus at 68°F and test results on the S1 mix are only available at 50, 77, and 104°F (see Appendix D of this report). Therefore the full temperature sensitivity characterization of Part III of the test procedure in Appendix B of this report must be extended one step further. Figure C.1 illustrates how the modulus at a temperature of 68°F is obtained with the existing data.

Although not a rigorous form for the theoretical relationship, the following regression model adequately captures the trend in the area of interest:

$$E = e^{(12.211195 + 0.056374F - 0.000619F^2)}$$

where *F* is the temperature in °F, and *e* or *exp* is the exponential function (the base of natural logarithms). Entering a temperature of 68°F into this equation results in a modulus of approximately 531,000 psi. Assuming that the fatigue factor from Figure 13 of the body of this report is approximately 1.0, the 531,000 psi modulus presents a problem for use in II-Figure 2.5. One must extrapolate the curve out beyond 500,000 to obtain a value for the layer coefficient. However, Figure GG.7 of Volume 2 of the Guide extends to 600,000 psi and results in a value of approximately 0.48 for a_1.

The structural number equation can now be expressed as follows:

$$D_1 = (SN-1.44)/0.48$$

The nomograph II-Figure 3.1 in the AASHTO Guide solves for SN. Enter the graph on the left side an proceed toward the right side. Draw a straight line from the reliability of 80% through the overall standard deviation of 0.44 to the first turning line (T_L). Draw a second straight line from the first turning line through the estimated number of 18kip ESALs of 10,000,000 to the second turning line. Draw a third straight line from this turning line through the effective roadbed soil resilient modulus of 10,000 psi to the left border of the design serviceability loss box. Proceed horizontally to intercept the ΔPSI of 1.5. Then proceed vertically downward to read the design structural number of

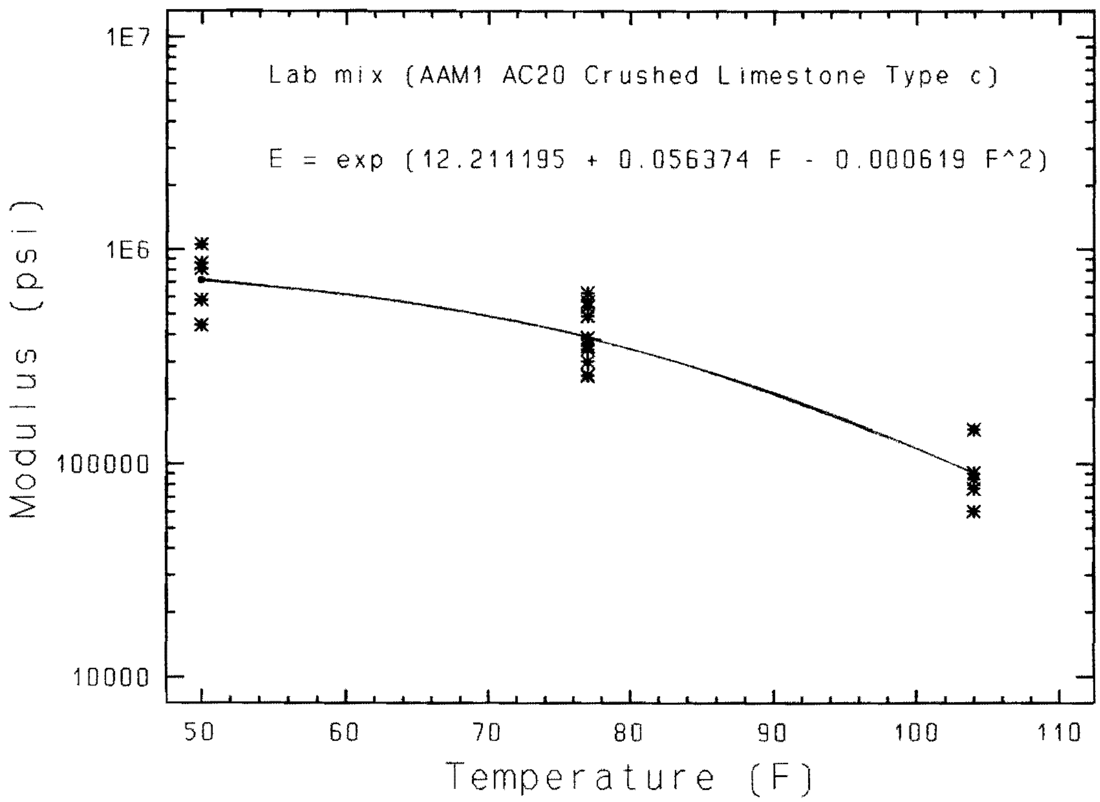


Figure C.1. Change of modulus with temperature.

approximately 4.4. It is now a simple matter to solve for the thickness, D_1.

$$D_1 = (4.4-1.44)/0.48 = 6.2 \text{ inches of mix S1}$$

PAVEMENT DESIGN AND ANALYSIS - TFPS

In its present form, the TFPS computer program allows entry of, but does not make use of, resilient modulus values of the asphalt mix in new pavement construction. It is only in the case of overlays that the modulus of the asphalt mix is used. In the case of overlays, the resilient modulus of the existing asphalt layers can be entered into the program and the entered value will override the normal procedure used for computing the modulus from mixture characteristics. The program automatically adjusts the modulus for each District in accordance with the climatological temperature and environmental conditions in the District. A fictitious example was formulated using the resilient modulus of the Mopac specimens tested in this study. An approximate modulus of 677,517 psi at 77°F obtained from the lower portion of Table 12 in the body of this report was used in the analysis. Since the program automatically takes care of the test temperature, there is no need to perform the full temperature sensitivity characterization that is required for the AASHTO procedure. Data files for the example are illustrated below.

Example problem input data:

```
County:   TRAVIS
District: 14
Highway:  MOPAC
Basic Design Criteria
        20      2.00      4.00      8.00     16.00 N
   200.0    .2 20000000.
  ADT at beginning of overlay:  48800.
  ADT at end of overlay:        90400.
  Modulus of existing surface: 677517.
  Existing surface temperature:    77.0
   1   .90
  Minimum serviceability: 2.50
  Maximum rut depth:       .5
  Maximum crack area:      600.0
  Planing depth:           .5
  Reliability code:        A
  Speed category:          H
  Aggregate quality:       H
Traffic Data
   ADT start: 48800.0              ADT end:90400.0
   Approach speed: 50.0mph         Average speed (overlay direction): 20.0
   Average speed (non-overlay): 50.0
   Proportion of ADT arriving each hour of construction (%): 5.0
   Percent truck in ADT:7.00
   One direction cumulative 18kip SAL at the end of 20 years: 13175000.0
Environment
  Monthly average air temperature (°F)
  49.1  52.8  60.2  69.2  75.4  81.4  84.6  84.1  79.1  70.0  59.0  52.2
  Monthly minimum air temperature
  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6
  Monthly average rainfall (in)
   1.9   2.7   1.5   2.8   4.1   3.3   1.8   2.8   3.6   4.0   2.3   2.0
Subgrade
   10000.0     CL       -14.3       .0       .0     30.0      40.0        Y  5  .00N > 30FT
 DONEO
Swelling and Frost
         0       .00     56.7
Construction and Maintenance Data
       8.0       2.0    150.0      12.0
     200.0     200.0     75.0      75.0     4.30     4.20       7.00
Detour Design for Overlay
         3         2        3        .7       .4       .0
Base Layer Material Data
   OGRAN
 10.00 10.00  GW         .0      .0     5.0     8.0       .0  25000. 5     10.00 30.
 N
Surface Layer Material Data
  7.00  7.00  622000.0 20.0      5.00      6.00      5.00     60.00 30.
    15.900     3.291     .854
Overlay Layer Material Data
  6.00  2.00  622000.0 20.0      5.00      6.00      5.00     60.00 30.
    15.900     3.291     .854
Transverse and Longitudinal Cracking
         1      1.00     120.0     182.0    600.00     55.0    2000.0
```

Example problem output data:

```
EXISTING CONSTRUCTION
T(1)=    7.00 T(2)=   10.00 T(3)=     .00     H SPEED

        MICRO   CRACKING  DAMAGE     CRACKING        RUT   RUTTING      CUMULATIVE
YR MTH  STRAIN   DAMAGE  VARIANCE LAYER1 LAYER2    DEPTH  VARIANCE EPSR    18KSAL
 0  0  .00E+00  .00E+00  .00E+00     0.      0.  .00E+00  .58E-03  4.30 .000E+00
 0 10  .20E+03  .65E-02  .17E-02     0.      0.  .13E+00  .54E-02  3.65 .392E+06
 1 10  .20E+03  .20E-01  .17E-01     1.      0.  .18E+00  .78E-02  3.43 .880E+06
 2 10  .20E+03  .21E-01  .18E-01    16.      0.  .21E+00  .92E-02  3.24 .139E+07
 3 10  .20E+03  .22E-01  .19E-01    54.      0.  .24E+00  .10E-01  3.08 .192E+07
CODE=5 ANALYSIS PERIOD OF 20 YEARS IS NOT REACHED
OVERLAY NO.   1

T(1)=    2.00 T(2)=    6.50 T(3)=   10.00      H SPEED     A REL LEVEL

        MICRO   CRACKING  DAMAGE     CRACKING        RUT   RUTTING      CUMULATIVE
YR MTH  STRAIN   DAMAGE  VARIANCE LAYER1 LAYER2    DEPTH  VARIANCE EPSR    18KSAL
 0  0  .00E+00  .00E+00  .00E+00     0.    200.  .12E-01  .11E-02  4.20 .000E+00
 0 10  .00E+00  .00E+00  .00E+00    25.    225.  .92E-01  .31E-02  3.74 .595E+06
 1 10  .00E+00  .00E+00  .00E+00    53.    253.  .12E+00  .39E-02  3.57 .134E+07
 2 10  .00E+00  .00E+00  .00E+00    83.    283.  .14E+00  .44E-02  3.47 .211E+07
 3 10  .42E+01  .21E-06  .14E-11   114.    314.  .15E+00  .47E-02  3.39 .291E+07
 4 10  .13E+02  .93E-05  .22E-08   145.    345.  .16E+00  .49E-02  3.32 .374E+07
 5 10  .23E+02  .62E-04  .11E-06   176.    376.  .17E+00  .51E-02  3.26 .460E+07
 6 10  .34E+02  .23E-03  .16E-05   207.    407.  .19E+00  .55E-02  3.19 .549E+07
 7 10  .46E+02  .67E-03  .14E-04   238.    438.  .22E+00  .69E-02  3.04 .641E+07
 8 10  .60E+02  .16E-02  .82E-04   268.    468.  .24E+00  .81E-02  2.91 .736E+07
 9 10  .75E+02  .34E-02  .38E-03   297.    497.  .27E+00  .93E-02  2.81 .834E+07
10 10  .91E+02  .66E-02  .15E-02   325.    525.  .29E+00  .10E-01  2.71 .935E+07
11 10  .11E+03  .12E-01  .52E-02   353.    553.  .32E+00  .11E-01  2.62 .104E+08
12 10  .13E+03  .21E-01  .16E-01   379.    579.  .34E+00  .12E-01  2.55 .115E+08
13 10  .15E+03  .35E-01  .46E-01   409.    603.  .36E+00  .13E-01  2.47 .126E+08
FAILURE MODE IS SERVICEABILITY
CODE=5 ANALYSIS PERIOD OF 16 YEARS IS NOT REACHED
OVERLAY NO.   2

T(1)=    2.00 T(2)=    8.00 T(3)=   10.00      H SPEED     A REL LEVEL

        MICRO   CRACKING  DAMAGE     CRACKING        RUT   RUTTING      CUMULATIVE
YR MTH  STRAIN   DAMAGE  VARIANCE LAYER1 LAYER2    DEPTH  VARIANCE EPSR    18KSAL
13  9  .00E+00  .00E+00  .00E+00     0.    603.  .18E-01  .11E-02  4.20 .125E+08
13 10  .17E+02  .10E-04  .29E-08     1.    604.  .91E-01  .90E-02  3.36 .126E+08
14 10  .19E+02  .39E-04  .41E-07    12.    616.  .15E+00  .12E-01  3.09 .137E+08
15 10  .20E+02  .49E-04  .65E-07    23.    627.  .18E+00  .14E-01  3.00 .148E+08
CODE=6 THIS DESIGN MEETS ALL THE DESIGN CRITERIA
*********************************************************************************

1                                     STATE OF TEXAS
                            NEW FLEXIBLE PAVEMENT SYSTEM
 NAME OF ENGINEER :
 PROB   DIST.  COUNTY           CONT.  SECT.  JOB  HIGHWAY       DATE     PAGE
 M-4     14    TRAVIS           0113   13      1   MOPAC        1/29/91      1
 ================================================================================

          GRANULAR  BL-BASE                     TIME      TIME
 PAVEMENT     BASE          SURFACE  OVERLAY  OF        OVERLAY          SEAL COATS
  SYSTEM      THICKNESS        THICKNESS     OVERLAY   FAILED  CODE       ADDED
           (in.)     (in.)    (in.)     (in.)    (yr.)    (yr.)
 --------------------------------------------------------------------------------
  1  1  5  10.00       .00      7.00      2.00      3.6      13.8   5     No Seal Coat
  1  1  5  10.00       .00      8.50      2.00     13.6      16.0   6     No Seal Coat
 --------------------------------------------------------------------------------
   Code 1= Thick pavement, Max. time to first overlay exceeded
   Code 2= Thin pavement, Min. time to first overlay not reached
   Code 3= Thick pavement, Max. time between overlays exceeded
   Code 4= Thin overlay, Min. time between overlays not exceeded
   Code 5= Analysis period not reached within overlay
   Code 6= All design criteria met.
*********************************************************************************
```

```
1                             STATE OF TEXAS
                        NEW FLEXIBLE PAVEMENT SYSTEM
                     LIST OF FEASIBLE DESIGN ALTERNATIVES
NAME OF ENGINEER :
PROB   DIST.  COUNTY          CONT.  SECT.  JOB  HIGHWAY       DATE    PAGE
M-4     14    TRAVIS          0113   13       1   MOPAC        1/29/91     1
================================================================================
1  SYSTEM : 1  1  5
                                OVERLAY MODE

   EXISTING CONSTRUCTION               PAVEMENT PARAMETERS AT YEAR  4.00
     Granular Base    :10.00 inches     CONDITION : PSI           :     3.08
     Black Base       :  .00 inches               : Cracked Area :      54.
     Asphalt Surface : 7.00 inches               : Rut Depth    :      .24
                                        TRAFFIC   :  .192E+07 18kSAL

     Asphalt Overlay : 2.00 inches

   SWELLING SOILS
     Not analyzed

   OVERLAY # 1        FAILED - 13 YRS  9 MNTHS- SERVICEABILITY
     Asphalt Overlay : 2.00 inches     CONDITION : PSI           :     2.47
     Mill Depth       :  .50 inches               : Cracked Area :     409.
                                                  : Rut Depth    :      .36
                                        TRAFFIC   :  .126E+08 18kSAL

   OVERLAY # 2        MET DESIGN CRITERIA 16 Years
     Asphalt Overlay : 2.00 inches     CONDITION : PSI           :     2.99
     Mill Depth       :  .50 inches               : Cracked Area :      24.
                                                  : Rut Depth    :      .18
                                        TRAFFIC   :  .151E+08 18kSAL

   LIFE CYCLE COSTS (in present value)
     Initial Construction :   .00      Overlay Constr. :   3.86
     Routine Maintenance  :   .36      Seal Coats      :    .00
     User Costs           :   .51      Salvage Value   :   -.68   TOTAL     4.05

--------------------------------------------------------------------------------
```

POTENTIAL USE FOR QUALITY CONTROL

If quality control is to be based on resilient modulus values, the checks must be made with the understanding that there must be a sufficient number of tests conducted so that the allowable error in the test procedure does not exceed the tolerance specified for the construction. For instance, consider Figure 34 of the body of this report. A figure such as this can be generated for each device and mix of interest. As an example, choose an S1 mix with a standard deviation of 133,019 psi and a mean of 412,824 psi. If the modulus of the material in place is specified on the plans as 300,000 psi minimum at 77°F, the maximum allowable sampling error could be estimated as 112,824 psi (the difference between the specification and the mean value). Using the equation in the body of the report

$$n = (2\sigma_o/e)^2$$

it is found that the minimum number of specimens necessary for testing to determine compliance is six (since n=5.56 in this case). The same type of approach can be taken to determine the uniformity of the quality of the mix. Note that, in general, between 10 and 25 specimens must be tested at the outset so that a good estimate of the standard deviation can be obtained for the computation of n. If laboratory compacted specimens are used, the air voids should match the expected voids in the field. While the test results may be useful in the quality control area, the engineer should be cautious when attempting to make judgmental inferences about distress based solely on resilient modulus, since the test and the current methods of interpretation of test results do not characterize adequately the failure mechanisms involved.

APPENDIX D

SUMMARIZED DATA

Poisson's ratios at 77°F and 104°F. (Type "C" aggregate with AC-10)

	77°F			104°F		
Cycle	P1	P2	P (avg)	P1	P2	P (avg)
1	0.541	0.533	0.538	0.622	0.725	0.673
2	0.547	0.534	0.542	0.656	0.735	0.695
3	0.550	0.536	0.545	0.658	0.709	0.683
4	0.555	0.543	0.550	0.664	0.735	0.700
5	0.558	0.546	0.553	0.680	0.725	0.702
6	0.556	0.548	0.553	0.704	0.720	0.712
7	0.556	0.550	0.554	0.721	0.715	0.718
8	0.563	0.562	0.562	0.726	0.727	0.738
9	0.566	0.568	0.567	0.730	0.746	0.738
10	0.569	0.569	0.569	0.714	0.737	0.739

Where,

P1 = Poisson's ratio in direction 1
P2 = Poisson's ratio in direction 2
(after rotating sample by 90°)
P(avg) = average Poisson's ratio.
Mean Poisson's ratio at 77°F is 0.553
Mean Poisson's ratio at 104°F is 0.709

Poisson's ratios at 77°F and 104°F. (Type "C" aggregate with AC-20)

	77°F			104°F		
Cycle	P1	P2	P (avg)	P1	P2	P (avg)
1	0.447	0.396	0.422	0.561	0.629	0.588
2	0.448	0.399	0.424	0.604	0.621	0.611
3	0.458	0.404	0.431	0.614	0.622	0.617
4	0.464	0.412	0.438	0.618	0.625	0.621
5	0.463	0.416	0.440	0.615	0.639	0.625
6	0.464	0.416	0.440	0.621	0.652	0.634
7	0.463	0.417	0.440	0.623	0.668	0.641
8	0.463	0.414	0.439	0.631	0.668	0.646
9	0.466	0.415	0.440	0.633	0.675	0.650
10	0.468	0.416	0.442	0.635	0.691	0.657

Mean Poisson's ratio at 77°F is 0.436
Mean Poisson's ratio at 104°F is 0.629

Poisson's ratios at 77°F and 104°F. (Type "D" aggregate with AC-10)

	77°F			104°F		
Cycle	P1	P2	P (avg)	P1	P2	P (avg)
1	0.485	0.480	0.483	0.713	0.711	0.712
2	0.485	0.481	0.483	0.720	0.713	0.716
3	0.490	0.486	0.488	0.713	0.741	0.727
4	0.494	0.489	0.492	0.714	0.741	0.728
5	0.501	0.495	0.498	0.715	0.748	0.731
6	0.503	0.499	0.501	0.727	0.755	0.741
7	0.506	0.504	0.505	0.738	0.763	0.750
8	0.512	0.512	0.512	0.741	0.766	0.753
9	0.519	0.523	0.521	0.760	0.763	0.761
10	0.530	0.536	0.533	0.768	0.760	0.764

Mean Poisson's ratio at 77°F is 0.501
Mean Poisson's ratio at 104°F is 0.739

Poisson's ratios at 77°F and 104°F. (Type "D" aggregate with AC-10)

	77°F			104°F		
Cycle	P1	P2	P (avg)	P1	P2	P (avg)
1	0.420	0.434	0.427	0.680	0.719	0.700
2	0.425	0.443	0.434	0.705	0.719	0.712
3	0.433	0.449	0.441	0.695	0.735	0.715
4	0.447	0.463	0.455	0.691	0.745	0.718
5	0.471	0.486	0.478	0.682	0.770	0.726
6	0.475	0.492	0.483	0.678	0.754	0.716
7	0.492	0.503	0.498	0.701	0.771	0.736
8	0.509	0.518	0.514	0.716	0.777	0.747
9	0.513	0.520	0.517	0.705	0.762	0.734
10	0.516	0.526	0.521	0.703	0.761	0.732

Mean Poisson's ratio at 77°F is 0.470
Mean Poisson's ratio at 104°F is 0.723

Resilient moduli at 77°F and 104°F. (Type "C" aggregate with AC-10)

	77°F			104°F		
Cycle	E1	E2	E (avg)	E1	E2	E (avg)
1	303542	271939	290900	175426	143928	159677
2	293361	268795	283534	156026	139002	147513
3	284475	264959	276669	150584	136362	143473
4	276659	257636	269049	143475	117852	130664
5	270102	254167	263727	132981	113583	123282
6	266557	247347	258873	123524	109400	116462
7	262635	244096	255219	117892	107026	112459
8	253855	234329	246045	115698	101488	108593
9	247023	228668	239681	114284	95762	105023
10	240272	226964	234949	110676	94924	102800

Where,
E1 = Resilient modulus in direction 1 (psi)
E2 = Resilient modulus in direction 2 (psi)
(after rotating sample by 90°)
E(avg) = average resilient modulus.
Mean resilient modulus at 77°F is 261865 psi.
Mean resilient modulus at 104°F is 124994 psi.

Resilient moduli at 77°F and 104°F. (Type "C" aggregate with AC-20)

77°F				104°F		
Cycle	E1	E2	E (avg)	E1	E2	E (avg)
1	430994	432371	431683	167835	136184	155174
2	420848	419478	420163	137777	132271	135575
3	393004	400800	396903	131099	125289	128775
4	375880	376820	376350	126624	120962	124359
5	371514	367640	369577	122247	110714	117633
6	366960	364846	365903	118307	104507	112787
7	364081	359121	361601	116166	96917	108466
8	357208	359207	358207	111806	95407	105246
9	350595	354982	352788	110817	93526	103900
10	343415	352353	347884	109638	89721	101671

Mean resilient modulus at 77°F is 378106 psi.
Mean resilient modulus at 104°F is 119359 psi.

Resilient moduli at 77°F and 104°F. (Type "D" aggregate with AC-10)

	77°F			104°F		
Cycle	E1	E2	E (avg)	E1	E2	E (avg)
1	280372	278339	279356	88772	94722	91747
2	276925	273190	275058	86063	93939	90001
3	267222	265813	266517	84089	83790	83939
4	259642	259186	259414	82817	83052	82934
5	249637	251209	250423	80267	78200	79234
6	244821	245054	244937	76311	76666	76488
7	238932	237585	238259	72834	74519	73676
8	230602	226494	228548	69464	70626	70045
9	220922	215067	217995	65505	67007	66256
10	210089	204463	207276	63746	65539	64643

Mean resilient modulus at 77°F is 224344 psi.
Mean resilient modulus at 104°F is 70815 psi.

Resilient moduli at 77°F and 104°F. (Type "D" aggregate with AC-20)

	77°F			104°F		
Cycle	E1	E2	E (avg)	E1	E2	E (avg)
1	609122	545874	577498	165118	151894	158506
2	585885	517400	551642	144493	148406	146449
3	545919	490144	518032	132266	131905	132085
4	498718	447169	472944	122584	121260	121922
5	437826	396141	416983	118647	111997	115322
6	426619	382145	404382	115353	107317	111335
7	389163	361243	375203	106459	97862	102160
8	358611	337834	348223	99636	94013	96825
9	349457	332613	341035	99016	94094	96555
10	339133	324502	33181	96798	92351	94574

Mean resilient modulus at 77°F is 433776 psi.
Mean resilient modulus at 104°F is 117573 psi.

DATA COLUMN ORDER:
Device code (see Table 9), Mix code (see Table 11), Air Voids, Load level (% of strength), Temperature (F), Last cycle contributing data to the analysis, Specimen orientation (degrees) or frequency (for axial specimens), Resilient modulus

0	RL	5.11	13.4	77.0	5	0	.1125940E+06
0	RL	5.09	16.3	77.0	5	0	.1183540E+06
0	RL	5.40	13.7	77.0	5	0	.1108260E+06
0	RL	4.88	12.1	77.0	5	0	.1028820E+06
0	RL	5.08	13.1	77.0	5	0	.1216000E+06
0	RL	5.35	14.8	77.0	5	0	.9057100E+05
0	RL	4.81	14.3	77.0	5	0	.9292060E+05
0	RL	4.84	14.2	77.0	5	0	.1032740E+06
0	RL	5.29	12.5	77.0	5	0	.5107440E+05
0	S1	2.72	6.9	77.0	5	0	.2348300E+06
0	S1	2.44	3.5	77.0	5	0	.2592820E+06
0	S1	3.09	16.1	77.0	5	0	.2383940E+06
0	S1	2.21	15.3	77.0	5	0	.2756380E+06
0	S1	2.82	16.8	77.0	5	0	.2806510E+06
0	S1	2.29	15.7	77.0	5	0	.2626110E+06
0	S1	3.04	13.6	77.0	5	0	.2679610E+06
0	S1	2.46	6.6	77.0	5	0	.2892300E+06
0	S1	2.59	6.6	77.0	5	0	.2794620E+06
0	S1	2.53	6.6	77.0	5	0	.2494050E+06
0	S1	2.59	6.6	77.0	5	0	.2992680E+06
0	S1	2.25	7.5	77.0	5	0	.2899570E+06
0	S1	2.00	6.6	77.0	5	0	.2949880E+06
0	S1	2.34	7.6	77.0	5	0	.2536800E+06
0	S1	2.79	7.4	77.0	5	0	.2929440E+06
0	S1	2.72	8.5	77.0	5	0	.2246370E+06
0	S1	2.77	5.1	77.0	5	0	.2637030E+06
0	S1	2.89	4.5	77.0	5	0	.2692370E+06
0	S1	2.48	3.4	77.0	5	0	.2876620E+06
0	S1	2.70	3.5	77.0	5	0	.3134920E+06
0	S2	3.26	6.8	77.0	5	0	.2514340E+06
0	S2	2.50	6.8	77.0	5	0	.2485340E+06
0	S2	2.72	6.9	77.0	5	0	.2035350E+06
0	S2	2.23	7.2	77.0	5	0	.2148280E+06
0	S2	2.56	6.6	77.0	5	0	.2311570E+06
0	S2	2.28	6.3	77.0	5	0	.2641630E+06
0	S2	2.58	6.4	77.0	5	0	.3259770E+06
0	S2	2.71	6.8	77.0	5	0	.2044990E+06
0	S2	2.00	6.8	77.0	5	0	.2420490E+06
0	S2	2.85	6.8	77.0	5	0	.2551680E+06
0	S2	2.55	6.8	77.0	5	0	.2472270E+06
0	S2	2.27	6.3	77.0	5	0	.2674570E+06
0	S2	2.90	6.8	77.0	5	0	.2216530E+06
0	S2	2.84	7.4	77.0	5	0	.2452120E+06
0	S2	2.58	7.0	77.0	5	0	.2447260E+06
0	S2	2.95	6.9	77.0	5	0	.2993490E+06
0	S2	2.24	6.1	77.0	5	0	.2505990E+06
0	S2	2.44	6.8	77.0	5	0	.2348690E+06
0	S2	2.09	8.4	77.0	5	0	.2160750E+06

0	S2	1.87	6.8	77.0	5	0	.2782140E+06
0	S3	2.38	5.4	77.0	5	0	.1843550E+06
0	S3	2.17	4.7	77.0	5	0	.2937460E+06
0	S3	2.10	4.5	77.0	5	0	.2639360E+06
0	S3	1.75	4.6	77.0	5	0	.2881820E+06
0	S3	2.93	4.0	77.0	5	0	.3784490E+06
0	S3	2.64	4.7	77.0	5	0	.3134810E+06
0	S3	2.92	5.1	77.0	5	0	.2311620E+06
0	S3	1.54	4.8	77.0	5	0	.2744340E+06
0	S3	3.22	4.8	77.0	5	0	.2703520E+06
0	S3	2.81	4.8	77.0	5	0	.2894550E+06
0	S3	2.63	4.8	77.0	5	0	.2966950E+06
0	S3	3.20	4.5	77.0	5	0	.2692110E+06
0	S3	2.71	4.8	77.0	5	0	.3127280E+06
0	S3	3.38	4.7	77.0	5	0	.2856590E+06
0	S3	2.26	4.9	77.0	5	0	.2682040E+06
0	S3	7.49	6.2	77.0	5	0	.2718160E+06
0	S3	3.03	4.4	77.0	5	0	.2811640E+06
0	S3	2.88	4.9	77.0	5	0	.2839760E+06
0	S3	2.63	5.1	77.0	5	0	.2763520E+06
0	S3	3.27	4.9	77.0	5	0	.2813490E+06
0	S4	2.39	11.9	77.0	5	0	.1926510E+06
0	S4	1.84	9.7	77.0	5	0	.2003920E+06
0	S4	2.80	12.6	77.0	5	0	.2037610E+06
0	S4	2.48	11.0	77.0	5	0	.2346320E+06
0	S4	2.94	10.6	77.0	5	0	.2005350E+06
0	S4	2.88	10.7	77.0	5	0	.2013660E+06
0	S4	2.65	10.9	77.0	5	0	.2020350E+06
0	S4	1.93	10.1	77.0	5	0	.2217200E+06
0	S4	2.56	10.5	77.0	5	0	.2399290E+06
0	S4	2.95	9.9	77.0	5	0	.2114760E+06
0	RL	5.11	13.4	77.0	5	90	.9160220E+05
0	RL	5.09	16.3	77.0	5	90	.9801960E+05
0	RL	5.40	13.7	77.0	5	90	.9012660E+05
0	RL	4.88	12.1	77.0	5	90	.9289490E+05
0	RL	5.08	13.1	77.0	5	90	.8782220E+05
0	RL	5.35	14.8	77.0	5	90	.9233880E+05
0	RL	4.81	14.3	77.0	5	90	.1018510E+06
0	RL	4.84	14.2	77.0	5	90	.4542200E+05
0	RL	5.29	12.5	77.0	5	90	.4595490E+05
0	S1	2.72	6.9	77.0	5	90	.2646780E+06
0	S1	2.44	3.5	77.0	5	90	.2618490E+06
0	S1	3.09	16.1	77.0	5	90	.2643580E+06
0	S1	2.21	15.3	77.0	5	90	.2859420E+06
0	S1	2.82	16.8	77.0	5	90	.2495560E+06
0	S1	2.29	15.7	77.0	5	90	.2283350E+06
0	S1	3.04	13.6	77.0	5	90	.3031780E+06
0	S1	2.46	6.6	77.0	5	90	.2508360E+06
0	S1	2.59	6.6	77.0	5	90	.2432350E+06
0	S1	2.53	6.6	77.0	5	90	.2831780E+06
0	S1	2.59	6.6	77.0	5	90	.3152170E+06
0	S1	2.25	7.5	77.0	5	90	.2770120E+06
0	S1	2.00	6.6	77.0	5	90	.2742870E+06
0	S1	2.34	7.6	77.0	5	90	.2671150E+06
0	S1	2.79	7.4	77.0	5	90	.2646780E+06

0	S1	2.72	8.5	77.0	5	90	.2330010E+06
0	S1	2.77	5.1	77.0	5	90	.2773510E+06
0	S1	2.89	4.5	77.0	5	90	.2411560E+06
0	S1	2.48	3.4	77.0	5	90	.2418260E+06
0	S1	2.70	3.5	77.0	5	90	.2666570E+06
0	S2	3.26	6.8	77.0	5	90	.2490620E+06
0	S2	2.50	6.8	77.0	5	90	.2174680E+06
0	S2	2.72	6.9	77.0	5	90	.2011400E+06
0	S2	2.23	7.2	77.0	5	90	.2167490E+06
0	S2	2.56	6.6	77.0	5	90	.2465680E+06
0	S2	2.28	6.3	77.0	5	90	.2241170E+06
0	S2	2.58	6.4	77.0	5	90	.2264680E+06
0	S2	2.71	6.8	77.0	5	90	.1878540E+06
0	S2	2.00	6.8	77.0	5	90	.2349000E+06
0	S2	2.85	6.8	77.0	5	90	.2433540E+06
0	S2	2.55	6.8	77.0	5	90	.2425180E+06
0	S2	2.27	6.3	77.0	5	90	.2277080E+06
0	S2	2.90	6.8	77.0	5	90	.2299070E+06
0	S2	2.84	7.4	77.0	5	90	.2168190E+06
0	S2	2.58	7.0	77.0	5	90	.2395730E+06
0	S2	2.95	6.9	77.0	5	90	.2720580E+06
0	S2	2.24	6.1	77.0	5	90	.2330130E+06
0	S2	2.44	6.8	77.0	5	90	.2577080E+06
0	S2	2.09	8.4	77.0	5	90	.3249500E+06
0	S2	1.87	6.8	77.0	5	90	.2838350E+06
0	S3	2.38	5.4	77.0	5	90	.2263820E+06
0	S3	2.17	4.7	77.0	5	90	.2861790E+06
0	S3	2.10	4.5	77.0	5	90	.2603530E+06
0	S3	1.75	4.6	77.0	5	90	.2931940E+06
0	S3	2.93	4.0	77.0	5	90	.3660410E+06
0	S3	2.64	4.7	77.0	5	90	.2773100E+06
0	S3	2.92	5.1	77.0	5	90	.2311620E+06
0	S3	1.54	4.8	77.0	5	90	.2848880E+06
0	S3	3.22	4.8	77.0	5	90	.2755020E+06
0	S3	2.81	4.8	77.0	5	90	.2704860E+06
0	S3	2.63	4.8	77.0	5	90	.2745600E+06
0	S3	3.20	4.5	77.0	5	90	.3438340E+06
0	S3	2.71	4.8	77.0	5	90	.2636580E+06
0	S3	3.38	4.7	77.0	5	90	.2908060E+06
0	S3	2.26	4.9	77.0	5	90	.2730370E+06
0	S3	7.49	6.2	77.0	5	90	.2538450E+06
0	S3	3.03	4.4	77.0	5	90	.2811640E+06
0	S3	2.88	4.9	77.0	5	90	.3008450E+06
0	S3	2.63	5.1	77.0	5	90	.2478750E+06
0	S3	3.27	4.9	77.0	5	90	.2721300E+06
0	S4	2.39	11.9	77.0	5	90	.1964010E+06
0	S4	1.84	9.7	77.0	5	90	.1857860E+06
0	S4	2.80	12.6	77.0	5	90	.1907230E+06
0	S4	2.48	11.0	77.0	5	90	.2479580E+06
0	S4	2.94	10.6	77.0	5	90	.1966780E+06
0	S4	2.88	10.7	77.0	5	90	.2066080E+06
0	S4	2.65	10.9	77.0	5	90	.1668630E+06
0	S4	1.93	10.1	77.0	5	90	.2157480E+06
0	S4	2.56	10.5	77.0	5	90	.2230110E+06
0	S4	2.95	9.9	77.0	5	90	.9708980E+05

1	RL	5.11	1.3	77.0	49	0	.3543025E+06
1	RL	5.11	1.3	77.0	49	90	.3383428E+06
2	RL	5.11	15.7	73.5	49	0	.3837983E+06
2	RL	5.11	21.4	50.0	49	0	.3849804E+07
3	RL	5.11	15.8	77.0	49	0	.1928452E+06
1	RL	5.09	1.6	77.0	49	0	.1316981E+05
1	RL	5.09	1.7	77.0	49	90	.1320484E+05
2	RL	5.09	19.3	73.5	49	0	.3169815E+06
2	RL	5.09	26.3	50.0	49	0	.6299903E+07
3	RL	5.09	19.3	77.0	49	0	.5328842E+06
1	RL	5.40	1.4	77.0	49	0	.2262142E+06
1	RL	5.40	1.4	77.0	49	90	.2272977E+06
2	RL	5.40	16.2	74.0	49	0	.3661066E+06
2	RL	5.40	22.0	50.0	49	0	.8532349E+07
3	RL	5.40	16.1	77.0	49	0	.1891613E+06
1	RL	4.88	1.1	77.0	49	0	.3179594E+06
1	RL	4.88	1.4	77.0	49	90	.2865596E+06
2	RL	4.88	14.2	74.0	49	0	.4149122E+06
2	RL	4.88	19.2	50.0	49	0	.1959285E+07
3	RL	4.88	14.1	77.0	49	0	.7841474E+05
1	RL	5.08	1.3	77.0	49	0	.5283424E+04
1	RL	5.08	1.3	77.0	49	90	.5245606E+04
2	RL	5.08	15.4	74.0	49	0	.3262963E+06
2	RL	5.08	21.0	50.0	49	0	.2079370E+07
3	RL	5.08	15.4	77.0	49	0	.1206847E+06
1	RL	5.35	1.5	77.0	49	0	.1956423E+05
1	RL	5.35	1.6	77.0	49	90	.1894441E+05
2	RL	5.35	17.4	74.0	49	0	.2947038E+06
2	RL	5.35	23.6	50.0	49	0	.2529423E+07
1	RL	4.81	1.4	77.0	49	0	.3837160E+06
1	RL	4.81	1.4	77.0	49	90	.3093868E+06
1	RL	4.81	1.5	77.0	49	90	.3535486E+06
2	RL	4.81	17.0	74.0	49	0	.3901578E+06
2	RL	4.81	23.2	50.0	49	0	.3654024E+07
1	RL	4.84	1.3	77.0	49	0	.8287588E+05
1	RL	4.84	1.5	77.0	49	90	.7911053E+05
2	RL	4.84	16.6	74.5	49	0	.3210151E+06
2	RL	4.84	22.5	50.0	49	0	.4097944E+07
1	RL	5.29	1.3	77.0	49	0	.8727991E+05
1	RL	5.29	1.3	77.0	49	90	.8701302E+05
2	RL	5.29	14.9	74.5	49	0	.4272198E+06
2	RL	5.29	20.4	50.0	49	0	.5810917E+07
1	S1	2.44	.4	77.0	49	0	.1745954E+06
1	S1	2.44	.4	77.0	49	90	.1710033E+06
1	S1	2.44	.4	77.0	49	90	.9192366E+05
2	S1	2.44	.4	77.0	49	0	.5817746E+06
2	S1	2.44	.4	77.0	49	90	.6811778E+06
2	S1	2.44	5.6	50.0	49	0	.8181931E+07
2	S1	2.44	4.1	76.0	49	0	.5364120E+06
3	S1	2.44	4.1	50.0	49	0	.1058954E+07
1	S1	3.09	1.8	77.0	49	0	.7096139E+05
1	S1	3.09	1.6	77.0	49	90	.7082949E+05
1	S1	3.09	-.1	77.0	49	90	.2253236E+04
2	S1	3.09	1.8	77.0	49	0	.7162053E+06
2	S1	3.09	1.7	77.0	49	90	.4577086E+06

2	S1	3.09	26.1	50.0	49	0	.5054760E+07
2	S1	3.09	19.1	76.0	49	0	.6525362E+06
3	S1	3.09	19.2	104.0	49	0	.7667447E+05
1	S1	2.21	1.6	77.0	49	0	.5520251E+04
1	S1	2.21	1.6	77.0	49	90	.5511247E+04
1	S1	2.21	1.6	77.0	49	90	.5516701E+04
2	S1	2.21	1.7	77.0	49	0	.5740653E+06
2	S1	2.21	1.6	77.0	49	90	.5882709E+06
2	S1	2.21	24.9	50.0	49	0	.5846503E+07
2	S1	2.21	18.2	76.0	49	0	.7379270E+06
3	S1	2.21	18.2	104.0	49	0	.9109372E+05
1	S1	2.82	1.7	77.0	49	0	.6184303E+04
1	S1	2.82	1.8	77.0	49	90	.6138346E+04
1	S1	2.82	1.8	77.0	49	90	.3886579E+04
2	S1	2.82	1.8	77.0	49	0	.6753943E+06
2	S1	2.82	1.8	77.0	49	90	.5304117E+06
2	S1	2.82	27.4	50.0	49	0	.1154605E+08
2	S1	2.82	20.0	76.0	49	0	.4983449E+06
3	S1	2.82	20.0	104.0	49	0	.6025263E+05
1	S1	2.29	1.6	77.0	49	0	.4094261E+04
1	S1	2.29	1.6	77.0	49	90	.4116030E+04
1	S1	2.29	1.6	77.0	49	90	.4078483E+04
2	S1	2.29	1.7	77.0	49	0	.7242779E+06
2	S1	2.29	1.8	77.0	49	90	.5222106E+06
2	S1	2.29	25.8	50.0	49	0	.4711780E+07
2	S1	2.29	18.8	76.0	49	0	.5128413E+06
3	S1	2.29	18.9	104.0	49	0	.1452985E+06
1	S1	3.04	1.4	77.0	49	0	.5983976E+06
1	S1	3.04	1.4	77.0	49	90	.4666536E+06
1	S1	3.04	-.1	77.0	49	90	.3980943E+05
2	S1	3.04	1.5	77.0	49	0	.4738348E+06
2	S1	3.04	1.5	77.0	49	90	.5992128E+06
2	S1	3.04	21.9	50.0	49	0	.5140659E+07
2	S1	3.04	16.1	76.0	49	0	.7824416E+06
3	S1	3.04	16.0	104.0	49	0	.8515600E+05
1	S1	2.46	.7	77.0	49	0	.5815061E+04
1	S1	2.46	.7	77.0	49	90	.5812254E+04
1	S1	2.46	.7	77.0	49	90	.5848192E+04
2	S1	2.46	.7	77.0	49	0	.3217447E+06
2	S1	2.46	.7	77.0	49	90	.5887439E+06
2	S1	2.46	10.7	50.0	49	0	.7058055E+07
2	S1	2.46	7.8	76.0	49	0	.5890604E+06
1	S1	2.59	.7	77.0	49	0	.3129524E+05
1	S1	2.59	.7	77.0	49	90	.3110688E+05
1	S1	2.59	.7	77.0	49	90	.3106508E+05
2	S1	2.59	.7	77.0	49	0	.5136690E+06
2	S1	2.59	.7	77.0	49	90	.6256152E+06
2	S1	2.59	10.7	50.0	49	0	.6114496E+07
2	S1	2.59	7.9	76.0	49	0	.8262382E+06
1	S1	2.53	.7	77.0	49	0	.2596821E+06
1	S1	2.53	.7	77.0	49	90	.2578209E+06
2	S1	2.53	.7	77.0	49	0	.5596634E+06
2	S1	2.53	.7	77.0	49	90	.5360674E+06
2	S1	2.53	10.8	50.0	49	0	.3547992E+07
2	S1	2.53	7.9	76.0	49	0	.6055251E+06

1	S1	2.59	.7	77.0	49	0	.3142269E+05
1	S1	2.59	.7	77.0	49	90	.3207549E+05
2	S1	2.59	.7	77.0	49	0	.5607271E+06
2	S1	2.59	.7	77.0	49	90	.5206898E+06
2	S1	2.59	.0	77.0	49	90	.2196537E+05
2	S1	2.59	10.7	50.0	49	0	.1407320E+08
2	S1	2.59	7.9	76.0	49	0	.3125442E+07
1	S1	2.72	.7	77.0	49	0	.1776158E+06
1	S1	2.72	.7	77.0	49	90	.1773458E+06
1	S1	2.72	.7	77.0	49	90	.1781307E+06
2	S1	2.72	.7	77.0	49	0	.6531184E+06
2	S1	2.72	.7	77.0	49	90	.5330737E+06
2	S1	2.72	11.2	60.0	49	0	.4329094E+07
2	S1	2.72	8.3	76.0	49	0	.6165729E+06
3	S1	2.72	8.2	77.0	49	0	.6247886E+06
3	S1	2.72	8.1	77.0	49	90	.3009461E+06
1	S1	2.00	.7	77.0	49	0	.2077065E+05
1	S1	2.00	.7	77.0	49	90	.2071920E+05
2	S1	2.00	.7	77.0	49	0	.7450471E+06
2	S1	2.00	.7	77.0	49	90	.6535619E+06
2	S1	2.00	10.8	50.0	49	0	.4420187E+07
2	S1	2.00	7.9	76.0	49	0	.1124787E+07
1	S1	2.25	.8	77.0	49	0	.1018334E+06
1	S1	2.25	.8	77.0	49	90	.1016887E+06
1	S1	2.25	.8	77.0	49	90	.1006402E+06
2	S1	2.25	.8	77.0	49	0	.5757432E+06
2	S1	2.25	.8	77.0	49	90	.6662541E+06
2	S1	2.25	12.3	58.1	49	0	.9390627E+07
2	S1	2.25	9.1	76.0	49	0	.5797542E+06
3	S1	2.25	9.0	77.0	49	0	.5409041E+06
3	S1	2.25	9.1	77.0	49	90	.4878820E+06
1	S1	2.34	.8	77.0	49	0	.5744724E+05
1	S1	2.34	.8	77.0	49	90	.5693011E+05
1	S1	2.34	.0	77.0	49	90	.3100130E+04
2	S1	2.34	.8	77.0	49	0	.5795162E+06
2	S1	2.34	.8	77.0	49	90	.5597887E+06
2	S1	2.34	12.4	59.0	49	0	.3735401E+07
2	S1	2.34	9.0	76.0	49	0	.5813706E+06
3	S1	2.34	9.1	77.0	49	0	.3869435E+06
3	S1	2.34	9.1	77.0	49	90	.3431294E+06
1	S1	2.79	.8	77.0	49	0	.4582926E+06
1	S1	2.79	.8	77.0	49	90	.4618140E+06
1	S1	2.79	.8	77.0	49	90	.4593199E+06
2	S1	2.79	.8	77.0	49	0	.5797931E+06
2	S1	2.79	.8	77.0	49	90	.5848629E+06
2	S1	2.79	8.8	76.0	49	0	.5860803E+06
2	S1	2.79	12.0	55.9	49	0	.7326244E+07
3	S1	2.79	8.8	77.0	49	0	.5680655E+06
3	S1	2.79	8.8	77.0	49	90	.3563321E+06
1	S1	2.72	.9	77.0	49	0	.5095625E+06
1	S1	2.72	.9	77.0	49	90	.5146912E+06
1	S1	2.72	.9	77.0	49	90	.5302909E+06
2	S1	2.72	.9	77.0	49	0	.6132560E+06
2	S1	2.72	.9	77.0	49	90	.5597137E+06
2	S1	2.72	10.2	76.0	49	0	.5152994E+06

2	S1	2.72	13.9	55.0	49	0	.2678762E+07
3	S1	2.72	10.2	77.0	49	0	.2583741E+06
3	S1	2.72	10.2	77.0	49	90	.2608724E+06
1	S1	2.77	.5	77.0	49	0	.2695538E+06
1	S1	2.77	.5	77.0	49	90	.3012834E+06
1	S1	2.77	.0	77.0	49	90	.1547784E+05
2	S1	2.77	.6	77.0	49	0	.6967685E+06
2	S1	2.77	.5	77.0	49	90	.5219307E+06
2	S1	2.77	8.3	54.8	49	0	.3364223E+07
2	S1	2.77	6.0	76.0	49	0	.1204764E+07
3	S1	2.77	6.0	50.0	49	0	.4431780E+06
1	S1	2.89	.5	77.0	49	0	.3070155E+05
1	S1	2.89	.5	77.0	49	90	.3060478E+05
1	S1	2.89	.5	77.0	49	90	.3011204E+05
2	S1	2.89	.5	77.0	49	0	.4891834E+06
2	S1	2.89	.5	77.0	49	90	.5140673E+06
2	S1	2.89	7.5	56.0	49	0	.2296808E+07
2	S1	2.89	5.4	76.0	49	0	.4503529E+06
3	S1	2.89	5.4	50.0	49	0	.5804808E+06
1	S1	2.48	.3	77.0	49	0	.3641535E+05
1	S1	2.48	.3	77.0	49	90	.3602049E+05
1	S1	2.48	.0	77.0	49	90	.2043669E+04
2	S1	2.48	.4	77.0	49	0	.5957550E+06
2	S1	2.48	.4	77.0	49	90	.4466191E+06
2	S1	2.48	5.5	52.0	49	0	.9823620E+07
2	S1	2.48	4.0	76.0	49	0	.9366881E+06
3	S1	2.48	4.0	50.0	49	0	.8125164E+06
1	S1	2.70	.4	77.0	49	0	.9888850E+05
1	S1	2.70	.4	77.0	49	90	.9751270E+05
1	S1	2.70	.0	77.0	49	90	.5445463E+04
2	S1	2.70	.4	77.0	49	0	.5027858E+06
2	S1	2.70	.4	77.0	49	90	.5020404E+06
2	S1	2.70	5.6	50.0	49	0	.3885993E+07
2	S1	2.70	4.1	76.0	49	0	.9206761E+06
3	S1	2.70	4.2	50.0	49	0	.8575858E+06
1	S2	2.50	.7	77.0	49	0	.5658363E+05
1	S2	2.50	.7	77.0	49	90	.5634427E+05
1	S2	2.50	.7	77.0	49	0	.4835442E+06
2	S2	2.50	8.2	76.0	49	0	.5055760E+06
2	S2	2.72	8.4	76.0	49	0	.3795205E+06
1	S2	2.23	.7	77.0	49	0	.3083064E+06
1	S2	2.23	.7	77.0	49	90	.3093133E+06
1	S2	2.23	.7	77.0	49	0	.4789467E+06
2	S2	2.23	8.4	76.0	49	0	.3803274E+06
1	S2	2.56	.7	77.0	49	0	.3979262E+06
1	S2	2.56	.7	77.0	49	90	.3976125E+06
1	S2	2.56	.7	77.0	49	0	.8408747E+06
2	S2	2.56	7.8	76.0	49	0	.1177261E+07
1	S2	2.28	.7	77.0	49	0	.8099173E+05
1	S2	2.28	.6	77.0	49	90	.7906539E+05
1	S2	2.28	.7	77.0	49	0	.5646444E+06
2	S2	2.28	7.5	76.0	49	0	.7838217E+06
1	S2	2.58	.7	77.0	49	0	.5524885E+05
1	S2	2.58	.6	77.0	49	90	.5415757E+05
1	S2	2.58	.7	77.0	49	0	.6756910E+06

2	S2	2.58	7.7	76.0	49	0	.8684561E+06
1	S2	2.71	.7	77.0	49	0	.6803026E+05
1	S2	2.71	.7	77.0	49	90	.6805834E+05
1	S2	2.71	.7	77.0	49	0	.5748438E+06
2	S2	2.71	8.2	76.0	49	0	.4473150E+06
1	S2	2.00	.7	77.0	49	0	.3418428E+06
1	S2	2.00	.7	77.0	49	90	.3430802E+06
1	S2	2.00	.7	77.0	49	0	.6487898E+06
2	S2	2.00	8.1	76.0	49	0	.5920256E+06
1	S2	2.85	.7	77.0	49	0	.9616686E+05
1	S2	2.85	.7	77.0	49	90	.9566350E+05
1	S2	2.85	.7	77.0	49	0	.9275845E+06
2	S2	2.85	8.1	76.0	49	0	.5286954E+06
1	S2	2.55	.7	77.0	49	0	.2842798E+05
1	S2	2.55	.7	77.0	49	90	.2802847E+05
1	S2	2.55	.7	77.0	49	0	.7940963E+06
2	S2	2.55	8.1	76.0	49	0	.7461261E+06
1	S2	3.26	.7	77.0	49	0	.3875432E+05
1	S2	3.26	.7	77.0	49	90	.3891110E+05
1	S2	3.26	.7	77.0	49	0	.6394080E+06
2	S2	3.26	8.2	76.0	49	0	.4310756E+06
1	S2	2.90	.7	77.0	49	0	.5148438E+06
1	S2	2.90	.7	77.0	49	90	.4773535E+06
1	S2	2.90	.7	77.0	49	0	.6711596E+06
2	S2	2.90	8.0	76.0	49	0	.4223982E+06
1	S2	2.27	.7	77.0	49	0	.2287336E+05
1	S2	2.27	.7	77.0	49	90	.2263199E+05
1	S2	2.27	.7	77.0	49	0	.5710485E+06
2	S2	2.27	7.6	76.0	49	0	.4710996E+06
1	S2	2.84	.8	77.0	49	0	.3940372E+06
1	S2	2.84	.8	77.0	49	90	.3890626E+06
1	S2	2.84	.8	77.0	49	0	.5904648E+06
2	S2	2.84	8.8	76.0	49	0	.3945552E+06
1	S2	2.58	.8	77.0	49	0	.2052498E+05
1	S2	2.58	.7	77.0	49	90	.2049218E+05
1	S2	2.58	.8	77.0	49	0	.5193309E+06
2	S2	2.58	8.4	76.0	49	0	.8461245E+06
1	S2	2.95	.7	77.0	49	0	.4634244E+05
1	S2	2.95	.7	77.0	49	90	.4626288E+05
1	S2	2.95	.7	77.0	49	0	.5632020E+06
2	S2	2.95	8.2	76.0	49	0	.6785474E+06
1	S2	2.24	.6	77.0	49	0	.3597707E+05
1	S2	2.24	.6	77.0	49	90	.3600471E+05
1	S2	2.24	.6	77.0	49	0	.5668020E+06
2	S2	2.24	7.3	76.0	49	0	.1021960E+07
1	S2	2.44	.7	77.0	49	0	.5692132E+05
1	S2	2.44	.7	77.0	49	90	.5805244E+05
1	S2	2.44	.7	77.0	49	0	.5789505E+06
2	S2	2.44	8.1	76.0	49	0	.6298004E+06
1	S2	2.09	.9	77.0	49	0	.7422543E+05
1	S2	2.09	.8	77.0	49	90	.7219969E+05
1	S2	2.09	.9	77.0	49	0	.8332285E+06
2	S2	2.09	9.7	76.0	49	0	.5202231E+06
1	S2	1.87	.7	77.0	49	0	.2797113E+05
1	S2	1.87	.7	77.0	49	90	.2796699E+05

1	S2	1.87	.7	77.0	49	0	.7929496E+06
2	S2	1.87	8.1	76.0	49	0	.5259201E+06
1	S3	2.17	.5	77.0	49	0	.3828253E+06
1	S3	2.17	.5	77.0	49	90	.3845255E+06
2	S3	2.17	.5	77.0	49	0	.4316392E+06
2	S3	2.17	.5	77.0	49	90	.4594425E+06
2	S3	2.17	5.7	78.4	49	0	.7223392E+06
2	S3	2.17	7.7	50.0	49	0	.5746152E+07
1	S3	2.10	.5	77.0	49	0	.1250658E+06
1	S3	2.10	.5	77.0	49	90	.1245293E+06
2	S3	2.10	.5	77.0	49	0	.5196389E+06
2	S3	2.10	.5	77.0	49	90	.5561484E+06
2	S3	2.10	5.5	78.4	49	0	.1967568E+07
2	S3	2.10	7.4	50.0	49	0	.1354045E+08
1	S3	1.75	.5	77.0	49	0	.5812381E+06
1	S3	1.75	.5	77.0	49	90	.5214740E+06
2	S3	1.75	.5	77.0	49	0	.5573079E+06
2	S3	1.75	.5	77.0	49	90	.5435102E+06
2	S3	1.75	5.8	78.4	49	0	.2933203E+07
2	S3	1.75	7.9	50.0	49	0	.3480314E+07
1	S3	2.93	.4	77.0	49	0	.5714898E+06
1	S3	2.93	.4	77.0	49	90	.5693834E+06
2	S3	2.93	.4	77.0	49	0	.5470696E+06
2	S3	2.93	.4	77.0	49	90	.5863992E+06
2	S3	2.93	4.8	78.4	49	0	.9550630E+06
2	S3	2.93	6.6	50.0	49	0	.3660110E+07
1	S3	2.64	.5	77.0	49	0	.1591579E+06
1	S3	2.64	.5	77.0	49	90	.1562478E+06
2	S3	2.64	.5	77.0	49	0	.6851122E+06
2	S3	2.64	.5	77.0	49	90	.5086768E+06
2	S3	2.64	5.7	78.4	49	0	.7287140E+06
2	S3	2.64	7.8	50.0	49	0	.6089917E+07
1	S3	2.92	.5	77.0	49	0	.1427479E+06
1	S3	2.92	.6	77.0	49	90	.1416255E+06
2	S3	2.92	.6	77.0	49	0	.4816639E+06
2	S3	2.92	.5	77.0	49	90	.3870220E+06
2	S3	2.92	6.2	78.4	49	0	.9445182E+06
2	S3	2.92	8.3	50.0	49	0	.3146136E+07
1	S3	1.54	.5	77.0	49	0	.7819211E+05
1	S3	1.54	.5	77.0	49	90	.7841094E+05
2	S3	1.54	.5	77.0	49	0	.6706206E+06
2	S3	1.54	.5	77.0	49	90	.4662844E+06
2	S3	1.54	5.8	78.4	49	0	.7427929E+06
2	S3	1.54	7.9	50.0	49	0	.3966491E+07
1	S3	3.22	.5	77.0	49	0	.6677149E+06
1	S3	3.22	.5	77.0	49	90	.5670127E+06
2	S3	3.22	.5	77.0	49	0	.6224754E+06
2	S3	3.22	.5	77.0	49	90	.4860664E+06
2	S3	3.22	5.8	78.4	49	0	.9489715E+06
2	S3	3.22	7.8	50.0	49	0	.6284725E+07
1	S3	2.81	.5	77.0	49	0	.1108064E+06
1	S3	2.81	.5	77.0	49	90	.1116624E+06
2	S3	2.81	.5	77.0	49	0	.6023310E+06
2	S3	2.81	.5	77.0	49	90	.4892139E+06
2	S3	2.81	5.8	78.4	49	0	.1275569E+07

2	S3	2.81	7.8	50.0	49	0	.2301662E+07
1	S3	2.63	.5	77.0	49	0	.9163496E+05
1	S3	2.63	.5	77.0	49	90	.9142943E+05
2	S3	2.63	.5	77.0	49	0	.5034391E+06
2	S3	2.63	.5	77.0	49	90	.5831722E+06
2	S3	2.63	5.8	78.4	49	0	.1028773E+07
2	S3	2.63	7.9	50.0	49	0	.1117128E+08
1	S3	2.38	.6	77.0	49	0	.1277833E+06
1	S3	2.38	.6	77.0	49	90	.1292506E+06
2	S3	2.38	.6	77.0	49	0	.5399819E+06
2	S3	2.38	.6	77.0	49	90	.6269112E+06
2	S3	2.38	6.6	78.4	49	0	.5727989E+06
2	S3	2.38	8.9	50.0	49	0	.6213740E+07
1	S3	2.71	.5	77.0	49	0	.5715282E+06
1	S3	2.71	.5	77.0	49	90	.5667384E+06
2	S3	2.71	.5	77.0	49	0	.5548177E+06
2	S3	2.71	.5	77.0	49	90	.5508350E+06
2	S3	2.71	5.7	78.4	49	0	.6737906E+06
2	S3	2.71	7.7	50.0	49	0	.3531340E+07
1	S3	3.20	.5	77.0	49	0	.8327861E+05
1	S3	3.20	.5	77.0	49	90	.8365178E+05
2	S3	3.20	.5	77.0	49	0	.4554405E+06
2	S3	3.20	.5	77.0	49	90	.5123742E+06
2	S3	3.20	5.3	78.4	49	0	.1079342E+07
2	S3	3.20	7.3	50.0	49	0	.1082637E+08
1	S3	3.38	.5	77.0	49	0	.1638601E+06
1	S3	3.38	.4	77.0	49	90	.1632269E+06
2	S3	3.38	.5	77.0	49	0	.5381142E+06
2	S3	3.38	.5	77.0	49	90	.4280230E+06
2	S3	3.38	5.6	78.4	49	0	.6935560E+06
2	S3	3.38	7.6	50.0	49	0	.4905091E+07
1	S3	2.26	.5	77.0	49	0	.1695510E+06
1	S3	2.26	.5	77.0	49	90	.1729100E+06
2	S3	2.26	.5	77.0	49	0	.5298577E+06
2	S3	2.26	.5	77.0	49	90	.5760089E+06
2	S3	2.26	6.0	78.4	49	0	.6242090E+06
2	S3	2.26	8.1	50.0	49	0	.9842480E+07
1	S3	7.49	.6	77.0	49	0	.3246204E+06
1	S3	7.49	.6	77.0	49	90	.3245894E+06
2	S3	7.49	7.0	78.4	49	0	.8929986E+06
2	S3	7.49	9.4	50.0	49	0	.3014713E+07
1	S3	3.03	.5	77.0	49	0	.6548827E+06
1	S3	3.03	.5	77.0	49	90	.5965449E+06
2	S3	3.03	.5	77.0	49	0	.4876096E+06
2	S3	3.03	.5	77.0	49	90	.5136793E+06
2	S3	3.03	5.2	78.4	49	0	.8370071E+06
2	S3	3.03	7.1	50.0	49	0	.4852545E+07
1	S3	2.88	.5	77.0	49	0	.2455486E+06
1	S3	2.88	.5	77.0	49	90	.2474191E+06
2	S3	2.88	.5	77.0	49	0	.5139581E+06
2	S3	2.88	.5	77.0	49	90	.5786173E+06
2	S3	2.88	5.9	78.4	49	0	.6965660E+06
2	S3	2.88	8.0	50.0	49	0	.7001482E+07
1	S3	2.63	.5	77.0	49	0	.3827245E+06
1	S3	2.63	.5	77.0	49	90	.3812211E+06

2	S3	2.63	.6	77.0	49	0	.5444030E+06
2	S3	2.63	.5	77.0	49	90	.5232147E+06
2	S3	2.63	6.2	78.4	49	0	.7809796E+06
2	S3	2.63	8.4	50.0	49	0	.9263164E+07
1	S3	3.27	.5	77.0	49	0	.1221608E+06
1	S3	3.27	.5	77.0	49	90	.1235177E+06
2	S3	3.27	.5	77.0	49	0	.5427057E+06
2	S3	3.27	.5	77.0	49	90	.5429874E+06
2	S3	3.27	5.8	78.4	49	0	.6414763E+06
2	S3	3.27	8.0	50.0	49	0	.4270572E+07
1	S4	1.84	1.0	77.0	49	0	.4408307E+06
1	S4	1.84	1.0	77.0	49	90	.4292505E+06
2	S4	1.84	1.1	74.0	49	0	.5550108E+06
2	S4	1.84	11.6	73.5	49	0	.4085517E+06
2	S4	1.84	15.9	50.0	49	0	.5831398E+07
1	S4	2.39	1.2	77.0	49	0	.7812226E+05
1	S4	2.39	1.2	77.0	49	90	.7764730E+05
2	S4	2.39	1.3	74.0	49	0	.6107139E+06
2	S4	2.39	14.5	73.0	49	0	.3126438E+06
2	S4	2.39	19.6	50.0	49	0	.1411363E+07
3	S4	2.39	14.2	77.0	49	0	.1325495E+06
1	S4	2.80	1.3	77.0	49	0	.8910477E+04
1	S4	2.80	1.3	77.0	49	90	.8929724E+04
2	S4	2.80	1.3	74.0	49	0	.1678641E+05
2	S4	2.80	15.1	73.0	49	0	.1229402E+07
2	S4	2.80	20.6	50.0	49	0	.4820069E+07
3	S4	2.80	15.1	77.0	49	0	.1336610E+06
1	S4	2.48	1.1	77.0	49	0	.9213428E+04
1	S4	2.48	1.1	77.0	49	90	.9110179E+04
2	S4	2.48	1.2	74.0	49	0	.3281607E+06
2	S4	2.48	13.1	73.0	49	0	.3379525E+06
2	S4	2.48	17.7	50.0	49	0	.4861296E+07
3	S4	2.48	13.0	77.0	49	0	.1821064E+06
1	S4	2.94	1.1	77.0	49	0	.1381875E+05
1	S4	2.94	1.1	77.0	49	90	.1408407E+05
2	S4	2.94	1.1	74.0	49	0	.5953891E+06
2	S4	2.94	12.6	73.0	49	0	.3716452E+06
2	S4	2.94	17.1	50.0	49	0	.1467068E+07
3	S4	2.94	12.7	77.0	49	0	.1038781E+06
1	S4	2.88	1.1	77.0	49	0	.2000455E+05
1	S4	2.88	1.1	77.0	49	90	.2015146E+05
2	S4	2.88	1.1	74.0	49	0	.6481035E+06
2	S4	2.88	12.7	73.0	49	0	.3000656E+06
2	S4	2.88	17.3	50.0	49	0	.3497053E+07
3	S4	2.88	12.6	77.0	49	0	.8633680E+05
1	S4	2.65	1.1	77.0	49	0	.4056472E+06
1	S4	2.65	1.2	77.0	49	90	.3726065E+06
2	S4	2.65	1.2	74.0	49	0	.5307248E+06
2	S4	2.65	13.0	73.0	49	0	.2802855E+06
2	S4	2.65	17.7	50.0	49	0	.4037691E+07
1	S4	1.93	1.0	77.0	49	0	.2103355E+06
1	S4	1.93	1.0	77.0	49	90	.2143711E+06
2	S4	1.93	1.1	74.0	49	0	.5993254E+06
2	S4	1.93	12.2	73.0	49	0	.3730099E+06
2	S4	1.93	16.5	50.0	49	0	.7867520E+07

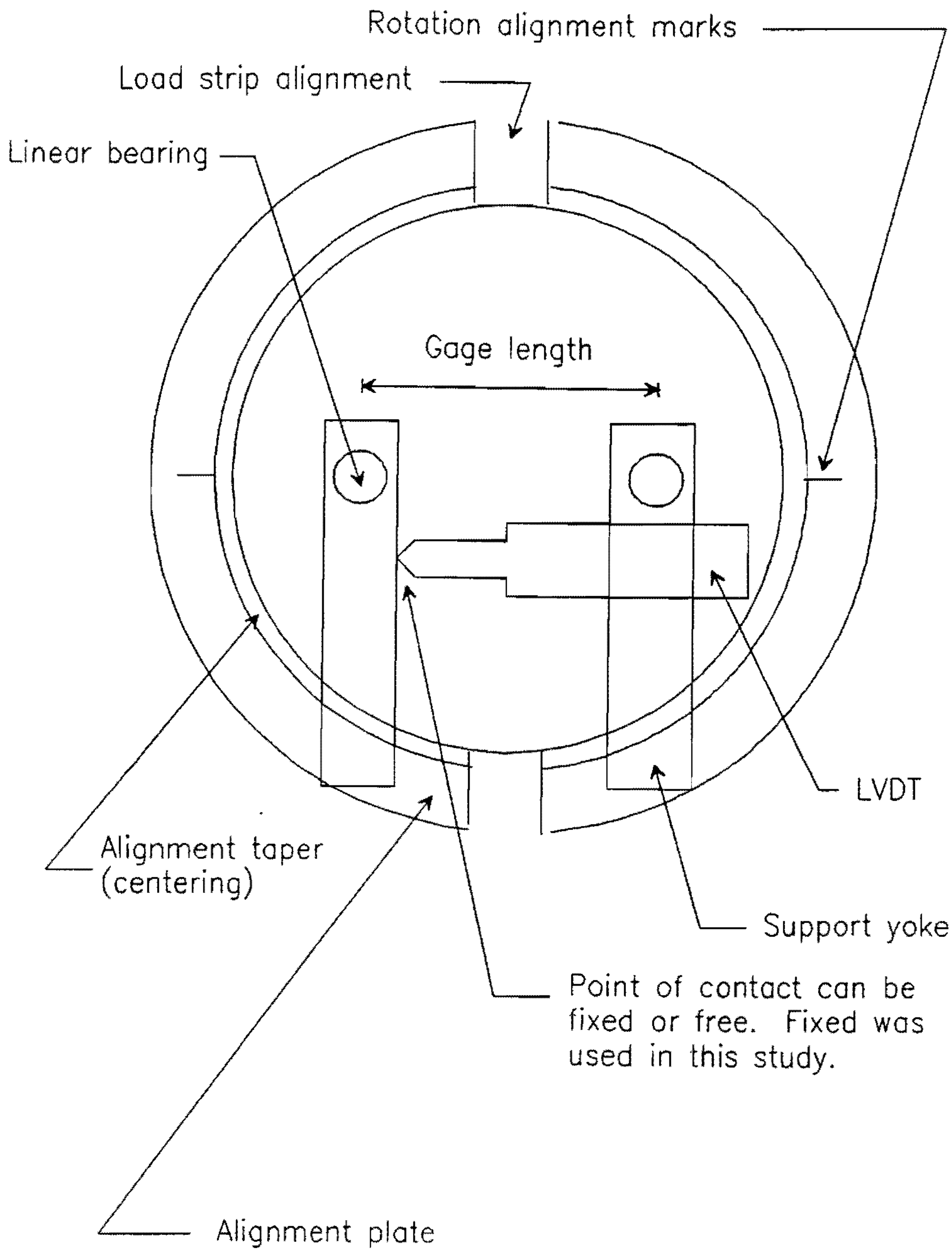
1	S4	2.56	1.1	77.0	49	0	.1121421E+06
1	S4	2.56	1.1	77.0	49	90	.1134156E+06
2	S4	2.56	1.1	74.0	49	0	.5743219E+06
2	S4	2.56	12.5	73.5	49	0	.4373664E+06
2	S4	2.56	17.0	50.0	49	0	.2478875E+07
1	S4	2.95	1.0	77.0	49	0	.4483075E+06
1	S4	2.95	1.0	77.0	49	90	.4440684E+06
2	S4	2.95	1.0	74.0	49	0	.5005893E+06
2	S4	2.95	11.8	73.5	49	0	.5857819E+06
2	S4	2.95	16.1	50.0	49	0	.3470512E+07
2	S3			77.0	49	0	.3992424E+07
2	S3			77.0	49	0	.1389817E+07
2	S3			77.0	49	0	.1207817E+07
2	S3			77.0	49	0	.1808305E+07
2	S3			77.0	49	0	.1528150E+07
2	S1			77.0	49	0	.5626839E+07
2	S1			77.0	49	0	.1997406E+08
2	S1			77.0	49	0	.1042294E+08
2	S1			77.0	49	0	.1133729E+08
2	S1			77.0	49	0	.1111965E+07
2	S2			77.0	49	0	.6847390E+07
2	S2			77.0	49	0	.2263566E+07
2	S2			77.0	49	0	.5139264E+07
2	S2			77.0	49	0	.2040848E+07
2	S2			77.0	49	0	.9209164E+07
4	S1			77.0	49	0	.5203378E+06
4	S1			77.0	49	0	.7494407E+06
4	S1			77.0	49	0	.6171371E+06
4	MO			77.0	49	0	.6831201E+06
4	MO			77.0	49	90	.6352284E+06
4	MO			77.0	49	0	.7160513E+06
4	MO			77.0	49	0	.6912169E+06
4	MO			77.0	49	90	.6956720E+06
4	MO			77.0	49	0	.6515983E+06
5	S1			77	295	10	212140.9
5	S1			77	25	1	124291.2
5	S1			77	295	10	293334.7
5	S1			77	25	1	155416.7
5	S1			77	295	10	306076.7
5	S1			77	25	1	158121.8
5	MO			77	295	10	1111877
5	MO			77	25	1	648882.9
5	MO			77	295	10	656884.1
5	MO			77	25	1	349675.7
5	MO			77	295	10	804949
5	MO			77	25	1	407921.1
5	MO			77	295	10	923647.9
5	MO			77	25	1	484380.7

APPENDIX D

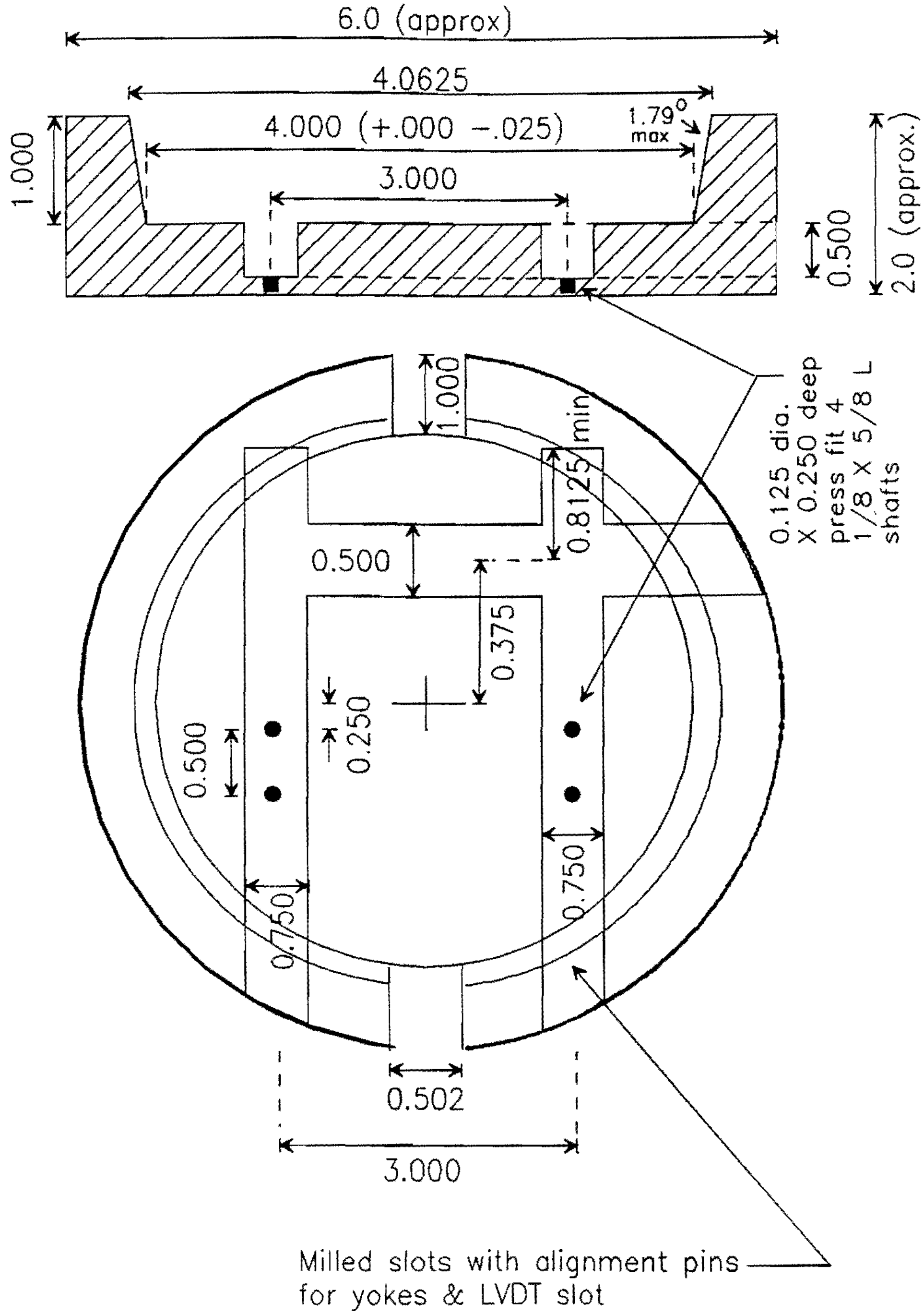
MACHINE DRAWINGS

ACCELERATED DEVICE

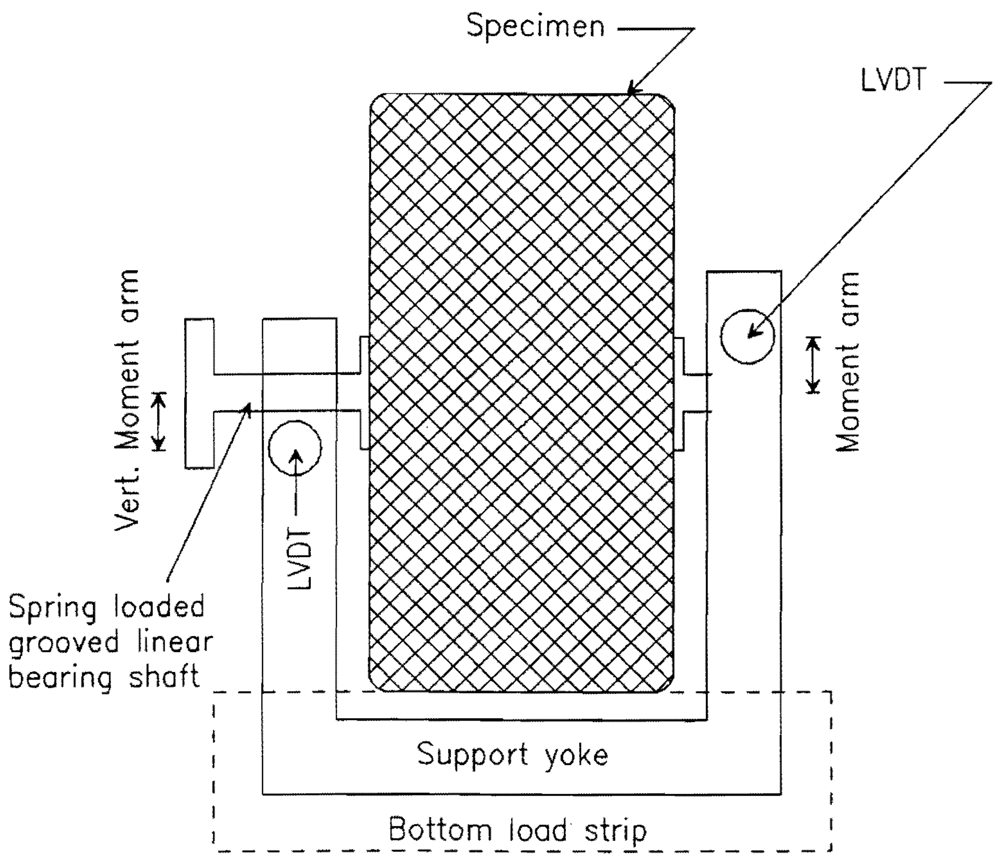
Alignment fixture assembly



Alignment plate
Material: Aluminum
Quantity: 1

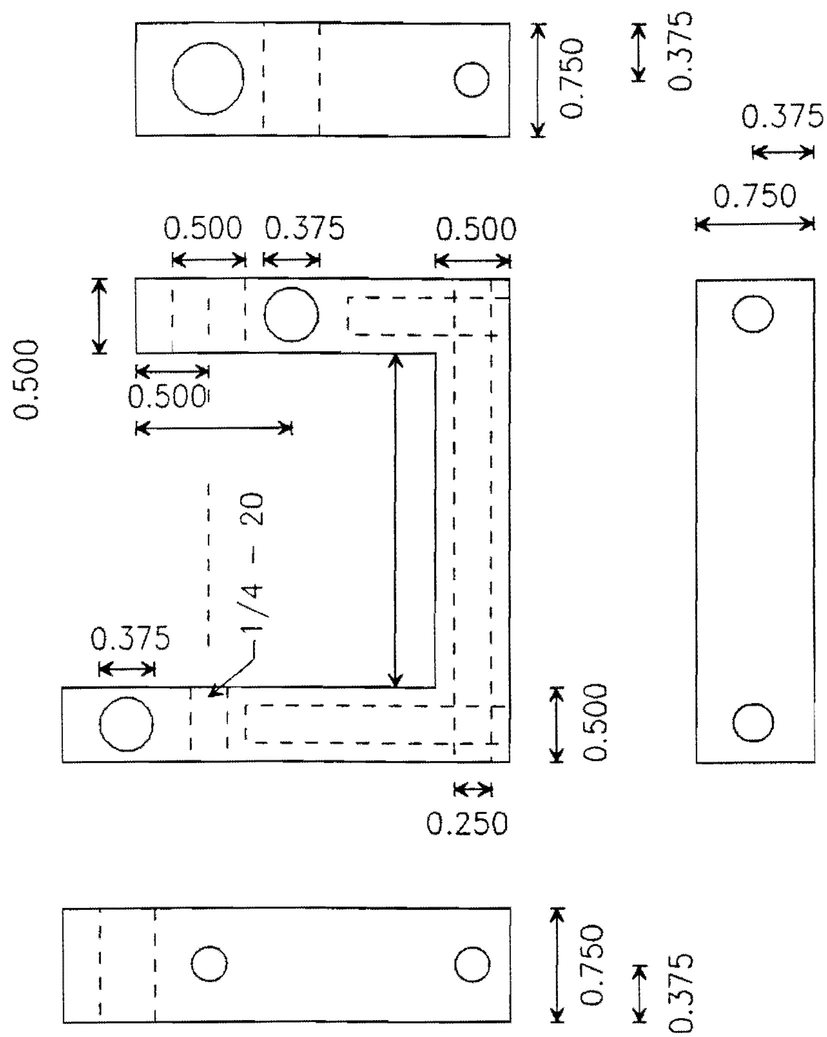


Yoke assembly

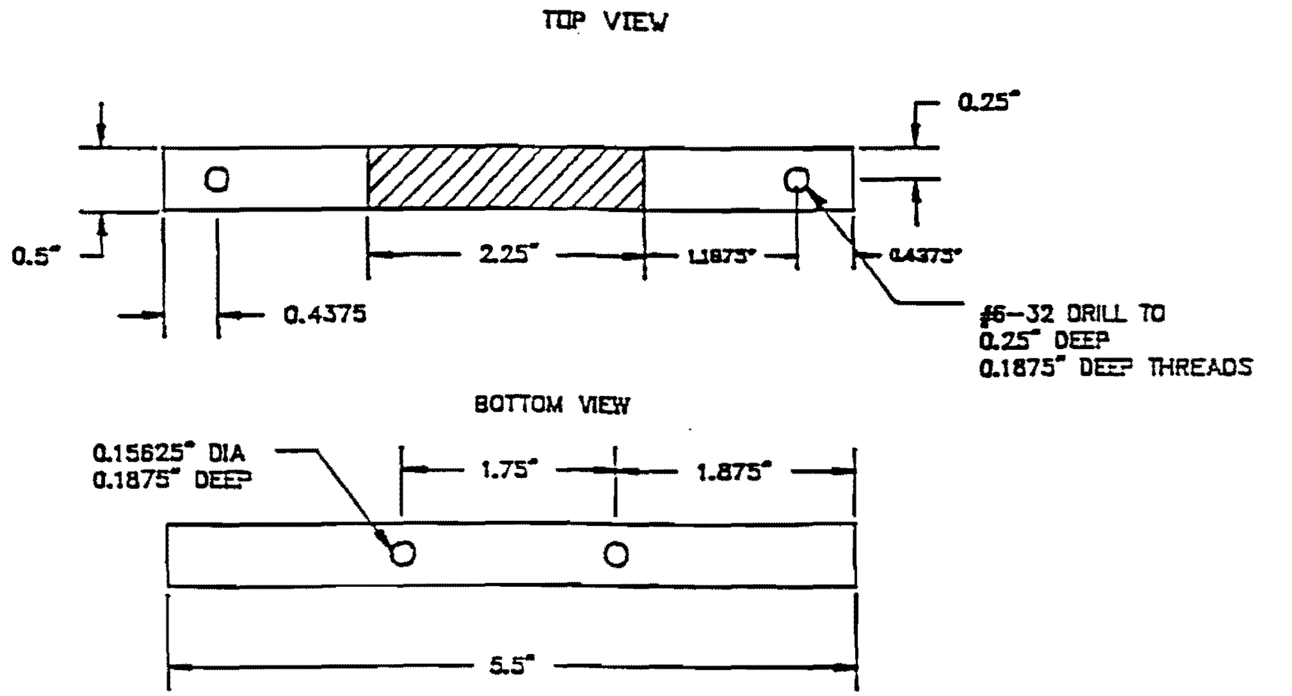


Note: Moments acting at vertical moment arms caused by LVDT spring forces exactly cancel.
A small horizontal shear stress at the contact disk due to the spring and a small vertical shear stress at the disk due to the weight of the support yoke assembly must be resisted by friction at the disk/asphalt interface. The LVDT springs were removed during the test program to decrease the horizontal shear stresses.

Yoke
Material: Aluminum
Quantity: 2

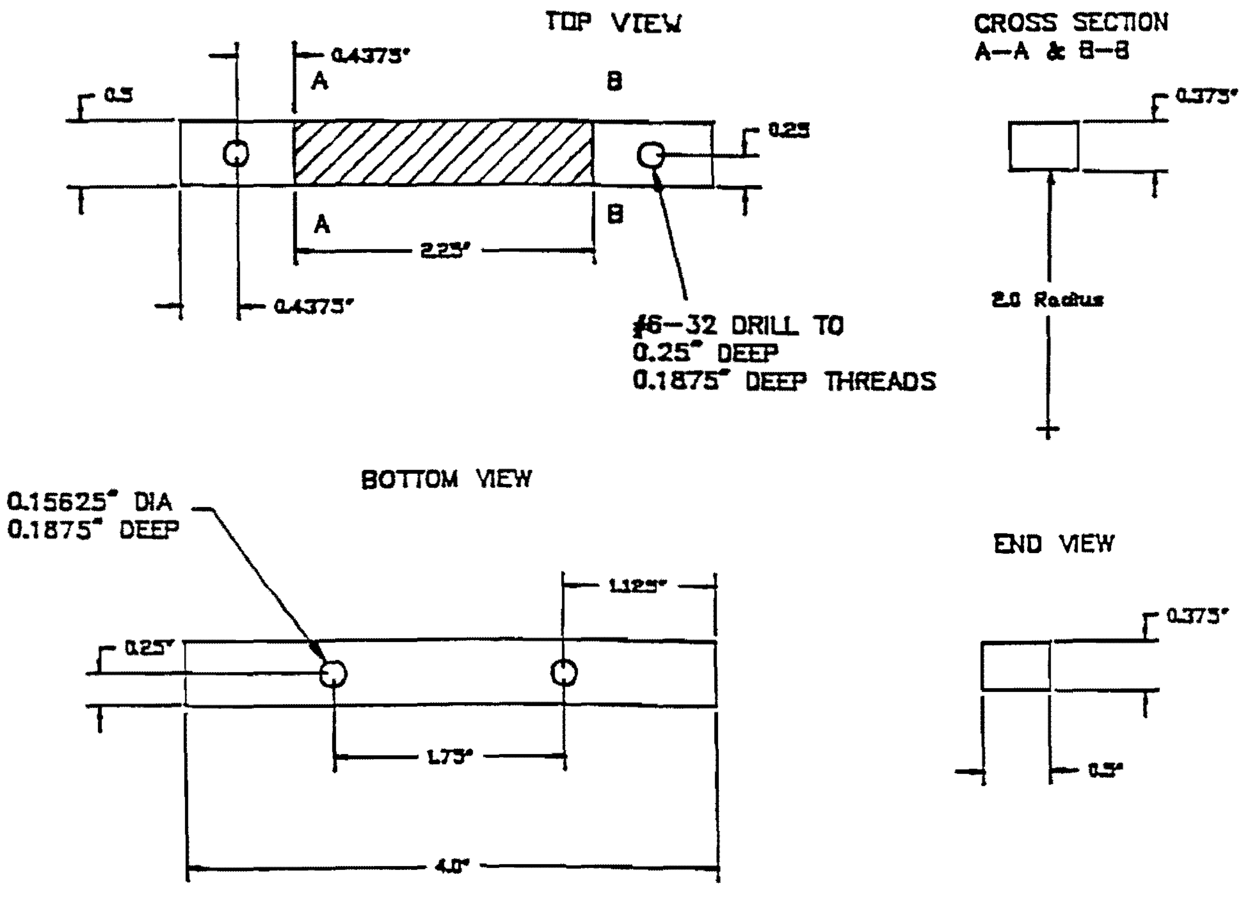


LOADING/GAUGING STRIP (LONG)



MATERIAL: STAINLESS STEEL QUANTITY: 4

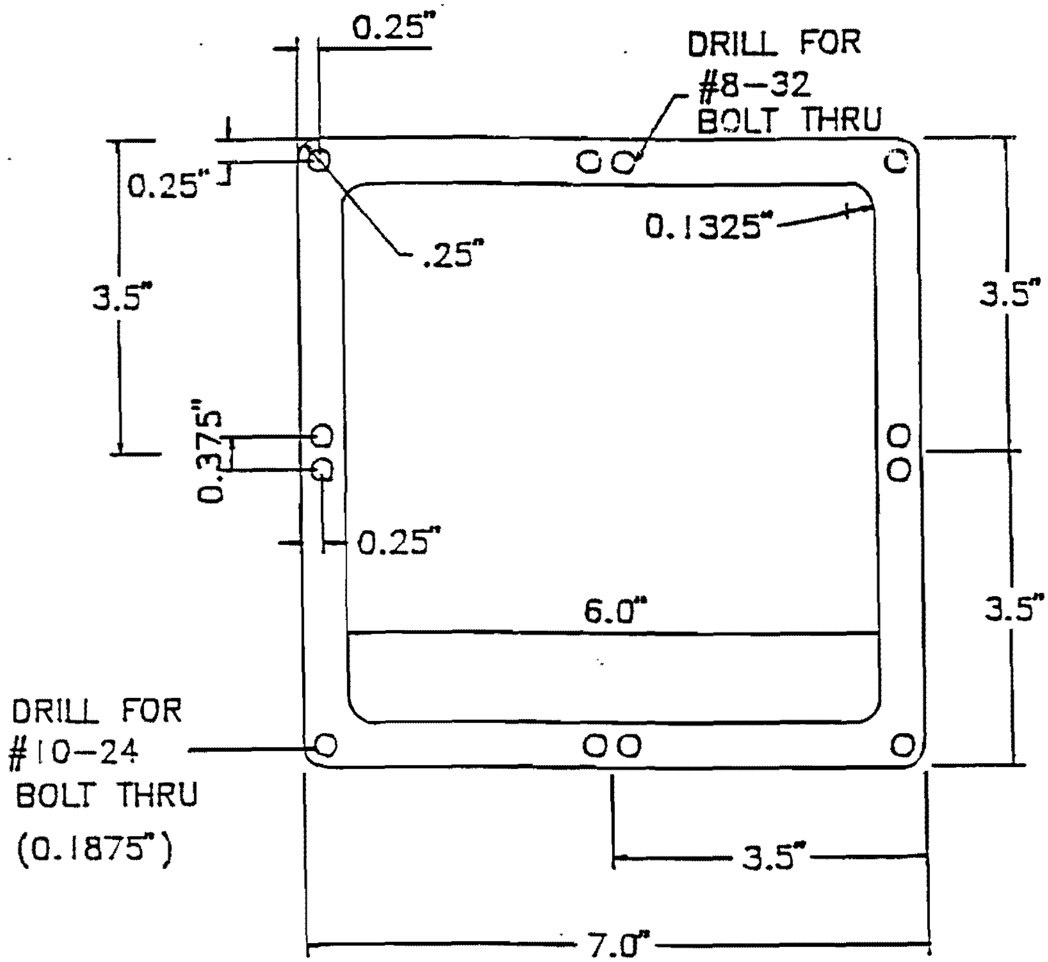
LOADING/GAUGING STRIP (SHORT)



MATERIAL: STAINLESS STEEL QUANTITY: 4

GAUGING/LOADING STRIP ALIGNMENT FRAME

TOP PLATE (TOP VIEW)

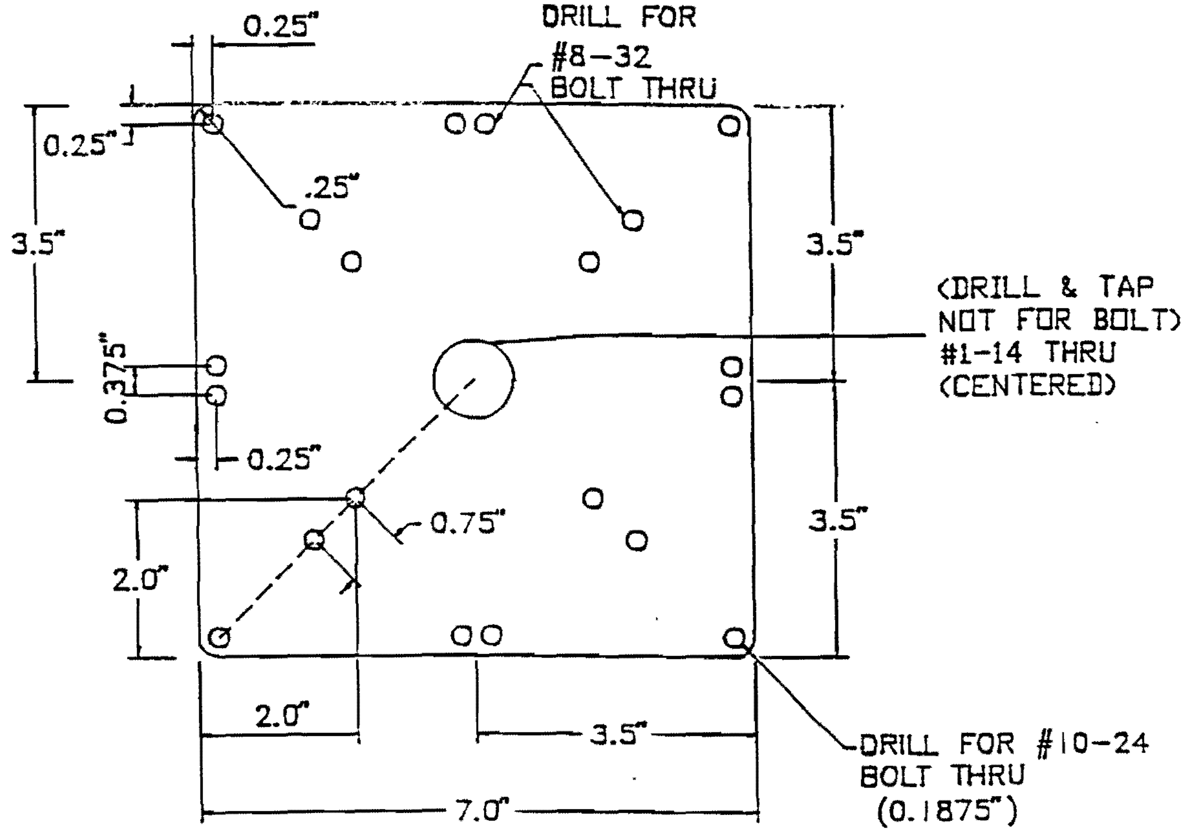


ALL BOLTS ARE ALLEN
HEAD AND RECESSED
INTO TOP SIDE
OF PLATE

MATERIAL:
1/2" ALUMINUM SHEET

GAUGING/LOADING STRIP ALIGNMENT FRAME

BOTTOM PLATE (TOP VIEW)

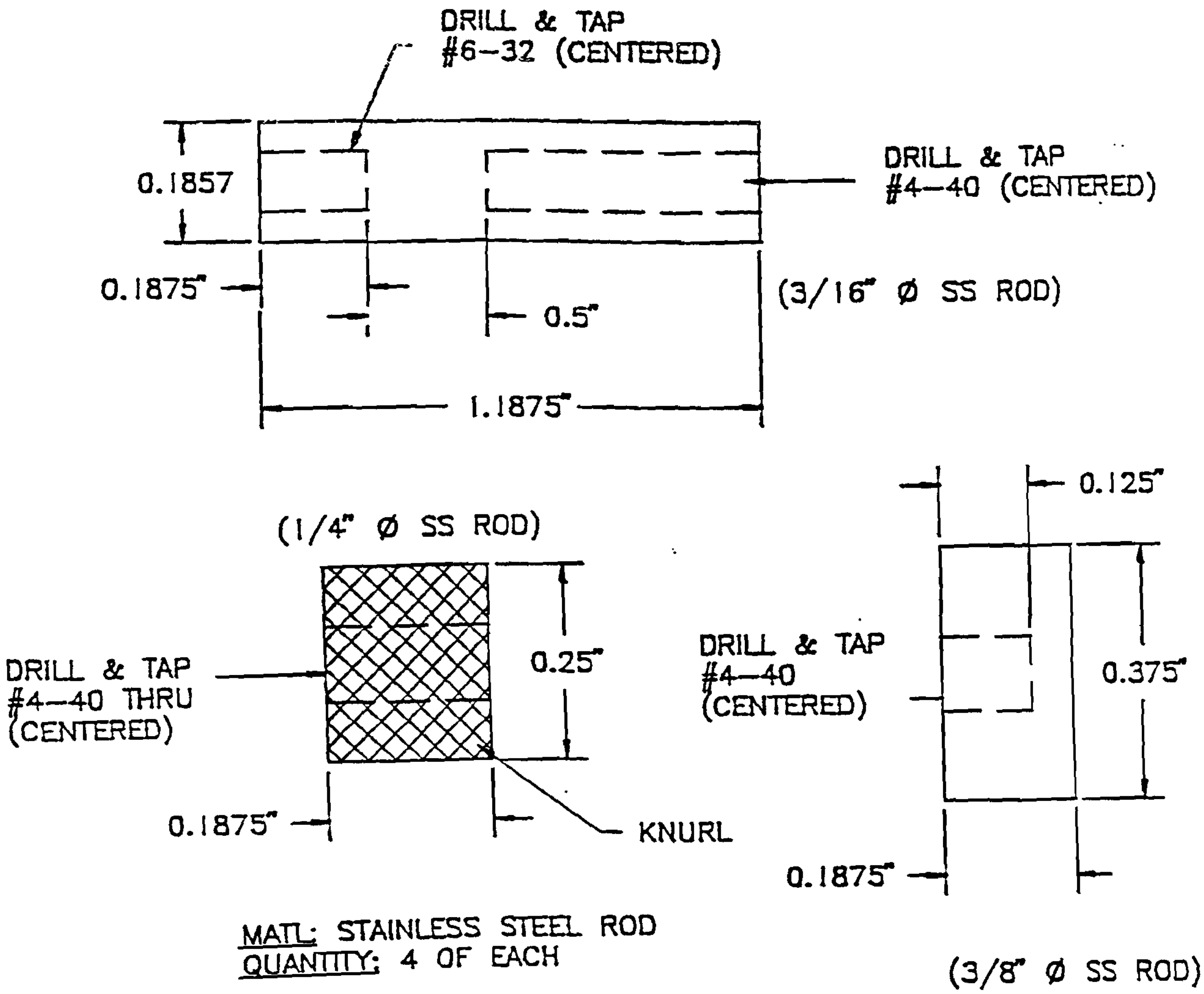


ALL BOLTS ARE ALLEN HEAD AND RECESSED INTO UNDERSIDE OF PLATE

MATERIAL:
1/2" ALUMINUM SHEET

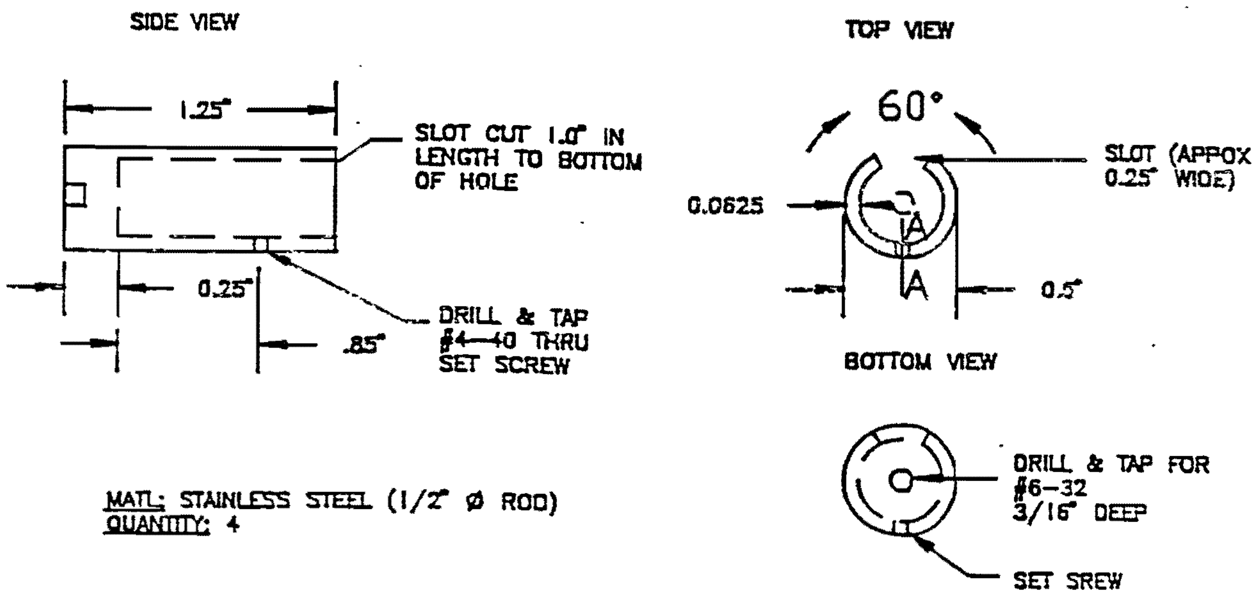
LVDT REFERENCE ROD ASSEMBLY PARTS

(SIDE VIEWS)



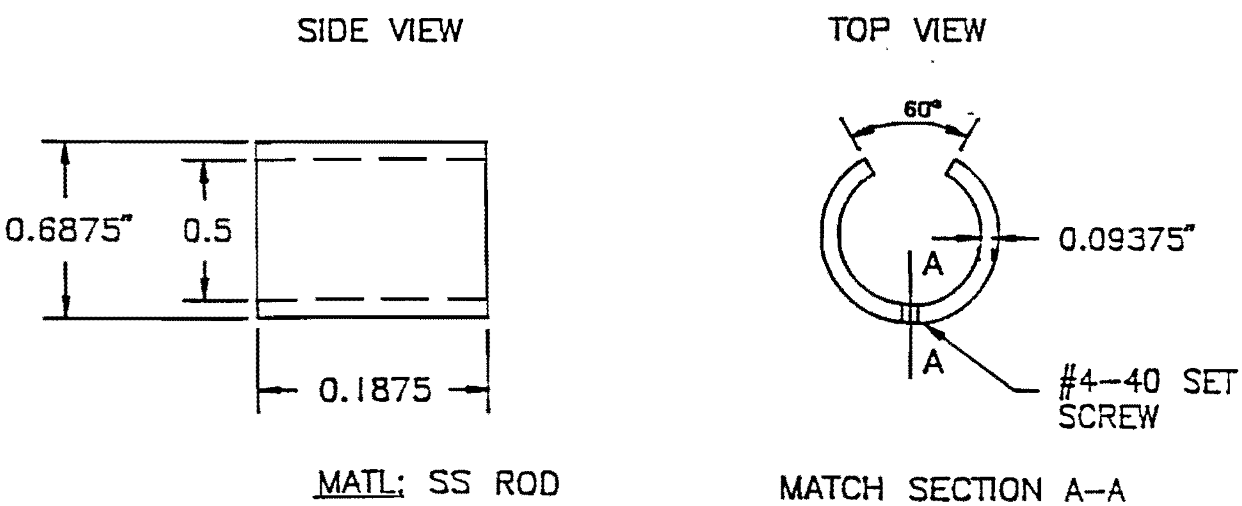
MATL: STAINLESS STEEL ROD
QUANTITY: 4 OF EACH

LVDT CLAMP/HOLDER

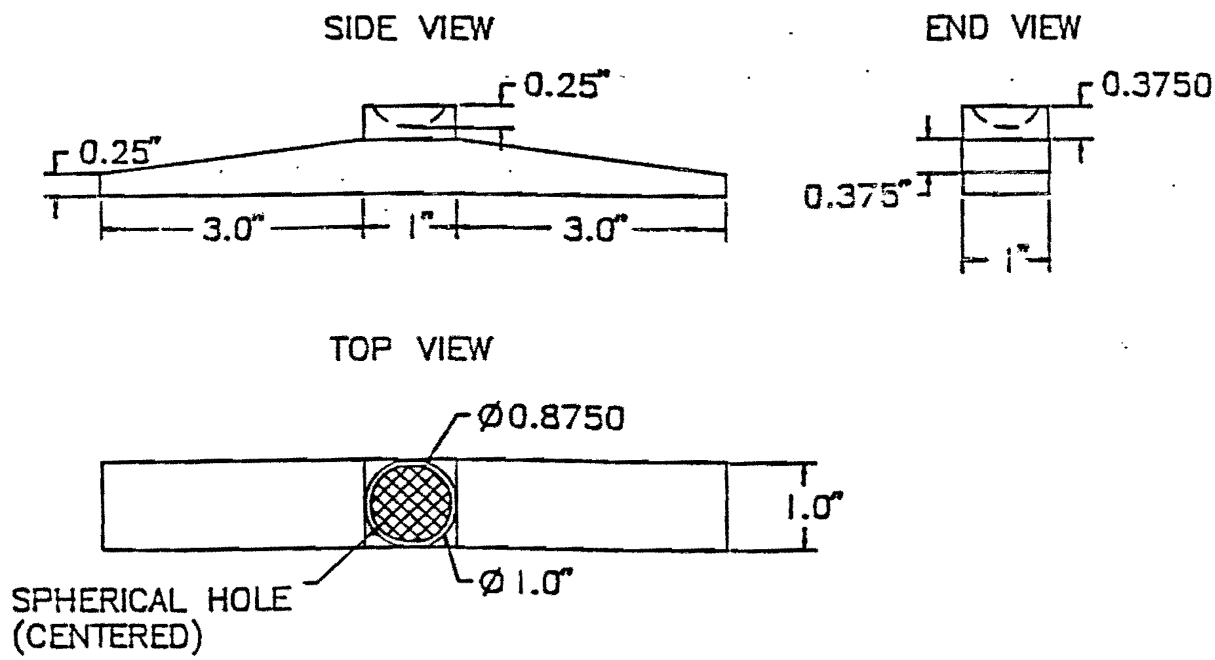


RETAINER RING

(To be sholdered over clamp/holder before drilling & tapping #4-40 set screw)

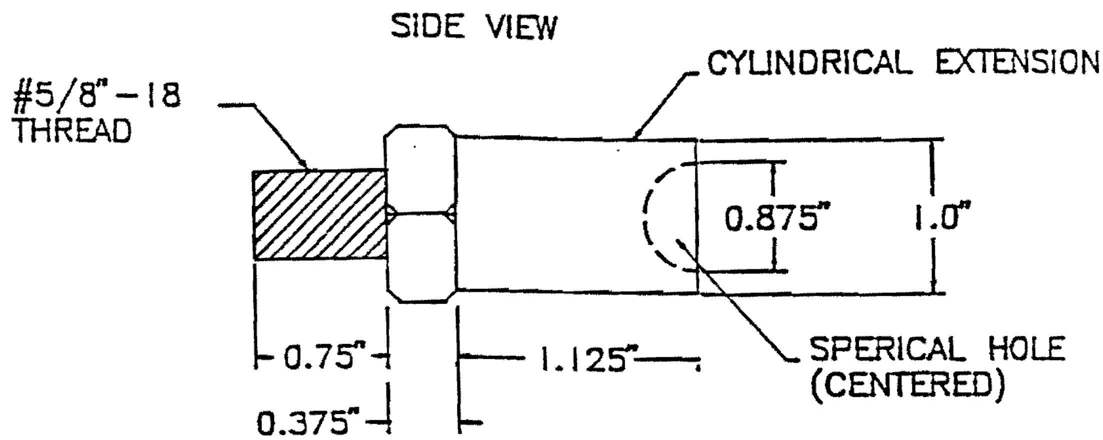


LOADING BLOCK



MATL: 1 1/4"X1 1/4" STAINLESS STEEL BAR

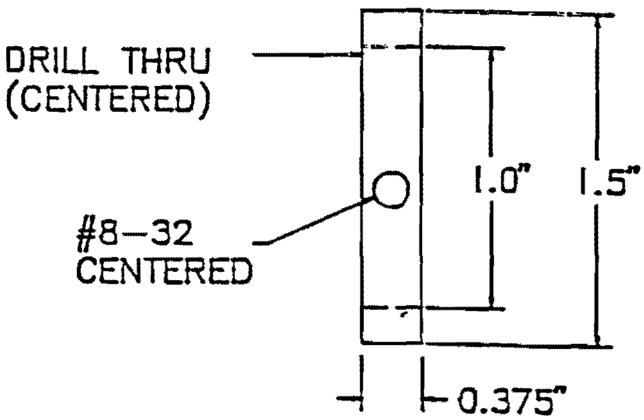
SWIVEL ATTACHMENT



MATL: 1 1/4" STAINLESS STEEL HEX BAR

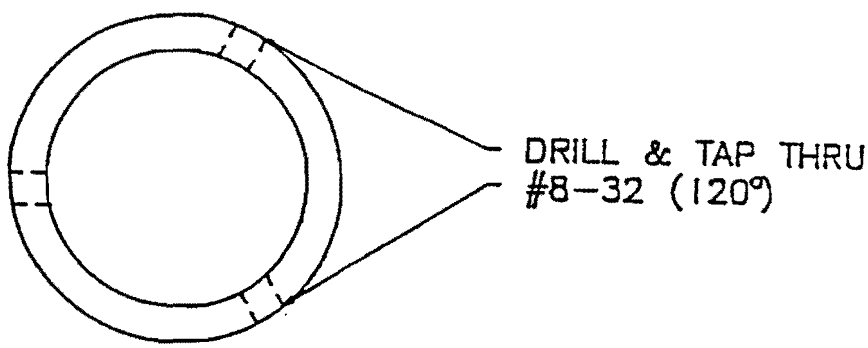
COLLAR

SIDE VIEW



MATL: 1.5" OR 2.0" Ø SS ROD   QUANTITY: 2

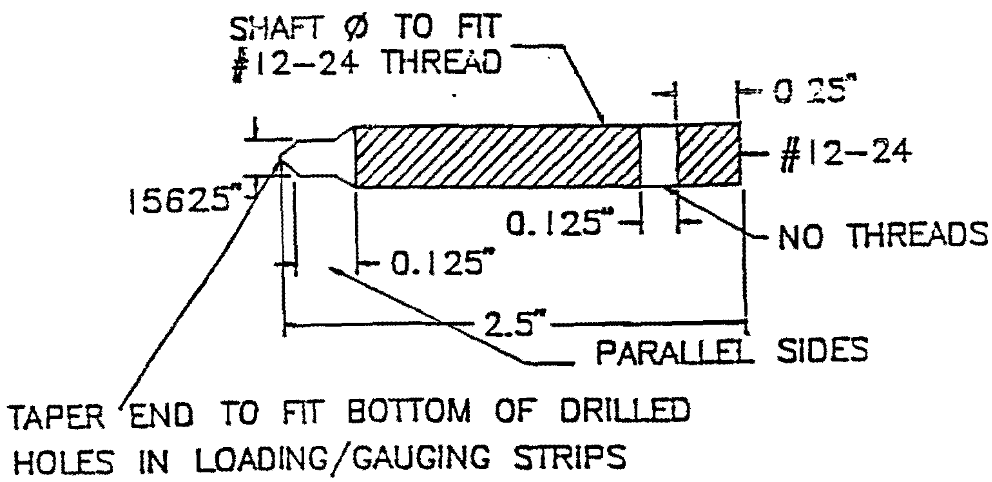
TOP VIEW



GAUGING/ALIGNMENT PINS

THREADED SHAFT

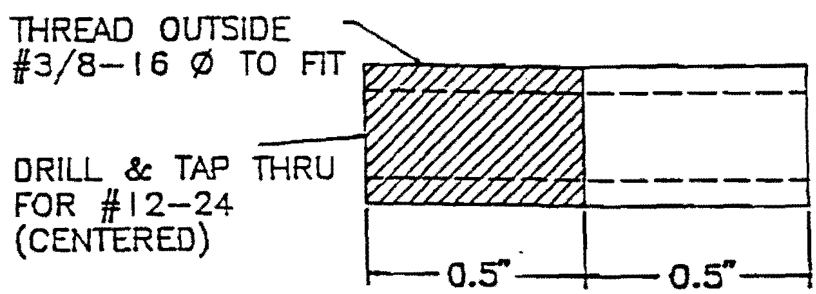
SIDE VIEW



MATL: 3/16" Ø SS ROD QUANTITY: 8

ALIGNMENT PIN COLLAR

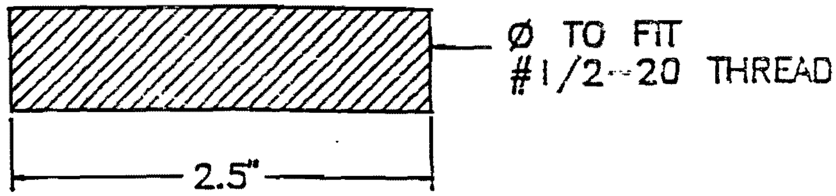
SIDE VIEW



MATL: 3/8" Ø SS ROD QUANTITY: 8

HEIGHT ADJUSTMENT THREADED SHAFT

SIDE VIEW

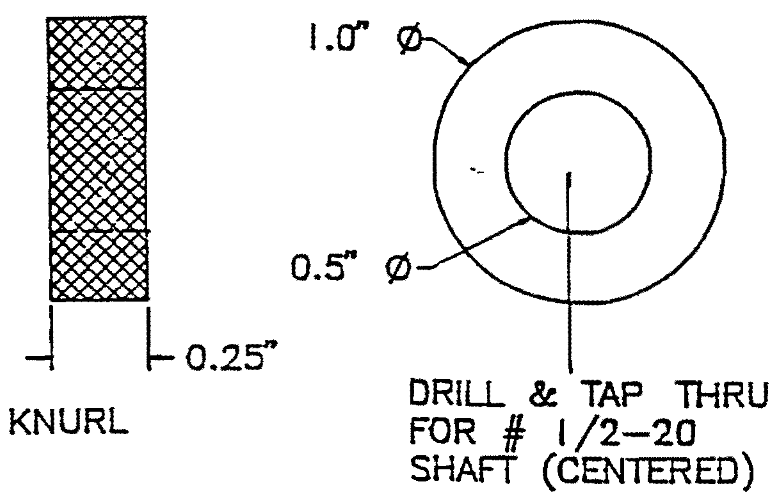


MATL: 1/2" Ø SS ROD

LOCK NUT

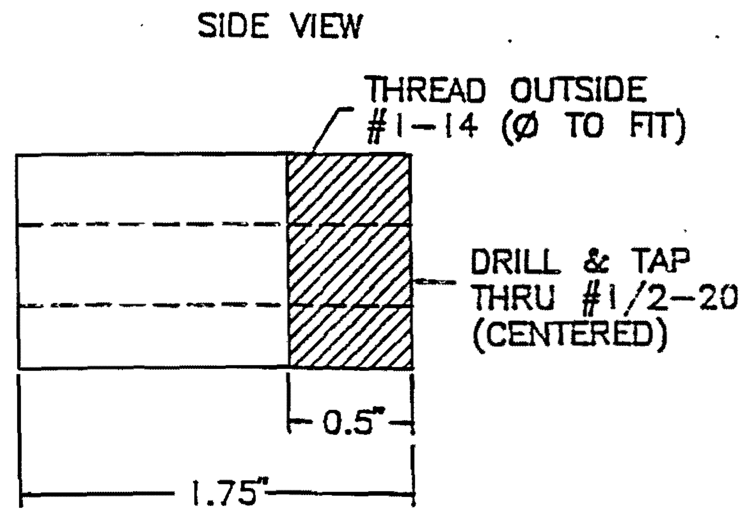
SIDE VIEW

FRONT VIEW



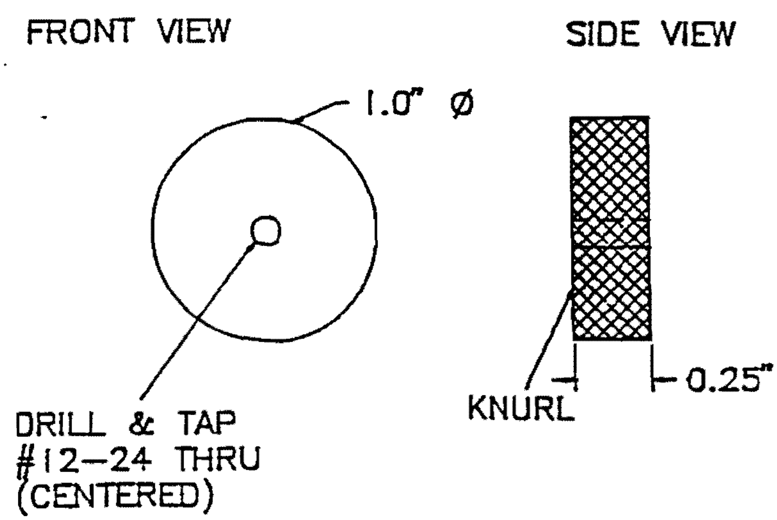
MATL: 1.0" Ø SS ROD QUANTITY: 2

HEIGHT ADJUSTMENT THREADED COLLAR



MATL: 1.0" Ø SS ROD

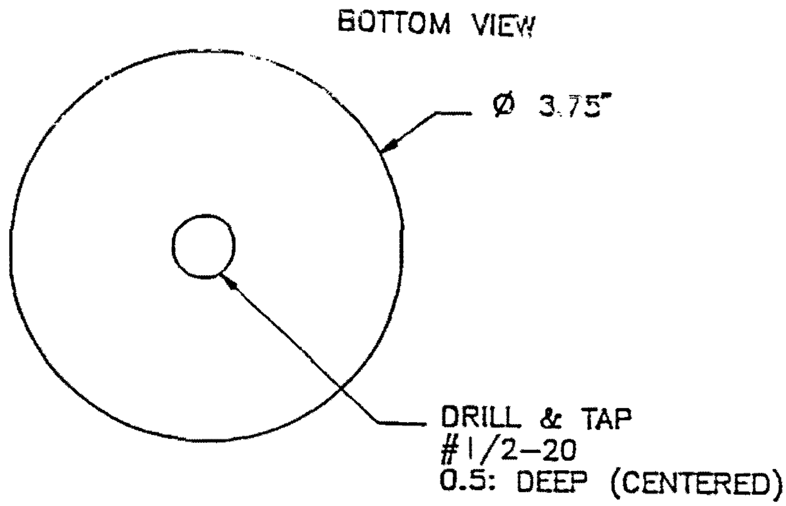
KNURLED KNOB



MATL: 1.0" Ø Stainless steel rod

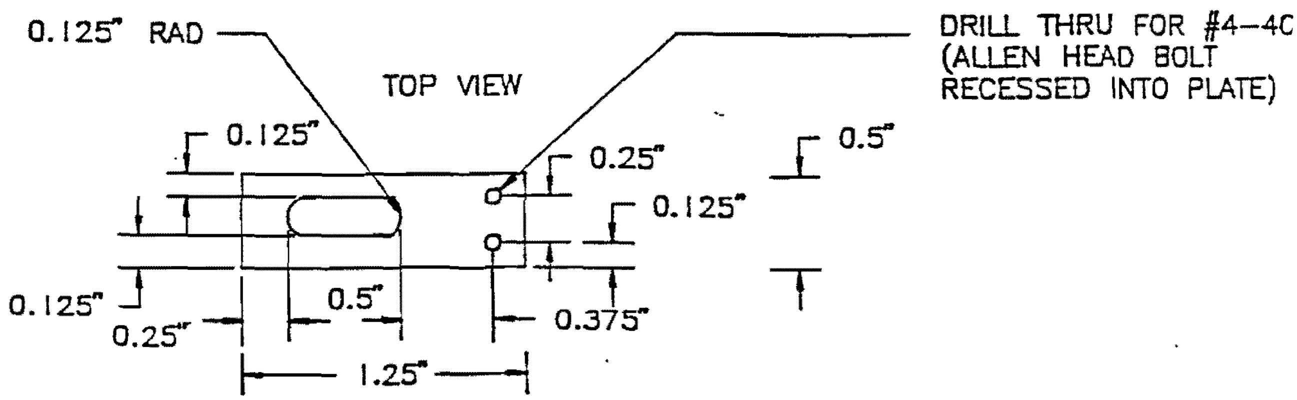
QUANTITY: 8

SPECIMEN BASE PLATTEN



MATL: 3/4" THICK AL SHEET

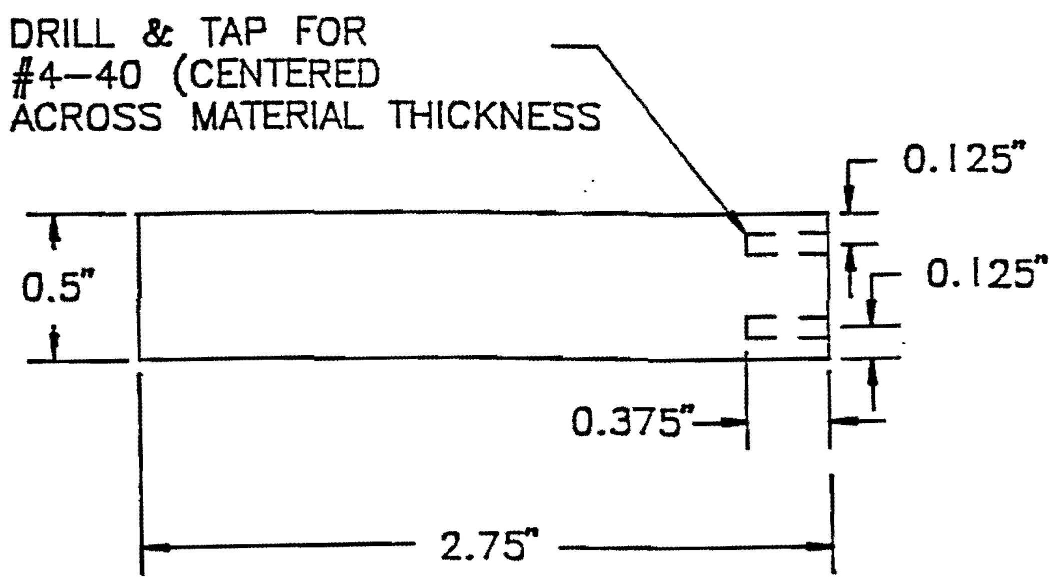
SLIDE PLATE



MATL: 1/4" THICK AL SHEET   QUANTITY: 4

ALIGNMENT REFERENCING SLIDE

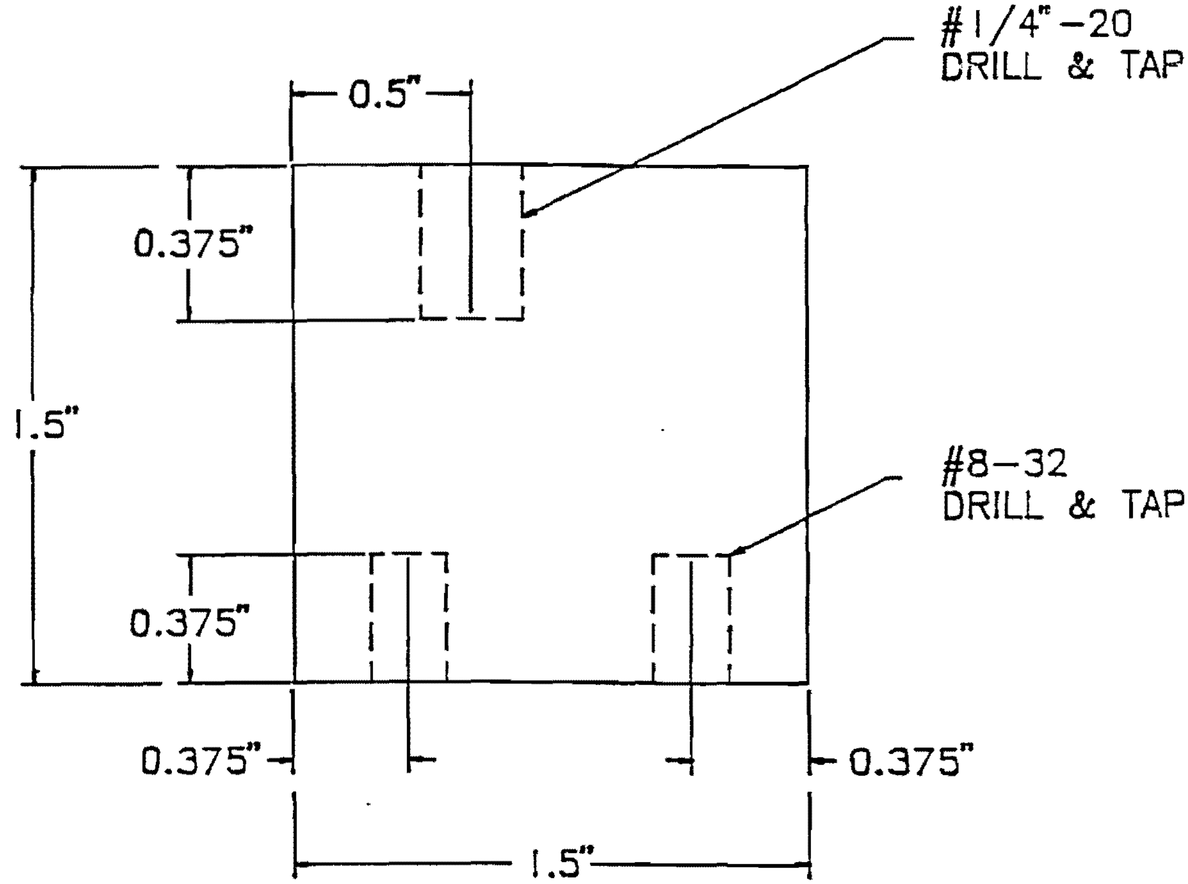
GUIDE BAR FRONT VIEW



MATL: 1/4" THICK AL SHEET QUANTITY: 4

ALIGNMENT SUPPORT BLOCK

SIDE VIEW

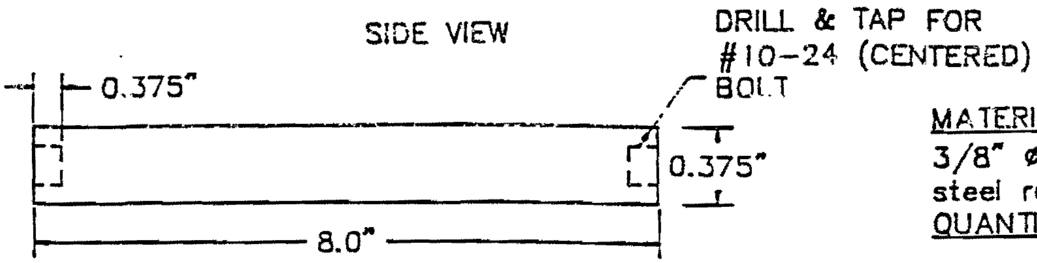


MATL: 1/2" THICK
AL SHEET

QUANTITY:4

SUPPORT RODS

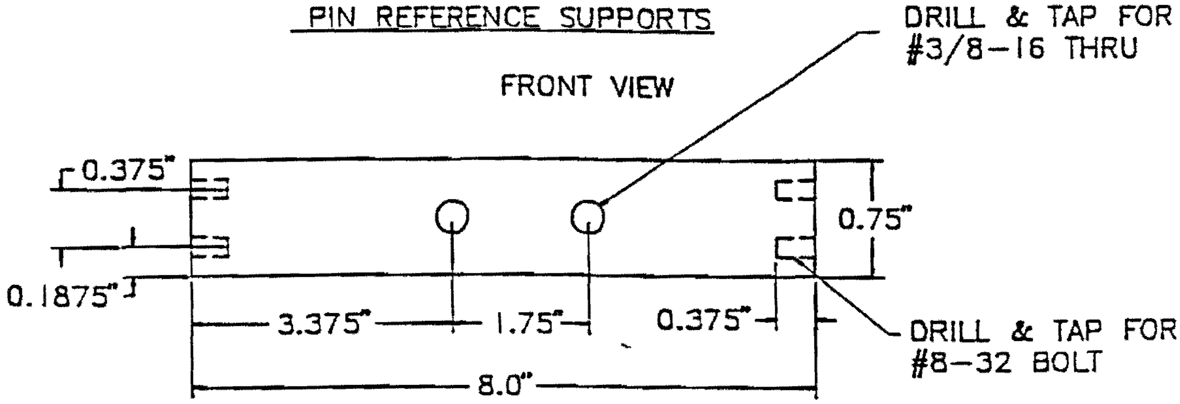
SIDE VIEW



MATERIAL:
3/8" ¢ Stainless
steel rod
QUANTITY: 4

PIN REFERENCE SUPPORTS

FRONT VIEW



MATL: 1/2" THICK
AL SHEET
QUANTITY:4

NOTE:

ALL HOLES CENTERED ACROSS
MATERIAL THICKNESS