DETERMINATION OF RESILIENT MODULUS AND ESTIMATION OF LAYER COEFFICIENTS FOR ASPHALT CONCRETE MIXES

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CHAPTER I

INTRODUCTION

Problem Statement

The characterization of highway construction materials is one of the most important factors in pavement design and analysis. The 1986 American Association of State Highway Officials (AASHTO) Guide for the Design of Pavement Structures uses the resilient modulus of the support and surface layers as a design input. The resilient modulus, a stress/strain relationship determined from a repeated load, is also used to estimate AASHTO layer coefficients. Layer coefficients are a measure of the relative ability of the material to function as a structural component of the pavements (1-3). The performance of flexible pavements is directly related to the stress, strain, and displacements calculated using elastic layer theory. Material properties are generally obtained from laboratory testing which attempts to simulate "in service" conditions as closely as possible. The resilient modulus essentially incorporates all the elements of elastic layer theory in a single laboratory based test.

At the "Workshop on Resilient Modulus Testing" held at Oregon State University in March 1989, the consensus among pavement engineers was that the standard procedure for determining the resilient modulus (ASTM D 4123), is unnecessarily time consuming and that the test results are difficult to reproduce. A recent survey of state transportation agencies showed that approximately 45 percent of these agencies now use the resilient modulus test to characterize asphalt concrete, base, subbase and subgrade materials. However, approximately 42 percent of the reporting agencies do not use the resilient modulus test because of its complexity (4). Therefore, development of a simplified resilient modulus test procedure or refinement of the existing procedure is warranted.

Current specifications for asphalt concrete (AC) mixes include several AC mixes which have maximum aggregate size of 1.5 inches (38.1 mm) to 2.5 inches (63.5 mm). The standard resilient modulus test procedure is not suitable for characterizing these materials because of aggregate size limitations. The test procedure requires that the laboratory or field compacted specimens, 4 inches (101.6 mm) in diameter, be loaded diametrally while elastic deformations are monitored on the perpendicular plane. The aggregate orientation within the specimen and the mold effects during compaction, can have a marked effect on the resilient modulus (M_R) value if the specimen size is less than four to six times the maximum aggregate size. In general, as the maximum aggregate size increases, the accuracy and repeatability of the M_R determinations decrease. Wallace and Monismith (5) concluded that 80% of the diametral tension occurs within the inner 2.5 inches (63.5 mm) of a 4 inch (101.6 mm) diameter specimen. Hence, there is a need to define the specimen size requirements with regards to the aggregate size and the reproducibility of the test.

Standard laboratory compaction techniques, including the Texas gyratory shear and the Marshall hammer, can be used to produce 4 inch (101.6 mm) diameter specimens. Modified gyratory shear and Marshall compaction techniques can be used to prepare 6 inch (152.4 mm) diameter specimens. Due to the large aggregate sizes evaluated in this study, development of a laboratory compaction apparatus suitable for preparing 4 inch (101.6 mm), 6 inch (152.4 mm), and 8 inch (203.2 mm) diameter specimens was required.

Objectives

The objectives of this study are:

1. To design and construct a laboratory compaction apparatus to facilitate specimen preparation of mixes containing aggregates up to 2.5 inches (63.5 mm).
2. To modify the existing resilient modulus test procedure to permit convenient testing of asphalt concrete mixes with "larger" aggregates.
3. To reduce the complexities of the existing resilient

modulus test procedure.

4. To determine the resilient modulus of selected AC mixes as specified by the Oklahoma Department of Transportation.
5. To estimate AASHTO structural layer coefficients using laboratory resilient modulus values.

Scope of Work

The scope of work included the determination of the resilient modulus for five sources of Oklahoma Department of Transportation (ODOT) type "B" mix, three sources of type "A" mix, and one source of type "G" mix. The differentiation of mixes is based on the gradation specification of the aggregates. Table 1 shows the gradation specification for A, B, and G mixes. Aggregates were supplied by ODOT from various project sites. Type "B" asphalt concrete specimens were prepared using the Texas gyratory shear, Marshall compaction hammer, and the dynamic compaction apparatus developed for this study. Type "A" and "G" asphalt concrete specimens were prepared using the dynamic compaction apparatus. A single source asphalt cement was used to prepare all specimens. Mix design data from the projects were used to obtain the optimum asphalt content for specimen preparation. The resilient modulus tests were performed in accordance with the recommendations of the Strategic Highway Research Program, dated July 1991

(6). All other tests were performed according to the appropriate standard test methods established by American Society of Testing and Minerals (ASTM) or AASHTO. All tests were performed at the Oklahoma State University Highway Materials laboratories.

CHAPTER II

LITERATURE REVIEW

An Overview of Resilient Modulus

Background

Asphalt concrete is a viscoelastic material. It exhibits elastic as well as viscous (time and temperature dependent) response to imposed loads. A material is said to be perfectly elastic if strains appear and disappear immediately on application and removal of stress. A perfectly linear elastic material can be characterized by two constants: modulus of elasticity and Poisson's ratio. In order to characterize viscoelastic materials, the modulus of elasticity, Poisson's ratio, and a time dependent term are required. Although asphalt concrete exhibits viscoelastic behavior, after the application of repeated stress, its behavior can be considered elastic if sufficient time is allowed between the stress repetitions for strain recovery.

Several procedures are used to determine the moduli of asphalt concrete including Young's modulus, resilient modulus (M_R), complex modulus, and dynamic modulus. The resilient modulus as measured in the indirect tensile mode

(ASTM D 4123), is the most popular form of stress/strain measurement used to characterize the elastic properties of asphalt concrete. Resilient modulus (M_R) is analogous to the modulus of elasticity (E) for asphalt concrete. However, the resilient modulus is determined from a repeated load test while the elastic modulus is typically determined from a single load cycle. Peak values of stress and recoverable (elastic) deformation occurring in the resilient modulus test are used to calculate an M_R value. The magnitude and load frequency in the M_R test are designed to closely approximate the dynamic loads induced by moving wheel loads on pavement structures. Repeated load indirect diametral tension tests are most frequently used to determine the resilient modulus of asphalt concrete in the laboratory.

Repeated Load

Highway traffic results in the application of rapidly applied stress pulses of varying magnitude. These stresses are distributed to each element within the surface and support layers. Barksdale (7) studied the compressive stress pulse times in flexible pavement and concluded that for moderate vehicle speeds, the stress pulse ranges from approximately 0.02 to 0.4 seconds. The pulse time increases with increasing depth below the pavement surface and decreasing vehicle speeds. Near the surface, the stress pulse has a pronounced haversine shape. Appropriate stress pulse times can be estimated using Figure 1. With increasing depth, the pulse duration becomes greater, and although it remains haversine in shape, a triangular loading gives a reasonably good approximation (Figure 2).

Pavement materials are subjected to distinct load pulses. It is desirable to have a test capable of duplicating this condition in the laboratory. The repeated load test has, for many years, been used to simulate the dynamic loading induced by highway vehicles. Repeated load tests use a series of load pulses separated by distinct rest periods (Figure 3). A rest interval between load pulses occurs in a pavement structure since the applied loads are separated by a finite period of time. The repeated load test concept can be incorporated into many conventional static tests such as diametral, triaxial, beam bending, and simple shear tests.

Significance of Resilient Modulus

A study of the AASHTO Pavement Design procedure and the concept of resilient modulus by Elliot and Thorton (8) concluded that resilient modulus is a fundamental material property that relates to pavement design and performance in the same manner as surface deflection relates to pavement design and performance. The resilient modulus provides a measure of the load induced stress-strain behavior, which governs the load response of the pavement system.

The AASHTO equation for the design of flexible pavements is as follows :

$$\text{Log}(W_{18}) = Z_R{*}S_o + 9.36\text{Log}(SN+1) - 0.20 + 2.32\text{Log}(M_R) + \text{Log}[(PSI/(4.2-1.5))/0.4+(1094/(SN+1)^{5.19})]$$

where:

M_R = Resilient Modulus (psi)

W_{18} = Predicted number of 18-Kip equivalent single axle load applications

S_o = Overall standard deviation

Z_R = Standard normal deviate associated with a selected reliability.

SN = Design structural number

PSI = Design serviceability loss

The structural number represents the required strength of a pavement for a given combination of soil support, traffic, loss of serviceability and environment. The structural number is a function of layer coefficients, layer thicknesses, and layer drainage coefficients. The structural number can be expressed as:

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3$$

where: a_i = layer coefficient for the ith layer,

D_i = layer thickness for the ith layer, and

m_i = drainage coefficient for the ith layer.

Layer coefficients are directly related to the resilient moduli and can be expressed as:

$$a_i = AM_R^B$$

where A and B are experimentally derived regression constants. An unknown layer coefficient (a_i) can also be estimated using a known coefficient (a_{ref}) through a ratio of resilient modulus values:

$$a_i = a_{ref}[M_{Ri}/M_{Rref}]^B$$

Practical Approach to Determine Resilient Modulus

The determination of resilient modulus of asphalt concrete has utilized various types of repeated load tests. The most commonly used tests are:

1. uniaxial tension test,
2. uniaxial compression test,
3. beam flexure (bending or rotating cantilever) test,
4. indirect diametral tension test, and
5. triaxial compression test.

Schmidt (9) compared the resilient modulus of asphalt concrete specimens using direct tension, compression, flexural, and repeated load indirect diametral methods. It was shown that the resilient modulus values obtained by the repeated load indirect diametral test compared favorably with those obtained from the other three tests (Figure 4).

The advantages of the indirect tensile strength test as concluded by many researchers (10-15) are summarized below:

1. The test is relatively simple.
2. The testing equipment and the post test specimens can be used for other tests.
3. The modulus values compare favorably with the values obtained from other repeated load tests.
4. The test is not overly effected by the surface conditions of a specimen.
5. A specimen can be tested across various diameters, and the results can be used to determine homogeneity of the specimen.

The main disadvantage of this test is its failure to fully simulate loading conditions in practice.

The indirect tensile test was developed simultaneously, but independently, in Brazil and Japan (16). The test involves diametral loading of a cylindrical specimen with compressive loads distributed along the thickness of the specimen. This loading condition creates a relatively uniform tensile stress distribution perpendicular to and along the diametral plane which contains the applied load. Failure usually occurs by splitting along the loaded plane (Figures 5 and 6). The theory of stress distribution was originally developed by Hertz for line loads and later modified by Hondros to account for distribution of loads over strips of finite width (17).

Wallace and Monismith (5) conducted tests on asphalt concrete cores subjected to long term traffic loading. They concluded that as a result of placement and compaction, the material was approximately twice as stiff in the radial direction as in the vertical direction. An asphalt layer of typical thickness is subjected to bending action which is primarily influenced by the radial rather than the vertical stiffness of the asphalt layer. Therefore, for vertical cores taken from the pavement or for laboratory molded specimens, the diametral test or flexural bending test should give a relevant assessment of the stiffness of the asphalt layer.

A study of "Resilient Characteristics of Asphalt Mixtures" by Adedimila and Kennedy (18) concluded that the indirect tensile test is suitable for the study of repeated load characteristics of asphalt mixtures.

A similar study by Gonzalez, Kennedy, and Anagnos (19) concluded that the resilient modulus of asphalt concrete, as tested by repeated load indirect tensile tests, should be used in pavement design procedures requiring elastic properties. In addition, an estimate of resilient modulus can be obtained without conducting a long term repeated load test. Reasonable estimates of the modulus can be obtained after approximately one percent of the fatigue life, but not less than twenty five load applications.

Standard Test Procedure

The standard test procedure for determining the resilient modulus of asphalt concrete is given by ASTM Method D 4123 82 (20). The Strategic Highway Research Program (SHRP) is currently investigating resilient modulus test procedures and conditions in order to improve the standardized test (6). A comparison between ASTM D 4123 and SHRP Protocol P07, July 1991, is summarized below:

Testing machine

ASTM: The test machine should have the capability of applying a load pulse over a range of frequencies, load duration, and load levels. Either an electro-hydraulic or an electro-pneumatic machine can be used.

SHRP: The test machine shall be a top-loading, closed loop machine (electro-hydraulic) with a function generator capable of applying a haversine load pulse over a range of load durations, levels, and rest periods.

Recommended Temperatures

ASTM: 41, 77 (or ambient laboratory temperature) & 104°F (5, 25 and 40°C).

SHRP: 41, 77, and 104°F (5, 25 and 40°C).

Recommended load for testing and preconditioning

ASTM: 10 to 50% of indirect tensile strength.

SHRP: 30%, 15%, and 5% of indirect tensile strength for test temperatures of 41, 77, and 104°F (5, 25 and 40°C) respectively.

Axes of Loading

ASTM: Specimens to be tested along two perpendicular axes.

SHRP: Specimens to be tested along two axes oriented 45° to one another.

Wave form

ASTM: Haversine or suitable waveform.

SHRP: Haversine.

Loading pattern

ASTM: Load duration: 0.1 to 0.4 seconds, frequency of load: 0.33, 0.5, and 1 Hertz.

SHRP: Load duration 0.1 seconds, rest periods 0.9, 1.9, and 2.9 seconds.

Period of preconditioning

ASTM: Precondition until the measured deformations are constant.

SHRP: Precondition until a minimum of 10 successive readings of horizontal deformation are within 10 percent.

Expected load repetitions

ASTM: A minimum of 50 to 200 load repetitions is typical.

SHRP: Expected ranges are 50-150, 50-100, and 20-50 for 41, 77, and 104°F (5, 25 and 40°C) respectively.

Number of Load cycles for M_R determination

ASTM: Following stable repeated elastic deformations, the average horizontal and vertical deformations should be measured over a minimum of three load cycles.

SHRP: A minimum of 30 load pulses are applied. The load pulses are continued until the horizontal deformation for five successive loads is less than 10% of the average. M_R is the average of the M_R values measured individually from 5 load cycles after the deformations are stabilized.

Poisson's ratio

ASTM: A Poisson's ratio of 0.35 is suggested as a representative value at 77°F (25°C).

SHRP: Poisson's ratios of 0.2, 0.35, and 0.5 are assumed for temperatures 41, 77, and 104°F (5, 25 and 40°C) respectively.

Test sequence

ASTM: Testing is initiated at the lowest temperature, shortest load duration, and smallest load. The test sequence should be so as to provide progressively lower moduli.

SHRP: The initial testing is performed at 41°F ($5^{\circ}C$) and 0.9 seconds rest period. The rest period is then changed to 1.9 seconds and finally to 2.9 seconds. After the testing is completed for the first axis, the same sequence is repeated for the second axis. Subsequent tests are then conducted in the same sequence at 77 and 104°F (25 & 40°C).

Relationships Between Resilient Modulus and Conventional Asphalt Concrete Properties

A study by Doty and Scrimsher (21) considered the relationship of Hveem stability, cohesion, and specific gravity with the resilient modulus of dense graded asphalt concrete mixes. The residual viscosity graded asphalts AR-2000 and AR-4000 obtained from three different sources were combined with three different aggregate gradations. A California kneading compactor was used to fabricate 2 1/2 inches (6.35 cm) high by 4 inch (10.16 cm) diameter specimens. The resilient modulus was determined using a pulsed load of 0.1 second duration and a load cycle duration of 3 seconds. The test temperatures ranged from 72 to 76°F. Following the resilient modulus test, the specimens were heated to 140°F (40°C) and tested for Hveem stability, cohesion, and specific gravity. Doty and Scrimsher discussed the effect of mix components, compaction method (static, Marshall, and Kneading), compaction temperature, temperature susceptibility of asphalt cement, and test temperature on the resilient modulus of the test specimens. In addition, the authors briefly discussed the relationship between resilient modulus and fatigue resistance. The results of this study showed that the resilient modulus of the mixes increased with Hveem stability and/or specific gravity. However, the authors concluded that the resilient modulus value can not be used to reliably determine optimum asphalt content from the standpoint of air voids, Hveem stability, or cohesion. They also concluded that the resilient modulus values measured at 72-76°F do not provide an accurate measure of asphalt concrete pavement fatigue resistance. However, a recent study by Kim et al (22) showed that the resilient modulus test can be used successfully to predict the fatigue life of asphalt concrete. Their findings also show an agreement with historical data indicating a correlation between fatigue life and air voids or asphalt content. An increase in air voids content shortens the fatigue life, while an increase in asphalt content improves the fatigue resistance.

A study by Almudaiheem and Alsugair (23) showed that an increase in asphalt content decreases the resilient modulus of asphalt concrete. The effect of loading magnitude is more pronounced at lower asphalt content.

Kemp and Predoehl (24) evaluated the durability of asphalt concrete mixes. In an attempt to evaluate the properties of non-aged and aged asphalt using resilient modulus, they have concluded that there was no definite relationship between the resilient modulus of test specimens and degree of aging. A similar study by Epps (25) supports their findings.

Resilient Modulus Test Aspects

Repeatability/Reproducibility: The repeatability of the resilient modulus test procedure found to be a significant problem. The precision of the ASTM D 4123 procedure has not been clearly established. Since pavement materials are non homogeneous and anisotropic, a relatively wide variance in test results can be expected. A study of test repeatability /reproducibility by Brown and Foo (26) considers three sources of variation in ASTM D 4123: a random error that occurs in the measurement of resilient modulus, an orientation error, and a specimen error. They concluded that the error due to specimen orientation was not significant. However, specimen variation was found to be the most important factor influencing the variation in resilient modulus values. Variation due to experimental error was also found to be significant.

Poisson's Ratio: Resilient modulus is a function of the specimen size, applied load, and Poisson's ratio. According to Monismith (27), a complex stress state exists in the diametral resilient modulus test. At elevated temperatures asphalt concrete is not an elastic material. Therefore the stress state will influence both horizontal and vertical deformations. Poisson's ratio can not be accurately determined if the horizontal and vertical deformations are subject to the stress state. Under these circumstances, it is suggested that the resilient modulus be determined by measuring the radial strains and assuming a value of Poisson's ratio.

Association with Pavement Distress: Flexible pavement structural section materials, including subgrade soils, exhibit various distress types and complex failure modes. In spite of the many studies that have developed models to predict fatigue and permanent deformation of flexible pavements, the degree to which resilient modulus is associated with pavement distress has yet to be determined. The resilient modulus value may not be an adequate indicator of the likelihood of pavement distress due to the complexity of flexible pavement systems.

Advantages of The Resilient Modulus Test

The resilient modulus test provides a means of evaluating paving materials under a variety of environmental conditions and states of stress. The test simulates the conditions that exist in pavements subjected to moving wheel loads. A study by Kim (28) summarized the advantages of the resilient modulus test as indicated below:

Dynamic Test: The resilient modulus test utilizes dynamic (cyclic) load applications. The load duration and load frequencies may be varied depending on the actual traffic conditions.

Nondestructive Test: The resilient modulus test is nondestructive. Additional tests can be performed on the previously tested specimens to assess the effects of curing, aging, and temperature or moisture conditioning. The resilient modulus test can be used in conjunction with other conventional destructive tests.

Use in Mechanistic/Elastic Design of Pavements: The resilient modulus test provides the basic constitutive relationship between the load and deformation of flexible pavements materials for use in the structural analysis of layered pavements systems.

Supplement to Conventional Tests: Conventional tests are not always suitable for characterizing some "new" pavement materials including asphalt concrete mixes with aggregates having a maximum aggregate size of up to 2.5 inches (6.35 cm). The resilient modulus test is useful when considering these materials due to the versatility of the test.

Mix Design: Resilient modulus tests can be incorporated in the asphalt concrete mix design process. The resilient modulus test can also aid in the evaluation of additives on the properties of asphalt concrete and emulsified mixes.

Estimation of Structural Layer Coefficients

According to the 1986 AASHTO guide, estimation of structural layer coefficients should based on the resilient modulus measured at 68°F in accordance with ASTM D 4123. However, the Asphalt-Aggregate Mixture Analysis System (AAMAS) recommends the consideration of seasonal temperatures. This procedure estimates the effects of temperature on the structural design by considering the seasonal fatigue damage. An effective asphalt concrete resilient modulus can be calculated considering the total annual damage, which in turn will be used to estimate the structural layer coefficient.

The following procedure is used to estimate the structural layer coefficients of asphalt concrete:

1. The average seasonal temperature is determined from historical meteorological data.

2. The resilient modulus is estimated for each seasonal temperature.
3. The fatigue factor is obtained for each seasonal resilient modulus.
4. The effective resilient modulus is calculated using the following equation:

$$E_{RE} = \Sigma(E_{RE}(i) x FF(i))/\Sigma FF$$

where: E_{RE} = Effective resilient modulus based on a fatigue damage approach.

$E_{RE}(i)$ = resilient modulus at the average pavement temperature for season i.

FF(i) = The fatigue factor for resilient modulus of season i.

5. The structural layer coefficient is estimated using effective resilient modulus.

Effect of Maximum Aggregate Size on AC Mixes

High tire pressures and increased wheel loads are believed to be the primary cause of premature rutting in heavy duty hot mix asphalt pavements. Incorporation of large size aggregates in hot mix asphalt design will help minimize the rutting of heavy duty asphalt pavements.

A study by E.R. Brown (29) summarized potential rutting factors including: excessive asphalt content, small aggregate size, low density, and a high percentages of fines. A similar study by Huber and Heimen (30) concluded that a correlation exists between rutting resistance and air voids, voids filled with asphalt, and asphalt content. The performance of asphalt concrete is directly effected if the voids filled with asphalt is greater than 70 percent.

Bissada (31), and Ford (32) show a clear separation of acceptable and unacceptable rutting potential based on air voids. A threshold asphalt content of approximately 5.1 percent differentiates acceptable and unacceptable rutting potentials.

An increase in the maximum aggregate sizes of asphalt concrete decreases the optimum asphalt content of the mix. The decreased asphalt content in conjunction with improved aggregate interaction, helps to improve the rutting resistance of asphalt concrete pavements.

Investigations of the effects of large aggregates on asphalt mix properties were conducted by Kandhal (33) and Kandhal and Brown (34). These studies indicate that increasing the aggregate size generally result in an asphalt mixture that is more resistant to permanent deformation. A linear relationship between the maximum aggregate size and permanent strain exists, where permanent strain decreases with an increase in the maximum aggregate size. The indirect tensile strength of asphalt concrete mixes also increases linearly with an increase in maximum aggregate size. It was concluded that 6 inch (15.24 cm) diameter specimens should be utilized to avoid inconsistency in test results for maximum aggregate sizes in excess of 1 inch (2.54 cm).

In addition to improving the rutting potential of asphalt concrete mixes, the use of larger aggregates tends to improve skid resistance and lower optimum asphalt content. An exception to this trend was noted by the Mississippi State Highway Department (MSHD). The MSHD reduced the maximum aggregate size for surface mix specifications from 1/2-inch (1.27 cm) to 3/8-inch (0.95 cm). The crushing operations necessary to produce the 1/2 inch (1.27 cm) size aggregates produced elongated pieces which exhibited poor skid resistance (35).

A study by Brown and Bassett (36) indicates that the resilient modulus increases with increasing aggregate size. A reduction in strain is noted in the asphalt concrete mixtures when subjected to a given in service load, thereby reducing stresses to the underlying layers. Improved performance in terms of creep behavior and tensile strength was noted. However, increased aggregate size does not have a significant effect on Marshall stability.

Khalifa and Herrin (37) investigated the effects of using aggregates up to 2 1/2 inches (6.35 cm) in size.

Their findings show an increase in the density of the compacted mixtures with increasing aggregate size. The voids in the mineral aggregates (V.M.A.) and percent air voids were reduced for a constant asphalt content. Mixture strengths were assessed using triaxial compression at a constant rate of deformation. These tests indicated that, for the same asphalt content and lateral pressure, the strength of the mixes tended to decrease with increased aggregate size. It was also concluded that high strength, large aggregate mixes was possible, but at a much lower asphalt content than conventional mixes.

The constructability and cost of producing large aggregate asphalt concrete mixes were also evaluated. It was concluded that construction problems were not significant and the cost of producing these mixes was estimated to be less than that of standard mixes. In general, the use of large sized aggregates in asphalt paving mixes can be advantageous, both economically and structurally.

CHAPTER III

EVALUATION OF MIX PROPERTIES

Specimen Preparation

Laboratory specimens were fabricated with the Texas gyratory shear, Marshall hammer, and the dynamic compaction apparatus.

Texas Gyratory Shear Compactor

The test specimens were prepared using the ASTM 4013 81 (38) procedure. The apparatus was preset for three revolutions at an gyratory angle of 3 degrees.

Marshall Hammer

The test specimens were fabricated using the Marshall compaction method described in ASTM-1559-89 (39). Seventy five blows were applied to simulate heavy traffic. The seventy five blow criteria is comparable to the selected gyratory compaction criteria.

Dynamic Compaction Apparatus

The dynamic compaction apparatus was developed (Figure 7) for this study in order to overcome the specimen size limitations of the other available compaction methods. A secondary objective was to fabricate specimens that closely approximate field compaction. The device was used to prepare 4 inch (10.16 cm), 6 inch (15.24 cm), and 8 inch (20.32 cm) diameter specimens.

The dynamic compaction apparatus consisted of the following components:

Base Plate: The apparatus was mounted on a 36 inch x 36 inch x 3/4 inch (91.44 cm x 91.44 cm x 1.9 cm) base plate, which was supported by castors for ease of transport. Two inch (5.08 cm) diameter vertical pipe supports are provided on both sides of the plate.

Vertical Carriage: The vertical carriage supports the compaction hammer and slides along the vertical pipe supports for adjustment. An electric winch with remote switch was attached to the vertical carriage to raise and lower the compaction hammer. To ensure that the specimens were compacted to the target density, the vertical pipe supports were drilled and pinned to provide a positive stop for the vertical carriage.

Compaction Platform: A spring supported platform 12 inch x 12 inch x 3/4 inch (30.48 cm x 30.48 cm x 1.9 cm) was affixed to the base plate. The purpose of the springs was to give a uniform response during compaction i.e., the rebounding plate aids in compaction. The specimen base was bolted to the spring supported platform during compaction.

Specimen Molds: A modified Marshall specimen mold (Figure 8) and collar were used to prepare 4 inch (10.16 cm) diameter specimens. Similar molds were fabricated to prepare 6 inch (15.24 cm) and 8 inch (20.32 cm) diameter specimens. All molds had tabs welded on opposite sides so that the collar/mold assembly could be bolted to the mold base.

Procedures

Specimen preparation procedures are vital in determining realistic resilient modulus values. It is desirable to produce specimens that approximate field compaction of asphalt concrete. All specimens were prepared using identical procedures with the exception of the compaction method.

Mixture Preparation: The aggregates were oven dried to a constant weight at 110°C (230°F). The aggregates were then blended, as per the job mix formula supplied by the Oklahoma Department of Transportation. The optimum amount of asphalt cement was added to the aggregates which were subsequently heated at 300°F (149°C). Thorough mixing was accomplished by hand mixing until uniform coating of the aggregates was obtained.

Amount of Mix: The amount of mix required for the gyratory and Marshall specimens was determined by preparing trial samples. An trial sample was prepared by weighing 1200 gms of aggregate in order to prepare a 4 inch (10.16 cm) diameter specimen. The asphalt mix was kept in the oven at 300°F (149°C) prior to compaction. The mixture was placed in the heated sample mold in several lifts, and the surface smoothed to a convex shape. The mixture was compacted and the height of the specimen was measured. The amount of mix was then adjusted to obtain the desired sample height of 2.5 inches (6.35 cm).

The amount of mix required for the dynamic compaction samples was equal to that required for the gyratory shear compacted specimens. The total quantity of mix required for the other specimen sizes was calculated using volume proportions. All specimens were compacted until they reached the target density as determined by sample height.

Number of Lifts: The number of lifts required to place the mix into the specimen molds were varied for the different specimen sizes. The 4 inch (10.16 cm) specimens required three lifts while the 6 inch (15.24 cm), and 8 inch (20.32 cm) diameter specimens required four lifts. In order to maintain uniform temperature during placement, the compaction was not performed in separate lifts, only mix placement. The following specimen configurations were prepared: 4 inch diameter (10.16 cm) 2 1/2 inches (6.35 cm) height, 6 inch (15.24 cm) diameter 3 inch (7.62 cm) height, and 8 inch (20.32 cm) diameter 4 inch (10.16 cm) height.

Alternate Specimen Preparation: ODOT type "G" mix is a relatively dense graded asphalt concrete having aggregates up to 2.5 inches (6.35 cm) in size. Due to the aggregate size, this mix required an alternate specimen preparation for uniform compaction. Four equal batches of aggregates were mixed according to the proportions required to fabricate one specimen. Each batch was placed in the mold in a single lift and was hand compacted using a spoon. Subsequent to the last batch a thin layer of "surfacing" asphalt concrete mix, (an equal amount of sand and screenings mixed with asphalt cement) was placed on the specimen approximately 1/8 inch thick. The additional mix covered the entire top face of the specimen, and was used to provide a smooth surface for instrumentation and to prevent the large aggregates from the specimen surface from being dislodged. The surface mix was removed following the resilient modulus tests. A limited number of surface flaws existed on the vertical sides of the specimen.

Laboratory Testing

A number of tests were performed to evaluate the properties of the asphalt concrete mix. The Standard ASTM procedures were followed in determining the bulk specific gravity (ASTM D 2726-86), maximum specific gravity (Rice's method) (ASTM D 2041), and Hveem stability of selected specimens (ASTM D 1560). The resilient modulus and indirect tensile strength of the asphalt concrete specimens were performed according to the Strategic Highway Research Program (SHRP) Protocol P07 of July 1991.

An electro-hydraulic apparatus was used for all load based testing. The components of the testing machine (Figure 9) included:

1. An electro-hydraulic actuator control panel manufactured by Material Testing System (MTS) performed the following functions:
    - A. Input control module - controls calibration and sensitivity of the internal Linear Variable Differential Transducer (LVDT) and load cell.
    - B. Transducer conditioner panel- signal conditioning for the load cell and LVDT signals.
    - C. Function generator- frequency control of load ram (load rate) and waveform generator for cyclic loading.
2. A hydraulic actuator (10-kip hydraulic ram) with an internally mounted LVDT and externally mounted load cell, manufactured by MTS.

3. A high pressure, high volume hydraulic pump, an accumulator, and assorted valving and piping.
4. A computer interfaced data acquisition and machine control system.

Control/Computer interface

A critical factor associated with resilient modulus testing is the rate at which load/displacement data can be recorded and processed. A computer interfaced control system was used to trigger the MTS system and subsequently acquire data from a single load cell and several displacement sensors. An analog/digital board (A/D) was used in conjunction with a 386-16MZ computer for data acquisition and machine control. Two control programs were written in connection with the PCLAB subroutines provided as support for the Data Translation A/D board. These programs were designed specifically for control of the resilient modulus and indirect tensile tests.

The computer program initializes the appropriate loading sequence for the specific test to be run and subsequently monitors the load/displacement data. A series of LVDT's were used to measure the vertical and horizontal displacements of the specimen. In both control programs, user prompts request detailed test information including: a specimen code which includes aggregate source and compaction type, specimen weight, height, diameter, test temperature, rest period, and the axis of loading. User prompts also request the approval or change of the default test parameters which include: the number of channels requiring data translation, the number of data points, clock frequency (sampling rate), load voltage and displacement voltage equivalency factors, and gain. Data acquisition consists of monitoring the voltages corresponding to the LVDT's and the load cell as per the program directives.

Test Procedures

A number of tests were selected to evaluate the properties of asphalt concrete mixes. Not all tests were performed on every specimen. The specific conditioned of each tests are included below:

The bulk specific gravity of all specimens was determined as per ASTM D 2726-86 (40). The Hveem stability of randomly selected specimens was determined as per the standard procedure designated by ASTM D 1560 (41). The maximum specific gravity (Rice's Method) of randomly selected specimens was determined as per ASTM D 2041 (42). The percent air voids was calculated.

Indirect tensile strength tests were conducted on a single randomly selected sample, prepared from each of the three compaction devices and using the five aggregate sources as per the procedure described in SHRP Protocol P07 (6). The resilient modulus test was conducted on samples as per the procedure described in SHRP Protocol P07. The tests were conducted at three temperatures (41, 77, and 104° F (5, 25, and 40° C)) along two diametral axes (second axis oriented 45° to the first) and at three rest periods (0.9s, 1.9s, and 2.9s). Load intensities of 30, 15, and 5 percent of the indirect tensile strength were used to determine the resilient modulus at 41, 77, and 104° F (5, 25, and 40° C) respectively. The load intensity for Marshall samples was reduced to 3 percent for tests conducted at 104°F (40°C) to ensure adequate deformations without breaking the sample.

Indirect Tensile Test

The indirect tensile strength test was conducted as per the procedure described in SHRP Protocol P07. Asphalt concrete specimens were loaded in compression along the diametral axis at a fixed deformation rate of 2 inches per minute (5.08 cm per minute). The specimens were preconditioned at a temperature of 77° F for 24 hours prior to testing.

The indirect tensile test is required to establish the load intensity to be used in the resilient modulus procedure. Load intensities of 30, 15, and 5 percent of the indirect tensile strength test were used to determine the resilient modulus at 41, 77, and 104°F (5, 25, and 40° C) respectively.

The indirect tensile strength was calculated using the following equation :

$$ITS = 1.273 * P_o/t[\ \text{Sin } 57.2958/D\ ) - 1\ /2D\ ]$$

where, ITS = Indirect tensile strength (psi)

P_o = Maximum load in pounds (lbs)

t = Specimen thickness (inches)

D = Specimen diameter (inches)

Resilient Modulus Test

Introduction: The resilient modulus test procedure as outlined by SHRP underwent several revisions during the course of this study. Therefore, a copy of the SHRP protocol on which this study is based is included in Appendix C.

The resilient modulus was determined by applying repetitive applications of diametral compressive loads in a haversine wave form. The load was applied along the vertical diametral plane of a cylindrical specimen of asphalt concrete. The resulting vertical and horizontal deformations were measured. The resilient modulus values were calculated using the applied load, specimen dimensions and the vertical and horizontal deformations. Figure 10 shows the specimen oriented for resilient modulus testing.

Temperature Control: The temperature control system adopted for all the resilient modulus tests consisted of an insulated enclosure with copper tubing running along the inside perimeter of the box. Water, maintained at a constant temperature of 41, 77, and 104°F (5, 25, and 40° C), was circulated through the tubing in order to maintain the enclosure at the test temperature. To further ensure constant specimen temperature, the room temperature was maintained at 50, 77, and 95°F (10, 25, and 35°C) during testing.

Specimen Orientation: The diameter and height of each test specimen was measured prior to testing. Two orientations, 45° apart, were evaluated for each specimen.

Preconditioning: The magnitude of applied loads used for preconditioning and testing at the three test temperatures was based on the indirect tensile strength of a similar specimen determined at 77° F (25° C). The resilient modulus tests were performed at 30, 15, and 5 percent of the indirect tensile strength of the specimens at 41, 77, and 104°F (5, 25, and 40° C), respectively. A minimum specimen contact load of 3, 1.5, and 0.5 percent of the tensile strength was maintained during the testing at 41, 77, and 104°F (5, 25, and 40° C), respectively. The sequence of resilient modulus testing consists of initial testing at 41° F (5° C), followed by intermediate testing at 77° F (25° C) and the final testing at 104° F (40° C).

The specimens were preconditioned along the vertical axis prior to testing by applying a repeated haversine load pulse of 0.1 second duration followed by a rest period of 0.9 seconds until a minimum of 10 successive horizontal deformation readings were within 10 percent. Generally, the number of load applications required depends upon the test temperature. The expected ranges are as follows:

41° F	50 - 150
77° F	50 - 100
104° F	20 - 50

Testing: A minimum of 30 load cycles (0.1 second load pulse and a rest period of 0.9 seconds) were applied and the measured deformations were recorded. The application of load cycles was continued until the deformation for 5 successive horizontal measurements (i.e. from lowest to highest value) was less than 10 percent of the average of the 5 deformation values. The rest period was then increased to 1.9 seconds and finally to 2.9 seconds. The recoverable horizontal and vertical deformations were determined from the 5 load cycles after the deformation stabilized.

Following testing on the first axis, the specimen was reoriented 45° and the above procedure was repeated. After testing was completed along both axes, the specimen was raised to the next higher temperature and the test was repeated. The resilient modulus was calculated along each axis for each rest period and temperature by averaging the measured deformations for the last 5 cycles.

The resilient modulus was calculated using the equation:

$$M_R = P*D\ (0.080 + 0.297V + 0.0425V^2)/(H_T*T)$$

where:

M_R = resilient modulus (psi),

P = repeated load (lb),

T = thickness of the test specimen (inch),

D = diameter of the specimen (inch),

H_T = total recoverable horizontal deformation (inch), and

V = Poisson's Ratio assumed for each temperature.

The assumed values of Poisson's ratio assumed were as follows:

41° F	0.20
77° F	0.35
104° F	0.50

Experimental Design

The study was divided into three major phases. The first phase focused on the determination of the resilient modulus for the Oklahoma Department of Transportation (ODOT) type "B" mixes. The relative effect of the laboratory compaction technique on asphalt concrete mix properties including resilient modulus, bulk specific gravity, maximum specific gravity, Hveem stability, and air voids was determined. The dynamic compaction apparatus was compared with the Marshall impact hammer and Texas gyratory shear to determine the relative differences in compaction.

Five different sources of ODOT type "B" mix aggregates were used to prepare asphalt concrete specimens. ODOT supplied data were used to prepare the specimens according to target job mix gradation and asphalt content.

In phase two of this study, modification of the existing resilient modulus test procedure was made to permit convenient testing of asphalt concrete specimens with a maximum aggregate size of 2.5 inches (63.5 mm). Repeatability of the resilient modulus test procedure and the correlation between specimens of different sizes were determined. All specimens were prepared using the dynamic compaction apparatus. Three specimen sizes were evaluated including: 4 inch diameter x 2.5 inch (101.6 mm x 63.5 mm), 6 inch diameter x 3 inch (152.4 mm x 76.2 mm) and 8 inch diameter x 4 inch (203.2 mm x 101.6 mm). All phase two specimens were prepared using a typical ODOT type "B" mix aggregate. Asphalt concrete properties including bulk specific gravity, maximum specific gravity, percent air voids, resilient modulus, and indirect tensile strength were determined. Eighteen specimens were fabricated in phase two, corresponding to six specimens for each specimen size evaluated.

In the final phase of this study resilient modulus values were determined for several asphalt concrete mix designations with larger maximum aggregate sizes. Three different sources of ODOT type "A" mixes and one type "G" mix were evaluated. In addition to the standard mix analysis test procedures, random specimens were evaluated for segregation of aggregates during compaction. Simplified flow charts for the three phases of work and a general project flow chart are provided in Figures 11-14, respectively.

Statistical Approach

The resilient modulus data were analyzed using the Statistical Analysis System (SAS). The statistical analysis was done to determine any differences in the resilient modulus value due to aggregate sources, compaction techniques, specimen sizes, temperature, rest period or orientation. The analysis also examined the interrelationship (interaction) among different factors (aggregate source, temperature, compaction technique, rest period, and orientation).

In determining the significance of the analysis, a significance level of 0.05 was used. Any factor being significant would imply that the resilient modulus values are different for different levels of that factor. Similarly, the interaction of two factors being significant would imply that the effect of one factor on the resilient modulus value is not independent of the other factor.

In the analysis, F was the test criterion for testing among factor means. The null hypothesis is that there are no differences among factor means, and the alternative hypothesis is that there are differences. The F value is determined by dividing the factor mean square by the corresponding error mean square. The calculated F value was compared with the tabulated value of F. The following is a hypothetical example of the analysis of variances using F as a test criterion.

Asphalt concrete specimens were fabricated using aggregates from four sources. Two compaction methods were used. Three specimens were prepared using each compaction method for each aggregate source. A total of twenty four specimens were fabricated. The effect of aggregate sources and compaction methods on the resilient modulus and the inter relationship (interaction) between these two factors are to be determined.

Number of aggregate sources, p = 4

Number of compaction methods, q = 2

Number of specimens in each group, r = 3

The total degrees of freedom is 23 (n-1=pqr-1=24-1), aggregate source degrees of freedom is 3 (p-1=4-1), compaction method degrees of freedom is 1 (q-1=2-1), and source * compaction interaction degrees of freedom is 3 ((p-1)*(q-1)=(4-1)*(2-1)). The error degrees of freedom is 16 (24-3-1-3). The procedure for calculating the sum of squares can be found in any book of statistics. The mean square of any factor is its sum of squares per degree of freedom.

Analysis of Variances

Source	df	Sum of Squares	Mean Square	F	Pr>F
Source	3	23116.30	7705.432	2.80	>0.05
Compac.	1	15135.67	15135.620	5.50	<0.05
Source* Compac.	3	18162.80	6054.268	2.20	>0.10
Error	16	44031.04	2751.940		
Total	23	100445.80			

The tabulated values of F and the probability of a larger F is determined in the analysis and would correspond to information from the F table provided by Steel, R. G. D. and Torrie, J. H. (43). The probability for a larger F of 0.05 is critical. A higher probability will accept the null hypothesis of no differences, and a lower will accept the alternate hypothesis of differences.

In the analysis of variance table, the F calculated for aggregate sources, compaction methods, and source*compaction interaction are 2.80, 5.50, and 2.20 respectively. To determine the significance level of the aggregate source and compaction interaction, the F table was entered with 3 and 16 degrees of freedom. The F value from the table is 3.24, which is larger than 2.20, i.e. the interaction is insignificant. The aggregate source and compaction technique interaction was determined not to be significant, which implies that the effect of compaction technique on resilient modulus values is independent of aggregate source; hence, we can proceed to tests for differences due to aggregate source and compaction techniques. To test the null hypothesis of no differences due to aggregate sources, the F table was entered with 3 and 16 degrees of freedom. The F value from the table is 3.24, which is larger than 2.80. Hence, the null hypothesis of no differences due to aggregate sources was accepted. Similarly, it can be concluded that there is a difference in the resilient modulus value due to different compaction techniques.

The following are definitions of some statistical terms frequently used in this study:

Completely Randomized Design: Completely randomized design (CRD) is a type of laboratory experiment where a quantity of material is thoroughly mixed and then divided into small groups to form the experimental units to which treatments are randomly assigned.

Variance: Variance is a measure of variability of the data, defined as the sum of the squared deviations divided by their total number.

Split Plot Experiments: The underlying principle of split plot experiments is that the whole units (asphalt concrete specimens), to which levels of one or more factors (aggregate source, specimen size, compaction method, and temperature) are applied, are divided into sub-units to which one or more additional factors (rest period and/or orientation) are applied. Thus, the whole unit becomes a block for the sub-unit treatments, and the experiment becomes an incomplete block design.

CHAPTER IV

RESULTS AND ANALYSIS

The study was conducted in three major phases. The results of each phase are analyzed and discussed independently.

Phase One

The primary objective of phase one was to determine the resilient modulus of a typical type "B" asphalt concrete mix. A secondary objective was to evaluate three compaction devices to determine their ability to produce specimens with identical mix properties. The compaction devices studied were the Marshall hammer, the Texas gyratory shear, and the dynamic compaction device which was developed specifically for this project.

Five different sources of "B" mix aggregates were used to fabricate asphalt concrete specimens. Details concerning the aggregate sources and mix design parameters are summarized in tables 35 through 39. Fifteen specimens were prepared for each source and compaction technique. A total of 225 specimens were tested in phase one. The following tests were performed on selected specimens: bulk specific gravity, Hveem stability, maximum specific gravity, indirect tensile strength, and resilient modulus. Air voids and other appropriate mix design characteristics were calculated.

Bulk Specific Gravity

The bulk specific gravity (BSG) of all the specimens was determined. The results of these tests are summarized in Tables 2 through 6 and are differentiated by aggregate source. The BSG of the gyratory shear molded specimens was the highest, followed by the dynamic compacted specimens, while the BSG of Marshall hammer compacted specimens was lowest. The BSG is an indicator of the relative compaction and percent air voids present in identically designed specimens. The primary reason for the gyratory molded specimens showing consistently higher BSG values is that the gyratory compaction methods applies normal forces to both top and bottom faces of the asphalt mix in a cylindrically confined mold. These normal forces supplemented with the gyratory motion tend to produce a denser mix due to the relative confinement and high degree of aggregate reorientation. The lower BSG values for the Marshall hammer compacted specimens indicate lesser densification. Figure 15 shows a comparison of the average BSG values for all specimens.

Hveem Stability Test

Hveem stability tests were performed on five specimens from each set of specimens molded with either the gyratory shear or dynamic compaction technique. Hveem stability determinations on the Marshall specimens were not conducted. The results of these tests are summarized in Tables 7 through 11. The stability of the dynamically compacted specimens was consistently higher than the gyratory shear compacted specimens, though the average air voids in dynamically compacted specimens were higher than the gyratory shear compacted specimens. Generally, higher air void accompanied lower Hveem stability. The dynamic impact along the vertical axis during compaction resulted in specimens with a high stiffness in the vertical direction for the dynamically compacted specimens. Hence, the dynamically compacted specimens show higher Hveem stabilities, which is a measure of the resistance to deformation expressed as a function of the ratio of the transmitted lateral pressure to that of the applied vertical pressure. Figure 16 shows a comparison of the Hveem stability values of gyratory and dynamically compacted specimens.

Maximum Specific Gravity and Air Voids

Maximum specific gravity (MSG) determinations were performed on three specimens from each group. The gyratory and dynamic specimens evaluated were randomly selected from specimens which were previously tested for resilient modulus and indirect tensile strength. Subsequent to the MSG determination, the percentage of air voids was calculated. The results of the maximum specific gravities and air voids are presented in Tables 12 and 13. The MSG of all the specimens is relatively constant regardless of the compaction technique utilized.

The percent air voids in the compacted mixes ranges from 3 to 10 percent. The Marshall compacted specimens show the widest variation in air voids (6 to 10 percent). The absence of kneading action or significant reorientation of the aggregates during compaction is the primary factor in the higher air voids.

The percent air voids in the gyratory or dynamically compacted specimens ranges from 3 to 7 percent. The gyratory specimens show a lower percentage of air voids, due in large part to the improved aggregate reorientation. Although the dynamic compaction technique results in slightly higher air voids, the difference is marginal in most cases. Absence of shear effects during compaction may have resulted in some air pockets, causing a higher percentage of air voids in the dynamically compacted specimens.

Resilient Modulus

Resilient modulus tests were performed on specimens fabricated with the three compaction techniques evaluated. Five random specimens from each of the fifteen specimen groups (five aggregate sources and three compaction techniques) were tested. A single random specimen from each group was tested to determine a baseline indirect tensile strength. The average of all indirect tensile strength values was used to determine the appropriate loading magnitude for the resilient modulus determinations.

Numerous difficulties were encountered in the initial phase of the resilient modulus testing. The modulus values of the specimens were unrealistic and widely varied. The calibration of the testing machine and instrumentation problems were the primary reasons. Recalibration of the testing apparatus and modification to the computer program solved the variability problems encountered. Resilient modulus tests were performed on a second set of gyratory shear and dynamically compacted specimens.

The Marshall compacted specimens did not perform well for resilient modulus determination. At the 104°F (40°C) test temperature several Marshall specimens were broken. Hence, resilient modulus determination on Marshall specimens was discontinued. A study by Von Quintus, et al. (44) and Mamlook, et al. (45) also have suggested that Marshall specimens are not suitable for resilient modulus determination.

The resilient modulus was evaluated for the following parameters:

1. Three temperatures i.e. 41, 77, and 104°F (5, 25, and 40°C).
2. Three rest periods: 0.9 sec., 1.9 sec., and 2.9 sec.
3. Two axes of loading; the second axis oriented 45° to the first.

The results of the resilient modulus tests are presented in Tables 14 through 16.

<u>Statistical Analysis:</u> The resilient modulus data were analyzed as a split split plot experiment with main units in a completely randomized design. The main unit was the specimens and the source and compaction were main unit treatments. Orientation and rest periods were first and second split respectively. Since the resilient modulus values had different variance at different temperatures, statistical analyses were conducted separately for each temperature. Statistical analyses are summarized in Tables 17 through 19.

The analyses of resilient modulus values show no statistical significant differences due to compaction technique, rest period, or orientation. The analyses also show no significant differences due to aggregate sources at

41°F (5°C) and 77°F (25°C). However, at 104°F (40°C) the various aggregate sources show significantly different modulus values. The differences are due to: the surface texture of the coarse aggregates, the amount of fines, and the more prominent viscous effect of asphalt cement at the higher temperature. Though there was no statistically significant effect of rest period on resilient modulus values, the values determined at 104°F (40°C) exhibit a lower resilient modulus value for longer rest periods. Figures 17 through 20 show the mean resilient modulus, resilient modulus for two compaction techniques, mean resilient modulus for each source, and rest period at 104°F (40°C).

The resilient modulus of Oklahoma type "B" mix is estimated, considering the mean of all sources and compaction, as 1099 ksi at 41°F (5°C), 593 ksi at 77°F (25°C), and 269 ksi at 104°F (40°C).

Indirect Tensile Strength

The indirect tensile strength was assessed for all specimens previously tested for resilient modulus. The indirect tensile strength of the gyratory shear compacted specimens was generally higher than the corresponding dynamically compacted specimens. Indirect tensile strength is correlated with specimen compaction and the radial stiffness of the specimen. Bulk specific gravity, which can be considered as a measure of relative compaction for identical specimens, indicates that the gyratory specimens have a higher degree of compaction compared to the dynamically molded specimens. The gyratory specimens, due to the shear effect during compaction, tend to have higher radial stiffness than the dynamically compacted specimens. Figure 21 presents the indirect tensile tests for the five aggregate sources and the two compaction techniques.

Phase Two

The primary objective of phase two was to modify the existing resilient modulus test procedure to permit testing of asphalt concrete specimens with a maximum aggregate size of 2.5 inch (6.35 cm). A secondary objective was to assess the effects of specimen size on the resilient modulus of a reference asphalt concrete mix. The three sizes evaluated were 4 inch diameter x 2.5 inches (10.16 cm x 6.35 cm), 6 inch diameter x 3 inch (15.24 cm x 7.62 cm) and 8 inch diameter x 4 inch (20.32 cm x 10.16 cm). All the specimens in phase two were fabricated using the dynamic compaction apparatus. The following tests were performed on selected specimens: bulk specific gravity, maximum specific gravity, air void determination, resilient modulus, and indirect tensile strength.

Bulk Specific Gravity

The bulk specific gravity (BSG) of five randomly selected specimens from each of the three size groups was determined. The BSG test results show a clear trend of decreasing BSG with an increase in specimen size (Table 20, Figure 22). A reduction in compactive effort, due to increasing specimen size and a fixed level of compaction energy, is responsible for this trend.

Resilient Modulus

One random specimen from each of the three size groups was tested for indirect tensile strength. The average of these tests was used to determine the appropriate load magnitudes for the resilient modulus determinations. Although the resilient modulus testing in phase one showed no significant effect of rest period and orientation, the phase two testing program re-evaluates these parameters.

The width of the loading strips was varied for the different specimen sizes to maintain a constant subtended contact angle of 1/4 radian. Loading strip widths of 1/2, 3/4, and 1-inch (1.27, 1.9, and 2.54 cm) were used for the 4, 6, and 8-inch (10.16, 15.24, and 20.32 cm) diameter specimens respectively. A 1/2-inch (1.27 cm) loading strip was evaluated for the 6-inch (15.24 cm) diameter specimens. A modified formula was required to calculate the resilient modulus due to the different stress distribution profile within the specimens using the narrower loading strip (46). Results of the phase two resilient modulus tests are presented in Table 21.

Statistical Analysis: The resilient modulus data were analyzed as a split split plot experiment with main units in a completely randomized design. The main unit was the specimens, and specimen size was main unit treatment. Orientation and rest period were the first and second splits respectively. Due to the differences in the variance of the modulus values at different temperatures, statistical analyses were carried out separately for each temperature and are tabulated in Tables 22 through 24.

The analyses of resilient modulus values show that at 41°F (5°C), a three way interaction including: size, orientation, and rest period was significant. This interaction implies that the effect of one factor (size, rest period, or orientation) over the range of any other factor is not the same. Hence, there are differences associated with size, rest period, and orientation at 41°F (5°C). The nearly identical specimens used in this phase produced resilient modulus values with low specimen variability, and hence a low error for the model. This low error value when used to determine the effect of size * rest period * orientation results in a statistical significance of differences. The average resilient modulus values considering size and orientation for all three rest periods (Figure 23) ranges from 1250 ksi to 1350 ksi. At 77°F (25°C) the resilient modulus values decrease with an increase in rest period. The effect of rest period on the resilient modulus values is not the same for all specimen sizes. Overall there is a trend of decreasing resilient modulus values with an increase of rest period as the specimen size increases (Figure 24). The average resilient modulus values considering size and orientation for all rest periods ranges from 770 ksi to 845 ksi. For all practical purposes the differences in resilient modulus values at 41 and 77°F (5 and 25°C) can be ignored. The analyses show no statistically significant differences due to specimen size, rest period, or specimen orientation at 104°F (40°C). Figures 25 and 26 illustrate the effects of size and rest period on the resilient modulus values.

The resilient modulus of the 6 inch (15.24 cm) diameter specimens tested with 1/2 (1.27 cm) and 3/4 inch (1.9 cm) loading strips was approximately the same (Figure 27). Hence, the effectiveness of the testing equipment and data acquisition system was verified.

Indirect Tensile Strength

The indirect tensile strength was assessed for all specimens previously tested for resilient modulus. The load rates used for the indirect tensile tests were 2, 3, and 4 inches (5.08, 7.62, and 10.16 cm) per minute for 4, 6, and 8 inch (10.16, 15.24, and 20.32 cm) diameter specimens, respectively. The test results are presented in Table 20. The indirect tensile strengths were approximately the same for the 4 and 6 inch (10.16 and 15.24 cm) diameter specimens, however the strengths were low for the 8 inch (20.32 cm) diameter specimens (Figure 28). The BSG, which is an indicator of the relative compaction for identical specimens showed a lower value for the 8 inch (20.32 cm) diameter specimens.

Maximum Specific Gravity and Air Voids

Maximum specific gravity (MSG) determinations were performed on all the specimens previously tested for resilient modulus and indirect tensile strength. Subsequent to the MSG determination, the percentage of air voids was calculated. The results of the maximum specific gravities and air voids are presented in Table 20. The MSG of all the specimens is relatively constant regardless of the specimen size. However, the percent air voids of the specimens were different for the three specimen sizes due to differences in the BSG. The average percent air voids increases with an increase in specimen size thereby accounting for the lower indirect tensile strength of the 8 inch (20.32 cm) diameter specimens (Figure 29).

The dynamic compactor was found not to compact 8 inch (20.32 cm) diameter specimens as well as 4 and 6 inch (10.16 and 15.24 cm) diameter specimens, however the difference was marginal in most cases. The slightly lower compaction for the 8 inch (20.32 cm) diameter specimens resulted in an increase in air voids of less than 1.5 percent, while the resilient modulus values were comparable for all the specimen sizes evaluated.

Phase Three

The objective of the third phase was to determine the resilient modulus of ODOT type "A" and "G" mixes. Three sources of type "A", and one source of type "G" mix were evaluated. Details concerning the aggregate sources and mix design parameters are summarized in tables 40 through 43. Thirty five specimens were prepared (five groups of seven specimens each) using the dynamic compaction apparatus. 6 and 8 inch diameter (15.24 and 20.32 cm) specimens were prepared for type "A" and "G" mixes respectively. The following tests were performed on selected specimens: bulk specific gravity, resilient modulus, indirect tensile strength, and maximum specific gravity. Air voids and other appropriate mix design characteristics were calculated.

Bulk Specific Gravity

The bulk specific gravity was determined for all specimens and is shown in Figure 30. The average BSG of type "A" and "G" mixes are 2.288 and 2.370 respectively. It can be observed that the BSG of asphalt concrete increases with the increase of maximum aggregate size.

Resilient Modulus

Five randomly selected specimens from each of the five specimen groups (three type "A" mixes and two batches of type "G" mixes) were tested. A single random specimen from each group was tested to determine a baseline indirect tensile strength. The resilient modulus values were determined for all three test temperatures, three rest periods, and two orientations. The results of the resilient modulus tests are presented in Tables 25 and 26.

Statistical Analysis: The resilient modulus data were analyzed for type "A" and type "G" separately, as split split plot experiment with the main units in a completely randomized design. The main unit was the specimens, and the source/batch was main unit treatment. Orientation and rest period were the first and second split respectively.

Type "A" mix: The resilient modulus values at 41°F

(5°C) were significantly different for the different aggregate sources. The size and rest period interaction was significant at 77°F (25°C), which implies that different sources do not respond in the same manner to rest periods. The analyses do not show any significant differences due to source and rest period at 104°F (40°C). In all cases, the specimen orientation shows no significant effect on resilient modulus. The overall analysis indicates that rest periods have a significant effect on the resilient modulus of type "A" mix. In general, a decrease in the resilient modulus value was noted for an increase in rest period. Figures 31 through 33 show the resilient modulus of type "A" mix, the effect of rest period, and the effect of rest period and sources at 77°F (25°C). Statistical analyses are presented in Tables 27 through 29.

Laboratory specimens fabricated with close tolerance on aggregate grading, asphalt content, and compaction produced almost identical specimens. The similarities in the specimen resulted in small variability among the specimens. Hence, a small difference in the resilient modulus at different rest period shows a significant difference in the analysis.

The average resilient modulus values for Oklahoma type "A" mix are 1591, 754, and 307 ksi at 41, 77, and 104°F (5, 25, and 40°C), respectively.

<u>Type "G" mix:</u> The statistical analyses shows no

significant differences in resilient modulus values due to batch, rest period or specimen orientation at 41° and 77°F (5 and 25°C). However, at 104°F (40°C) there is an orientation * rest period interaction, which implies that the effect of rest period on the resilient modulus values is not the same for the two specimen orientations. The performance of the "G" mix specimens at 104°F (40°C) was substandard. The larger aggregates had a tendency to become dislodged from the surface during preconditioning. The relatively poor performance of the specimens at 104°F (40°C) may have resulted in significant orientation*rest period interaction. Tables 30 through 32 present the statistical analyses of the type "G" mix.

The average resilient modulus values of type "G" mix are 2151, 1076, and 350 ksi at 41, 77, and 104°F (5, 25, and 40°C), respectively. Figure 34 shows the resilient modulus of type "G" mix. Figure 35 shows the resilient modulus of type "A", "B", and "G" mixes.

Indirect Tensile Strength Test

The indirect tensile strength was assessed on three specimens from each source/batch of type "A" and "G" mixes. The test results are presented in Table 33. A strain rate of 3 inches/minute (7.62 cm/minute) was used for the 6 inch (15.24 cm) diameter specimens (type "A") and 4 inch/minute

(10.16 cm/minute) for the 8 inch diameter (20.32 cm) specimens (type "G").

The average indirect tensile strength of different sources can not be used for comparison because of the limited number of specimens tested for each sources. However, averaging over one particular mix will give an estimate of the indirect tensile strength for that mix type.

Maximum Specific Gravity and Air Voids

Two random specimens from each source/batch were saw cut to assess segregation in the specimen during compaction. The maximum specific gravity was determined, and the air voids calculated using these specimens. Prior to performing the maximum specific gravity, the surface leveling materials was removed. The test results are presented in Table 34. It was observed that the maximum specific gravity of the top and bottom portions of all the specimens were the same, however the percent air voids was generally higher in the lower section. These results indicate a reduction in the compactive effort at the bottom section of the larger specimens.

Example of Determining A Structural Layer Coefficient

The seasonal average pavement temperatures are assumed as follows:

Fall: 70°F

Winter: 40°F

Spring: 70°F

Summer: 104°F

Comparing the test results of the typical asphalt mix types evaluated with the recommendations in Figure 36, it can be seen that the average moduli are within the appropriate range at all test temperatures. The only exception is for the type "G" asphalt concrete 77°F (25°C), which has an average moduli that is too high according to Figure 36. However the study on which Figure 36 is based did not consider large aggregate mixes with higher moduli.

Figure 36 shows that the moduli at 41, 70, and 104°F (5, 25, and 40°C) for a typical "B" mix are 1099, 680 and 269 ksi, respectively. The corresponding fatigue factors are 0.23, 0.55 and 3.5 as shown in Figure 37. The effective resilient modulus is then calculated as 402 ksi. Figure 38 indicates that the structural layer coefficient for this material should be 0.42. Similarly the layer coefficients for the type "A" and type "G" mixes are both 0.44.

The procedure shown should be used to determine the layer coefficients to be used in pavement design. However, realistic average seasonal pavement temperatures should be used instead of the assumed temperatures.

CHAPTER V

SUMMARY AND CONCLUSIONS

Five sources of type "B", three sources of type "A" and a typical type "G" mix were evaluated in this study to determine their resilient modulus and hence, AASHTO layer coefficients. A new method of compacting asphalt concrete mixtures, the dynamic compaction, was evaluated. Four-inch (10.16 cm) diameter specimens were fabricated using the Gyratory shear apparatus, Marshall hammer, and the dynamic compactor. Larger specimens, 6 and 8 inch diameter (15.24 and 20.32 cm) were prepared using the dynamic compactor. The current resilient modulus test procedures (ASTM 4123 and SHRP protocol P07) were evaluated.

Within the limits of the aggregate sources, compaction methods, temperature, and rest periods evaluated in this study, the following conclusions are made:

Resilient Modulus Test

The standard resilient modulus test procedure ASTM D 4123 can be modified to reduce it's complexities and accommodate asphalt concrete mixes with large maximum size aggregates.

1. The specimen orientation in resilient modulus

determinations does not effect the resilient modulus values of asphalt concrete mixes.

2. The three rest periods evaluated in this study including 0.9 seconds, 1.9 seconds, and 2.9 seconds, do not effect the resilient modulus values of standard size specimens (4 inch (10.16 cm) diameter and 2.5 inch (6.35 cm) long). However as the specimen size increases, the effect of rest period becomes significant. The resilient modulus values tend to decrease with an increase in rest period. Though the difference is statistically significant, it is very marginal. The resilient modulus for a rest period of 2.9 seconds was approximately 96 percent of the resilient modulus value for a rest period of 0.9 seconds. Hence, for all practical purposes, the effect of the rest period can be neglected and a rest period of 0.9 seconds used to determine the resilient modulus of asphalt concrete mixes.
3. Large asphalt concrete specimens including 6 inch (15.24 cm) diameter x 3 inch (7.62 cm) and 8 inch (20.32 cm) diameter x 4 inch (10.16 cm), can be successfully evaluated for resilient modulus. The resilient modulus can be calculated using the equation proposed by the Strategic Highway Research

Program (SHRP) in the P07 protocol. However, the loading strip for the different specimen sizes needs to be varied to assure that the angle subtended remains a constant 1/4 radian.

Evaluation of Compaction Methods

The gyratory shear and dynamic compaction apparatus produce nearly identical specimens for evaluating resilient modulus. The Marshall hammer molded specimens perform poorly in resilient modulus determinations. An advantage of the dynamic compaction apparatus is that it can be used to prepare large specimens to accommodate large aggregate mixes.

1. The bulk specific gravity was highest for the gyratory shear molded specimens followed by the dynamically molded specimens, and finally the Marshall molded specimens.
2. The Hveem stability of dynamically compacted specimens was higher than that of the gyratory shear compacted specimens.
3. The gyratory shear molded specimens and the dynamically compacted specimens showed similar air voids. The Marshall compacted specimens air voids tended to be high and highly variable.
4. The resilient modulus values for the gyratory shear and dynamic apparatus compacted specimens were

approximately the same.

5. The indirect tensile strength of the gyratory shear specimens was higher than those of dynamically compacted specimens, however the difference was marginal.

Evaluation of Mixes

The diametral resilient modulus of the Oklahoma Department of Transportation (ODOT) type "A", "B", and "G" mixes are within the acceptable range as specified by AASHTO. However, the standard practice of assuming a layer coefficient of 0.44 for type "B" mix seems a slight overestimate.

1. The resilient modulus of ODOT type "B" mix is estimated to be 1099 ksi at 41°F, 593 ksi at 77°F, and 269 ksi at 104°F.
2. The resilient modulus of ODOT type "A" mix is estimated to be 1591 ksi at 41°F, 754 ksi at 77°F, and 307 ksi at 104°F.
3. The resilient modulus of ODOT type "G" mix is estimated to be 2151 ksi at 41°F, 1076 ksi at 77°F, and 350 ksi at 104°F.
4. The higher resilient modulus noted for asphalt mixes with larger aggregates implies that the use of larger aggregates would structurally improve asphalt concrete pavements.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE RESEARCH

1. The use of AASHTO layer coefficients in pavement design would be a more direct and effective approach if a mix design procedure based on the resilient modulus is developed.
2. Mixtures containing asphalt modifiers and/or antistripping agents, including polymer modified and rubber asphalt, should be evaluated to determine the resilient modulus values.
3. Field cores from "newly constructed" pavements should be evaluated and correlated with laboratory specimen in order to develop more realistic pavement performance models.
4. The effect of air voids on the resilient modulus of asphalt concrete mixes should be studied.
5. The aging effects of asphalt concrete needs to be correlated with the resilient modulus value to help estimate the service life of asphalt concrete pavements.

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APPENDIXES

APPENDIX A

FIGURES

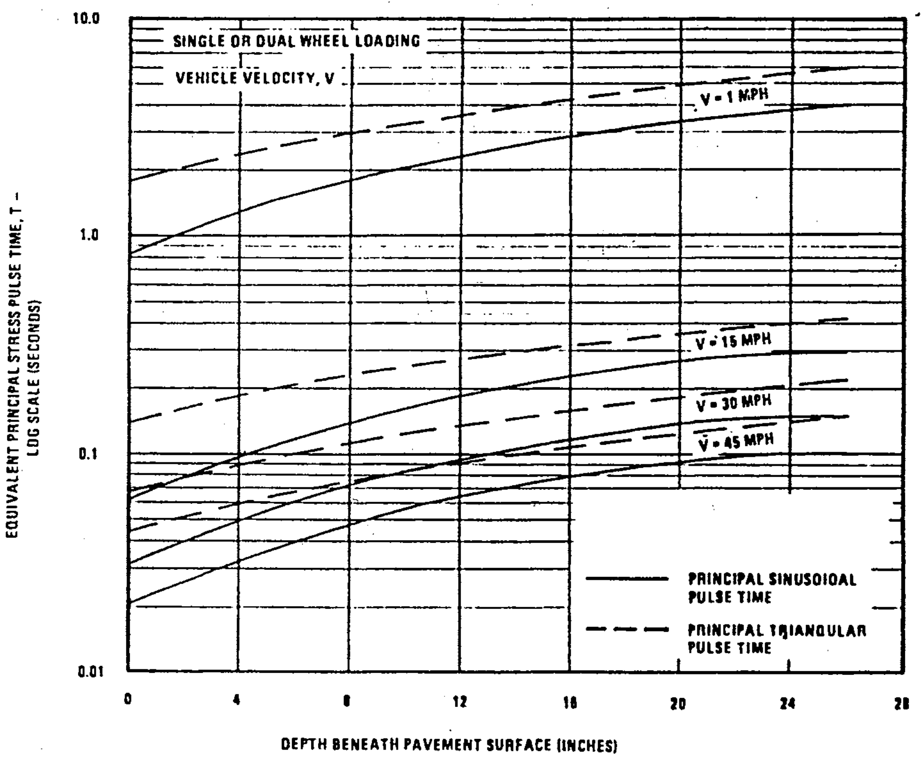


Figure 1. Variation of Stress Pulse Time with Vehicle Velocity and Depth (6).

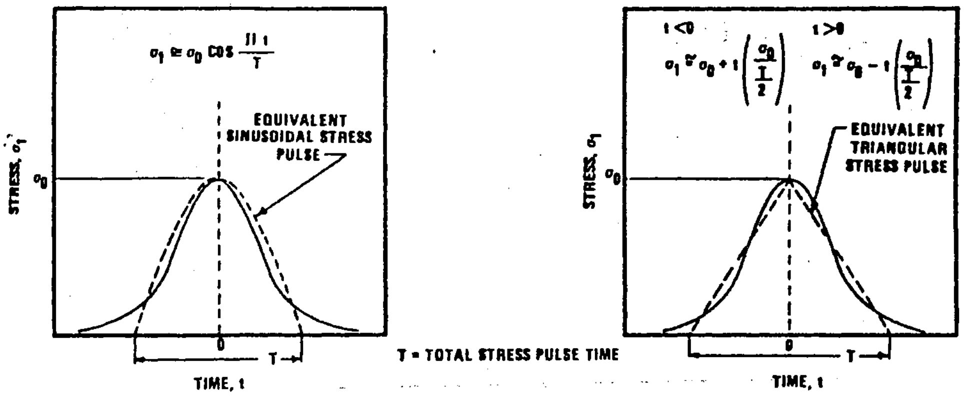


Figure 2. Equivalent Sinusoidal and Triangular Stress Pulses (6).

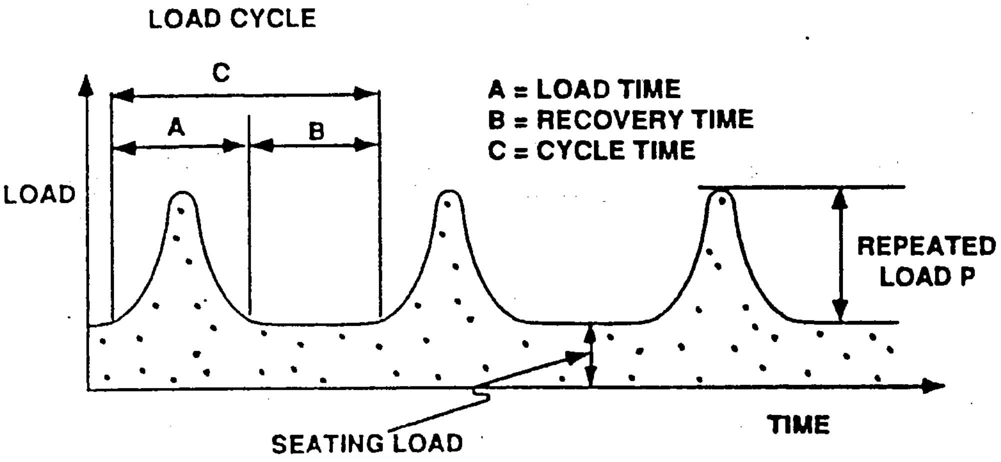
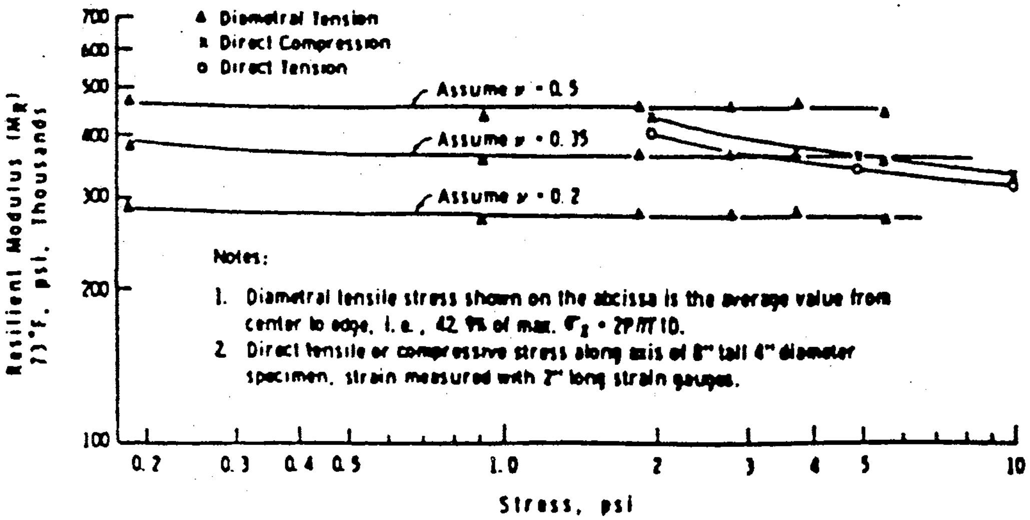
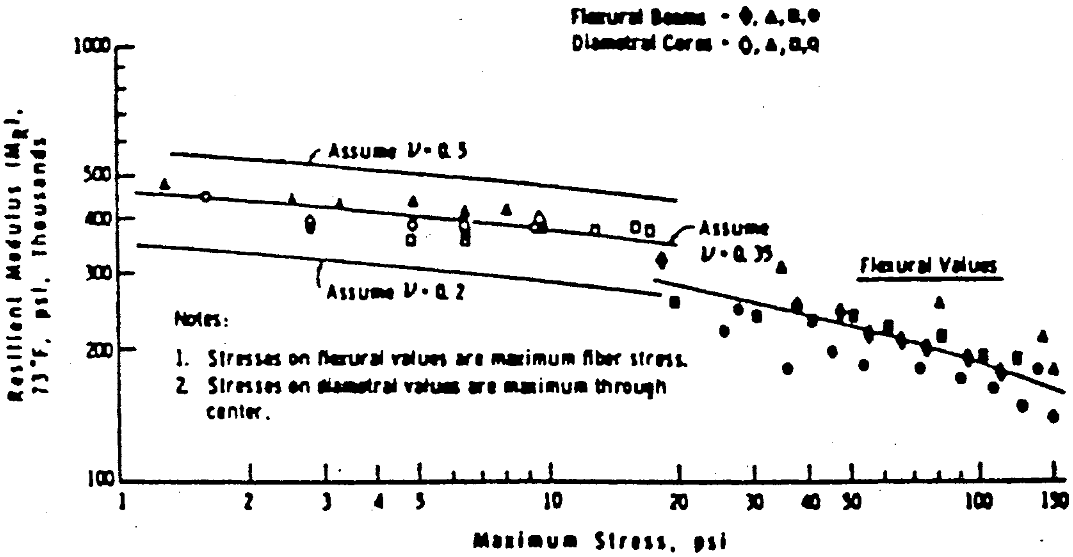


Figure 3. Repeated Loading.



(a) Direct tension, compression, and diametral methods



(b) Flexural and diametral methods

Figure 4. Comparison of Resilient Modulus of AC Specimens using Direct Tension, Compression, Flexural, and Diametral Methods (11).

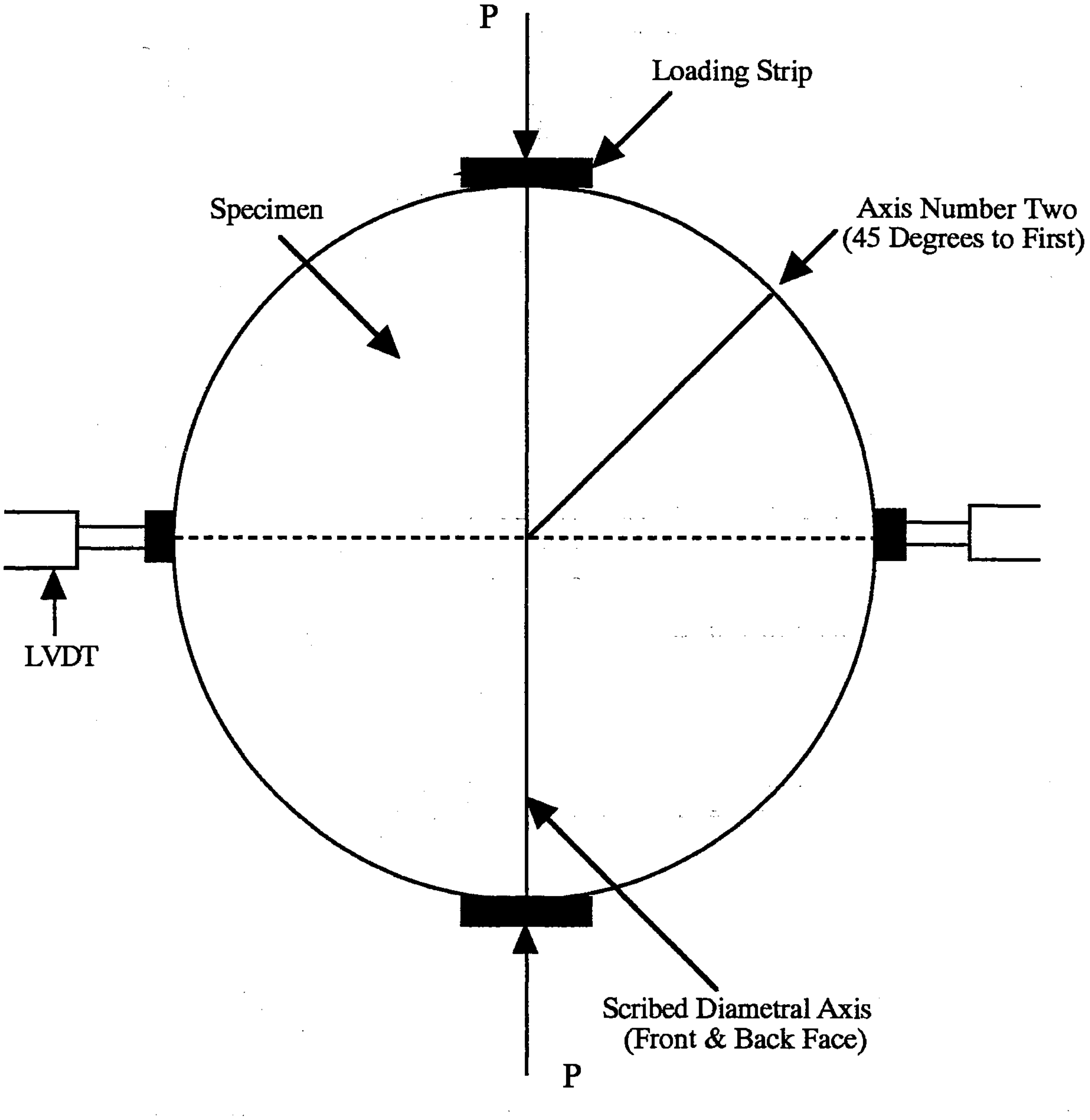


Figure 5. Repeated Load Indirect Tensile Test.

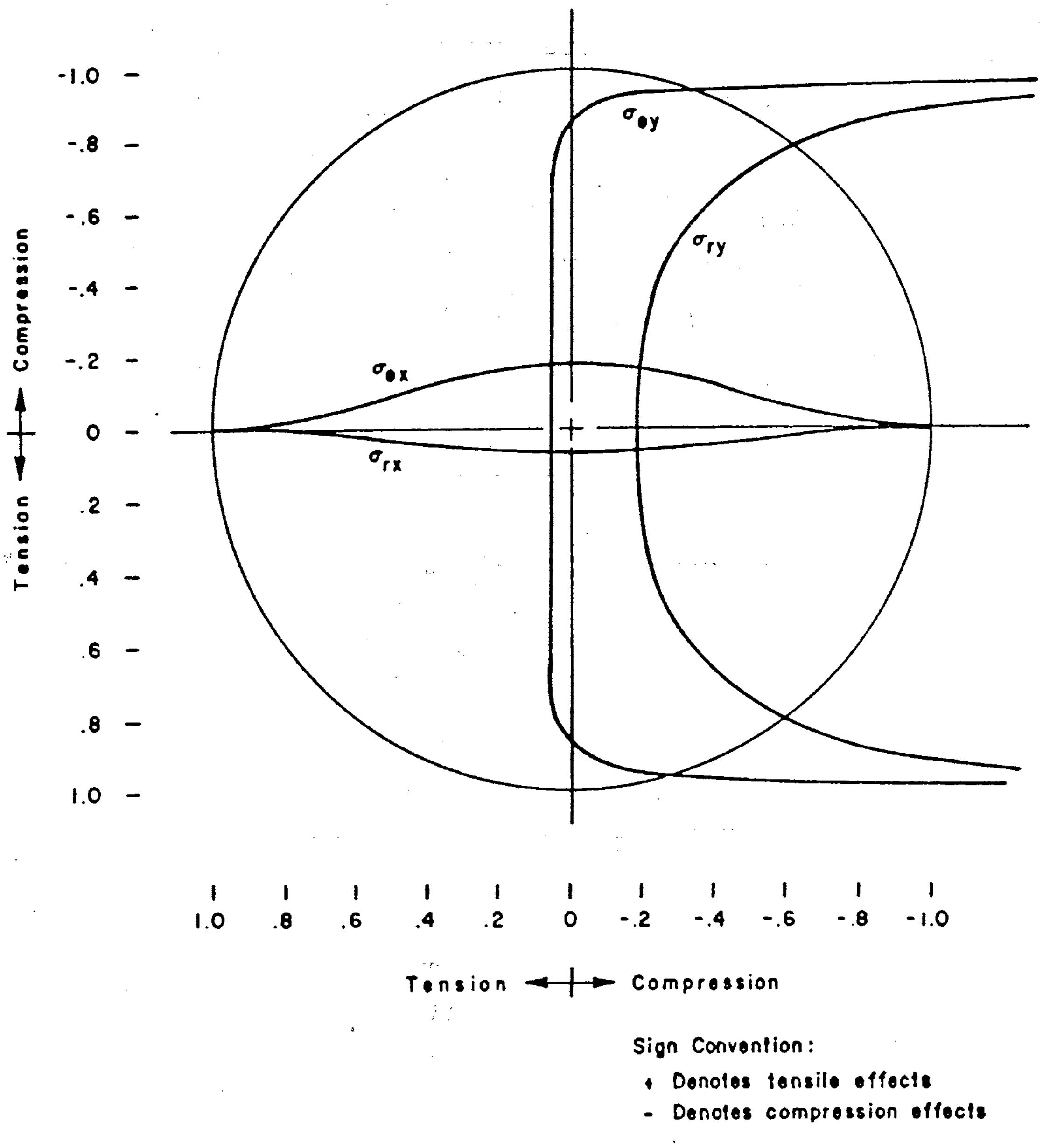


Figure 6. Stress Distribution Along The Principal Axes (10).

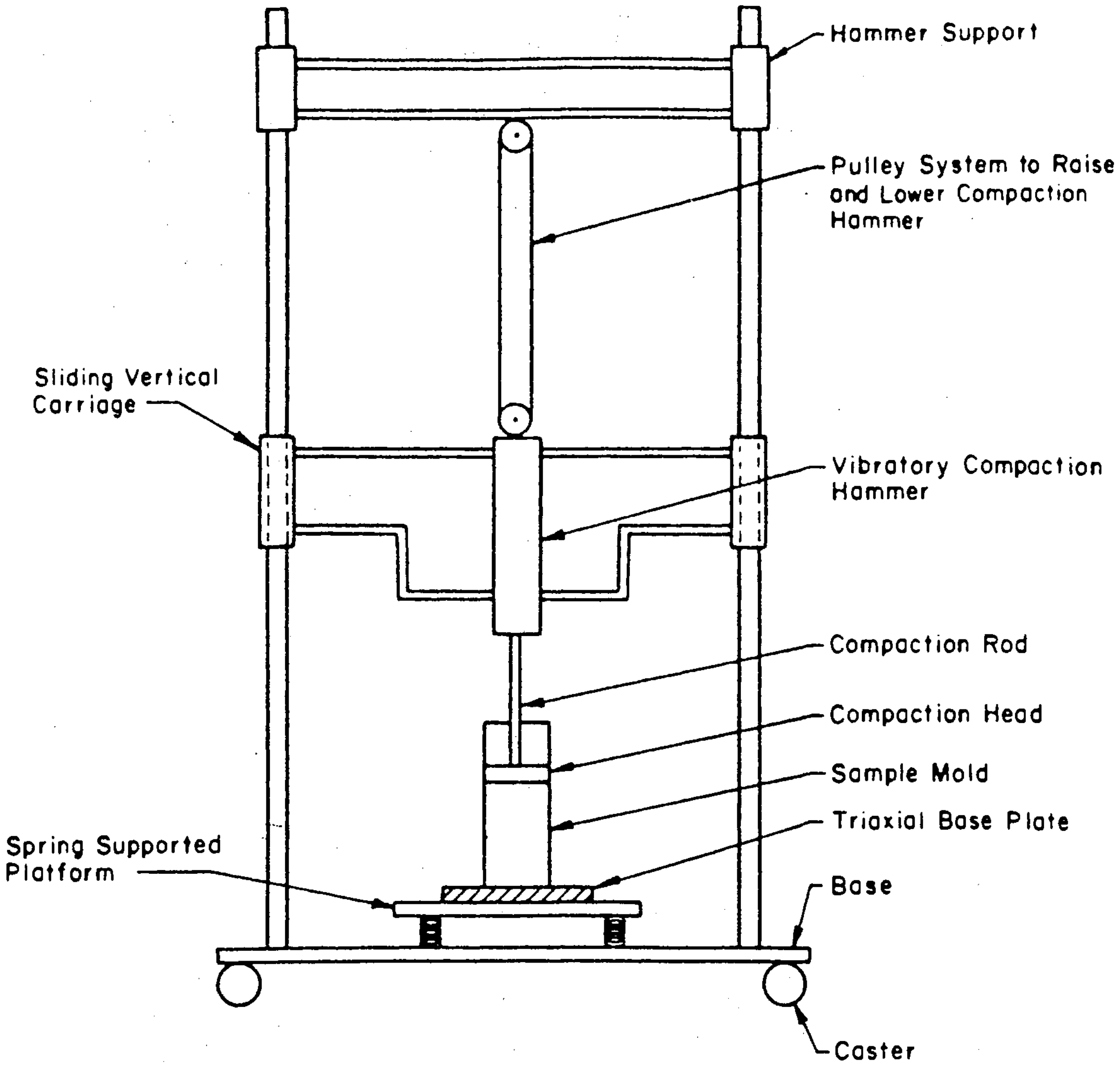


Figure 7. Dynamic Compaction Apparatus.

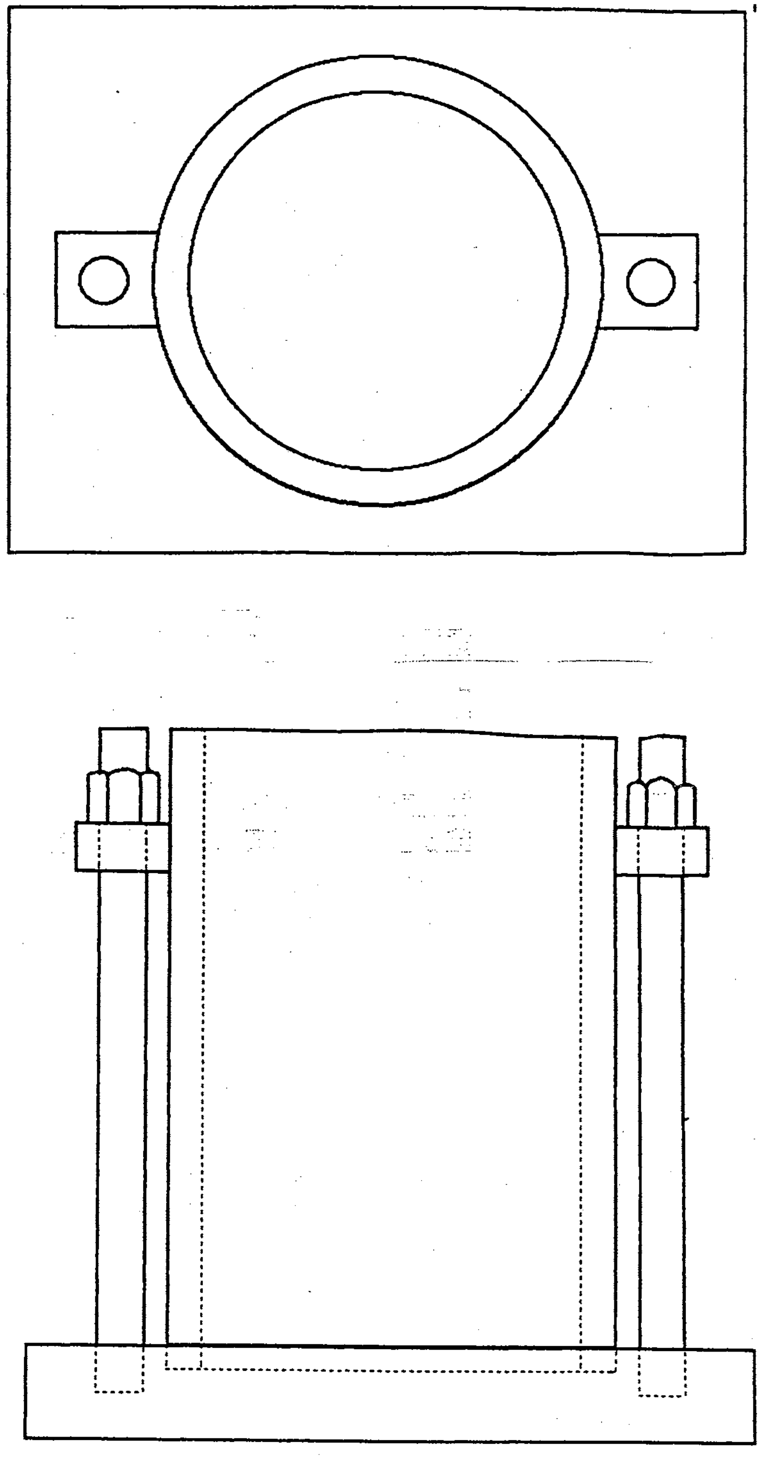


Figure 8. Mold Assembly for Dynamic Compaction Apparatus.

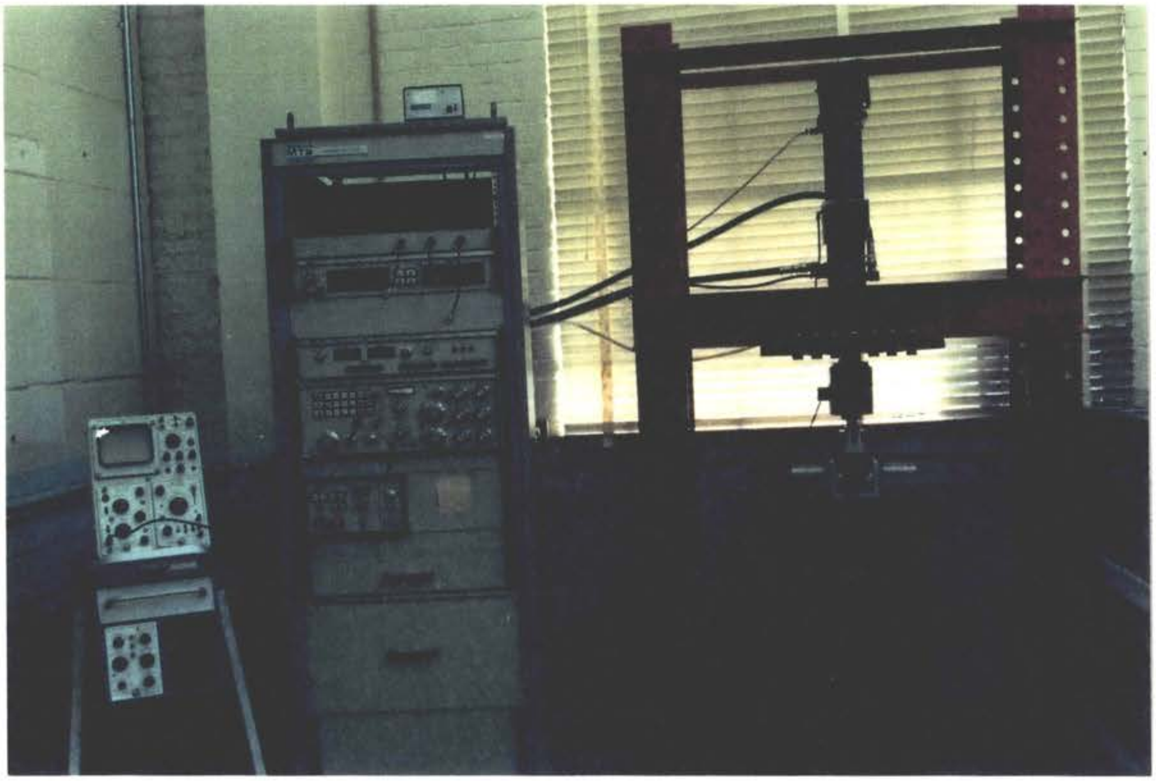


Figure 9. Resilient Modulus Testing Machine.

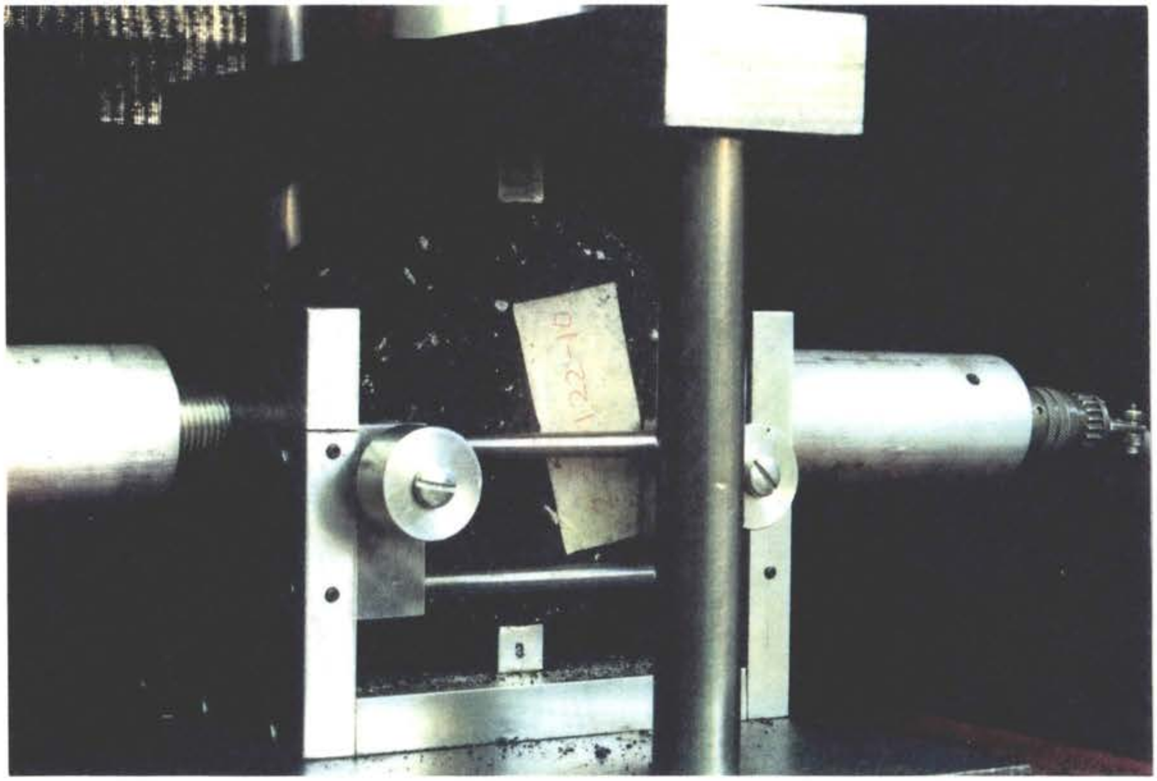


Figure 10. Specimen Setup for Resilient Modulus Testing.

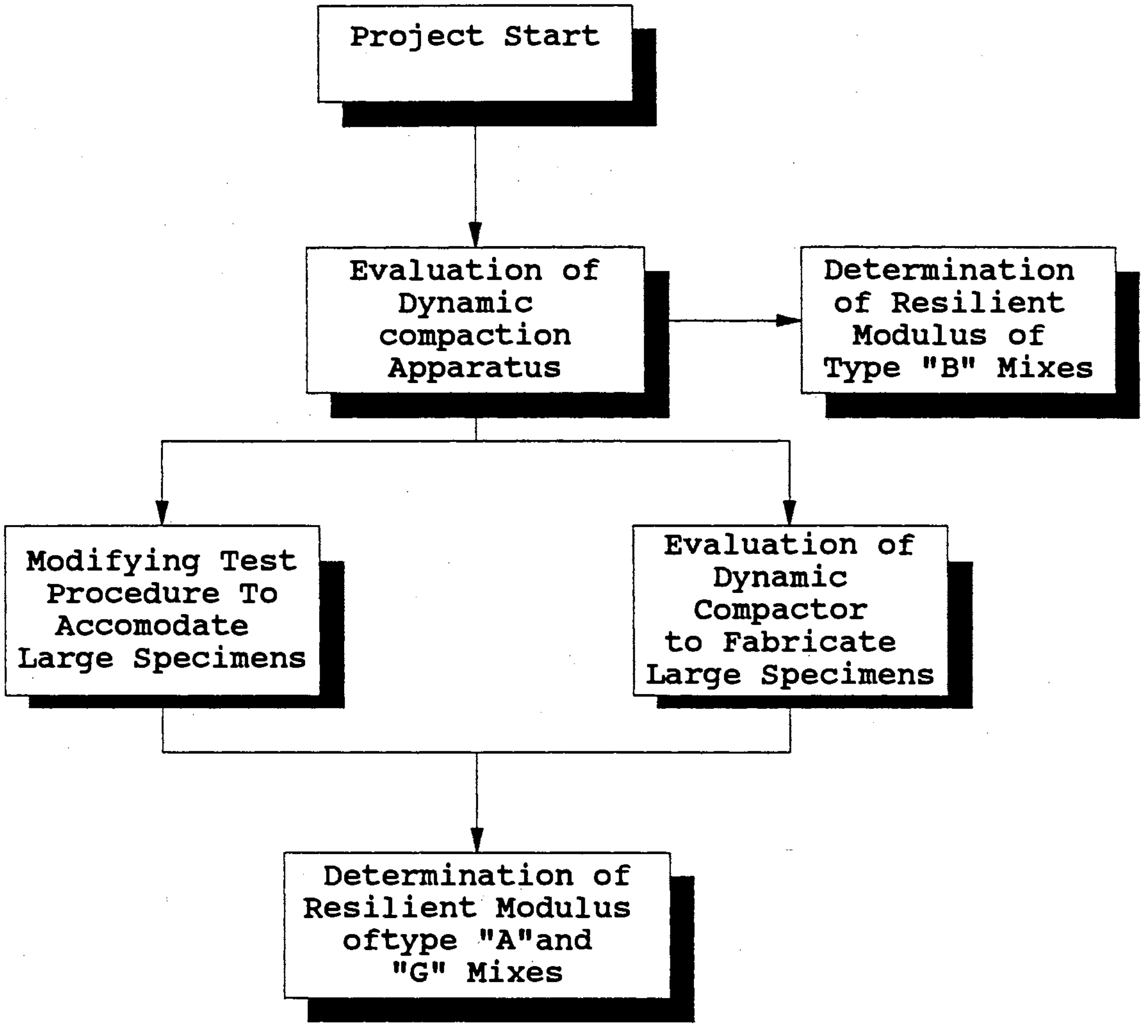


Figure 11. Overall Flow Chart for the Project.

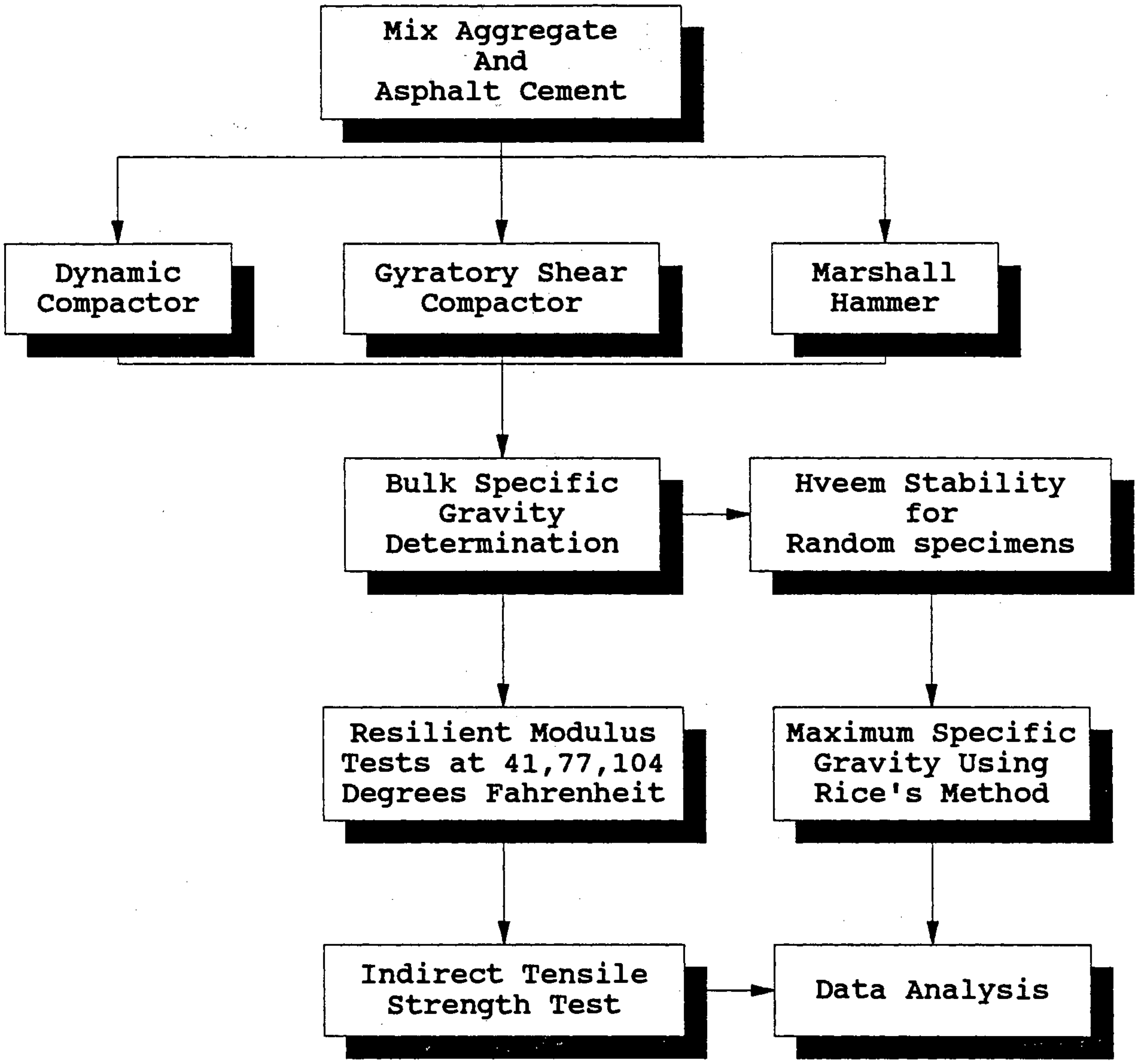


Figure 12. Flow Chart for Phase I.

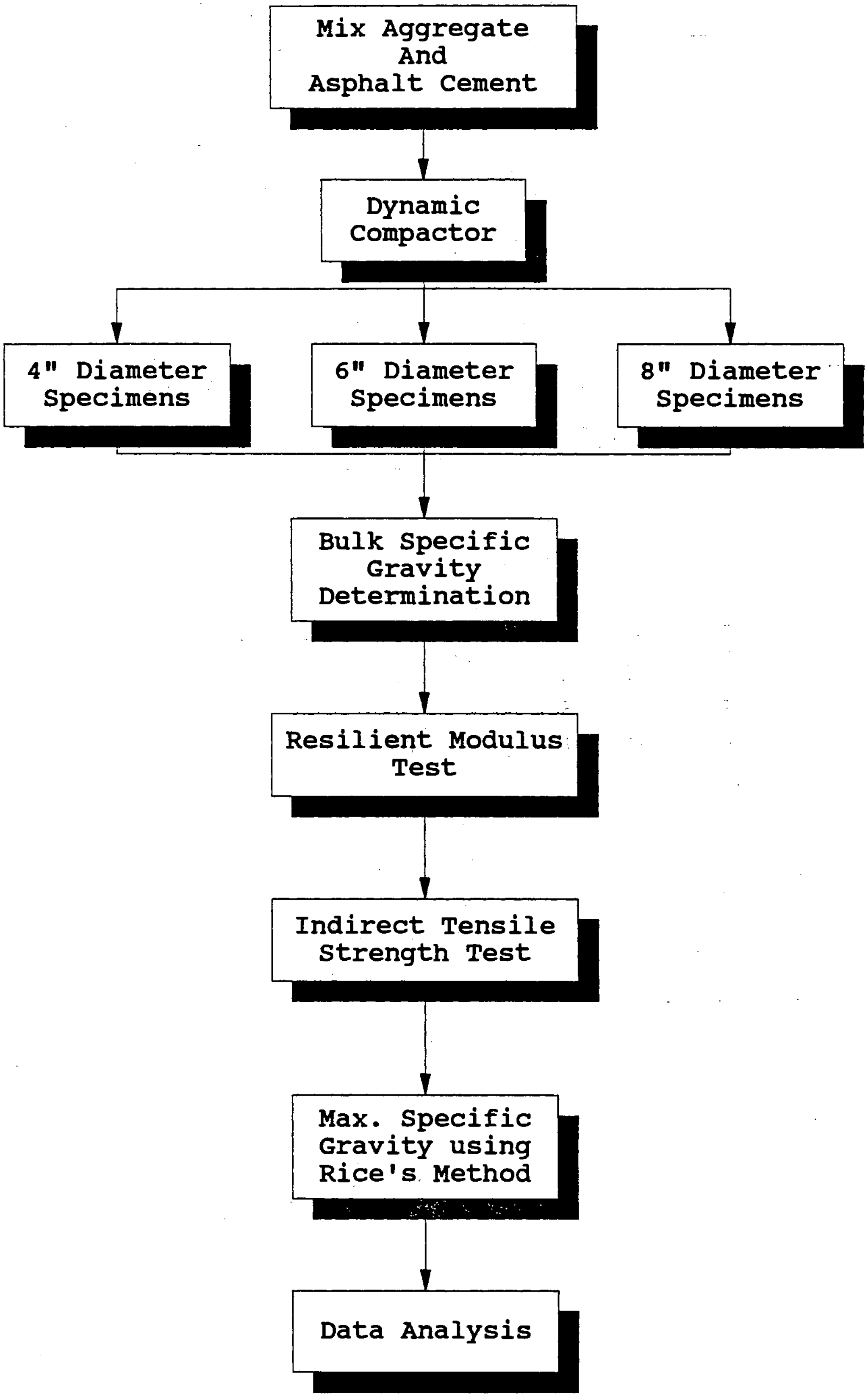


Figure 13. Flow Chart for Phase II.

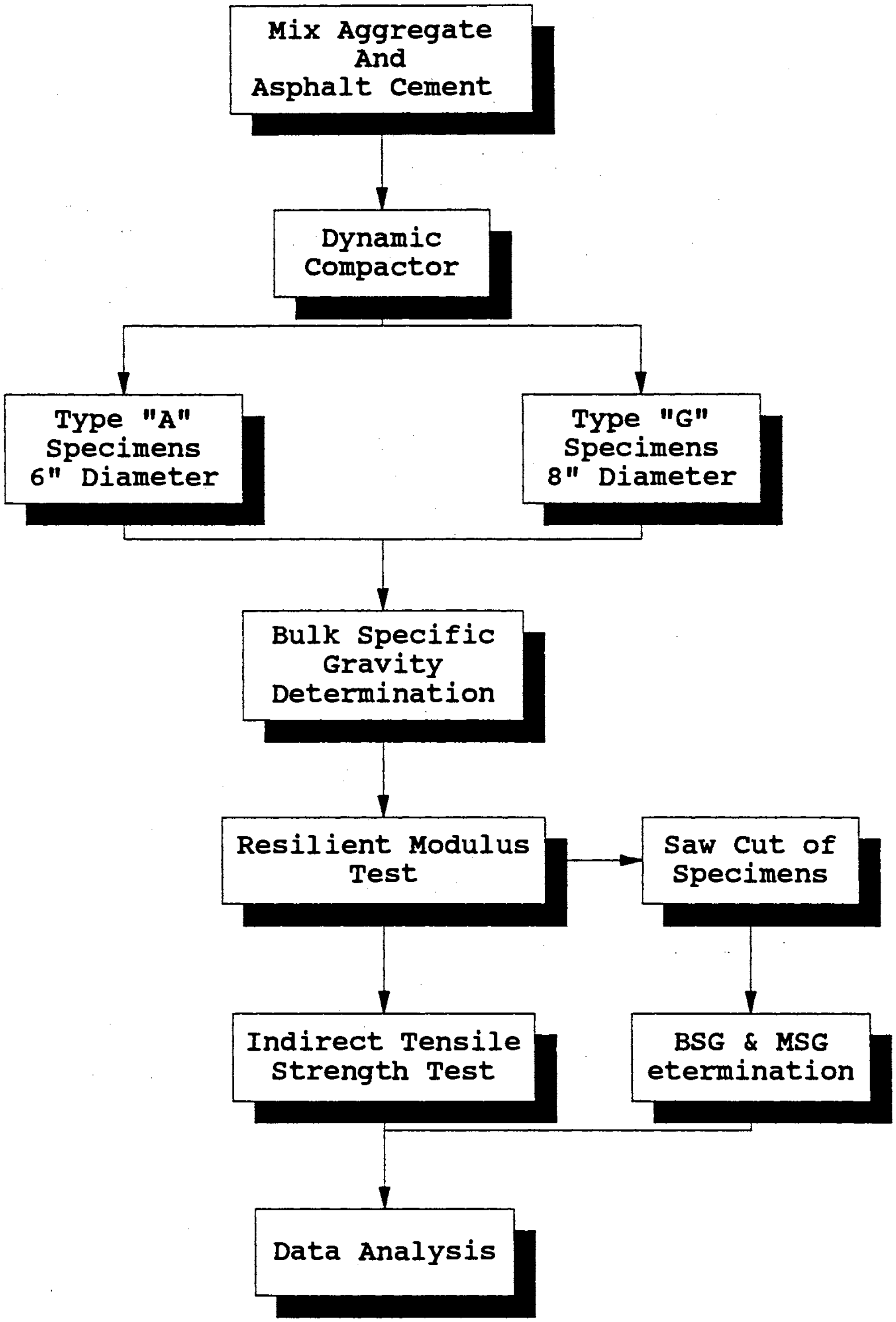


Figure 14. Flow Chart for Phase III.

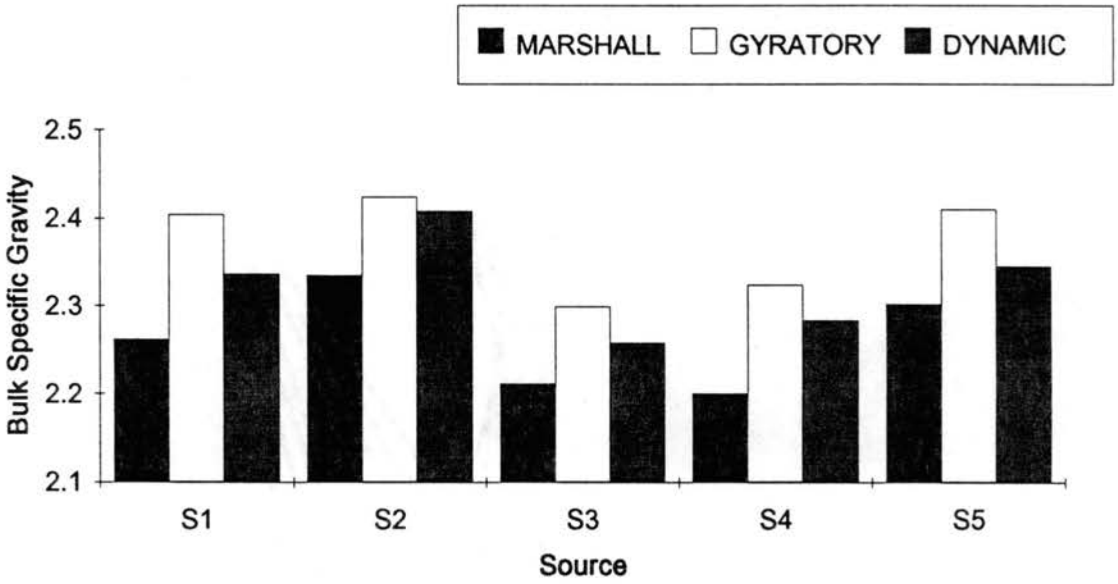


Figure 15. Bulk Specific Gravity of Type "B" Asphalt Concrete Mixes.

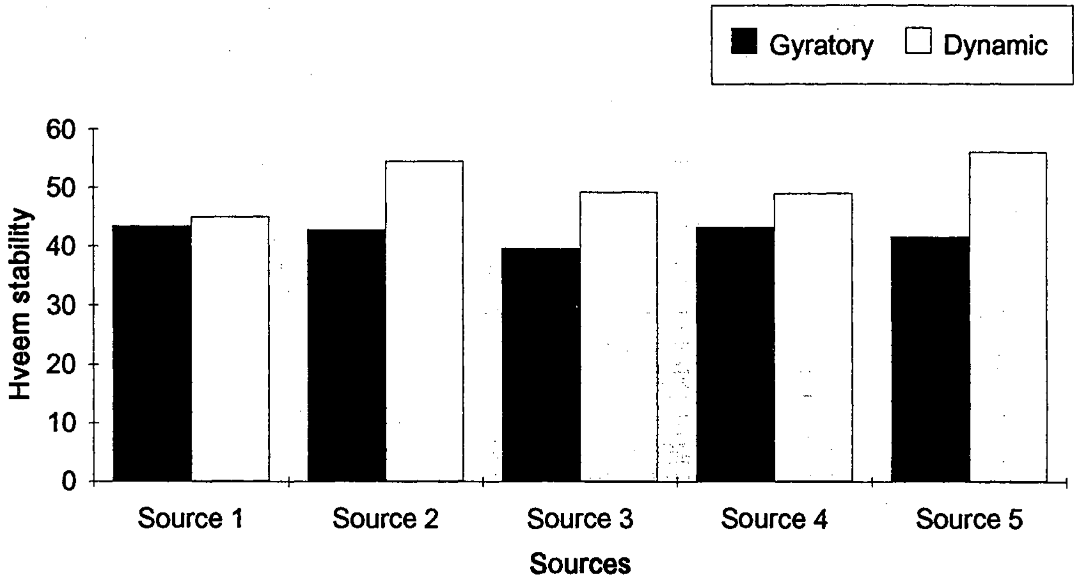


Figure 16. Hveem Stability Values of Dynamic and Gyratory Compacted Specimens.

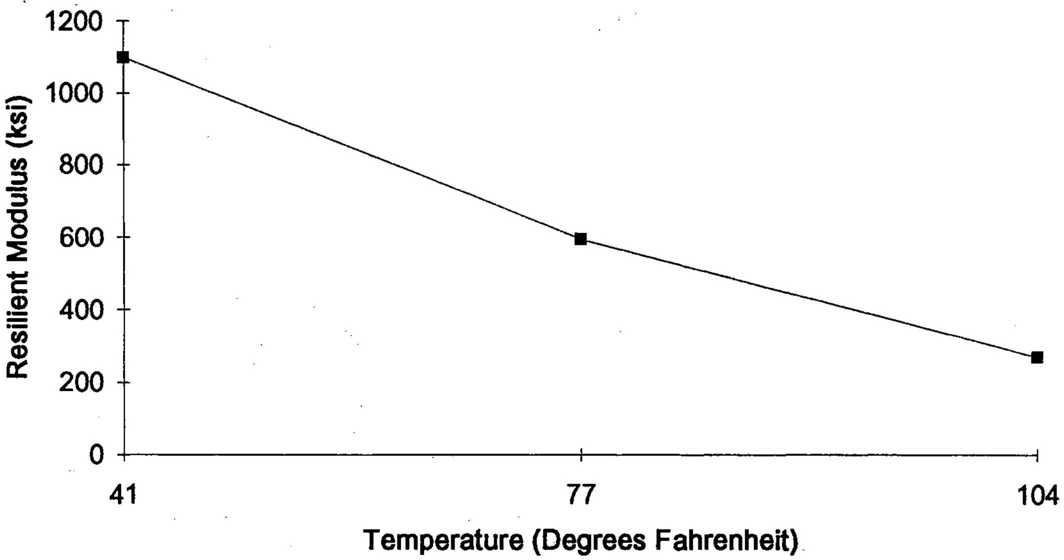


Figure 17. Resilient Modulus of Type "B" Asphalt Concrete Mixes.

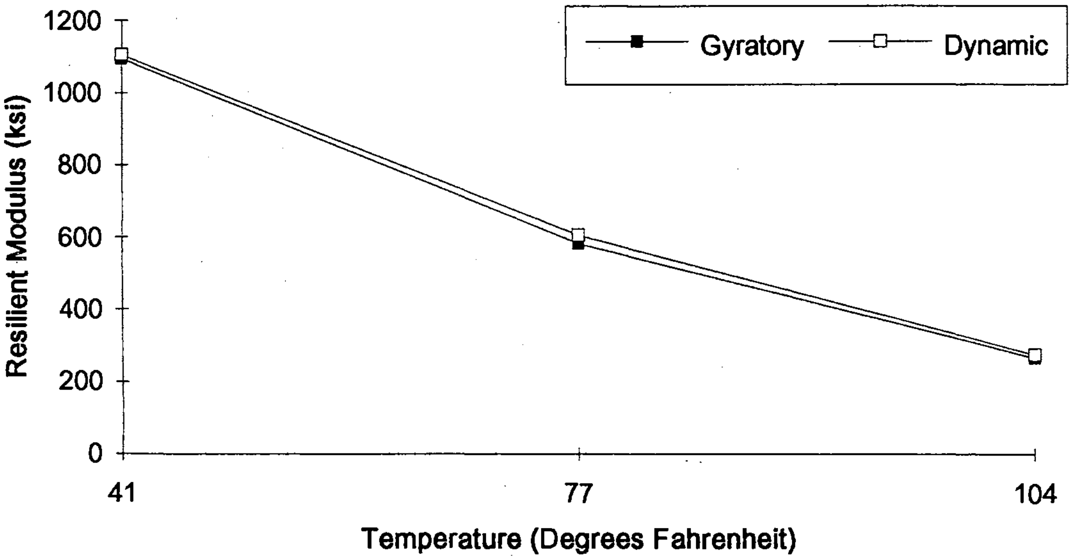


Figure 18. Resilient Modulus of Dynamic and Gyratory Shear Compacted Specimens.

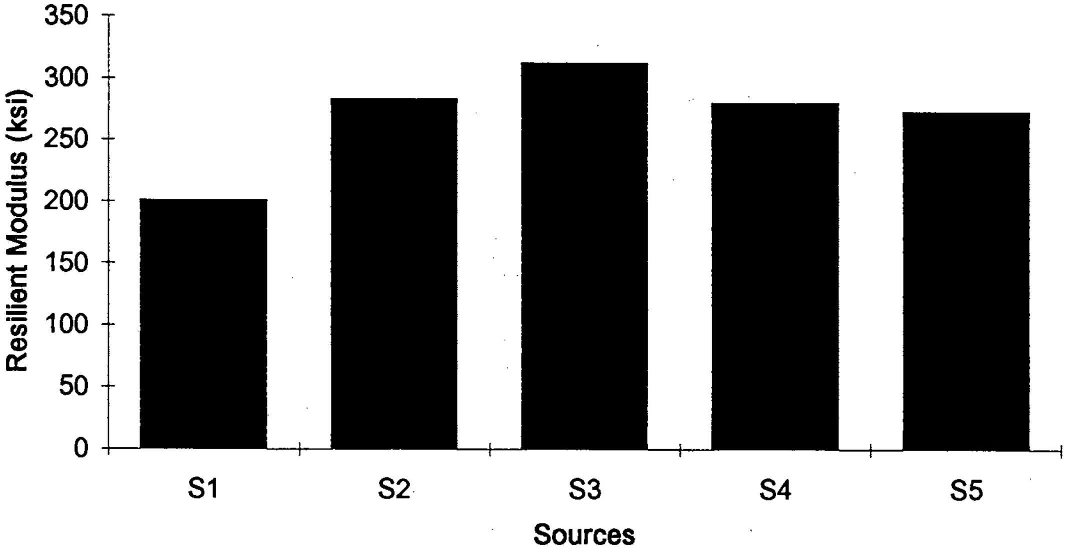


Figure 19. Mean Resilient Modulus of Type "B" Asphalt Concrete Mixes at 104°F.

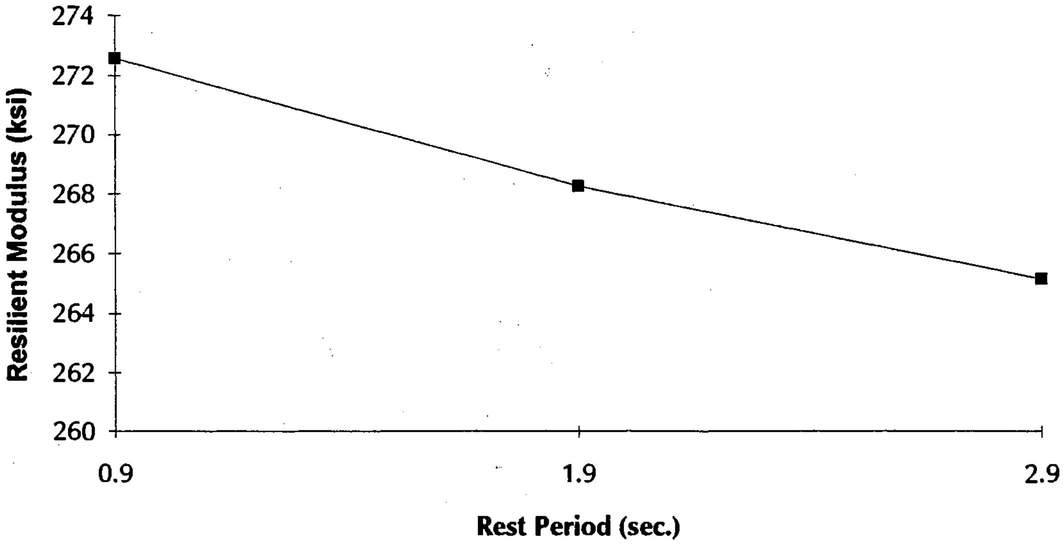


Figure 20. Mean Resilient Modulus of Type "B" Asphalt Concrete Mixes -Three Rest Periods at 104°F.

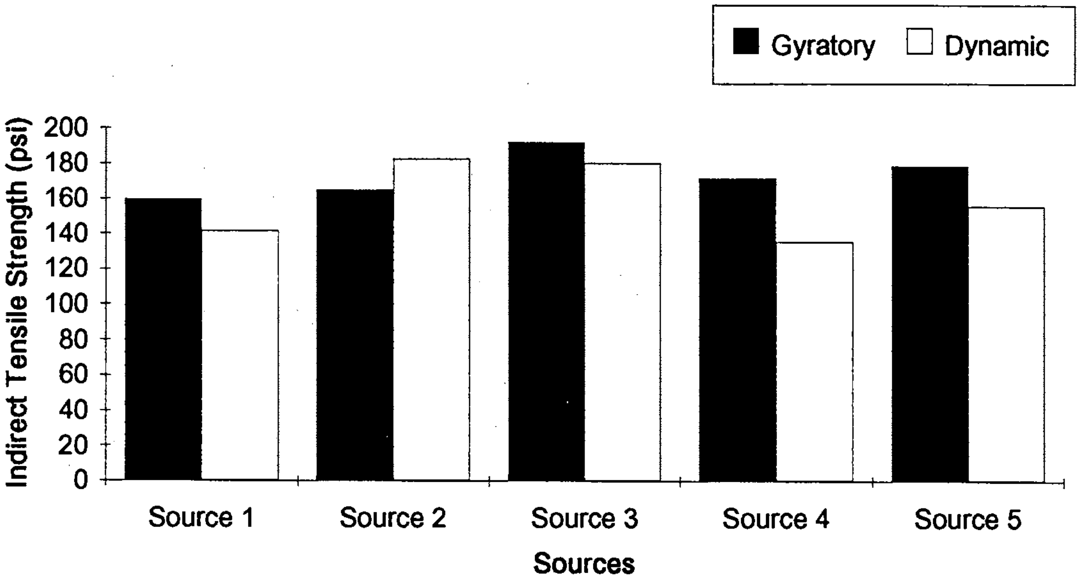


Figure 21. Indirect Tensile Strength of Type "B" Asphalt Concrete Mixes.

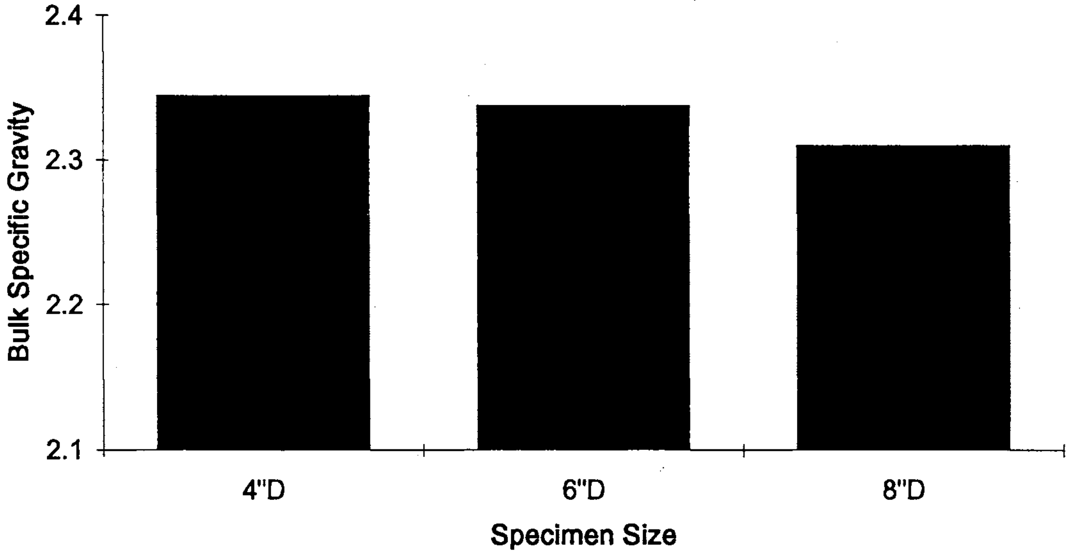


Figure 22. Bulk Specific Gravity of Dynamically Compacted Specimens (Differentiated by Sizes).

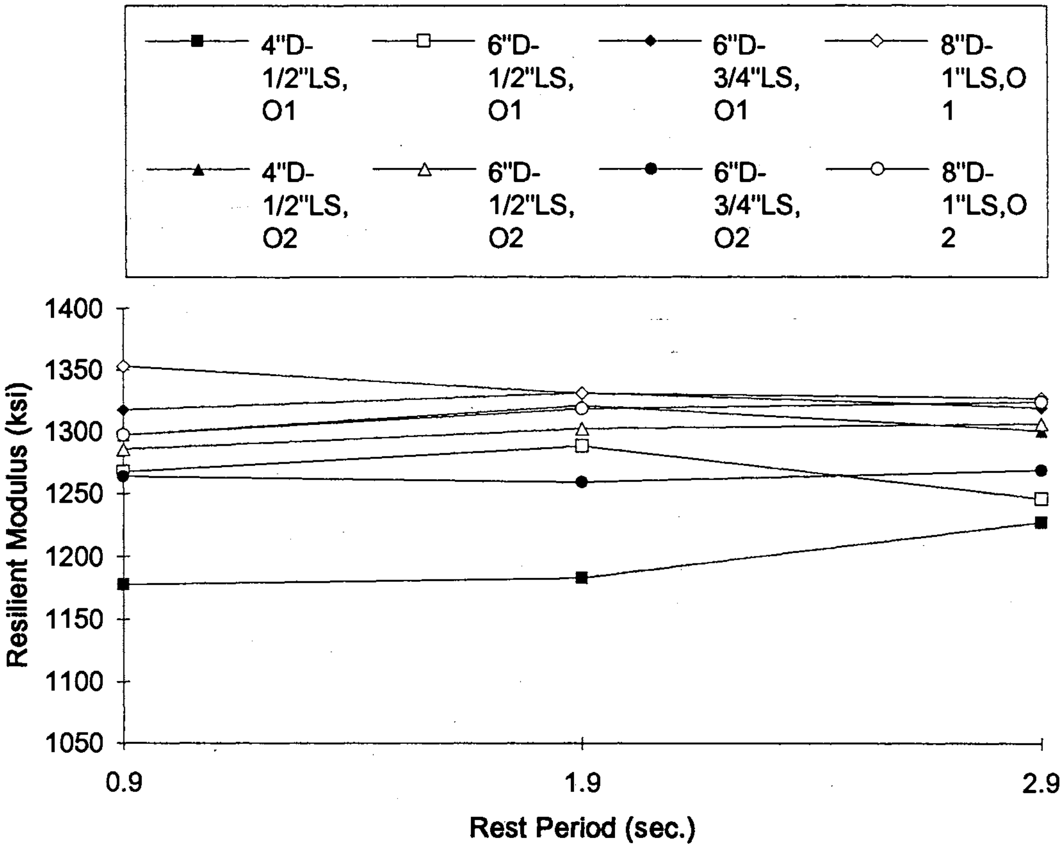


Figure 23. Three Way Interaction, Size * Orientation * Rest Period, at 41°F (Phase II).

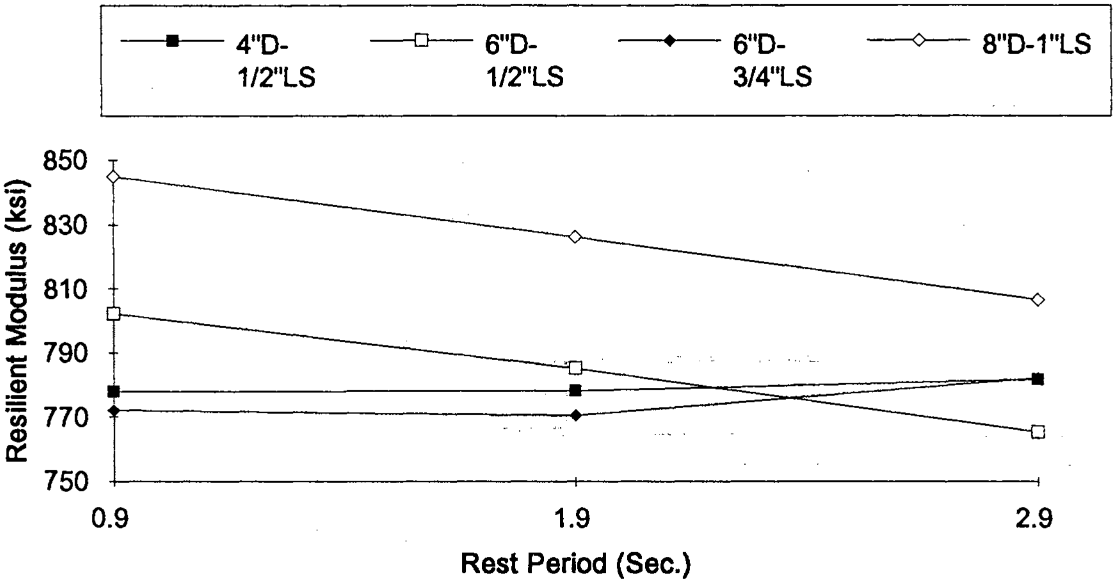


Figure 24. The Effect of Size and Rest Period Resilient Modulus of a Typical Type "B" Asphalt Concrete mixes at 77°F.

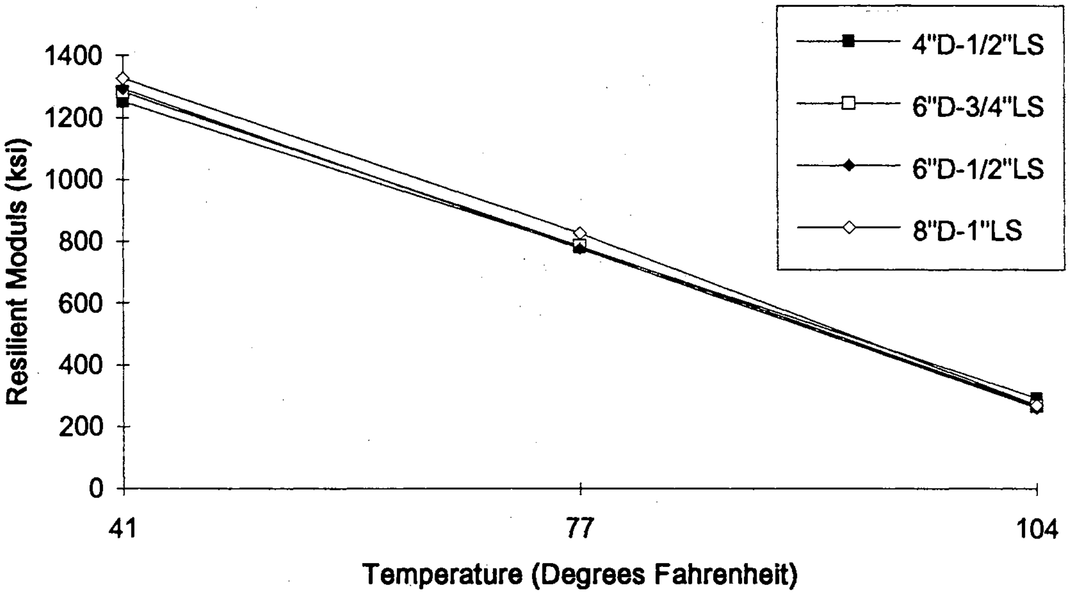


Figure 25. Resilient Modulus of Typical type "B" Asphalt Concrete Mixes (Differentiated by Sizes).

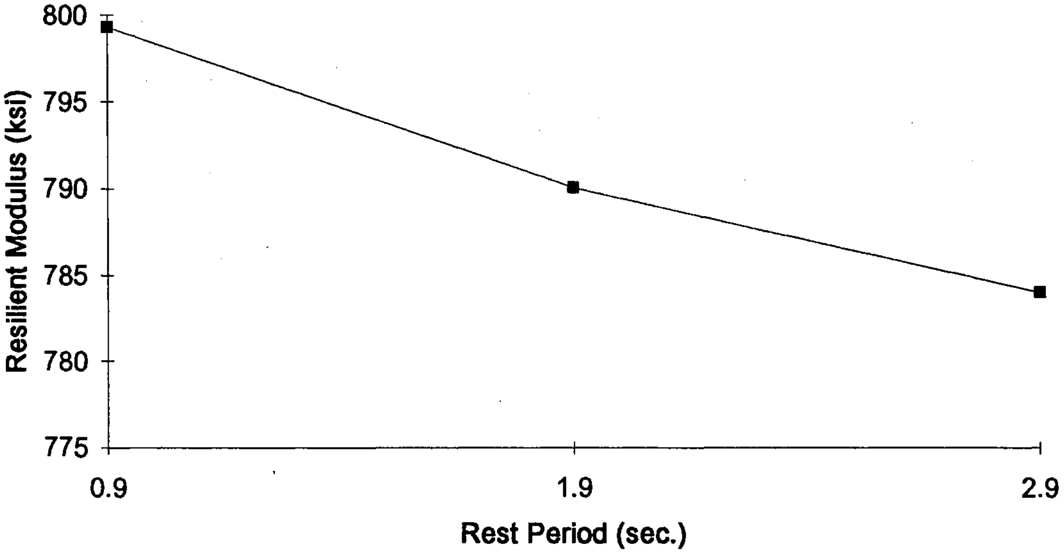


Figure 26. The Effect of Rest Period on the Resilient Modulus of Typical Type "B" Asphalt Concrete Mixes at 77°F (Phase II).

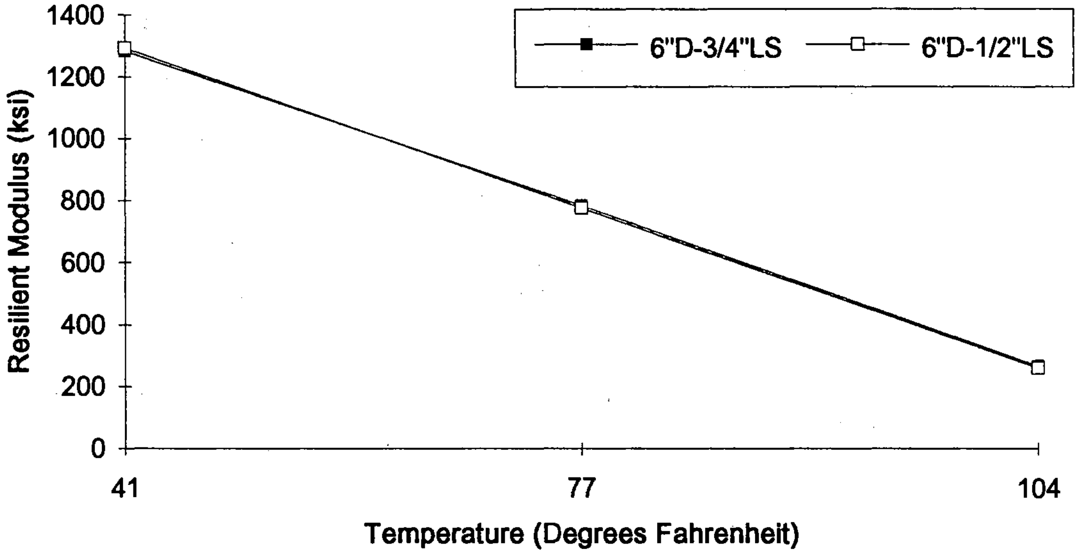


Figure 27. Resilient Modulus of Typical type "B" Six Inch Diameter Specimens Tested With 1/2 and 3/4 Inch Loading Strip.

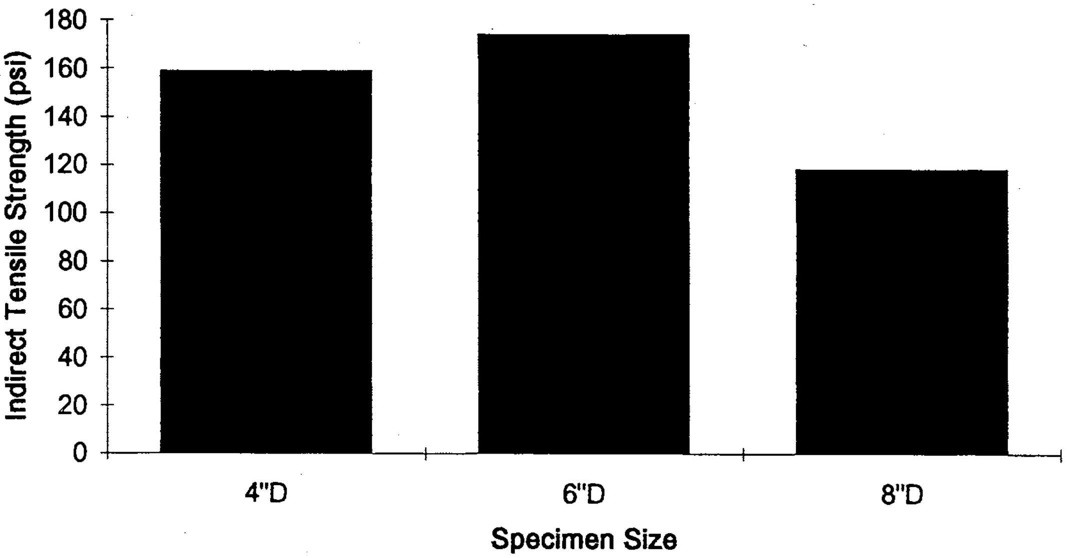


Figure 28. Indirect Tensile Strength of Typical Type "B" Asphalt Concrete Mixes.

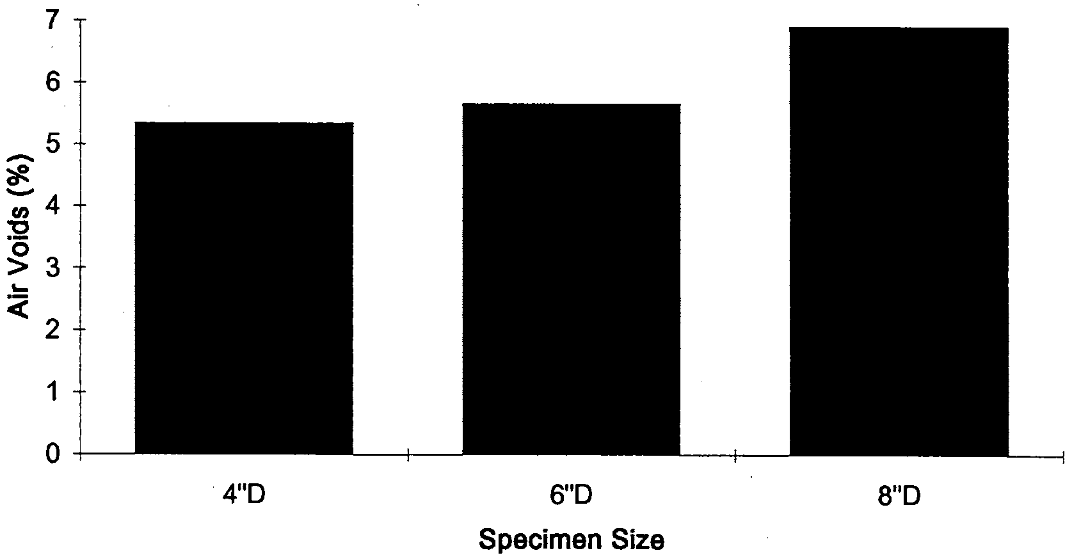


Figure 29. Percent Air Void of Dynamically Compacted Specimens of Typical Type "B" Mixes.

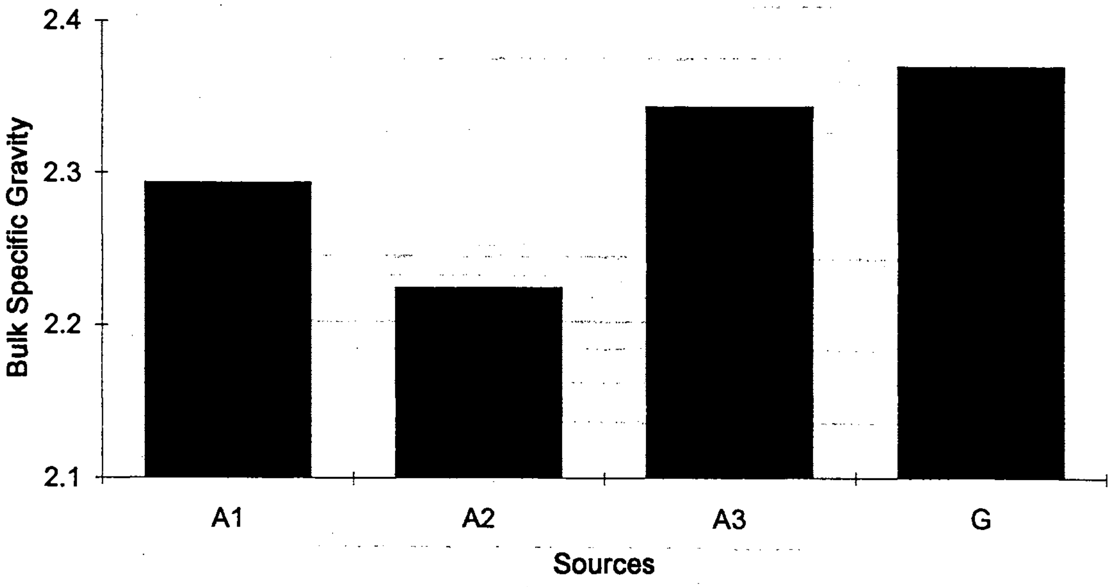


Figure 30. Bulk Specific Gravity of Type "A" and "G Asphalt Concrete Mixes.

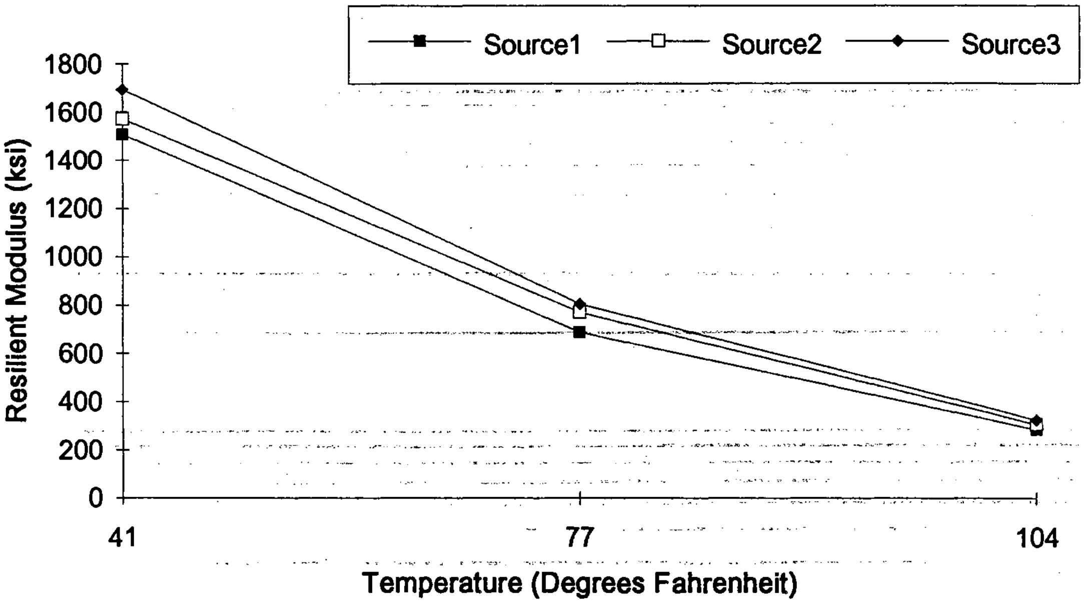


Figure 31. Resilient Modulus of Type "A" Asphalt Concrete Mixes.

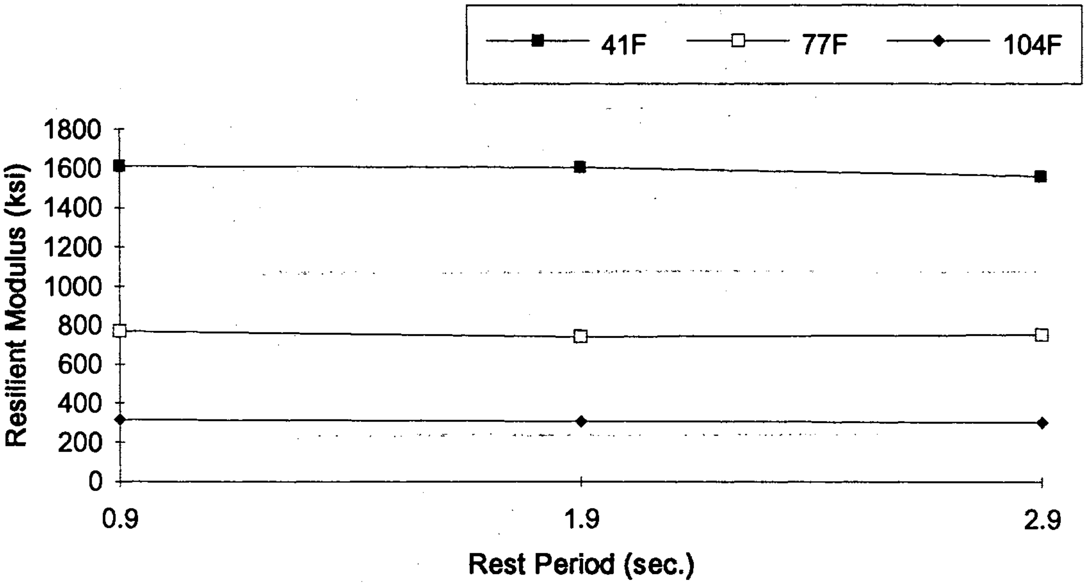


Figure 32. The Effect of Rest Period on Resilient Modulus of Type "A" Asphalt Concrete Mixes.

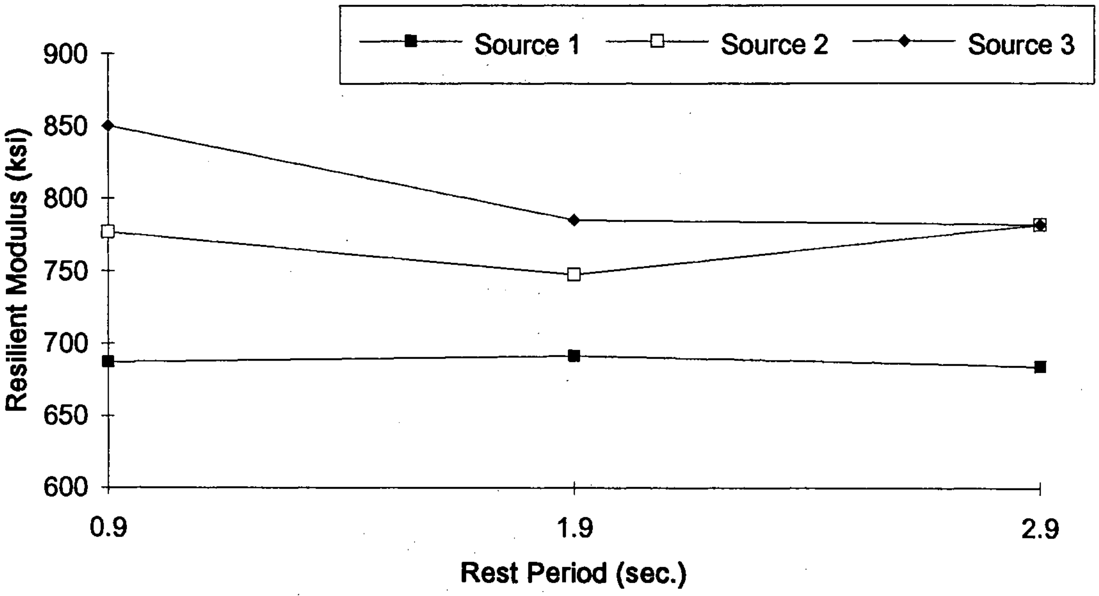


Figure 33. The Effect of Rest Period and Source on Resilient Modulus of Type "A" Asphalt Concrete Mixes at 77°F.

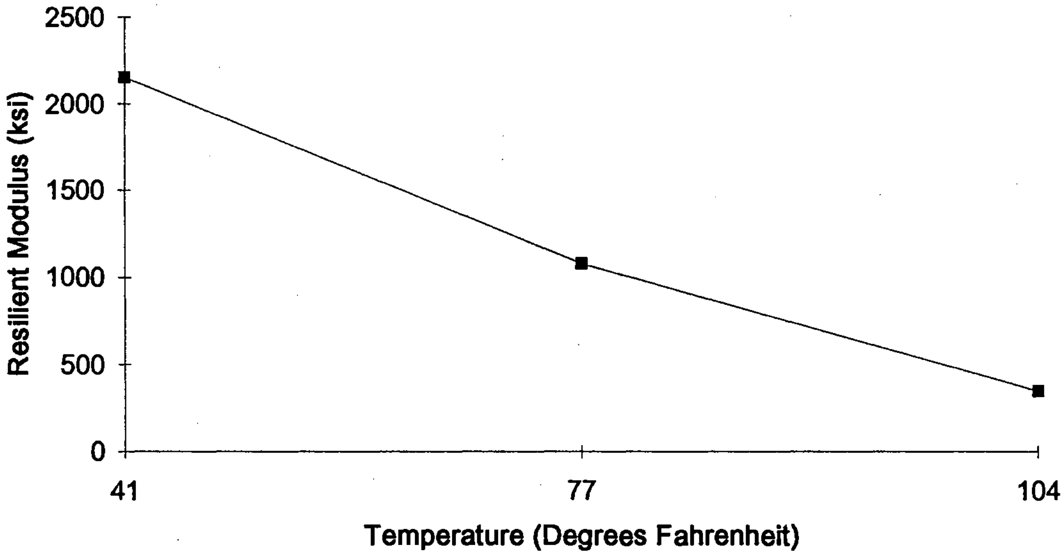


Figure 34. Resilient Modulus of Type "G" Asphalt Concrete Mixes.

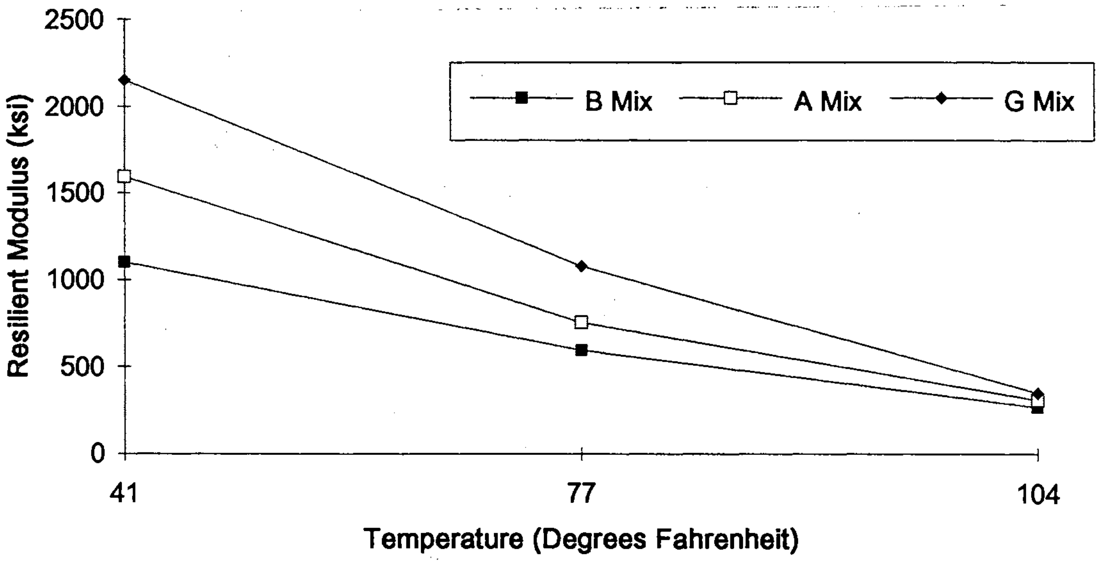


Figure 35. Resilient Modulus of Type "A", "B", and "G" Asphalt Concrete Mixes.

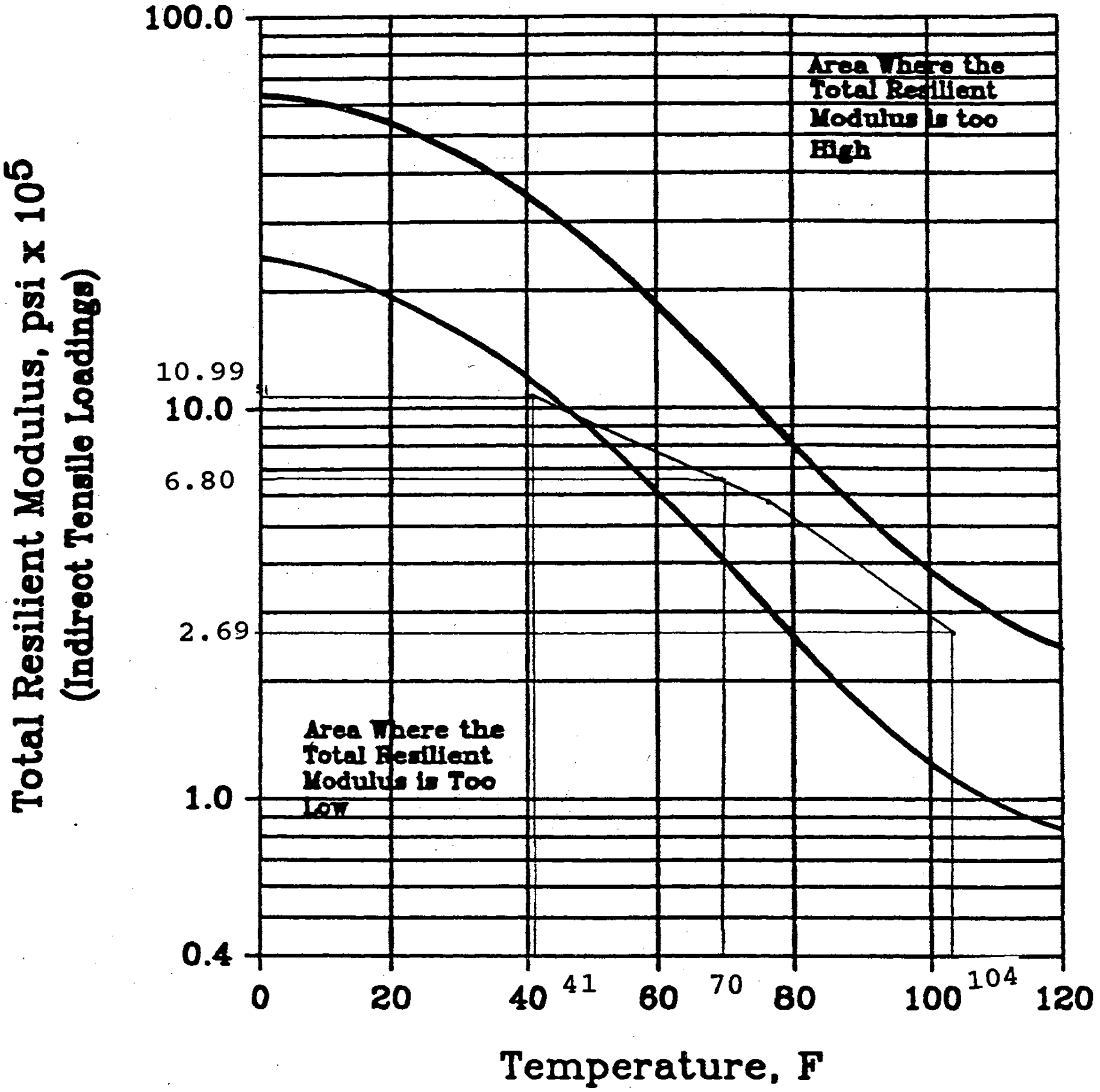


Figure 36. Chart for Total Resilient Modulus vs. Temperature Using Indirect Tensile Loading Condition (44).

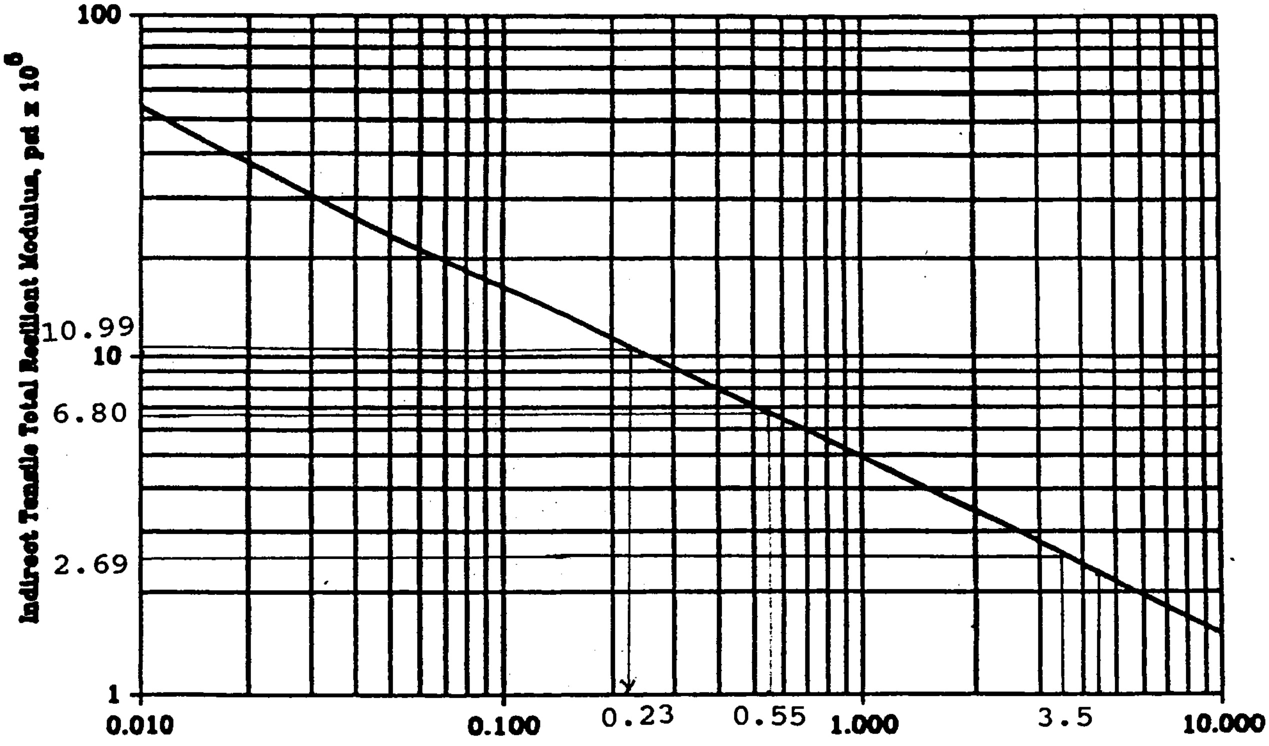


Figure 37. Estimation of Fatigue Factor to Determine Equivalent Annual Modulus (47).

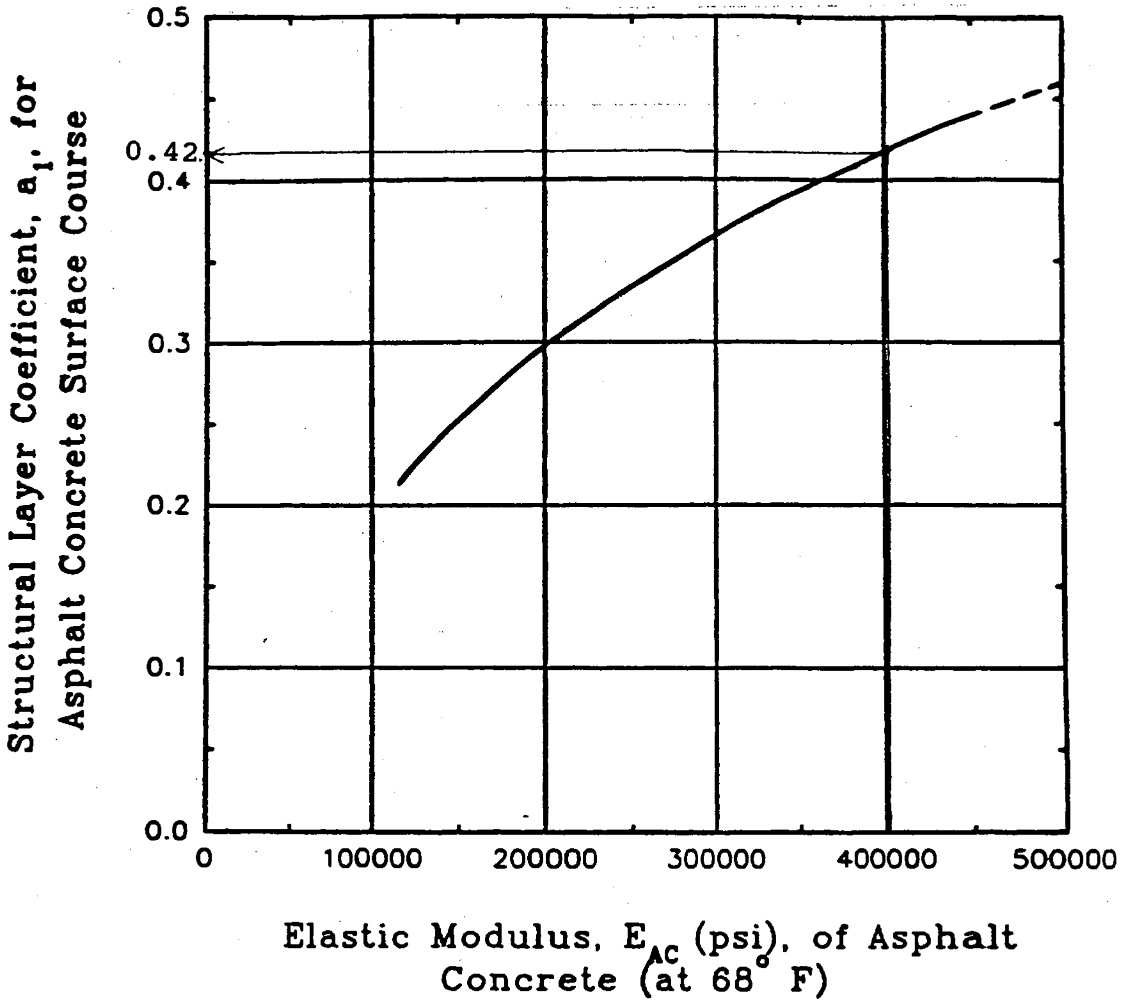


Figure 38. Chart for Estimating Structural Layer Coefficient (1).

APPENDIX B

TABLES

TABLE 1

AGGREGATE GRADATION FOR OKLAHOMA DEPARTMENT OF TRANSPORTATION ASPHALT CONCRETE MIXES

	Asphalt Concrete Mixture Type		
	A	B	G
Sieve Size	Percent Passing (By Weight)		
2-1/2"	-	-	100
2"	-	-	95-100
1-1/2"	100	-	85-100
1"	90-100	-	60-75
3/4"	-	100	-
1/2"	70-90	90-100	40-55
3/8"	-	70-90	-
No. 4	40-65	45-70	20-40
No. 10	25-45	25-50	13-27
No. 40	10-26	12-30	5-14
No. 80	6-18	7-20	3-10
No. 200	*	*	*

* The ratio of the percent passing the No. 200 sieve to the percent asphalt cement shall be a minimum of 0.6 to a maximum of 1.2.

TABLE 2

BULK SPECIFIC GRAVITY OF SPECIMENS AGGREGATE SOURCE 1

Specimen No.	Type of Compaction Marshall	Gyratory	Dynamic
1	2.279	2.400	2.338
2	2.276	2.412	2.352
3	2.246	2.400	2.323
4	2.233	2.412	2.343
5	2.270	2.410	2.321
6	2.250	2.411	2.341
7	2.261	2.411	2.330
8	2.255	2.395	2.350
9	2.260	2.408	2.336
10	2.269	2.405	2.329
11	2.252	2.402	2.333
12	2.266	2.401	2.346
13	2.278	2.394	2.320
14	2.270	2.400	2.345
15	2.267	2.405	2.326

TABLE 3

BULK SPECIFIC GRAVITY OF SPECIMENS AGGREGATE SOURCE 2

Specimen No.	Type of Compaction Marshall	Gyratory	Dynamic
1	2.343	2.458	2.403
2	2.348	2.450	2.399
3	2.339	2.420	2.394
4	2.354	2.458	2.370
5	2.336	2.417	2.417
6	2.320	2.423	2.417
7	2.312	2.413	2.392
8	2.341	2.404	2.399
9	2.335	2.425	2.437
10	2.310	2.429	2.420
11	2.338	2.386	2.412
12	2.331	2.386	2.412
13	2.334	2.428	2.405
14	2.349	2.420	2.399
15	2.340	2.406	2.416

TABLE 4

BULK SPECIFIC GRAVITY OF SPECIMENS
AGGREGATE SOURCE 3

Specimen No.	Type of Compaction Marshall	Gyratory	Dynamic
1	2.197	2.302	2.252
2	2.220	2.301	2.257
3	2.242	2.303	2.254
4	2.172	2.294	2.262
5	2.217	2.318	2.260
6	2.209	2.294	2.267
7	2.202	2.289	2.280
8	2.210	2.294	2.258
9	2.223	2.301	2.276
10	2.201	2.315	2.249
11	2.217	2.280	2.247
12	2.213	2.313	2.234
13	2.209	2.285	2.249
14	2.223	2.303	2.258
15	2.216	2.292	2.245

TABLE 5

BULK SPECIFIC GRAVITY OF SPECIMENS
AGGREGATE SOURCE 4

Specimen No.	Type of Compaction Marshall	Gyratory	Dynamic
1	2.202	2.335	2.337
2	2.154	2.330	2.333
3	2.222	2.353	2.345
4	2.221	2.379	2.319
5	2.180	2.349	2.243
6	2.204	2.246	2.259
7	2.194	2.265	2.288
8	2.212	2.355	2.304
9	2.203	2.285	2.269
10	2.200	2.358	2.282
11	2.217	2.280	2.247
12	2.179	2.345	2.261
13	2.215	2.366	2.259
14	2.214	2.367	2.261
15	2.190	2.254	2.244

TABLE 6

BULK SPECIFIC GRAVITY OF SPECIMENS
AGGREGATE SOURCE 5

Specimen No.	Type of Compaction Marshall	 Gyratory	 Dynamic
1	2.293	2.408	2.363
2	2.308	2.410	2.351
3	2.314	2.404	2.362
4	2.289	2.410	2.368
5	2.306	2.402	2.373
6	2.284	2.419	2.372
7	2.298	2.406	2.332
8	2.302	2.407	2.335
9	2.290	2.409	2.314
10	2.332	2.411	2.319
11	2.307	2.417	2.343
12	2.322	2.406	2.361
13	2.296	2.414	2.332
14	2.291	2.413	2.332
15	2.302	2.413	2.315

TABLE 7

STABILITY TEST RESULTS
AGGREGATE SOURCE 1

Source	Compaction	AC%[1]	BSG[2]	Stability
1	G[3]	5.0	2.412	45
1	G	5.0	2.410	42
1	G	5.0	2.408	44
1	G	5.0	2.405	41
1	G	5.0	2.405	45
1	D[4]	5.0	2.343	51
1	D	5.0	2.320	49
1	D	5.0	2.329	44
1	D	5.0	2.336	49
1	D	5.0	2.345	50

[1] AC% = Percent Asphalt Content
[2] BSG = Bulk Specific Gravity
[3] G = Gyratory Shear
[4] D = Dynamic Compaction Apparatus

TABLE 8

STABILITY TEST RESULTS
AGGREGATE SOURCE 2

Source	Compaction	AC%[1]	BSG[2]	Stability
2	G[3]	4.6	2.417	42
2	G	4.6	2.425	43
2	G	4.6	2.426	44
2	G	4.6	2.418	43
2	G	4.6	2.420	42
2	D[4]	4.6	2.394	48
2	D	4.6	2.370	47
2	D	4.6	2.417	58
2	D	4.6	2.412	57
2	D	4.6	2.416	62

[1] AC% = Percent Asphalt Content
[2] BSG = Bulk Specific Gravity
[3] G = Gyratory Shear
[4] D = Dynamic Compaction Apparatus

TABLE 9

STABILITY TEST RESULTS
AGGREGATE SOURCE 3

Source	Compaction	AC%[1]	BSG[2]	Stability
3	G[3]	5.3	2.302	39
3	G	5.3	2.303	40
3	G	5.3	2.301	40
3	G	5.3	2.280	39
3	G	5.3	2.285	39
3	D[4]	5.3	2.254	48
3	D	5.3	2.267	51
3	D	5.3	2.258	49
3	D	5.3	2.249	47
3	D	5.3	2.245	51

[1] AC% = Percent Asphalt Content
[2] BSG = Bulk Specific Gravity
[3] G = Gyratory Shear
[4] D = Dynamic Compaction Apparatus

TABLE 10

STABILITY TEST RESULTS
AGGREGATE SOURCE 4

Source	Compaction	AC%[1]	BSG[2]	Stability
4	G[3]	5.2	2.335	40
4	G	5.2	2.330	45
4	G	5.2	2.265	41
4	G	5.2	2.309	45
4	G	5.2	2.366	45
4	D[4]	5.2	2.337	55
4	D	5.2	2.345	41
4	D	5.2	2.304	50
4	D	5.2	2.253	50
4	D	5.2	2.261	41

[1] AC% = Percent Asphalt Content
[2] BSG = Bulk Specific Gravity
[3] G = Gyratory Shear
[4] D = Dynamic Compaction Apparatus

TABLE 11

STABILITY TEST RESULTS
AGGREGATE SOURCE 5

Source	Compaction	AC%[1]	BSG[2]	Stability
5	G[3]	4.7	2.404	43
5	G	4.7	2.402	44
5	G	4.7	2.406	42
5	G	4.7	2.414	41
5	G	4.7	2.413	38
5	D[4]	4.7	2.360	61
5	D	4.7	2.362	50
5	D	4.7	2.372	57

[1] AC% = Percent Asphalt Content
[2] BSG = Bulk Specific Gravity
[3] G = Gyratory Shear
[4] D = Dynamic Compaction Apparatus

TABLE 12

MIX DESIGN CHARACTERISTICS OF TYPE "B" MIXES

Source	Sample No.	BSG[1]	MSG[2]	% Air Voids	Density (lb/ft^3)	ITS[3] (psi)
Gyratory Shear Compacted Specimens						
1	1	2.362	2.475	4.57	147.39	166
	2	2.352	2.434	3.37	146.76	157
	3	2.350	2.438	3.61	146.64	155
2	1	2.445	2.525	3.17	152.57	162
	2	2.458	2.543	3.34	153.38	178
	3	2.386	2.511	4.98	148.89	155
3	1	2.294	2.432	5.67	143.15	203
	2	2.318	2.440	5.00	144.64	191
	3	2.303	2.439	5.58	143.71	182
4	1	2.355	2.441	3.52	146.95	186
	2	2.285	2.439	6.31	142.58	122
	3	2.358	2.432	3.04	147.14	208
5	1	2.406	2.487	3.26	150.13	201
	2	2.407	2.512	4.18	150.20	167
	3	2.409	2.499	3.60	150.32	169
Dynamically Compacted Specimens						
1	1	2.340	2.490	6.02	146.02	165
	2	2.355	2.478	4.96	146.95	126
	3	2.366	2.490	4.98	147.64	134
2	1	2.410	2.510	3.98	150.38	178
	2	2.420	2.520	3.97	151.01	197
	3	2.410	2.520	4.37	150.38	172
3	1	2.330	2.460	5.28	145.39	164
	2	2.320	2.460	5.69	144.77	187
	3	2.340	2.450	4.49	146.02	190
4	1	2.270	2.430	6.58	141.65	145
	2	2.260	2.440	7.38	141.02	144
	3	2.257	2.430	7.12	140.84	118
5	1	2.370	2.460	3.66	147.89	168
	2	2.340	2.480	5.65	146.02	151
	3	2.340	2.470	5.26	146.02	149

---

[1] BSG = Bulk Specific Gravity
[2] MSG = Maximum Specific Gravity
[3] ITS = Indirect Tensile Strength

TABLE 13

MIX DESIGN CHARACTERISTICS OF TYPE "B" MIXES (MARSHALL HAMMER COMPACTED SPECIMENS)

Source	Sample#	BSG[1]	MSG[2]	%Air
1	1	2.348	2.527	7.1
	2	2.312	2.532	8.7
	3	2.310	2.530	8.7
	4	2.331	2.531	7.9
	5	2.334	2.527	7.6
			Average:	8.0
2	1	2.220	2.461	9.7
	2	2.223	2.443	8.8
	3	2.217	2.450	9.5
	4	2.213	2.446	10.0
	5	2.216	2.440	9.0
			Average:	9.4
3	1	2.308	2.483	7.0
	2	2.314	2.472	6.4
	3	2.289	2.471	7.4
	4	2.298	2.478	7.3
	5	2.307	2.471	6.6
			Average:	6.9
Percent Air Voids of Marshall Specimens:				8.1

---

[1] BSG = Bulk Specific Gravity
[2] MSG = Maximum Specific Gravity

TABLE 14

RESILIENT MODULUS (KSI) OF OKLAHOMA TYPE "B" MIXES - (41°F)

						Rest Period			
				0.9 Sec.		1.9 Sec.		2.9 Sec.	
				Orientation		Orientation		Orientation	
Source	Compaction	Temp.		1	2	1	2	1	2
1	Gyratory	41	1	1118	1028	1112	1142	1157	1143
		41	2	868	1282	929	1256	949	1226
		41	3	1220	918	1140	864	1129	887
	Dynamic	41	1	1113	982	1045	926	1070	966
		41	2	1030	1014	1057	919	991	904
		41	3	1101	1167	1154	1140	1150	1093
2	Gyratory	41	1	933	948	837	918	820	860
		41	2	1211	1343	1224	1229	1351	1234
		41	3	1031	1078	1068	1058	1028	1169
	Dynamic	41	1	1105	1156	1185	1261	1183	1301
		41	2	1073	1245	1040	1003	1026	1004
		41	3	1133	1076	1153	1019	1113	1059
3	Gyratory	41	1	1135	1289	1180	1226	1244	1282
		41	2	964	1015	953	1024	919	952
		41	3	1024	1130	1005	1193	958	1216
	Dynamic	41	1	1169	995	1226	943	1119	991
		41	2	1120	1122	1100	1069	1140	1029
		41	3	1017	1119	1025	1129	1018	1157

TABLE 14 (Contd.)

RESILIENT MODULUS (KSI) OF OKLAHOMA TYPE "B" MIXES - (41°F)

Source	Compaction	Temp.		0.9 Sec.		Rest Period 1.9 Sec.		2.9 Sec.	
				Orientation		Orientation		Orientation	
				1	2	1	2	1	2
4	Gyratory	41	1	1016	1110	1053	995	1082	984
		41	2	1195	1105	1221	1057	1216	1039
		41	3	1028	1224	970	1182	999	1072
	Dynamic	41	1	1316	1134	1247	1138	1282	1114
		41	2	1121	1232	1100	1244	1082	1215
		41	3	1028	1111	967	1119	987	1072
5	Gyratory	41	1	1264	1206	1265	1198	1260	1212
		41	2	1120	1093	1148	1034	1186	1024
		41	3	993	1118	851	1250	973	1303
	Dynamic	41	1	1120	1269	1076	1262	1060	1212
		41	2	1096	1163	1104	1263	1108	1076
		41	3	1012	1188	1060	1134	1083	1080

TABLE 15

RESILIENT MODULUS (KSI) OF OKLAHOMA TYPE "B" MIXES - (77°F)

				Rest Period					
				0.9 Sec.		1.9 Sec.		2.9 Sec.	
				Orientation		Orientation		Orientation	
Source	Compaction	Temp.		1	2	1	2	1	2
1	Gyratory	77	1	637	642	618	578	616	566
		77	2	602	613	612	629	566	622
		77	3	670	651	693	663	673	644
	Dynamic	77	1	617	657	654	641	692	627
		77	2	679	638	638	621	676	623
		77	3	635	584	642	566	629	629
2	Gyratory	77	1	424	520	419	519	431	506
		77	2	562	502	568	531	536	483
		77	3	608	603	616	586	593	558
	Dynamic	77	1	642	442	589	434	583	481
		77	2	632	577	612	579	585	581
		77	3	710	798	730	813	793	794
3	Gyratory	77	1	545	605	565	548	546	542
		77	2	520	480	516	513	538	498
		77	3	568	583	580	571	550	544
	Dynamic	77	1	720	714	712	722	707	730
		77	2	536	507	554	575	553	558
		77	3	626	752	622	731	593	762

TABLE 15 (Contd.)

RESILIENT MODULUS (KSI) OF OKLAHOMA TYPE "B" MIXES - (77°F)

				Rest Period					
				0.9 Sec.		1.9 Sec.		2.9 Sec.	
				Orientation		Orientation		Orientation	
Source	Compaction	Temp.		1	2	1	2	1	2
4	Gyratory	77	1	732	601	749	617	693	639
		77	2	563	520	566	518	570	539
		77	3	550	682	585	660	568	679
	Dynamic	77	1	488	567	473	542	508	509
		77	2	643	678	680	685	635	702
		77	3	583	502	577	499	579	510
5	Gyratory	77	1	551	545	540	497	528	501
		77	2	548	567	609	568	583	571
		77	3	642	691	644	672	651	688
	Dynamic	77	1	599	532	622	526	572	507
		77	2	524	493	538	501	542	574
		77	3	481	523	478	522	491	519

TABLE 16

RESILIENT MODULUS (KSI) OF OKLAHOMA TYPE "B" - (104°F)

						Rest Period			
				0.9 Sec.		1.9 Sec.		2.9 Sec.	
				Orientation		Orientation		Orientation	
Source	Compaction	Temp.		1	2	1	2	1	2
1	Gyratory	104	1	212	263	202	261	210	264
		104	2	215	258	198	292	188	260
		104	3	232	227	215	192	215	184
	Dynamic	104	1	250	158	187	165	177	162
		104	2	160	180	155	148	156	138
		104	3	168	207	194	194	174	180
2	Gyratory	104	1	385	267	372	258	380	238
		104	2	286	283	281	323	269	309
		104	3	223	256	193	235	196	226
	Dynamic	104	1	260	290	231	303	241	282
		104	2	296	366	375	367	366	358
		104	3	278	217	279	206	275	219
3	Gyratory	104	1	290	296	289	279	283	270
		104	2	254	262	260	251	277	261
		104	3	271	253	271	247	267	255
	Dynamic	104	1	378	363	341	317	301	332
		104	2	317	349	312	368	318	339
		104	3	365	372	374	358	366	361

TABLE 16 (Contd.)

RESILIENT MODULUS (KSI) OF OKLAHOMA TYPE "B" - (104°F)

				Rest Period					
				0.9 Sec.		1.9 Sec.		2.9 Sec.	
				Orientation		Orientation		Orientation	
Source	Compaction	Temp.		1	2	1	2	1	2
4	Gyratory	104	1	234	248	255	239	256	250
		104	2	359	354	389	370	335	360
		104	3	265	301	235	205	216	297
	Dynamic	104	1	313	261	285	270	277	272
		104	2	336	281	319	292	307	298
		104	3	193	240	229	236	225	259
5	Gyratory	104	1	230	200	243	239	266	239
		104	2	240	251	239	249	241	245
		104	3	310	297	314	287	303	299
	Dynamic	104	1	319	249	303	243	285	221
		104	2	245	241	223	254	216	246
		104	3	301	380	303	381	311	388

TABLE 17

RESILIENT MODULUS DATA ANALYSIS
TYPE "B" MIXES AT 41°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Source	4	110090.59	27522.65	0.55	0.6998
Comp	1	4080.27	4080.27	0.08	0.7778
Source*Comp	4	49251.03	12312.76	0.25	0.9081
Specime(Source*Comp)	20	997176.33	49858.82		
Orient	1	24012.45	24012.45	0.69	0.4146
Source*Orient	4	45637.97	11409.49	0.33	0.8546
Comp*Orient	1	11826.01	11826.01	0.34	0.5653
Source*Comp*Orient	4	63153.52	15788.38	0.46	0.7667
Orie(Sour*Comp*Spec)	20	691820.56	34591.03		
Restperiod	2	9334.01	4667.01	1.91	0.1548
Source*Restp	8	7328.21	916.03	0.37	0.9310
Comp*Restp	2	5633.01	2816.51	1.15	0.3211
Source*Comp*Restp	8	10586.43	1323.30	0.54	0.8219
Orient*Restp	2	8218.30	4109.15	1.68	0.1926
Source*Orient*Restp	8	13780.70	1722.59	0.70	0.6864
Comp*Orient*Restp	2	716.41	358.21	0.15	0.8639
Sour*Comp*Orie*Restp	8	18785.81	2348.23	0.96	0.4725

TABLE 18

RESILIENT MODULUS DATA ANALYSIS
TYPE "B" MIXES AT 77°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Source	4	99786.83	24946.71	0.89	0.4901
Comp	1	24546.69	24546.69	0.87	0.3615
Source*Comp	4	206661.59	51665.39	1.84	0.1616
Specime(Source*Comp)	20	563007.33	28150.37		
Orient	1	1596.09	1596.09	0.24	0.6318
Source*Orient	4	9785.08	2446.27	0.36	0.8320
Comp*Orient	1	138.69	138.69	0.02	0.8874
Source*Comp*Orient	4	13491.70	3372.93	0.50	0.7357
Orie(Sour*Comp*Spec)	20	134771.11	6738.56		
Restperiod	2	257.38	128.69	0.28	0.7593
Source*Restp	8	845.73	105.72	0.23	0.9849
Comp*Restp	2	2586.18	1293.09	2.78	0.0682
Source*Comp*Restp	8	2542.38	317.79	0.68	0.7057
Orient*Restp	2	959.51	479.76	1.03	0.3616
Source*Orient*Restp	8	1767.15	220.89	0.47	0.8709
Comp*Orient*Restp	2	824.18	412.09	0.88	0.4167
Sour*Comp*Orie*Restp	8	2647.93	330.99	0.71	0.6812

TABLE 19

RESILIENT MODULUS DATA ANALYSIS
TYPE "B" MIXES AT 104°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Source	4	230306.58	57576.64	5.80	0.0029
Comp	1	3836.45	3836.45	0.39	0.5413
Source*Comp	4	82891.47	20722.87	2.09	0.1206
Specime(Source*Comp)	20	198637.00	9931.85		
Orient	1	22.05	22.05	0.01	0.9355
Source*Orient	4	2323.20	580.80	0.18	0.9476
Comp*Orient	1	0.45	0.45	0.00	0.9908
Source*Comp*Orient	4	7977.24	1994.31	0.61	0.6617
Orie(Sour*Comp*Spec)	20	65636.56	3281.83		
Restperiod	2	1672.84	836.42	2.67	0.0755
Source*Restp	8	1627.82	203.48	0.65	0.7340
Comp*Restp	2	187.60	93.80	0.30	0.7421
Source*Comp*Restp	8	2097.73	262.22	0.84	0.5731
Orient*Restp	2	224.93	112.47	0.36	0.6996
Source*Orient*Restp	8	2302.07	287.76	0.92	0.5060
Comp*Orient*Restp	2	27.73	13.87	0.04	0.9567
Sour*Comp*Orie*Restp	8	1621.49	202.69	0.65	0.7361

TABLE 20

MIX DESIGN CHARACTERISTICS OF TYPICAL TYPE "B" ASPHALT CONCRETE MIXES (DIFFERENT SPECIMEN SIZES)

Sp. Diameter (inches)		Sp. Height (inch)	BSG[1]	MSG[2]	%AIR Voids	Density (lb/ft^3)	ITS[3] (psi)
4	1	2.48	2.33	2.47	5.66	145.39	168
	2	2.42	2.38	2.48	4.03	148.51	188
	3	2.47	2.32	2.48	6.45	144.77	131
	4	2.48	2.35	2.48	5.24	146.64	149
6	1	3.05	2.35	2.48	5.24	146.64	173
	2	3.07	2.33	2.47	5.67	145.39	167
	3	3.05	2.35	2.48	5.24	146.64	204
	4	3.05	2.32	2.47	6.07	144.77	144
	5	3.03	2.34	2.48	5.65	146.02	180
8	1	4.10	2.30	2.48	7.26	143.52	111
	2	4.11	2.30	2.48	7.26	143.52	124
	3	4.10	2.32	2.48	6.85	144.77	121
	4	4.06	2.32	2.49	6.60	144.77	117
	5	4.09	2.31	2.48	6.85	144.14	116

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[1] BSG = Bulk Specific Gravity
[2] MSG = Maximum Specific Gravity
[3] ITS = Indirect Tensile Strength

TABLE 21

RESILIENT MODULUS (KSI) OF TYPICAL TYPE "B" ASPHALT CONCRETE MIX

			Rest Period 0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Size	Temp.		1	2	1	2	1	2
4" Diameter (1/2" Loading Strip)	41	1	952	1157	997	1144	1023	1130
	41	2	1265	1618	1272	1600	1353	1567
	41	3	1202	1279	1150	1243	1236	1217
	41	4	1086	1211	1080	1312	1108	1296
	41	5	1384	1222	1415	1306	1420	1296
6" Diameter (1/2" Loading Strip)	41	1	1205	1710	1207	1751	1223	1750
	41	2	1142	1070	1150	1071	1147	1077
	41	3	1128	1310	1112	1332	1031	1335
	41	4	1360	1120	1438	1131	1333	1139
	41	5	1504	1220	1535	1227	1498	1233
6" Diameter (3/4" Loading Strip)	41	1	1247	1350	1330	1303	1325	1342
	41	2	1271	1077	1228	1063	1237	1070
	41	3	1566	1301	1541	1309	1560	1299
	41	4	1091	1366	1112	1369	1108	1372
	41	5	1414	1227	1446	1252	1369	1263
8" Diameter (1" Loading Strip)	41	1	1241	1068	1177	1084	1144	1085
	41	2	1139	1291	1141	1272	1137	1280
	41	3	1607	1213	1638	1253	1639	1235
	41	4	1469	1710	1412	1722	1423	1740
	41	5	1310	1204	1288	1261	1295	1281

TABLE 21 (Contd.)

RESILIENT MODULUS (KSI) OF TYPICAL TYPE "B" ASPHALT CONCRETE MIX

			Rest Period					
			0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Size	Temp.		1	2	1	2	1	2
4" Diameter (1/2 Loading Strip)	77	1	720	790	701	805	731	808
	77	2	910	770	896	771	899	775
	77	3	652	720	666	705	668	723
	77	4	723	897	744	899	741	880
	77	5	787	810	792	802	797	796
6" Diameter (1/2" Loading Strip)	77	1	848	757	855	764	818	748
	77	2	804	681	790	680	811	650
	77	3	719	778	674	781	668	710
	77	4	751	894	711	908	717	864
	77	5	948	843	876	813	863	804
6" Diameter (3/4" Loading Strip)	77	1	757	826	772	782	768	828
	77	2	723	741	737	776	762	734
	77	3	934	706	960	695	906	734
	77	4	689	710	685	705	725	762
	77	5	846	788	785	809	770	832
8" Diameter (1" Loading Strip)	77	1	855	829	839	859	842	829
	77	2	760	746	715	734	708	810
	77	3	933	755	906	745	885	741
	77	4	911	959	930	965	935	839
	77	5	961	741	909	660	851	627

TABLE 21 (Contd.)

RESILIENT MODULUS (KSI) OF TYPICAL TYPE "B" ASPHALT CONCRETE MIX

			Rest Period					
			0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Size	Temp.		1	2	1	2	1	2
4" Diameter (1/2" Loading Strip)	104	1	238	252	243	234	244	240
	104	2	286	301	277	253	293	285
	104	3	303	255	307	242	307	261
	104	4	297	291	283	277	259	268
	104	5	378	368	377	354	391	377
6" Diameter (1/2" Loading Strip)	104	1	251	209	226	211	232	217
	104	2	222	252	238	263	342	274
	104	3	321	338	322	359	324	344
	104	4	209	210	197	202	204	193
	104	5	305	303	296	307	302	303
6" Diameter (3/4" Loading Strip)	104	1	261	249	257	241	255	277
	104	2	218	221	223	247	216	237
	104	3	274	247	258	236	282	254
	104	4	348	293	315	313	302	332
	104	5	222	241	209	230	256	303
8" Diameter (1" Loading Strip)	104	1	245	286	237	262	241	259
	104	2	210	350	219	318	226	280
	104	3	255	249	258	251	265	253
	104	4	329	359	308	377	371	320
	104	5	238	184	263	200	237	218

TABLE 22

RESILIENT MODULUS DATA ANALYSIS
TYPICAL TYPE "B" AC MIX AT 41°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Size	3	83688.16	27896.05	0.22	0.8804
Specimen(Size)	16	2019516.60	126219.79		
Orient	1	6380.21	6380.21	0.07	0.7999
Size*Orient	3	122341.09	40780.36	0.42	0.7381
Orient(Size*Spec)	16	1537018.20	96063.64		
Restperiod	2	1946.12	973.06	1.41	0.2510
Size*Restp	6	4133.22	688.87	1.00	0.4332
Orient*Restp	2	899.32	449.66	0.65	0.5241
Size*Orient*Restp	6	12615.88	2102.65	3.05	0.0109

TABLE 23

RESILIENT MODULUS DATA ANALYSIS
TYPICAL TYPE "B" AC MIX AT 77°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Size	3	49945.40	16648.47	0.87	0.4790
Specimen(Size)	16	307654.07	19228.38		
Orient	1	10944.30	10944.30	0.56	0.4646
Size*Orient	3	44767.10	14922.37	0.77	0.5300
Orient(Size*Spec)	16	311969.93	19498.12		
Restperiod	2	4766.45	2383.23	3.80	0.0277
Size*Restp	6	10310.75	1718.46	2.74	0.0198
Orient*Restp	2	529.85	264.93	0.42	0.6576
Size*Orient*Restp	6	2447.75	407.96	0.65	0.6901

TABLE 24

RESILIENT MODULUS DATA ANALYSIS
TYPICAL TYPE "B" AC MIX AT 104°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Size	3	16572.30	5524.10	0.43	0.7343
Specimen(Size)	16	205538.33	12846.15		
Orient	1	28.03	28.03	0.02	0.8935
Size*Orient	3	4004.70	1334.90	0.88	0.4717
Orient(Size*Spec)	16	24240.60	1515.04		
Restperiod	2	1566.47	783.23	2.44	0.0956
Size*Restp	6	1996.00	332.67	1.03	0.4112
Orient*Restp	2	204.87	102.43	0.32	0.7283
Size*Orient*Restp	6	3996.40	666.07	2.07	0.0688

TABLE 25

RESILIENT MODULUS (KSI) OF TYPE "A" ASPHALT CONCRETE MIXES

					Rest Period			
			0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Source	Temp.		1	2	1	2	1	2
1	41	1	1455	1865	1420	1785	1290	1791
	41	2	1501	1371	1489	1301	1470	1320
	41	3	1576	1314	1626	1284	1594	1224
	41	4	1516	1412	1538	1414	1471	1482
	41	5	1720	1515	1735	1506	1779	1437
2	41	1	1575	1672	1511	1592	1456	1575
	41	2	1521	1303	1505	1333	1527	1341
	41	3	1445	2078	1373	2003	1304	1956
	41	4	1778	1452	1873	1464	1450	1322
	41	5	1573	1609	1564	1720	1590	1666
3	41	1	1887	1750	1993	1686	1871	1733
	41	2	1650	1433	1818	1498	1735	1529
	41	3	1538	1813	1520	1770	1524	1676
	41	4	1715	1783	1652	1704	1669	1574
	41	5	1724	1804	1608	1784	1587	1795
1	77	1	890	766	869	790	901	783
	77	2	688	659	603	703	642	712
	77	3	703	676	710	721	718	689
	77	4	675	608	611	692	619	634
	77	5	587	620	583	631	542	603

TABLE 25 (Contd.)

RESILIENT MODULUS (KSI) OF TYPE "A" ASPHALT CONCRETE MIXES

			Rest Period					
			0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Source	Temp.		1	2	1	2	1	2
2	77	1	793	810	708	699	738	782
	77	2	801	577	780	569	834	568
	77	3	750	757	787	739	798	749
	77	4	740	1072	719	1007	785	1076
	77	5	795	673	797	671	799	688
3	77	1	792	974	774	925	740	935
	77	2	954	701	970	643	922	639
	77	3	782	929	768	713	784	636
	77	4	645	941	559	872	609	886
	77	5	1062	723	937	689	970	697
1	104	1	291	219	280	205	277	197
	104	2	270	257	207	268	217	263
	104	3	363	381	383	373	400	393
	104	4	282	274	281	280	255	263
	104	5	280	326	239	314	236	316
2	104	1	386	220	357	198	334	192
	104	2	390	376	351	326	306	324
	104	3	429	372	415	338	413	296
	104	4	278	230	306	212	328	215
	104	5	232	291	240	289	261	301

TABLE 25 (Contd.)

RESILIENT MODULUS (KSI) OF TYPE "A" ASPHALT CONCRETE MIXES

			Rest Period 0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Source	Temp.		1	2	1	2	1	2
3	104	1	331	367	352	356	342	386
	104	2	243	339	235	341	210	309
	104	3	255	221	246	272	242	268
	104	4	347	420	365	412	385	401
	104	5	426	341	352	354	358	353

TABLE 26

RESILIENT MODULUS (KSI) OF TYPE "G" ASPHALT CONCRETE MIX

			Rest Period					
			0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Batch	Temp.		1	2	1	2	1	2
1	41	1	2106	2058	2126	2009	2131	1896
	41	2	2234	1758	2187	2003	2123	1975
	41	3	2590	2258	2611	2268	2613	2310
	41	4	2280	2010	2185	1917	2136	1877
	41	5	1930	2456	1858	2492	1896	2459
2	41	1	1831	2244	1927	2188	2053	2220
	41	2	2068	2525	2120	2592	2366	2509
	41	3	2353	1755	2310	1725	2373	1720
	41	4	2081	2259	1999	2201	2027	2205
	41	5	2250	1970	2241	1971	2252	1993
1	77	1	1274	881	1192	922	1128	826
	77	2	1010	1127	1037	1178	1005	1240
	77	3	1027	1022	1111	1308	1116	1390
	77	4	1240	1349	1029	1248	963	1282
	77	5	941	929	903	876	1029	859
2	77	1	1086	1010	1004	1087	1026	1042
	77	2	970	1201	914	1253	885	1215
	77	3	1131	945	1058	929	1211	1004
	77	4	1009	815	967	880	961	898
	77	5	1232	1317	1259	1301	1209	1299

TABLE 26

RESILIENT MODULUS (KSI) OF TYPE "G" ASPHALT CONCRETE MIX

					Rest Period			
			0.9 Sec.		1.9 Sec.		2.9 Sec.	
			Orientation		Orientation		Orientation	
Batch	Temp.		1	2	1	2	1	2
1	41	1	2106	2058	2126	2009	2131	1896
	41	2	2234	1758	2187	2003	2123	1975
	41	3	2590	2258	2611	2268	2613	2310
	41	4	2280	2010	2185	1917	2136	1877
	41	5	1930	2456	1858	2492	1896	2459
2	41	1	1831	2244	1927	2188	2053	2220
	41	2	2068	2525	2120	2592	2366	2509
	41	3	2353	1755	2310	1725	2373	1720
	41	4	2081	2259	1999	2201	2027	2205
	41	5	2250	1970	2241	1971	2252	1993
1	77	1	1274	881	1192	922	1128	826
	77	2	1010	1127	1037	1178	1005	1240
	77	3	1027	1022	1111	1308	1116	1390
	77	4	1240	1349	1029	1248	963	1282
	77	5	941	929	903	876	1029	859
2	77	1	1086	1010	1004	1087	1026	1042
	77	2	970	1201	914	1253	885	1215
	77	3	1131	945	1058	929	1211	1004
	77	4	1009	815	967	880	961	898
	77	5	1232	1317	1259	1301	1209	1299

TABLE 27

RESILIENT MODULUS DATA ANALYSIS
TYPE "A" AC MIXES AT 41°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Source	2	544029.42	272014.71	5.29	0.0225
Specimen(Source)	12	616641.47	51386.79		
Orient	1	852.54	852.54	0.01	0.9370
Source*Orient	2	80888.89	40444.44	0.31	0.7398
Orient(Source*Spec)	12	1570586.39	130882.20		
Restperiod	2	49350.02	24675.01	6.12	0.0043
Source*Restp	4	9025.84	2256.46	0.56	0.6930
Orient*Restp	2	4346.69	2173.34	0.54	0.5868
Source*Orient*Restp	4	6299.58	1574.89	0.39	0.8143

TABLE 28

RESILIENT MODULUS DATA ANALYSIS
TYPE "A" AC MIXES AT 77°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Source	2	218938.20	109469.10	3.31	0.0718
Specimen(Source)	12	397138.47	33094.87		
Orient	1	4080.40	4080.40	0.07	0.7941
Source*Orient	2	1623.27	811.63	0.01	0.9859
Orient(Source*Spec)	12	687337.00	57278.08		
Restperiod	2	14628.47	7314.23	6.59	0.0030
Source*Restp	4	22305.73	5576.43	5.03	0.0018
Orient*Restp	2	804.20	402.10	0.36	0.6979
Source*Orient*Restp	4	10872.53	2718.13	2.45	0.0587

TABLE 29

RESILIENT MODULUS DATA ANALYSIS
TYPE "A" AC MIXES AT 104°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Source	2	25462.15	12731.08	0.68	0.5235
Specimen(Source)	12	223519.13	18626.59		
Orient	1	1166.40	1166.40	0.21	0.6584
Source*Orient	2	29638.87	14819.43	2.61	0.1144
Orient(Source*Spec)	12	68103.40	5675.28		
Restperiod	2	2768.42	1384.21	3.31	0.4510
Source*Restp	4	1180.38	295.09	0.71	0.5923
Orient*Restp	2	188.87	94.43	0.23	0.7988
Source*Orient*Restp	4	1322.87	330.72	0.79	0.5372

TABLE 30

RESILIENT MODULUS DATA ANALYSIS
TYPE "G" AC MIX AT 41°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Batch	1	2996.27	2996.27	0.02	0.8843
Specimen(Batch)	8	1062607.07	132825.88		
Orient	1	34272.60	34272.60	0.15	0.7120
Batch*Orient	1	19656.60	19656.60	0.08	0.7794
Orient(Batch*Spec)	8	1873819.47	234227.43		
Restperiod	2	1048.93	524.47	0.13	0.8790
Batch*Restp	2	14776.93	7388.47	1.82	0.1776
Orient*Restp	2	9414.40	4707.20	1.16	0.3255
Batch*Orient*Restp	2	16484.80	8242.40	2.04	0.1472

TABLE 31

RESILIENT MODULUS DATA ANALYSIS
TYPE "G" AC MIX AT 77°F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Batch	1	1749.60	1749.60	0.02	0.8867
Specimen(Batch)	8	647231.40	80903.93		
Orient	1	8307.27	8307.27	0.13	0.7270
Batch*Orient	1	416.07	416.07	0.01	0.9375
Orient(Batch*Spec)	8	508303.00	63537.88		
Restperiod	2	436.80	218.40	0.04	0.9593
Batch*Restp	2	145.60	72.80	0.01	0.9862
Orient*Restp	2	23468.93	11734.46	2.24	0.1232
Batch*Orient*Restp	2	1492.93	746.47	0.14	0.8679

TABLE 32

RESILIENT MODULUS DATA ANALYSIS
TYPE "G" AC MIX AT 104^{o}F

General Linear Models

Source	DF	Type I SS	Mean SQR	F Value	Pr>F
Batch	1	12384.07	12384.07	0.94	0.3612
Specimen(Batch)	8	105629.93	13203.74		
Orient	1	141.07	141.07	0.01	0.9133
Batch*Orient	1	2257.07	2257.07	0.20	0.6650
Orient(Batch*Spec)	8	89388.87	11173.61		
Restperiod	2	411.23	205.62	0.47	0.6301
Batch*Restp	2	928.63	464.32	1.06	0.3589
Orient*Restp	2	5516.43	2758.22	6.29	0.0050
Batch*Orient*Restp	2	2873.43	1436.72	3.27	0.0508

TABLE 33

MIX DESIGN CHARACTERISTICS OF OKLAHOMA TYPE "A" AND "G" MIXES

Mix Type	Source	Section (T/B)		BSG[1]	MSG[2]	%Air Voids
A	1	1	T	2.30	2.45	6.1
			B	2.27	2.45	7.3
		2	T	2.33	2.46	5.3
			B	2.30	2.46	6.5
	2	1	T	2.23	2.38	6.3
			B	2.21	2.38	7.1
		2	T	2.21	2.39	7.5
			B	2.20	2.39	7.9
	3	1	T	2.39	2.52	5.2
			B	2.38	2.53	5.9
		2	T	2.37	2.52	6.0
			B	2.36	2.52	6.4
G		1	T	2.44	2.57	5.1
			B	2.42	2.56	5.5
		2	T	2.42	2.55	5.5
			B	2.41	2.55	5.5
		3	T	2.43	2.55	4.7
			B	2.38	2.54	6.3
		4	T	2.43	2.54	4.3
			B	2.42	2.56	5.5

[1] BSG = Bulk Specific Gravity
[2] MSG = Maximum Specific Gravity

TABLE 34

INDIRECT TENSILE STRENGTH (PSI) TYPE "A" AND "G" AC MIXES

Mix Type	Source	Specimen No.	Indirect tensile Strength
A	1	3	120
		4	156
		5	135
	2	3	134
		4	140
		5	140
	3	3	121
		4	149
		5	120
G		5	156
		6	118
		7	150
		8	125

TABLE 35

DESIGN MIX FOR TYPE "B", SOURCE 1
PROJECT NO:IR40-5(171)181 05487

Percent Passing	5/8" Chips	5/8" Mill Run	Stone Sand	Sand	Job Formula
3/4"	100	100			100
1/2"	95	97			98
3/8"	70	86	100		87
No 4	14	61	99		63
No 10	3	49	68	100	47
No 40	2	19	20	77	24
No 80	1	13	9	19	10
No 200	0.9	8.8	4.3	1.5	4.8

% Asphalt Cement Used: 5.0

Material	Source	%Used
5/8" Chips	Meridian Aggregate @ Mill Creek, OK	25
5/8" Mill Run	Meridian Aggregate @ Mill Creek, OK	40
Stone Sand	Dolese Co. @ Konawa, OK	20
Sand	White Pit @ Harrah, OK	15

TABLE 36

DESIGN MIX FOR TYPE "B", SOURCE 2
PROJECT NO:IR40-4(340)86 11255

Percent Passing	5/8" Chips	5/8" Mill Run	Stone Sand	Sand	Job Formula
3/4"	100				100
1/2"	93				98
3/8"	42	100			80
No 4	5	96	100	100	66
No 10	3	53	81	99	48
No 40	2	21	24	90	25
No 80	2	14	8	27	11
No 200	1.9	10.1	4.3	3.1	5.0

% Asphalt Cement Used: 4.6

Material	Source	%Used
3/4" Chips	The Dolese Co. @ Cooperton, OK	35
Screenings	The Dolese Co. @ Cooperton, OK	32
Stone Sands	The Dolese Co. @ Richard Spur, OK	18
Fill Sand	The Dolese Co. @ Yukon, OK	15

TABLE 37

DESIGN MIX FOR TYPE "B", SOURCE 3
PROJECT NO:RS-4720(110)06877

Percent Passing	3/4" Rocks	Mine Chat	Sand	Job Formula
3/4"	100			100
1/2"	76	100		98
3/8"	49	99	100	87
No 4	9	76	78	60
No 10	5	45	36	32
No 40	32	21	13	14
No 80	3	14	7	9
No 200	2.4	10.0	3.2	6.1

% Asphalt Cement Used: 5.2

Material	Source	%Used
3/4" Rock	Cummins Materials @ Tulsa, OK	25
Mine Chat	Bingham S & G @ Miami, OK	45
Manufacturing Sand	Cummins Materials @ Tulsa, OK	30

TABLE 38

DESIGN MIX FOR TYPE "B", SOURCE 4
PROJECT NO: CMC-66(286)1224

Percent Passing	3/4" Chips	Mine Chat	Stone Sand	Screenings	Sand	Job Formula
3/4"	100					100
1/2"	86	100	100			96
3/8"	46	99	100	100	100	90
No 4	7	49	61	95	98	66
No 10	3	6	19	64	88	39
No 40	32	1	6	26	21	13
No 80	3	1	4	23	2	9
No 200	2.4	0.3	2.4	15.5	0.2	6.0

% Asphalt Cement Used: 5.2

Material	Source	%Used
3/4" Chips	Anchor Stone Co. @ Tulsa, OK	18
Mine Chat	Bingham S & G @ Miami, OK	23
Stone Sands	Anchor Stone Co. @ Tulsa, OK	10
Screenings	Anchor Stone Co. @	34
Sand	Loman Sand Co. @ Bixby, OK	15

TABLE 39

DESIGN MIX FOR TYPE "B", SOURCE 5
PROJECT NO: VARIOUS PURCHASES

Percent Passing	5/8" Chips	5/8" Mill Run	Stone Sand	Sand	Job Formula
3/4"	100				100
1/2"	65	100			97
3/8"	33	92	100		91
No 4	4	6	96	100	56
No 10	23	1	61	98	40
No 40	2	1	25	80	23
No 80	2	1	17	17	10
No 200	1.4	0.3	12.3	2.5	5.5

% Asphalt Cement Used: 4.7

Material	Source	%Used
3/4" Chips	Bellco Materials Co. @ Snyder, OK	10
3/8" Mill Run	Bellco Materials Co. @ Snyder, OK	35
Screenings	Bellco Materials Co. @ Snyder, OK	40
Sands	CC Sand @ Jenks, OK	15

TABLE 40

DESIGN MIX FOR TYPE "A", SOURCE 1
PROJECT NO: MARS5420(107)C07853

Percent Passing	M.A.P	1-1/2" Rock	5/8" M.R.	Sand	Job Formula
1-1/2"	100	100			100
1"	100	100	100		100
1/2"	99	23	95		72
No 4	63	1	68	100	48
No 10	45	1	46	99	36
No 40	28	1	21	78	22
No 80	16	1	14	23	11
No 200	9.1	0.5	8.6	1.8	5.3

% Asphalt Cement Used: 4.4

Material	Source	%Used
Milled Asphalt Pavement	Stockpile and Plant Site.	23
1-1/2" Rock	Dolese Company @ Konawa, OK	34
5/8" Mill Run	Meridian Aggregate @ Mill Creek, OK	30
Sand	White Sand Pit @ Harrah, OK	11

TABLE 41

DESIGN MIX FOR TYPE "A", SOURCE 2
PROJECT NO: F-236(113)05744(06)

Percent Passing	1-1/2" Rock	3/8" Chips	Screenings	Sand	Job Formula
1-1/2"	100				100
1"	79				94
1/2"	20	100	100		76
No 4	3	41	99		59
No 10	2	10	75		38
No 40	2	2	26	100	21
No 80	2	1	14	65	13
No 200	1.1	1.5	7.5	15.5	5.1

% Asphalt Cement Used: 5.1

Material	Source	%Used
1-1/2" Rock	Amis Materials @ Stringtown, OK	30
3/8" Chips	Amis Materials @ Stringtown, OK	20
Screenings	Amis Materials @ Stringtown, OK	40
Sand	Eaves Construction Company @ Atoka, OK	10

TABLE 42

DESIGN MIX FOR TYPE "A", SOURCE 3
PROJECT NO: ACF-153(051) 08889

Percent Passing	1-1/2" Rock	1/4" Chips	Screenings	Sand	Job Formula
1-1/2"	100				100
1"	91				96
1/2"	37	100	100	100	74
No 4	2	67	100	98	54
No 10	1	6	67	95	34
No 40	1	1	27	75	19
No 80	1	1	18	25	9
No 200	0.5	0.4	13.6	3.0	4.5

% Asphalt Cement Used: 3.8

Material	Source	%Used
1-1/4" Rock	Belco @ Dewey, OK	42
1/4" Chips	Belco @ Dewey, OK	15
Screenings	Belco @ Dewey, OK	28
Sand	C C Amous S & G @ Jenks, OK	15

TABLE 43

DESIGN MIX FOR A TYPICAL TYPE "G"
PROJECT NO: F-324(79)05252(14)

Percent Passing	2" Rock	1-1/2" #57	#4 Screenings	Sand	Job Formula
2-1/2"					100
2"	100				100
1-1/2"	94	100			98
1"	38	94			75
1/2"	5	40	100	100	46
No 4	2	7	95	99	34
No 10	1	3	46	94	25
No 40	1	1	19	45	12
No 80	1	1	14	5	4
No 200	1	0.7	10.0	0.3	1.8

% Asphalt Cement Used: 3.1

Material	Source	%Used
2" Special #1	The Dolese Co. @ Cooperton, OK	37
1-1/2" #57	The Dolese Co. @ Cooperton, OK	31
#4 Screenings	The Dolese Co. @ Cooperton, OK	13
Sand	Kline Sand @ Woodward, OK	19

APPENDIX C

SHRP PROTOCOL P07

SHRP PROTOCOL: P07
For SHRP Test Designation: AC07
RESILIENT MODULUS FOR ASPHALT CONCRETE

1. SCOPE

1.1 General

This SHRP Protocol describes procedures for the determination of the resilient modulus of asphalt concrete (bituminous concrete) using repeated load indirect tensile test techniques. The procedure involves resilient modulus testing for a range of temperatures, loads, rest periods, and axis of loading.

1.2 Testing Prerequisites

Resilient modulus testing shall be conducted after; (1) approval by the SHRP Regional Engineer to begin AC resilient modulus testing, (2) approval of Form L04 by the SHRP RCOC, (3) visual examination and thickness of asphaltic concrete (AC) cores and thickness determination of layers within the AC cores using Protocol P01 have been completed, (4) final layer assignment based on the P01 test results (corrected Form L04, if needed, have been made) and (5) bulk specific gravity of asphalt concrete using Protocol P02 on each specimen designated for resilient modulus testing has been attained. To attain approval under Item (1), the laboratory must successfully complete (a) the synthetic specimen AC resilient modulus sample proficiency testing program and (b) the AC core specimen resilient modulus sample proficiency testing program.

1.3 Sample Size

Resilient modulus testing shall be conducted on asphalt concrete specimens that are greater than 1.5 inches in thickness and that are less than 3.0 inches in thickness. The desired thickness for testing is 2 inches.

1.4 Pretest Tensile Strength

Prior to performing the resilient modulus test, the indirect tensile strength shall be measured on one test specimen from the same layer and near the same location as the core specimen(s) to be tested for resilient modulus. The indirect tensile strength test is performed to assist in selecting a stress (or applied load) level for subsequent resilient modulus testing. The test shall be performed in accordance with Attachment A of this protocol. Normally, cores obtained from sample locations C7 and C19 are used for the indirect tensile strength test.

1.5 Test Core Locations and Assignment of SHRP Laboratory Test Numbers

Eight AC core locations have been designated for the P07 test on every pavement section included in GPS-1, GPS-2, GPS-6, and GPS-7 (i.e., asphalt concrete over granular base, asphalt concrete over bound base, AC overlay over asphalt concrete, and AC overlay over JPC, respectively), which has an asphalt layer thickness greater than 1.5 inches. Normally, only the cores designated by the SHRP RCOC shall be used for P07 testing .

(a) Beginning of the Section (Stations 0-):

The designated locations for nominal 4-inch diameter cores are: C7 (for indirect tensile strength test using Attachment A of Protocol P07); and C8, C9, C10 (for resilient modulus test using Protocol P07). The test results determined for each test specimen from these specified core locations shall be assigned SHRP Laboratory Test Number "1". SHRP will specify which cores, of those designated, to be used for testing.

(b) End of the Section (Stations 5+):

The designated locations for nominal 4-inch diameter cores are: C19 (for indirect tensile strength test using Attachment A of Protocol P07); and C20, C21, C22 (for resilient modulus test using Protocol P07). The test results determined for each test specimen from these specified core locations shall be assigned SHRP Laboratory Test Number "2". SHRP will specify which cores, of those designated, to be used for testing.

If any of the test specimens obtained from the specified core locations are damaged or untestable, other cores within the same grouping, but which have not been identified for other testing, can be substituted for P07 testing. It is inappropriate, however, to substitute test specimens from one end of the GPS Section for test specimens at the other end. An appropriate comment code shall be used in reporting the test results and any specimen substitution.

1.6 Definitions

The following definitions are used throughout this protocol:

(a) Layer: That part of the pavement produced with similar material and placed with similar equipment and techniques. The layer thickness can be equal to or less than the core thickness or length.

(b) Core:An intact cylindrical specimen of pavement materials which is removed from the pavement by drilling and sampling at the designated core location. A core may consist of, or include, one, two or more different layers.

(c) Test Specimen: That part of the layer which is used for, or in, the specified test. The thickness of the test specimen can be equal to or less than the layer thickness.

2. APPLICABLE DOCUMENTS

SHRP Protocols

P01 Visual Examination and Thickness of Asphaltic Concrete Cores.

3. SUMMARY OF METHOD

3.1 The repeated-load indirect tension resilient modulus test of asphalt concrete cores is conducted through repetitive applications of compressive loads in a haversine waveform. The compressive load is applied along a vertical diametral plane of a cylindrical core of Asphalt Concrete (Figure 1). The resulting horizontal and vertical deformations of the core are measured. The resilient modulus is calculated using an assumed Poisson's ratio. A value of resilient Poisson's ratio can also be calculated using recoverable vertical and horizontal deformations.

3.2 Two separate resilient modulus values are obtained. One, termed instantaneous resilient modulus, is calculated using the recoverable horizontal deformation that occurs during the unloading portion of one load-unload cycle. The other, termed 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 rest-period portion of one cycle.

3.3 For each resilient modulus test, the following general procedures must be followed:

(a) The tensile strength is determined on a test specimen at 77 ± 2°F (normally specimens from core locations C7 and C19) using the procedure described in Attachment A to Protocol P07. The value of tensile strength determined by this procedure is used to estimate the indirect tensile stress and corresponding compressive load to be repetitively applied to the test specimens during the resilient modulus determinations.

(b) The test specimen(s) are to be tested along two diametral axes at three rest periods (i.e., 0.9, 1.9, and 2.9 seconds) and at testing temperatures of 41, 77 and 104°F plus or minus two degrees F (5, 25, and 40°C plus or minus one degree C). For each test temperature, repetitive haversine load pulses of 0.1-second duration are applied to the individual test specimens to produce a predefined indirect tensile stress on the specimen. The stress is based on a percentage of the indirect tensile strength (see Section 3.3 [a] above), with rest periods of varying duration between load pulses as described in the Procedures section. The temperature testing sequence includes initial testing at 41°F followed by testing at 77°F, and final testing at 104°F.

(c) After completion of resilient modulus testing at 104°F, the test specimen shall be returned to 77°F and an indirect tensile strength test shall be performed in accordance with Attachment A of this protocol. This test is performed to determine the tensile strength of the specific specimen actually used in resilient modulus testing.

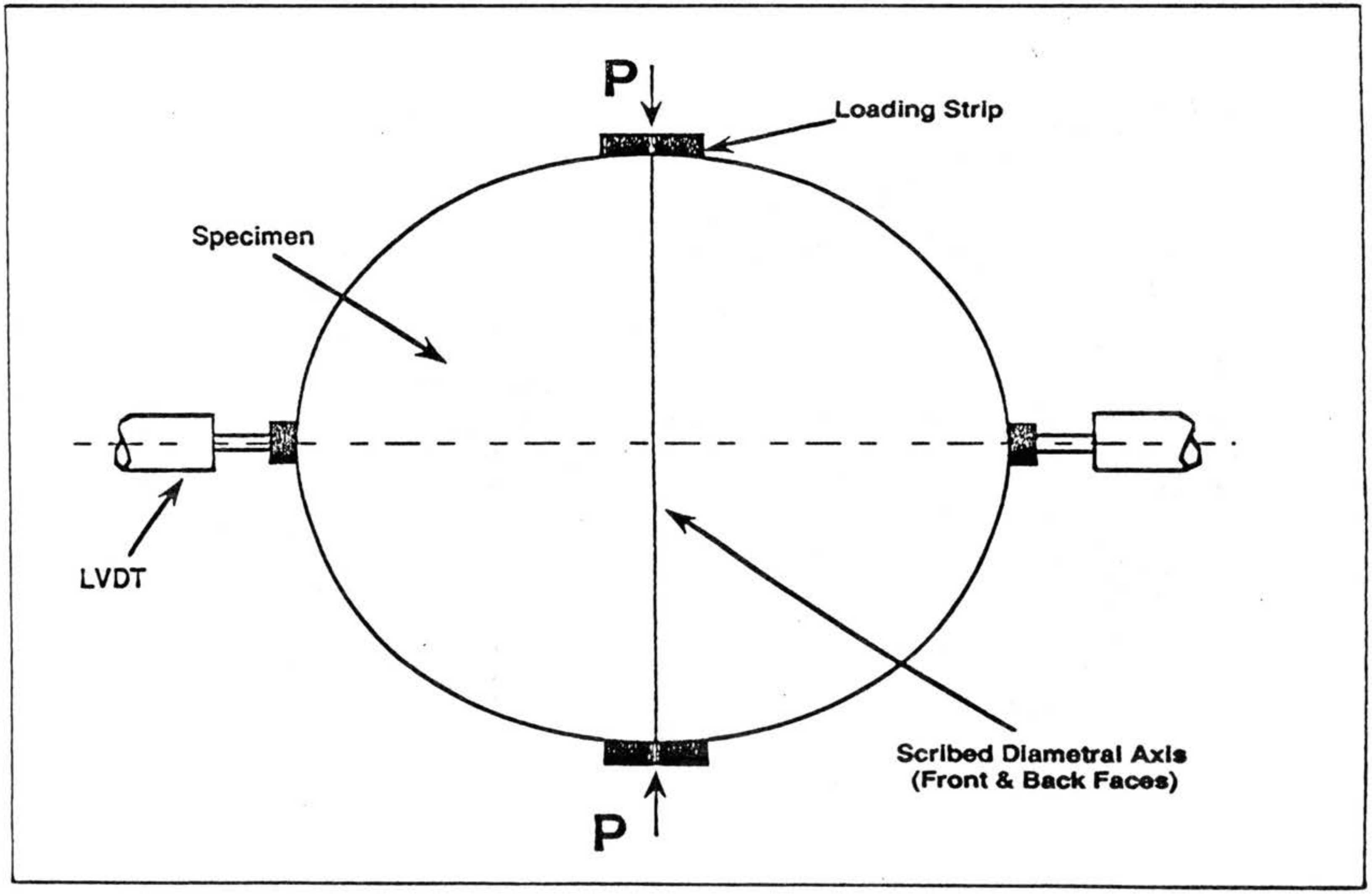

Figure 1. Proper Loading of AC Specimen.

4. SIGNIFICANCE AND USE

Resilient modulus can be used in evaluations of materials quality and can be used as an input for pavement design, evaluation and analysis. The effects of temperature, load axis, loading and rest periods can also be investigated. This test method is presently not intended for specification use.

5. APPARATUS

5.1 Testing Machine

The testing machine shall be a top loading, closed loop, electrohydraulic testing machine with a function generator which is capable of applying a haversine shaped load pulse over a range of load durations, load levels, and rest periods.

5.2 Temperature Control System

The temperature-control system should be capable of attaining temperature control ranging from 41°F (5°C) to 104°F (40°C) while maintaining the specified temperature within ± 2°F (± 1.1°C). The system shall include a temperature-controlled cabinet large enough to hold at least three test specimens for a period of 24 hours prior to testing.

5.3 Measurement and Recording System

The measuring and recording system shall include sensors for measuring and recording horizontal and vertical deformations. The system shall be capable of recording horizontal deformations in the range of 0.00001 inch (0.00025 mm) of deformation. Loads shall be accurately calibrated prior to testing.

5.3.1 Recorder - The measuring or recording devices must provide real time deformation and load information and should be capable of monitoring readings on tests conducted to 1 Hz. Computer monitoring systems can be used as long as real time plots can be provided as the test progresses.

5.3.2 Deformation Measurement - The values of vertical and horizontal deformation shall be measured with linear variable differential transducers (LVDT's).

<u>Horizontal LVDT's</u>. LVDT's used to measure horizontal deformations should be located at mid-height and opposite each other along the specimen's horizontal diameter (see Figure 2). The sensitivity of these measurement devices shall be selected to provide the deformation readout required in Section 5.3. A positive contact between the LVDT's and specimen shall always be maintained during the test procedure. This can be assured by using spring loaded LVDT's and attaching a suitable head as a contact point. In addition, the two horizontal LVDT's shall

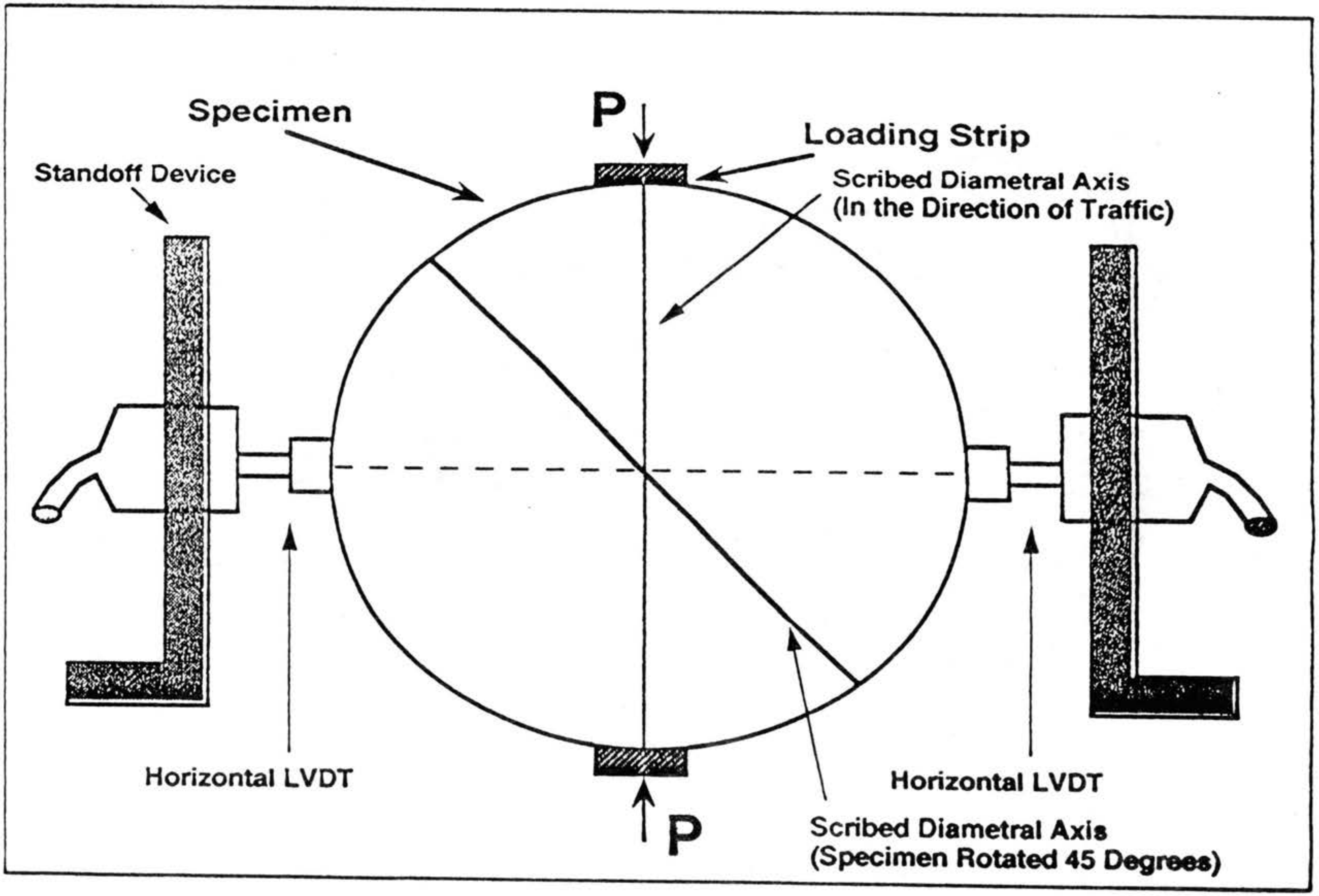

Figure 2. Positioning of Horizontal LVDT's and Illustration of Correct Specimen Alignment.

be wired so that each transducer can be read independently and the results summed during the test program.

Vertical LVDT's. The two LVDT's used to measure vertical deformations should be located on opposite sides of the upper platen of the load frame (see Figure 3). These two transducers shall be located equidistant from the actuator shaft and on a line coincident with the center of the two guide posts of the load frame and the center of the actuator shaft. The sensitivity of these measurement devices shall be selected to provide the deformation readout required in Section 5.3. A positive contact between the vertical LVDT's and the upper platen of the load frame shall always be maintained during the test procedure. In addition, the two LVDT's shall be wired so that each transducer can be read independently and the results averaged during the test program. If the transducers are temperature sensitive, then the test machine must be located within a temperature controlled chamber.

5.3.3 Load Measurement - The repetitive loads shall be measured with an electronic load cell which meets the requirements for load in Section 5.3.

5.4 Loading Strip

A steel loading strip with a concave surface having a radius of curvature equal to a nominal 4.0 inch diameter specimen is required to apply load to the asphalt core. The loading strip shall be 1/2 inch wide and the outer edges of the curved surface shall be ground to remove sharp edges that might cut the core during testing.

6. TEST SPECIMENS

6.1 Core Specimens - Cores should have smooth and uniform curved surfaces as well as, smooth and parallel top and bottom diametral faces. The cores shall conform to the height and diameter requirements specified in Sections 1.3 and 1.5.

6.2 The test specimens designated for M_r testing shall be selected and prepared for resilient modulus testing. The test specimen(s) shall represent one AC layer at each end of the GPS section. If the field core includes two or more different AC layers, the layers shall be separated at the layer interface by sawing the field core with a diamond saw in the laboratory. Layers which contain more than one lift of the same material may be tested as is. The lifts do not need to be separated. The traffic direction symbol shall be marked on each layer below the surface layer. Any testable layers identified in the P01 test (Form T01B) shall be separated. Thin layers shall be removed from other testable layers. Any combination of thin layers which do not meet the testable layer criteria shall not be separated from each other by sawing.

6.3 Diametral Axes - Mark two diametral axes on each test specimen to be tested using a suitable marking device (see Figure 4). One axis shall be parallel to the traffic direction symbol (arrow) or "T" marked

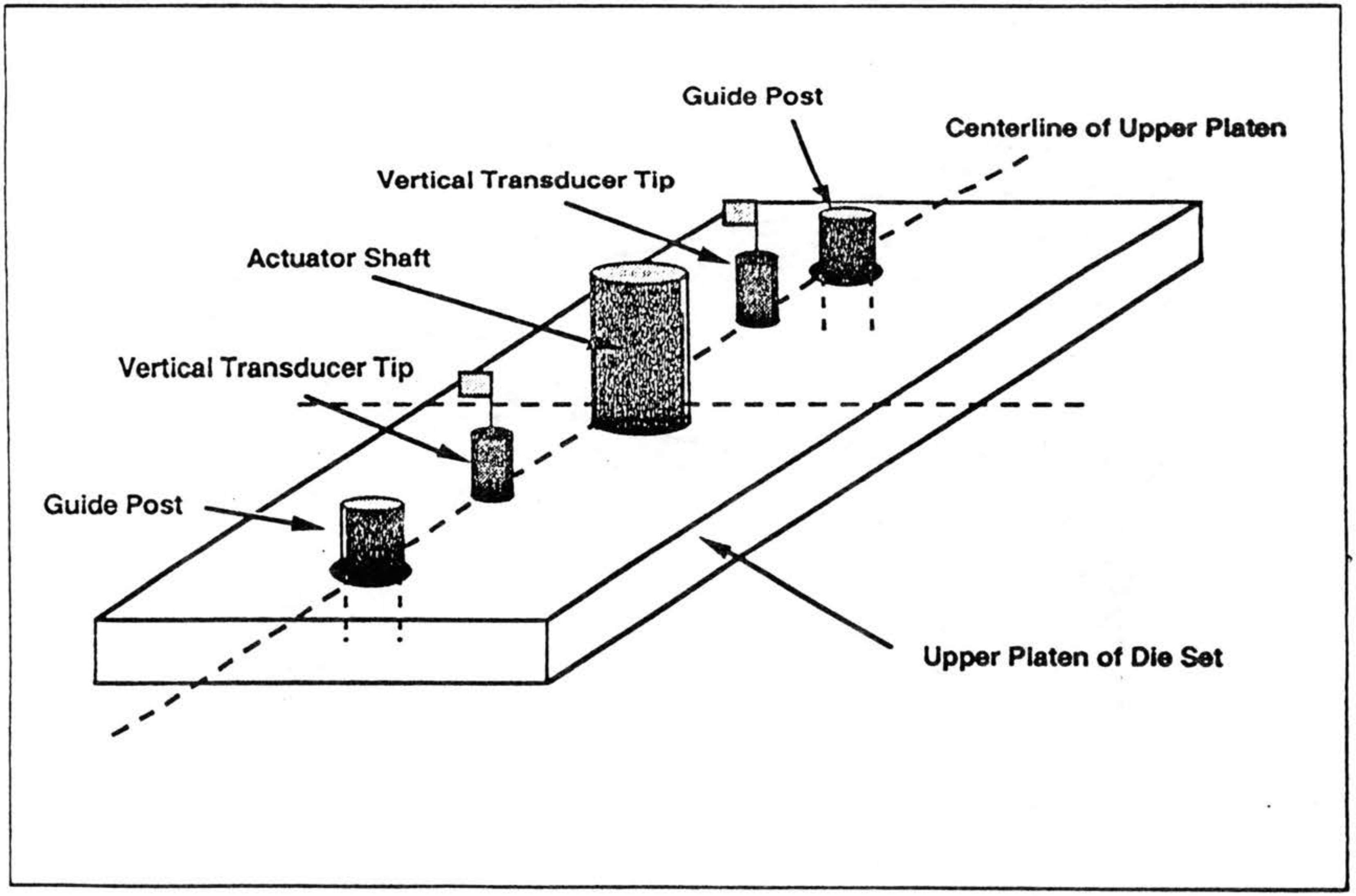

Figure 3. Positioning of Vertical LVDT's.

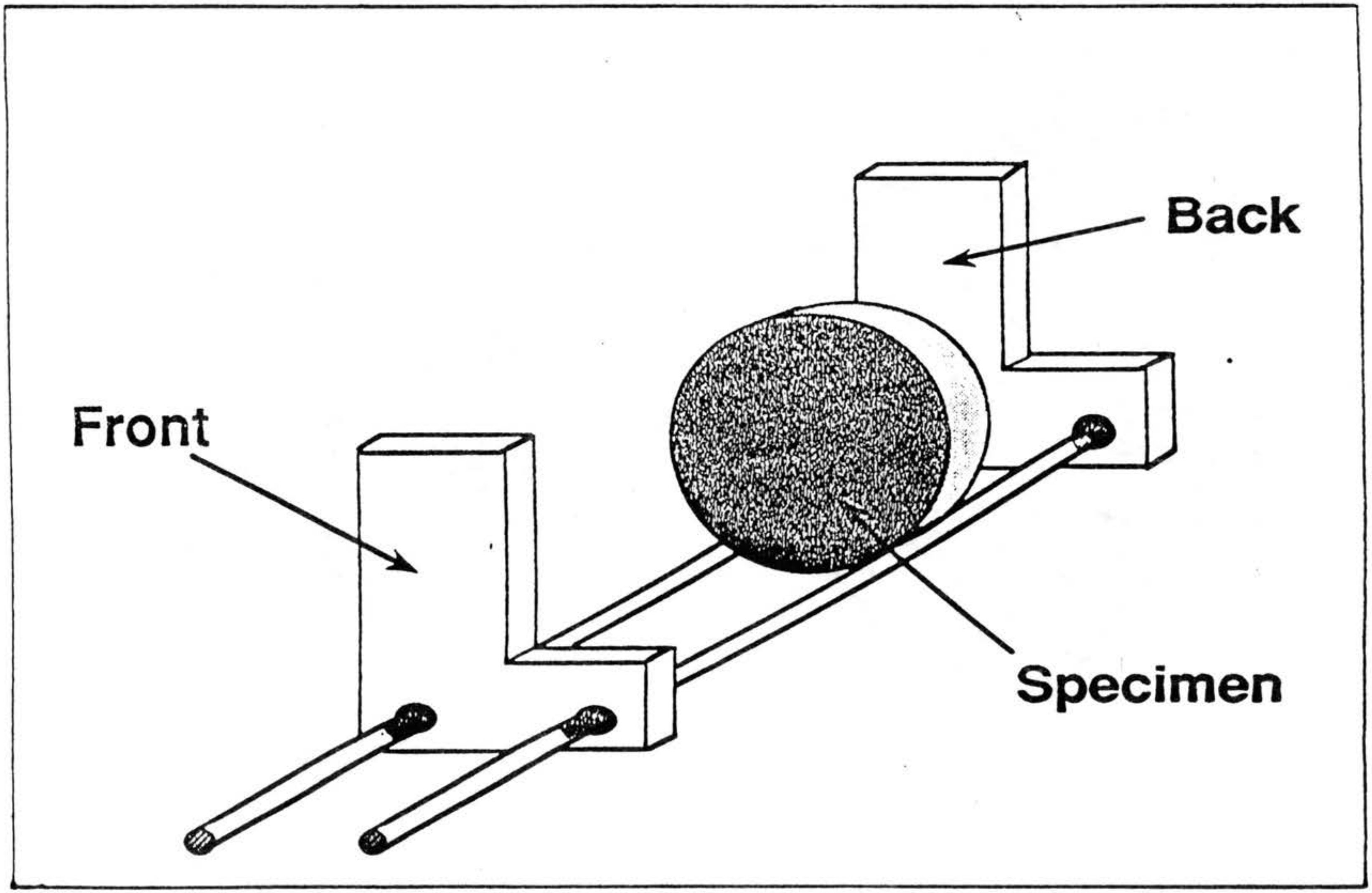

Figure 4. Illustration of a Suitable Specimen Marking Device.

during the field coring operations. The other axis shall be marked at a 45 degree angle from the arrow (or "T") placed on the specimen during field coring operations, as required by SHRP Protocol P01 (Section 4.4).

6.4 The thickness (t) of each test specimen shall be measured to the nearest 0.1 inch (2.5 mm) prior to testing. The thickness shall be determined by averaging three measurements equally spaced around the test specimen with a single center measurement. A test specimen shall consist of a single pavement material or layer greater than 1.5 inches in thickness. The desired thickness for testing is approximately 2 inches. If the thickness of a particular AC layer scheduled for testing is one inch or more greater than the desired testing thickness of 2 inches, then the 2 inch specimen to be used for testing shall be obtained from the middle of the AC layer by sawing the specimen. If a core from an AC layer is between 1.5 and 3.0 inches and has relatively smooth front and back faces then no sawing is required and the specimen for this layer may be tested as is.

6.5 The diameter (D) of each test specimen shall be determined prior to testing using a caliper to the nearest 0.01 inch (0.25 mm) by averaging two diametral measurements. Measure (1) the diameter of the axis parallel to the direction of traffic and (2) the diameter of the axis perpendicular (90 degrees) to the axis measured in (1) above. These two measurements shall be averaged to determine the diameter of the test specimen.

6.6 If the average diameter of the core is less than 3.85 inches or exceeds 4.15 inches, the core shall not be tested. A replacement core shall be selected for the resilient modulus test.

7. PROCEDURE

7.1 General

The asphalt cores shall be placed in a controlled temperature cabinet/chamber and brought to the specified test temperature. Unless the core specimen temperature is monitored in some manner and the actual temperature known, the core samples shall remain in the cabinet/chamber for a minimum of 24 hours prior to testing.

(a) Determine the tensile strength of the designated test specimens at 77° ± 2°F (normally specimens obtained from sample locations C7 and C19) using the procedure described in Attachment A to Protocol P07.

(b) The test specimen(s) designated for resilient modulus testing shall be brought to the first test temperature (41 ± 2°F) as specified in Section 7.1.

(c) The procedure described in Section 7.1 shall be completed to bring the test specimens to the remaining desired test temperatures (77 ± 2°F, 104 ± 2°F).

7.2 Alignment and Specimen Seating

At each temperature, the test specimen shall be placed in the loading apparatus and positioned so that the diametral markings (Section 6.3) are centered top to bottom within the loading strips on both the front and back face of the specimen along the axis parallel to the direction of traffic (see Figure 2). The marked diametral axis (axis parallel to the direction of traffic) should then be located so that the diametral line intersects the center of the curved portion of both top and bottom loading strips. The diametral markings then are used to insure that the specimen is aligned from top to bottom, front to back. The alignment of the front face of the specimen can be checked by insuring that the diametral marking is centered on the top and bottom loading strips. With the use of a mirror, the back face can be similarly aligned. The first axis to be tested (Section 6.4) is to be the axis parallel to the direction of traffic (i.e. the load is being applied along the axis parallel to traffic). The head of the arrow should always be located at the top (twelve o'clock) position and the upper surface (i.e., the newer pavement surface facing to the front).

The second axis to be tested is the axis 45 degrees from the axis parallel to the direction of traffic. This axis should be similarly aligned prior to resilient modulus testing. The electronic measuring system shall be adjusted and balanced as necessary. Prior to testing and after the horizontal deformation transducers are mounted in the standoff device, adjustments are required in the relative position of the transducers in order to match the mechanical "null" position with the electrical "null" or a near zero voltage position (a similar "null" position shall be produced for the LVDT's used to measure the vertical deformations during testing). When starting from the "null" position, the "travel" of the transducer shaft should be sufficient to require no further adjustment in the transducer position for the duration of a test.

The line of contact between the specimen and each loading strip is critical for proper test results. The specimen shall be free of any projections or depressions higher or deeper than 0.1 inch (2.54 mm). Specimens having projections or depressions greater than 0.1 inch should not normally be tested. However, if no suitable replacement specimen is available that meets the 0.1 inch criteria, that test shall be conducted on the designated specimen. Code 39 has been provided to document this situation.

7.3 Preconditioning

Preconditioning and testing shall be conducted while the specimen is located in a temperature-control cabinet meeting the requirements of Section 5.2.

7.3.1 Selection of the applied loads for preconditioning and testing at the three test temperatures is based on the tensile strength, determined as specified in Section 7.1(a) of this protocol and Attachment A to Protocol P07. Tensile stress levels of 30, 15, and 5 percent of the tensile strength, measured at 77°F (25°C), are to be used in conducting the resilient modulus determinations at the test temperatures of 41 ± 2, 77 ± 2 and 104 ± 2°F (5, 25 and 40°C ± 1°C), respectively. Minimum specimen contact loads of 3, 1.5 and .5 percent of the 77°F tensile strength value shall be maintained during resilient testing for test temperatures, respectively, of 41 ± 2, 77 ± 2 and 104 ± 2°F (5, 25 and 40 ± 1°C).

7.3.2 The sequence of resilient modulus testing shall consist of initial testing at 41°F, followed by intermediate testing at 77°F and final testing at 104°F. The test specimens shall be brought to the specified temperature prior to each test (i.e. initial, intermediate and final), in accordance with Section 7.1. The test specimen shall be preconditioned along the axis prior to testing by applying a repeated haversine-shaped load pulse of 0.1-second duration with a rest period of 0.9 second, until a minimum of ten (10) successive horizontal deformation readings agree within 10 percent. The number of load applications to be applied will depend upon the test temperature. The expected ranges in number of load applications for preconditioning are 50-150 for 41 ± 2°F, 50-100 for 77 ± 2°F and 20-50 for 104 ± 2°F. The minimum number of load applications for a given situation must be such that the resilient deformations are stable (Section 7.5.1).

7.3.3 If adequate deformations (greater than .0001 inches) cannot be recorded using 5, 15 and 30% of the tensile strength measured at 77°F (25°C), then the loads can be increased in load increments of 5 (i.e. 10, 15, 20, 25%). If load levels different from 5, 15 and 30% of the tensile strength measured at 77°F (25°C) are used, these should be noted on the data sheet.

7.4 Both the horizontal and vertical deformations shall be monitored during preconditioning of the test specimen. If total cumulative vertical deformations greater than .025 inch (.625 mm) for 41°F or .050 inch (1.25 mm) for 77° and 104°F occur, reduce the applied load to the minimum value possible and still retain an adequate deformation for measurement purposes (loads as low as 10 lbf. and load repetitions as few as 5 (for loads between 10 and 25 lbf.) have been used). If use of smaller load levels does not yield adequate deformations for measurement purposes, discontinue preconditioning and generate 10 load pulses for resilient modulus determination, and so indicate on the test report.

7.5 Testing

After preconditioning a specimen at a specific test temperature, the resilient modulus test shall be conducted as specified below.

7.5.1 Apply a minimum of 30 load pulses (each 0.1-second load pulse has a rest period of 0.9 seconds) and record measured deformations as specified in Section 7.6 of this protocol. The application of load pulses shall continue beyond 30 until the range in deformation values of five (5) successive horizontal deformation values (i.e. from lowest to highest values) is less than 10% of the average of the five (5) deformation values. The rest period is then increased to 1.9 seconds and a minimum of 30 load repetitions are applied. The rest period is then increased to 2.9 seconds and a minimum of

30 load repetitions are applied (see Section 7.6 of this protocol).

7.5.2 After testing is completed for the first axis (load applied along the axis parallel to the direction of traffic) rotate the specimen to the axis 45 degrees from the axis parallel to traffic and repeat Steps 7.3.2 through 7.5.1 of this protocol.

7.5.3 After the specimen(s) have been tested along both axes at a specific test temperature, bring the specimen to the next higher temperature in accordance with 5.2 and repeat 7.3.2 through 7.5.2 of this protocol.

7.5.4 After testing is completed at 104°F, the specimen shall be brought to a temperature of 77 ± 2°F and an indirect tensile strength test conducted on the test specimen as specified in Attachment A.

7.6 Measure and record the recoverable horizontal and vertical deformations over the last 5 loading cycles (see Figure 5) after the repeated resilient deformations have become stable. One loading cycle consists of one load pulse and a subsequent rest period. The vertical deformation measurements shall also be measured and reported. The resilient modulus will be calculated along each axis for each rest period and temperature by averaging the deformations measured for the last 5 load cycles as defined in Section 7.5.1.

8. CALCULATIONS

8.1 Calculate the resilient modulus of elasticity, E, in pounds-force per square inch as follows:

$$E_{RI} = \frac{P \times D(.080 + .297v + .0425v^2)}{H_I \times t}$$

$$E_{RT} = \frac{P \times D(.080 + .297v + .0425v^2)}{H_T \times t}$$

where:

E_{RI} = instantaneous resilient modulus of elasticity, psi.,

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

P = repeated load, lbf.,

t = thickness of test specimen, in.,

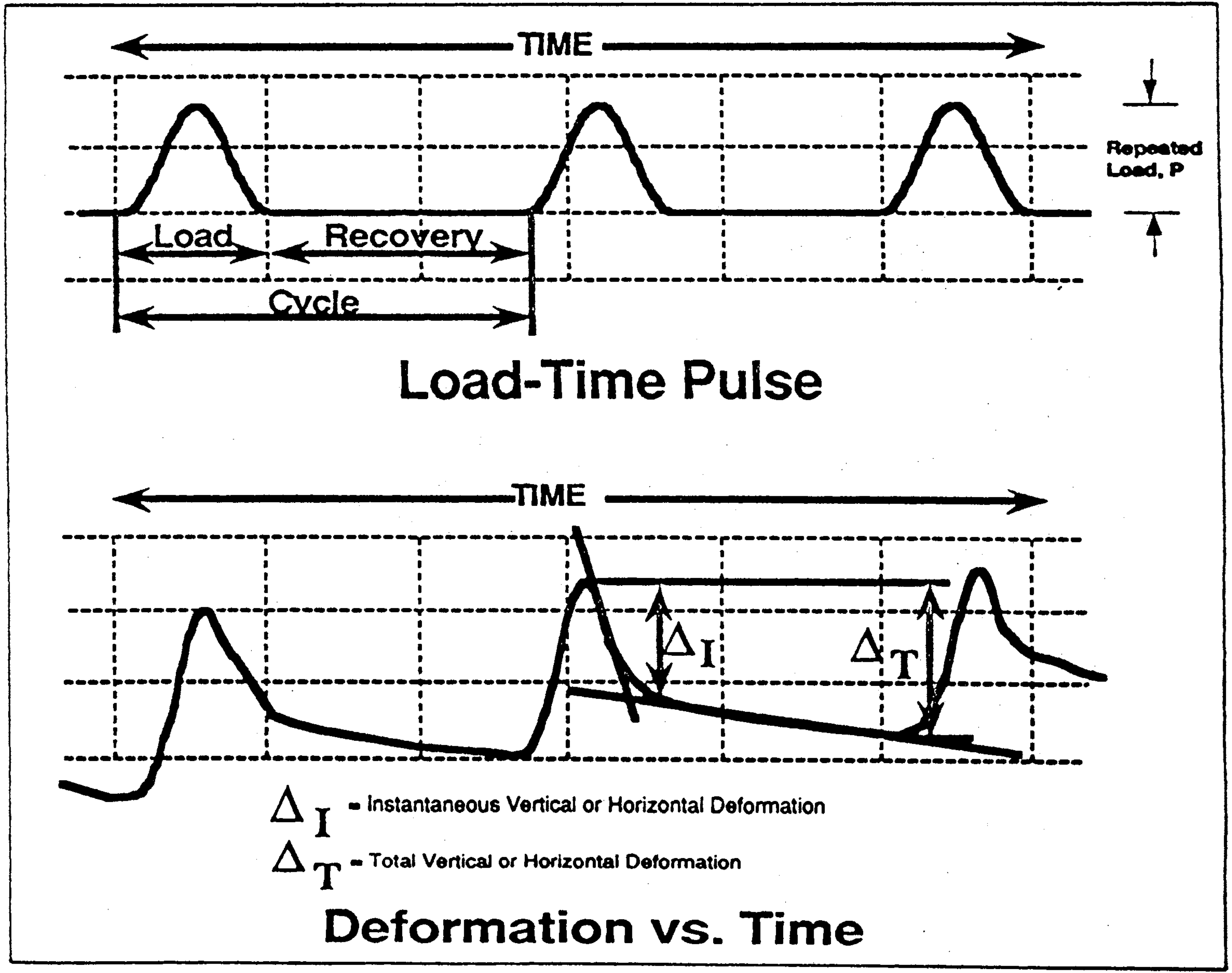

Figure 5. Typical Load and Deformation Versus Time Relationships.

D - diameter of specimen, in.,

H_I - instantaneous recoverable horizontal deformation, in. and

H_T - total recoverable horizontal deformation, inches.

v - Poisson's Ratio assumed for each temperature.

8.2 In calculating the resilient moduli using the equations identified in 8.1, Poisson's Ratio shall be assumed. A value of 0.35 has been found to be reasonable for bituminous mixtures at 77°F (25°C). Values of 0.20 and 0.50 are to be used for 41° and 104°F (5, 40°C), respectively.

9. REPORT

9.1 The following general information is to be recorded on Form T07A:

9.1.1 Sample Identification shall include: Laboratory Identification Code, State Code, SHRP Section ID, Layer Number, Field Set Number, Sample Location Number, and SHRP Sample Number.

9.1.2 Test identification shall include: SHRP Test Designation, SHRP Protocol Number, SHRP Laboratory Test Number and Test Date.

9.1.3 Report the following specific information for each test specimen on Form T07A.

(a) Record a "yes" to indicate whether the layer to be tested was sawed (so as to obtain the desired thickness for testing, i.e. approximately 2 inches) or a "no" if sawing was not required.

(b) Average thickness of the test specimen, (t), to the nearest 0.1 inch (per Section 6.5 of this protocol).

(c) Average diameter of the test specimen (D), to nearest 0.01 inch (per Section 6.6 of this protocol).

(d) Test temperature, to the nearest °F.

(e) Indirect tensile strength, to the nearest psi, (Previously reported on Form T07B). This is the indirect tensile test result that was used to assist in selecting a stress (or applied load) level for resilient modulus testing.

(f) Contact load used at each temperature, to the nearest lbf.

(g) Resilient load used at each temperature, to the nearest lbf.

(h) Poisson's ratio assumed for each test temperature.

(i) The rest period, secs.

(j) Average instantaneous and total resilient moduli at each test temperature (as calculated in accordance with Section 8.1 of this protocol).

Comments shall include SHRP standard comment code(s) as shown on Page E.3-1 of the SHRP Laboratory Testing Guide and any other note, as needed. Additional codes for special comments associated with Protocol P07 are given below.

Code	Comment
25	The specimen was skewed (either end of the specimen departed from perpendicularity to the axis by more than 0.5 degrees or 1/8 inch in 12 inches), as observed by placing the specimen on a level surface and measuring the departure from perpendicularity.
29	A "dummy" specimen was used to monitor the temperature of the test specimen during M_r testing.
30	The designated specimen did not meet minimum specimen standards and was not tested. A replacement specimen from another location was used for the M_r testing.
31	Tests for all three temperatures could not be performed because the specimen was damaged and/or excessively deformed during testing.
39	The projections/depressions on the test surface were higher or deeper than 0.1 inch. The specimen was tested because there was no other replacement specimen (use the accompanying note ("7(b) NOTE") portion of Form T07A to record the average projection/depression(s) of the tested specimen).
40	The test specimen did not have any traffic direction symbol (arrow or "T"). An arbitrary line was drawn to show the axis of the specimen during resilient modulus testing.

9.2 The following general information is to be recorded on "Worksheet 1 for Test Data Sheet T07A" and "Worksheet 2 for Test Data Sheet T07B":

9.2.1 Sample Identification shall include: SHRP Section ID, Layer Number, Field Set Number, Sample Location Number, and SHRP Sample Number.

9.2.2 Test identification, shall include: SHRP Laboratory Test Number and Test Date.

9.2.3 Report the following specific information for each test specimen at each test temperature on the worksheets:

(a) The resilient and total vertical load levels and recoverable horizontal and vertical deformations measured over the last 5 loading cycles for each test temperature. The vertical and horizontal movement for each LVDT shall be reported separately.

(b) The seating load used over the last 5 loading cycles for each test temperature.

(c) The instantaneous and total resilient modulus for each load cycle.

(d) The average resilient modulus (M_r) for the last 5 load cycles and standard deviation calculated at each test temperature.

(e) The number of preconditioning cycles used for each test temperature and the amount of cumulative permanent horizontal and vertical deformations that occurred during each of the tests.

(f) The total number of applied load cycles obtained in determining the resilient modulus values.

9.3 The summary test data for one test specimen at one temperature are recorded on one sheet of Form T07A. For each test specimen and temperature, Form T07A shall be accompanied by both pages of Worksheet "1" and both pages of Worksheet "2". For a complete set of tests on <u>one</u> specimen, a total of (1) three Form T07A's, (2) three Worksheet "1"'s, (3) three Worksheet "2"'s, and (4) one Form T07B is required.

VITA

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