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

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CHAPTER I

INTRODUCTION

The AASHTO Guide for the Design of Pavement Structures [1-3] requires the estimation of resilient modulus for flexible pavement design. Resilient modulus is considered a fundamental material property and is determined from a repeated load tests and is based on the resilient (recoverable) portion of the strain. The resilient modulus is the ratio of the repeated stress to the corresponding recoverable (resilient) strain during loading i.e., it is the elastic stiffness of a material after a predetermined number of load repetitions have been applied.

The resilient modulus test is designed to simulate the behavior of bituminous materials under in service conditions found in a pavement system. The compaction methodology used in the preparation of specimens should closely correspond to field compaction techniques. Three compaction procedures were evaluated in this study including: gyratory shear, Marshall hammer, and dynamic compaction apparatus. Aggregates were obtained from five different sources located in different parts of Oklahoma. The resilient modulus test was conducted by applying a haversine compressive load on a sample at three temperatures (41^{o} Fahrenheit (5^{o} Centigrade), 77^{o} Fahrenheit (25^{o} Centigrade), 104^{o} Fahrenheit (40^{o} Centigrade) along two diametral axes (second axis is oriented 45^{o} to the first), and at three rest periods (0.9s, 1.9s, 2.9s) using a predetermined stress that differs for each temperature. The stresses to be applied on the sample at three temperatures is obtained by conducting the indirect tensile strength test on a sample. 30.15, and 5 percent of the stresses obtained at failure are the stresses applied at 41^{o} Fahrenheit (5^{o} Centigrade), 77^{o} Fahrenheit (25^{o} Centigrade), 104^{o} Fahrenheit (40^{o}

Centigrade) respectively.

Based on the test results obtained during the course of the study, it was concluded that the samples prepared using the gyratory shear compactor and the dynamic compaction apparatus exhibit similar characteristics and the Marshall hammer tends to exhibit a poor behavior. The resilient modulus values of the gyratory shear and dynamic compaction apparatus compacted samples lie close to each other at the three testing temperatures. Overall it was determined that the resilient modulus increases with decreasing temperatures and the effect of three rest periods and two axes is not significant.

Objective

The primary objective of this study was to determine a representative resilient modulus value for several Oklahoma Department of Transportation "Type B" bituminous mixes. A secondary objective was to establish a reproducible and realistic compaction methodology for molding laboratory specimens.

Scope of Work

The compaction procedures used in this study were chosen to determine the best laboratory compaction procedure for simulating field compaction. The devices evaluated were : The gyratory shear compactor, Marshall hammer, and dynamic compaction apparatus (Figure 2). Samples were prepared using these techniques and their engineering properties determined.

The variability in sample preparation was assessed using the following tests : resilient modulus tests, Hveem stability, indirect tensile strength test, and Air voids determination.

Resilient modulus tests were performed at 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), 104° Fahrenheit (40° Centigrade) to obtain the effect of varying temperature. The samples are tested at different load intensities [(30.15, and 5 percent of the stresses obtained at failure on the indirect tensile strength test conducted on a sample are the stresses applied at 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), 104° Fahrenheit (40° Centigrade) for different temperatures respectively], at three rest periods (0.9s, 1.9s, 2.9s), and the sample is tested along two diametral axes (second axis is oriented 45° to the first)

A typical mix gradation is shown in Table 1. Samples were prepared using aggregates obtained from five different sources within Oklahoma.

CHAPTER II

LITERATURE REVIEW

Background

The implementation of the AASHTO Pavement Design procedure for flexible pavements requires the estimation of "layer coefficients" for bituminous mixes. AASHTO layer coefficients for asphalt concrete and granular materials are defined in terms of resilient or dynamic modulus value.

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

$$\log_{10}(W_{18}) = Z_R * S_o + 9.36 \text{ Log}_{10}(SN+1) - 0.20 + 2.32 \text{ Log}_{10}(M_R) + \text{Log}_{10}[(\Delta PSI/(4.2-1.5))/(0.4 + \{1094/(SN+1)^{5.19}\})] - 8.07$$

where

M_R = Resilient modulus of subgrade soil (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 = Structural number

Where the structural number is expressed as

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3$$

where :

a_i = i^{th} layer coefficient

D_i = i^{th} layer thickness (inches)

m_i = i^{th} layer drainage coefficient

ΔPSI = Design serviceability loss
(Initial serviceability index minus terminal serviceability index)

The structural number is a abstract number expressing the structural strength of the pavement required for a given combination of soil support , total traffic expressed as a 18-kip single axle loads, terminal serviceability and environment. The required structural number must then be converted to the actual thickness of the surface, base, and subbase, using the appropriate layer coefficients representing the relative strengths of these materials. The layer coefficients are based on elastic moduli M_R and are to be determined based on stress and strain measurements in a multilayered pavement system. The layer coefficient expresses the empirical relationship between SN and layer thickness and is a measure of the relative ability of the material to function as a structural component of the pavement system. The layer coefficient a_i is related directly to the resilient modulus as follows :

$$a_i = A\,M_R^B \qquad \text{(AASHTO Guide 1986)}$$

where A, B are experimentally derived regression constants

M_R is the resilient modulus of Asphalt Concrete

An unknown layer coefficient a_i can also be estimated from a known coefficient a_{ref} using the following relationship:

$$a_i = a_{ref}\,[\, M_{Ri} / M_{RRef}\,]^B \qquad [4]$$

where:

a_i = i^{th} layer coefficient

a_{ref} = layer coefficient for the reference material

M_{Ri} = resilient modulus for the material in the i^{th} layer

M_{Rref} = resilient modulus for the reference material

A, B are experimentally derived regression constants

Need For Resilient Modulus in Pavement Design

A study of resilient modulus as used in the AASHTO pavement design procedure was conducted by Elliot and Thorton [5]. The effect of variations in subgrade resilient modulus on the various design parameters and on the AASHTO design thickness were examined. They concluded that resilient modulus is a fundamental material property relating to pavement design and performance. Resilient modulus provide a measure of the load induced stress - strain behavior and governs the load response of the pavement system.

Evaluation of Compaction Devices

A study conducted as part of the Asphalt Aggregate Mixture Analysis System (AAMAS) [6] was to ensure that laboratory molded specimens will be fabricated in a manner that will adequately simulate field conditions and yield reliable engineering properties. Five compaction devices were selected as a part of this study including : The Mobile steel wheel simulator, Texas gyratory compactor, Marshall impact hammer, California kneading compactor, and the Arizona vibratory kneading compactor. The compaction devices were selected on the basis of their availability, uniqueness in mechanical manipulation, and potential for use by agencies responsible for asphalt mixture design.

The ability of these devices to simulate field compaction was based on the similarity between engineering properties such as resilient moduli, indirect tensile strength, strains at failure, and tensile creep data. Project locations were in Texas, Virginia, Michigan, Wyoming, and Colorado. The compaction procedures used at each of the locations was the standard method used by that State Department of Transportation. Indirect tensile and resilient modulus tests were performed at 41^{o} Fahrenheit (5^{o} Centigrade), 77^{o} Fahrenheit (25^{o} Centigrade), 104^{o} Fahrenheit (40^{o} Centigrade), and the creep compliance tests were performed at 77^{o} Fahrenheit (25^{o} Centigrade). The resilient modulus tests were performed in accordance with ASTM D 4123-82 and the indirect tensile tests were performed. Ten percent of the stress to failure as measured in the indirect tensile strength test was applied to the specimens during the resilient modulus procedure to produce deformations in the elastic range without damaging the sample.

The study concluded that of the five devices evaluated, the Texas gyratory shear compactor demonstrated the ability to produce mixtures with engineering properties nearest those determined from field cores. Because of its operational simplicity and the potential to produce 4 inch (10.16 cm) and 6 inch (15.24 cm) diameter specimens the Texas gyratory was selected as the most applicable device for preparation of specimens used in mix design analysis.

A study of the AASHTO flexible pavement design equation by Baus and Fogg [7] determined the relative importance of the input parameters. This study assessed the relative changes in the required thickness of the pavement structure that would result from errors in input parameters. The design equation for structural number (SN) uses a converging iterative procedure as a basis for the study. The input parameters were chosen to represent a wide range of design values for flexible pavement.

The following parameters were evaluated to assess the change in structural number : 18 kip equivalent single axle load repetitions (W_{18}), resilient modulus (M_R), reliability (R), and standard Error (S_o) was assessed. It was concluded that the variation in resilient modulus value has the most pronounced effect on SN.

Mamlouk and Sarofim [8] conducted research on the numerous moduli values typically used to characterize asphalt mixtures. The moduli evaluated include: Young's, shear's, bulk, complex, dynamic, resilient, and shell nomographic moduli.

An elastic material is defined as the material in which strains completely appear and disappear immediately on the application and removal of stresses. The effects of temperature are neglected in the theory of linear elasticity and a material can be fully characterized by Young's modulus and Poisson's ratio. Young's modulus is the slope of the straight line representing the stress-strain relation, and Poisson's ratio is defined as the absolute value of the lateral strain divided by the axial strain when an axial stress is applied on an specimen. The other moduli i.e., shear, bulk, can be expressed in terms of Young's modulus. The stress-strain relation of an asphalt concrete specimen is non linear. These moduli are applicable to static loading conditions as opposed to dynamic (repetitive) load conditions. The dynamic modulus was found to be insufficient to explain material response because it ignores the loading frequency and the phase lag between deformation and load.

Viscoelastic materials exhibit a combination of elastic and viscous (time dependent) responses, and are highly temperature dependent. The stress - strain relation depends on the rate of load application and is largely temperature dependent. The responses of asphaltic mixes are time and temperature dependent and they should be analyzed. Repetitive load - type laboratory tests have been developed in an attempt to simulate traffic loads (diametral resilient modulus test, triaxial resilient modulus test, and the sinusoidal unconfined compression tests). The stress - strain relation of asphalt concrete is essentially linear after several load applications. The resilient modulus is the slope of the stress - strain curve after the application of load repetitions and is the current modulus of the material, given the repetitive nature of the traffic load.

It was concluded that of all the moduli available to characterize asphalt concrete mixtures, the resilient modulus is more appropriate for use in multi layer elastic programs. It represents the elastic stiffness of the material after numerous load repetitions.

A study was conducted by the New York State Department of Transportation [9] to evaluate a resilient modulus device for measuring resilient and creep moduli at 40^o Fahrenheit (5^o Centigrade), 77^o Fahrenheit (25^o Centigrade), and 100^o Fahrenheit (38^o Centigrade). The study was conducted since the engineering properties of asphalt concrete mixes, including their elastic and fatigue characteristics and their Poisson's ratio, are required for the structural analysis of flexible pavements for cross section design, to detect problem mixes, and to evaluate alternative materials efficiently.

Marshall specimens were fabricated using seven state - approved top course mixes that were sampled from trucks. The resilient and creep moduli were measured at each temperature and the repeatability of the test was evaluated at the three testing temperatures, and Marshall parameters determined. The repeatability criteria used was the measurements on mutually perpendicular axes of the same specimen should not deviate more than 15 percent of the average of the two values. The test data was analyzed using a single - classification analysis of variance model.

The study concluded that acceptable moduli values were obtained at 77° Fahrenheit (25° Centigrade), and 100° Fahrenheit (38° Centigrade), but test results for both the properties were unacceptable at 40° Fahrenheit (5° Centigrade). The differences among the mixes were found to be significant at the 95 - percent confidence level, and the sample sizes required to assure a maximum error of 20 percent 95 percent of the time were found to be 4 and 30 for resilient modulus and 9 and 12 for creep parameters at 100° Fahrenheit (38° Centigrade) and 77° Fahrenheit (25° Centigrade) respectively. The sample sizes were unacceptably large at 40° Fahrenheit (5° Centigrade).

Gonzalez, Kennedy, and Anagnos [10] conducted a study to develop a technique to estimate the resilient elastic characteristics of asphalt mixtures using the repeated load indirect tensile test. The study also evaluated the resilient and static moduli of elasticity and their relationships with fatigue life for the purpose of mixture design.

Laboratory prepared specimens of two asphalt mixtures containing gravel or limestone and various percentages of asphalt were tested at different temperatures. The fundamental elastic properties estimated include the instantaneous resilient modulus of elasticity, the instantaneous resilient Poisson's ratio, static modulus of elasticity, and Poisson's ratio.

The following trends were observed : The instantaneous resilient modulus of elasticity decreased with increasing temperature and increased number of load applications, and was not affected by the magnitude of applied stress. The instantaneous resilient modulus values were generally higher than the static moduli. The study concluded that a repeated load indirect tensile test be conducted to estimate the repeated - load elastic properties, i.e., resilient modulus of elasticity, and Poisson's ratio. It was also concluded that, an estimate of resilient modulus can be obtained without conducting a long term repeated load test. Reasonable estimates of the modulus could be obtained after about one percent of the fatigue life, but a test specimen should be subjected to a minimum of twenty five load applications before the modulus is estimated.

Kennedy and Adedimila [11] conducted a similar study on the resilient characteristics of asphalt mixtures. The study concluded that the indirect tensile test is suitable for the study of repeated load characteristics of asphalt mixtures because of the ease and simplicity in conducting the test.

Variability in Resilient Modulus Test Results

In a 1991 ASTM paper, Brown and Foo [12] evaluated the repeatability of the ASTM D 4123 procedure for determining resilient modulus. The primary factor evaluated was the effect of the repeated stress on the measured resilient modulus. The ASTM D 4123 procedure averages the resilient modulus values of three specimens and two orientations. The following sources of error were investigated:

1. The experimental error (σ_1), which is a function of the resilient modulus test apparatus and the operator.

2 Orientation variation error associated with the variation of resilient modulus values at different orientations in a specimen.

3. The Sample variation error (σ_3) which is associated with the variation of resilient modulus of different samples.

Repeatability was measured for a single operator using a specific type of test equipment. The repeatability associated with different operators and different apparatus was not determined. The results were analyzed using the statistical analysis system (SAS) to investigate their repeatability and interaction.

The ASTM method of placing spring loaded Linear Variable Differential Transducers (LVDT's) in direct contact with the sample surface was studied. Two alternate procedures were investigated in which a thin membrane (paper, aluminium foil) is placed between the spring loaded LVDT's and the sample surface. A thin membrane (paper, aluminium foil)between the sample and LVDT tip was used to minimize experimental error associated with placement on small depressions or aggregates. It was concluded that of the three methods of measuring deformation, the ASTM method resulted in the least error. The study quantified the repeatability of the ASTM D 4123 procedure as a function of the stiffness of asphalt concrete. It was also concluded that the repeatability is relatively low and an increase in the number of samples would improve repeatability.

CHAPTER III

SAMPLE PREPARATION, EQUIPMENT AND TEST PROCEDURES

Specimens were fabricated in the laboratory using the gyratory shear compactor, Marshall hammer, and the dynamic compaction apparatus. The samples were prepared as per standardized procedures, when available. The laboratory compacted samples resemble as closely as possible the in service mixtures i.e , those produced by mixing, placement, and compaction in the field.

A coding system was developed to identify the specimens prepared with the three compaction techniques and the various sources of aggregates. Every specimen has a unique code by which the compaction technique, source of aggregate, type of mix, and the date of preparation can be identified. An example of the coding system is shown below : Sources were numbered 1 through 5 randomly.

Legend:

First digit:	Mix Type
Second Digit:	Source Number
Third Digit:	Compaction Technique
Fourth through Seventh digit :	Date of Sample Preparation
Eight Digit:	Specimen Number

COMPACTION TECHNIQUE:	CODE
MARSHALL HAMMER:	1
GYRATORY SHEAR:	2
DYNAMIC COMPACTION:	3

A specimen having a code of B111012-1 can be decoded as the specimen prepared using a type B mix from aggregate source 1 using Marshall compaction technique, and prepared on the 12th day in October.

The Dynamic Compaction Apparatus

The dynamic compaction apparatus (Figure 3) was developed specifically for this study in an attempt to approximate field compaction. The device is used to prepare of 4-inch (10.16 cm), 6-inch (15.24 cm), and 8- inch (20.32 cm) in diameter specimens. The different size specimens require changing the compaction head and mold, refer to Figure 1 for a schematic of the device.

The compaction apparatus is mounted on a 3-foot (91.44 cm) *3-foot (91.44 cm) *3/4-inch (1.9 cm) thick base plate which is supported by castors for ease of transport. 2 inch (5.08 cm) diameter vertical pipe supports are provided on both sides of the base plate. The vertical carriage, which supports the compaction hammer slides along the vertical pipe supports. An electric winch with remote switch is provided to raise and lower the compaction hammer.

A spring supported platform 1-foot (30.48 cm)*1-foot (30.48 cm)*3/4-inch (1.9 cm) thick is affixed to the base plate. The purpose of the springs is to give a uniform response during compaction i.e., the rebounding plate aids in compaction. The sample base is bolted to the spring supported platform during compaction. A modified Marshall sample mold (Figure 2) and collar are used for preparing 4 inch (10.16 cm) specimens. The Marshall collar has two tabs welded on opposite sides, so that the collar / mold assembly can be bolted to the sample base. The vibration and subsequent misalignment of the sample mold and compaction head necessitated this modification. To ensure that the samples are 2 1/2-inches (6.35 cm) thick, the vertical pipe supports are drilled and pinned to provide a positive stop for the vertical carriage. The stop locations require a different pin location for the 6-inch (15.24 cm) and 8-inch (20.32 cm) diameter specimens.

Sample Preparation Procedures

Sample preparation procedures are vital in determining realistic resilient modulus values. It is desirable to produce specimens that closely resemble field compacted asphalt concrete. Samples were prepared using the standardized procedures where available. Fifteen samples were prepared for each source and each compaction technique. All samples used identical preparation procedures with the exception of the compaction method.

The aggregates are dried to a constant weight between 105° Centigrade (221° Fahrenheit) to 110° Centigrade (230° Fahrenheit). The aggregates were then blended as per the designated percentages at an optimum asphalt content obtained from the Oklahoma Department of Transportation mix design data. A sample mixture is prepared by weighing 1200 gms of the aggregate as per the design mix requirements at an optimum asphalt content. A two minute mixing time was used on all mixes to assure uniform aggregate coating. The mixture was placed in the heated sample mold in three lifts and the surface smoothened into a convex shape.

The mixture was compacted and the height of the sample measured to ensure that it is 2 1/2-inches (6.35 cm). The samples were allowed to cool prior to removal from the mold until no deformation results while removing it from the mold. The weight of the mix is adjusted (increased / decreased) accordingly to obtain a 2 1/2-inch (6.35 cm) specimen if required.

Texas Gyratory Shear Compactor:

The test specimens were prepared using the ASTM 4013- 81 (Reapproved 87) [15] procedure. The apparatus was set at three revolutions at an gyratory angle of 3 degrees.

Marshall Hammer:

All Marshall specimens were prepared using the Marshall method described in

ASTM D - 1559- 89 [14]. Seventy Five blows were applied on each face of the specimen to simulate heavy traffic. The seventy five blow criteria is comparable to the gyratory compaction.

Dynamic Compaction Apparatus :

The final compaction methodology evaluated for specimen preparation is by using the dynamic compaction apparatus (Figure 1). There is no standard procedure for fabricating specimens using this apparatus. The specimens were prepared by following a using a combination of the previous two compaction methods.

The combined weight of the aggregate was equal to the weight of the aggregate used to prepare a specimen using the gyratory shear method of compaction. The percent air voids was used as the basis for comparison between the compaction techniques.

Material Test System

The Material Test System (MTS) or hydraulic load apparatus used in this study included the following components:

1. An electronic hydraulic actuator panel performing the following functions:
    A. Input control module - controls calibration and sensitivity of the internal 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 an externally mounted load cell.
3. A rigid frame which supports the hydraulic actuator assembly.
4. A high pressure, high volume hydraulic pump, an accumulator, and

assorted valving and piping.

5. A computer interfaced, data acquisition system.

MTS Control / Computer Interface

An important 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 control the MTS system and read the load/displacement data [Figure 5].

An analog/digital board (A/D) installed in a 386 - 16MZ computer was used for machine control and data acquisition. The operational details of the system are as follows:

1. A Control Program (CP) was developed that initiates the MTS load apparatus and subsequently monitors the load displacement data. A series of three Linear Differential Variable Transducers (LVDT's)are used to measure the displacement data. A subroutine was developed for conducting the indirect tensile test for use in the resilient modulus test procedure.
2. The control program operates as follows:
   A. User prompts request detailed test information including : sample code which includes aggregate source and type of compaction, sample weight, height of the sample, sample diameter, test temperature, rest period,and the axis of testing.

   B. User prompt also requests the approval of default program parameters that include : the number of channels requiring data translation, number of data points, clock frequency (sampling rate), load - voltage and displacement - voltage equivalency factors, gain etc.,.

   C. A selected load based on percentage of the indirect tensile strength depending on the testing temperature is made to act on the specimen and the MTS is initiated.

   D. The program inputs voltages from four separate channels corresponding to the LVDT's and the load cell. The stress and horizontal deformations are measured and the resilient modulus is calculated.

Test Procedures

A number of tests were selected to evaluate the properties of asphalt concrete mixtures. A comprehensive outline of the test plan is presented in Figure 3

All specimens were prepared with the optimum asphalt content as determined by the Oklahoma Department of Transportation Materials Laboratory. After molding of the specimens, bulk specific gravity of all the samples was determined as per ASTM D 2726-86 [16]. Five random samples were selected from each of the three compaction devices and each of the five sources.

The Hveem stability of the selected specimens was determined as per the standard procedure designated by ASTM D 1560 [16]. The specimens were maintained at a temperature of 140° Fahrenheit (60° Centigrade) for 15 hours prior to measuring the stability. The maximum specific gravity (Rice's Method) of the specimens were determined as per ASTM.D 2041 [16]. The percent air voids was then calculated using the bulk specific gravity and maximum specific gravity.

The indirect tensile strength test was conducted on one random sample prepared from each of the three compaction devices and using the five aggregate sources as per the procedure described in SHRP Protocol PO7 [13]. Resilient modulus test was conducted on samples as per the procedure described in SHRP Protocol PO7. The test was conducted at three temperatures (41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), and 104° Fahrenheit (40° Centigrade)) along two diametral axes (second axis is 45° to the first) at three rest periods (0.9s, 1.9s, 2.9s). Load intensities of 30, 15, and 5 percent of the indirect tensile strength test were used to determine the resilient modulus at 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), and 104° Fahrenheit (40° Centigrade) respectively. The load intensity for Marshall samples was reduced to

3 percent when testing was conducted at 104° Fahrenheit to ensure adequate deformations without breaking the sample.

Indirect Tensile Test

The indirect tensile strength test was conducted by following the procedure described in Strategic Highway Research Program (SHRP) Protocol PO7 [13]. The asphalt concrete specimen is loaded in compression along the diametral axis at a fixed deformation rate (2 inches per minute (5.08 cm per minute)). This test is required to establish the load intensity to be used in the resilient modulus procedure.

The specimen must be allowed to stand at a temperature of 77° F for 24 hours prior to testing. A modification to this procedure was used to assess the tensile strength of specimens at 104° Fahrenheit (40° Centigrade). Load intensities of 30, 15, and 5 percent of the indirect tensile strength test were used to determine the resilient modulus at 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), and 104° Fahrenheit (40° Centigrade) respectively. The indirect tensile strength is calculated using the following equation :

$$S_t = 1.273 * P_o / t \, [(\mathrm{Sin}\ 57.2958 / D) - 1 / 2D]$$

OR

$$S_t = 0.156 * P_o / t \qquad \text{for a 4 inch (10.16 cm) diameter specimen}$$

Where

P_o = Maximum load in pounds (lbs)

t = Specimen thickness (inches)

D = Specimen diameter (inches)

Resilient Modulus Test

Introduction :

The resilient modulus test of asphalt concrete is determined by applying repetitive applications of compressive loads in a haversine wave form. The compressive load is applied along the vertical diametral plane of a cylindrical specimen of asphalt concrete (Figure 7). The resulting vertical and horizontal deformations are measured. The resilient modulus value is calculated using the applied load, specimen dimensions and the vertical and horizontal deformations. The following test procedure is a summarization of the Strategic Highway Research Program (SHRP) Protocol PO7 procedure of July 1991 [13]. Figure 8 shows the specimen setup for resilient modulus testing.

Resilient modulus tests are conducted by repetitive application of compressive loads in a haversine wave form. Determinations are made at testing temperatures of 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), and 104° Fahrenheit (40° Centigrade with a tolerance of ±2° Fahrenheit (1.1° Centigrade). The specimens should be maintained at the testing temperature for 24 hours.

Temperature Control:

The temperature control system used for testing consisted of a insulated enclosure with copper tubing running along the inside perimeter of the box. Water maintained at a constant temperature of 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), and 104° Fahrenheit (40° Centigrade) was circulated through the tubing in order to maintain the sample at that temperature of testing. In addition to the above the room temperature was maintained at 50° Fahrenheit (10° Centigrade), 77° Fahrenheit (25° Centigrade) , 95° Fahrenheit (35° Centigrade) during the time of testing in order to ensure the proper control of temperature.

Sample Placement & Machine Setup :

The diameter and the height of each test specimen is measured prior to testing. Two orientations are evaluated for each specimen, axis one and axis two are 45° apart. The first axis is centered top to bottom within the loading strips, refer to Figure 7. The line of contact between the specimen and the loading strip is critical for reliable results.

Preconditioning :

The magnitude of applied loads used for preconditioning and testing at the three test temperatures is based on the tensile strength of a similar specimen determined at 77° Fahrenheit (25° Centigrade). The applied load ranges from 30 to 5 percent of the tensile strength. Tensile stress levels of 30, 15, and 5 percent of the tensile strength is used in conducting the resilient modulus determinations at 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), and 104° Fahrenheit (40° Centigrade). Minimum specimen contact loads of 3, 1.5, and 0.5 percent of the tensile strength shall be maintained during the testing at all the three test temperatures. The sequence of resilient modulus testing consists of initial testing at 41° Fahrenheit (5° Centigrade), followed by intermediate testing at 77° Fahrenheit (25° Centigrade) and the final testing at 104° Fahrenheit (40° Centigrade).

The test specimen is preconditioned along the axis prior to testing by applying a repeated haversine - shaped load pulse of 0.1 second duration followed by a rest period of 0.9 seconds duration (Figure 6)until a minimum of 10 successive horizontal deformation readings agree within ten percent. The number of load applications depend upon the test temperature. The expected ranges are

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

The minimum number of load applications for a given situation must be such that the resilient deformations are stable.

Testing :

A minimum of 30 load pulses (each 0.1 second load pulse has a rest period of 0.9 seconds) are applied and the measured deformations are recorded. The application of load pulses is continued beyond 30 until the range in deformations values of five successive horizontal deformation values (i.e. from lowest to highest value) is less than ten percent of the average of the five 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. The recoverable horizontal and vertical deformations over the last five loading cycles are measured after the resilient deformations have become stable. A loading cycle consists of a load pulse and a subsequent rest period.

Once the testing is completed along the first axis the specimen is then oriented 45^{o} from the first axis and the above procedure is repeated. After the testing is completed along both the axes, the specimen is raised to the next higher temperature and the test is conducted. The resilient modulus is calculated along each axis for each rest period and temperature by averaging the measured deformations for the last five cycles.

The resilient modulus is calculated using the following equation

$$E_{RI} = \frac{P^{*}D\,(\,0.080 + 0.297V + 0.0425V^{2})}{H_{I}^{*}\,T}$$

$$E_{RT} = \frac{P^{*}D\,(\,0.080 + 0.297V + 0.0425V^{2})}{H_{T}^{*}\,T}$$

Where

E_{RI} = Instantaneous modulus of elasticity, psi

E_{RT} = Total modulus of elasticity, psi

P = repeated load, lbf.,

T = thickness of the test specimen, inches.,

D = diameter of the specimen, inches.,

H_I = instantaneous recoverable deformation, inches.,

H_T = total recoverable horizontal deformation, inches.

V = Poisson's Ratio assumed for each temperature.

The values of Poisson's Ratio shall be assumed as follows :

41° Fahrenheit	0.20
77° Fahrenheit	0.35
104° Fahrenheit	0.50

CHAPTER IV

RESULTS AND ANALYSIS

The following tests were performed in this study : bulk specific gravity, Hveem stability, maximum specific gravity, Air void determination, indirect tensile strength test, and the resilient modulus test. The results of those tests are presented in this chapter.

Bulk Specific Gravity

The bulk specific gravity (BSG) of all the samples was determined. The BSG results are summarized in Tables 2 through 6. The following trend was observed : The BSG of the gyratory shear specimens was the highest, followed by dynamic samples, and Marshall samples. The BSG is an indicator of the relative compaction and percent air voids. The primary reason for the gyratory samples giving consistently a higher BSG is, the gyratory compaction method applies normal forces to both top and bottom faces of the asphalt mix in a cylindrically confined mold. These normal forces supplemented with a gyratory motion work the mix into a denser configuration while it is totally confined resulting in better compaction and lower air voids.

Hveem Stability Test

Hveem stability tests were conducted on five random samples from each of the ten source compaction combinations (Five sources and two compaction techniques). Hveem stability determinations on the Marshall samples were not conducted during the course of this study. The results of the stability tests are summarized in Tables 7 through 11. The following trends were observed : The stabilities of the dynamic samples was high followed by the gyratory compacted samples. Generally, the higher the percent air voids the lower the Hveem stability. But inspite of the higher air voids the dynamic samples resulted in consistently higher stabilities. During the dynamic compaction, some of the larger aggregates may have broken resulting in higher percentage air voids, but still behaves as a well compacted sample resulting in higher stabilities.

Maximum Specific Gravity and Air Voids

The maximum specific gravity of a five random samples selected from each source and compaction technique was conducted (Rice Method) and the results were summarized. The percentage of air voids in the compacted specimens is then calculated. The results of the air voids and the maximum specific gravities are tabulated in Tables 7 through 11. From the results, it can be observed that the maximum specific gravities of the specimens prepared by the three compaction techniques are relatively close to each other.

The percent air voids in the compacted mixes vary between 3 and 10 percent. The Marshall compacted specimens show a wide variation in air voids (6 percent to 10 percent). The absence of kneading action during the compaction operation, is a primary factor in the higher air voids.

The gyratory shear and dynamic compaction apparatus facilitate reorientation of the aggregate particles. The percent air voids in these range between 3 percent and 9 percent.with the gyratory samples having a lower percent air voids. The gyratory samples consistently gave a lower percent air voids for the same weight of the mixture taken. The gyratory compaction method applies normal forces to both top and bottom faces of the asphalt mix in a cylindrically confined mold. These normal forces supplemented with a gyratory motion work the mix into a denser configuration while it is totally confined resulting in better compaction and lower air voids. The better orientation of the aggregate particles as a result of the gyratory action also result in the inter granular voids getting filled with more fines which result in a lower percent air voids.

Indirect Tensile Strength Test

The indirect tensile strength test was conducted on one sample from each source and compaction technique for use in estimating the loads to be used in the resilient modulus test. as per the designated test procedure and the results are summarized in Table 12. The following trends were observed : indirect tensile strength of gyratory shear compacted specimens was the highest followed closely by dynamic samples with the Marshall samples having the least strength. For similar type of aggregates prepared with the same percentage of asphalt cement the better the sample is compacted, the higher is the indirect tensile strength. Bulk specific gravity which can be considered a measure of compaction, shows that the gyratory samples have a higher degree of compaction when compared to dynamic and Marshall samples. This agrees with the results obtained.

Resilient Modulus Test

Resilient modulus tests were conducted on samples prepared from five different aggregate sources obtained from different locations in Oklahoma. Five sources were evaluated to assess the range in resilient modulus values for a typical type " B " mix.This was done primarily to observe a range in resilient modulus values. The results of the resilient modulus tests are tabulated in Tables 13 through 15. The resilient modulus test was conducted on asphalt concrete samples prepared using different aggregate sources and the three compaction techniques. The resilient modulus was evaluated for the following parameters :

1. Three temperatures i.e., 41° Fahrenheit (5° Centigrade), 77° Fahrenheit (25° Centigrade), 104° Fahrenheit (40° Centigrade).
2. Three different rest periods (0.9s, 1.9s, 2.9s).
3. Two axes of loading (second axis oriented 45° to the first).

Testing on the two axes at three different rest periods result in six combinations of test conditions. It was observed that all the six combinations of test conditions for every source of aggregate, compacted with any of the compaction techniques give approximately the same resilient modulus values. The mean for the the different test combinations and the F values for different sources and compaction techniques are tabulated in Tables 16 through 20.

The difference in resilient modulus values along the two axes may be due to the application of repeated load for preconditioning and subsequent testing along the first axis before testing along the second axis (oriented 45° to the first). Another reason may be the variability that exists in the sample preparation procedures and general experimental error. Overall, it can be observed that the mean values lie approximately close to each other.

The effect of different compaction techniques on the resilient modulus for each aggregate source will be analyzed on an individual basis. Testing for any interaction between the compaction technique and testing temperature, it can be observed that all the samples behave similarly with temperature, irrespective of the compaction technique. The test results also show that there is a significant difference in the resilient modulus values of samples prepared using different compaction techniques. The difference in resilient modulus values may be a result of the different actions used to compact the aggregates i.e shearing, dynamic, and impact by gyratory, dynamic and marshall compaction procedures respectively. The gyratory and dynamic compacted samples exhibit similar characteristics and the resilient modulus values are close to each other. The difference in the resilient modulus values that can be observed among different sources may be due to the variation in source as a result of their location. Figures 14 through 16 show the range in the resilient modulus values for different sources, different compaction techniques, and different temperatures. Since the differences in the resilient modulus values were not found to be significant, the mean value will be used for further analysis.

<u>Aggregate Source One</u> :

Analyzing the resilient modulus values of samples obtained from source one using three different compaction techniques (Table 16), it can be observed that there is no interaction between the compaction technique and temperature i.e., the resilient modulus values vary similarly with temperature for three different compaction techniques. The following trends were observed : The resilient modulus of gyratory samples was the highest followed by dynamic samples , and Marshall samples. Figure 9 shows that gyratory and dynamic compaction techniques exhibit similar characteristics when compared to Marshall compaction technique.

Aggregate Source Two :

Analyzing the resilient modulus values of samples prepared from aggregates obtained from from source two using three different compaction techniques at three temperatures (Table 17), it can be observed that there is no interaction between the compaction technique and temperature. The following trends were observed : The resilient modulus of gyratory samples was the highest followed by dynamic samples , and Marshall samples. Figure 10 shows that gyratory and dynamic compaction techniques exhibit similar characteristics when compared to Marshall compaction technique.

Aggregate Source Three :

Analyzing the resilient modulus values of samples prepared from aggregates obtained from source three using three compaction techniques at three temperatures (Table 18), it can be observed that the resilient modulus for three different compaction techniques does not vary similarly with temperature ($F = 11.56$, $OSL < 0.05$). Therefore overall comparison of three techniques is not feasible for this source. The following trends were observed : The resilient modulus of gyratory samples was the highest followed by dynamic samples , and Marshall samples. Figure 11 shows that gyratory and dynamic compaction techniques exhibit similar characteristics when compared to Marshall compaction technique.

Aggregate Source Four :

Analyzing the resilient modulus values of samples prepared from aggregates obtained from from source four using three different compaction techniques at three temperatures (Table 19), it can be observed that there is no interaction between the compaction technique and temperature. The following trends were observed : The resilient modulus of gyratory samples was the highest followed by dynamic samples , and Marshall samples. Figure 12 shows that gyratory and dynamic compaction techniques exhibit similar characteristics when compared to Marshall compaction technique.

Aggregate Source Five :

Marshall samples prepared using this particular aggregate source were not tested, since the depressions present in the sample were higher than the minimum values [11], and hence the samples were not used for testing and evaluation. Analyzing the resilient modulus values of samples prepared from aggregates obtained from source five (Table 20) it can be observed that there is no interaction between compaction technique and temperature. The following trends were observed : The resilient modulus of gyratory samples was higher than the dynamic samples. Figure 13 shows that gyratory and dynamic compaction techniques exhibit similar characteristics when compared to Marshall compaction technique.

Overall Trends

The resilient modulus test was conducted on asphalt concrete samples prepared using different aggregate sources and the three compaction techniques. The resilient modulus was evaluated for the following parameters :

1. Three temperatures i.e., 41^{o} Fahrenheit (5^{o} Centigrade), 77^{o} Fahrenheit

(25° Centigrade), 104° Fahrenheit (40° Centigrade).

2. Three different rest periods (0.9s, 1.9s, 2.9s).

3. Two axes of loading (second axis oriented 45° to the first).

Based on the test results obtained and their discussion the following trends can be inferred : The resilient modulus of the gyratory samples are the highest followed by the dynamic samples, and the Marshall samples for all the five aggregate sources and different temperatures. A similar trend is observed between resilient modulus and temperature i.e., the resilient modulus decreases with an increase in temperature for each of the five different sources and the compaction techniques. Previous studies [7] on the evaluation of compaction devices have shown that gyratory compaction is more effective than Marshall compaction. Thus Marshall hammer will not be evaluated for further analysis. A comparison of the resilient modulus values on samples prepared by using the gyratory shear compactor and the dynamic compaction apparatus at three different temperatures can be observed in Figure 17.

CHAPTER V

CONCLUSIONS

The purpose of the study was to determine the resilient modulus of a typical type 'B' mix. A secondary objective was the evaluation of three compaction devices to determine their ability to approximate field compaction. The resilient modulus tests were conducted at three temperatures, three rest periods, and along two axes. Based on the results obtained from this test program, it can be concluded that

1. The resilient modulus values of all compacted mixes increase with decreasing temperatures independent of the compaction technique.
2. The effect of varying the rest period is not significant.
3. The difference in resilient modulus values measured on the two axes (second is 45 degrees to the first) is not significant.
4. The resilient modulus of the gyratory compacted samples and the dynamic compacted samples are approximately equal.
5. The dynamic compaction apparatus, to produce reliable results may be used for preparing and testing large size samples [6 inch (15.24 cm), and 8 inch (20.32 cm) diameter respectively] by changing the compaction head and mold.

CHAPTER VI

RECOMMENDATIONS

1. Field cores of "newly constructed" pavements using the aggregate sources considered in the study should be tested for resilient modulus. A comparison should be made with laboratory compacted samples and the effectiveness of the dynamic compaction apparatus to approximate field compaction should be determined
2. The effectiveness of the dynamic compaction apparatus to produce large size samples [i.e., 6 inch (15.24 cm) and 8 inch (20.32 cm)] prepared using aggregate with sizes greater than 1 inch (2.54 cm) should be determined by comparing it with 4 inch (10.16 cm) diameter samples prepared using the same aggregate size.
3. Since different rest periods, and two axes do not give any significantly different resilient modulus values, future resilient modulus testing can be conducted along one axis with one rest period..
4. The effect of applying various percentages of indirect tensile strength on the specimen for resilient modulus determinations should be studied.
5. There is a need to look at an increased scope of temperature effect on the resilient modulus.
6. Assess gradation changes in aggregate due to various compaction techniques, principally the dynamic compaction apparatus.

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APPENDIXES

APPENDIX A

FIGURES

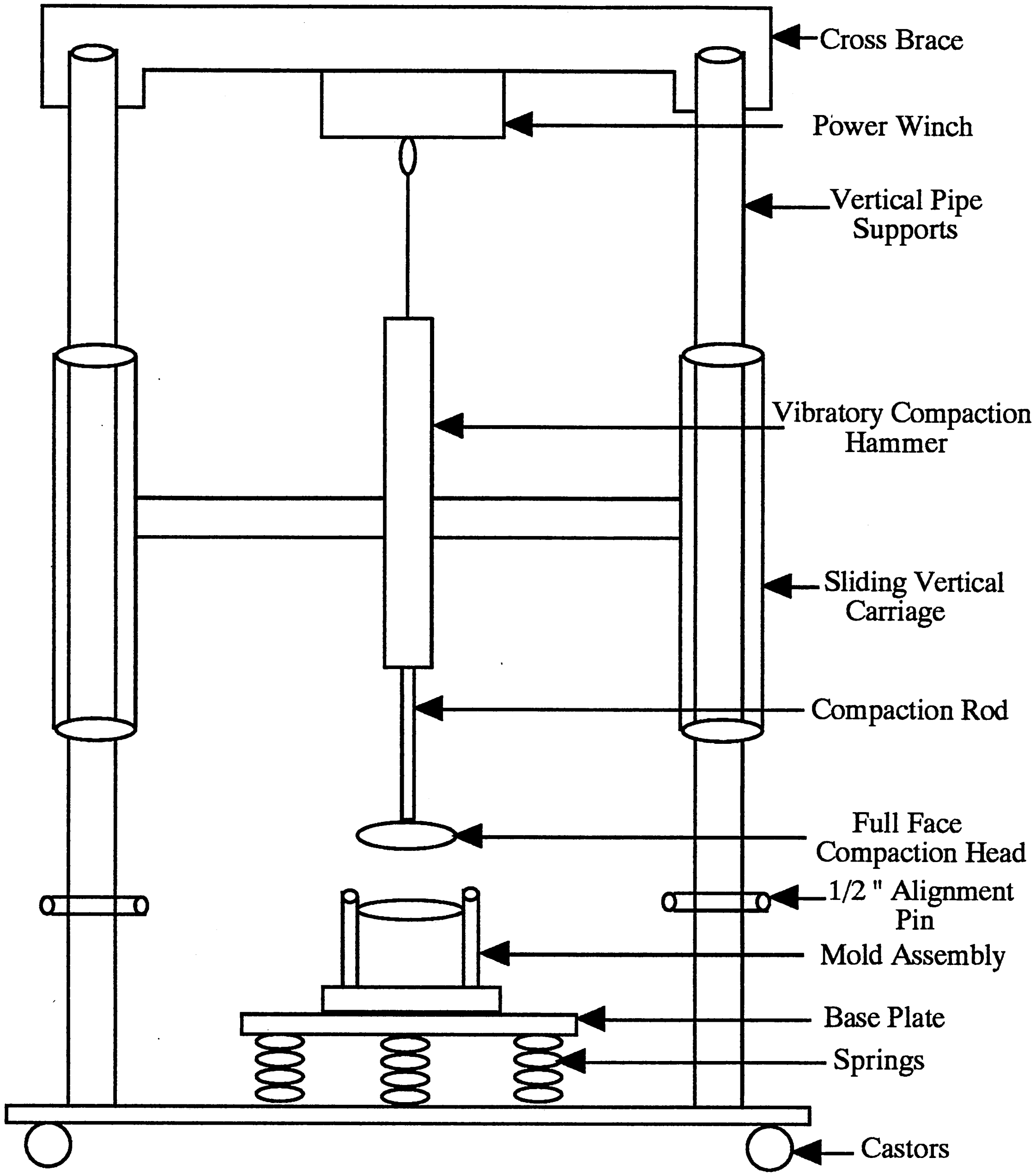


Figure 1. Schematic of the Dynamic Compaction Apparatus

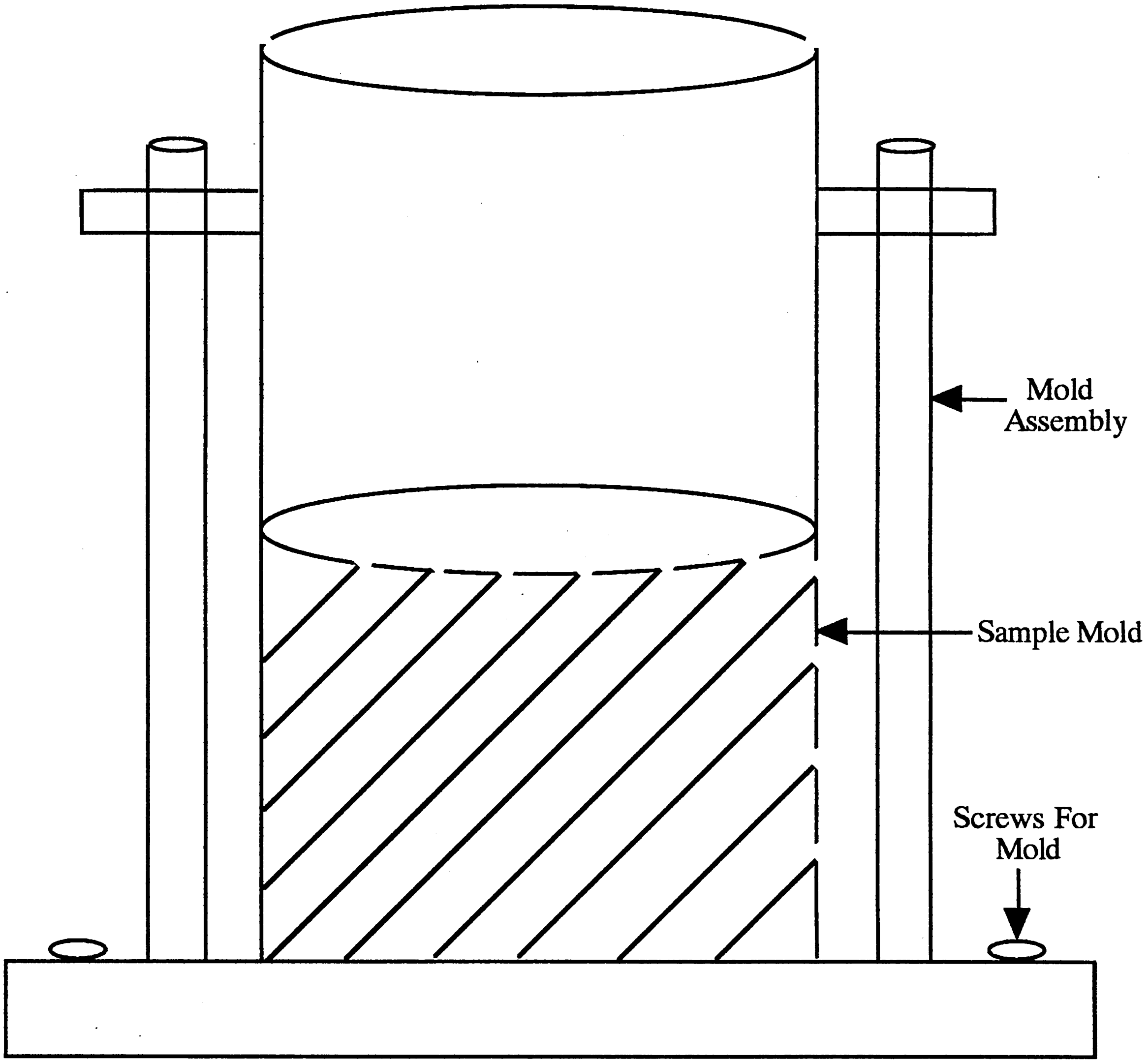


Figure 2. Sample Mold Assembly For Dynamic Compaction Apparatus

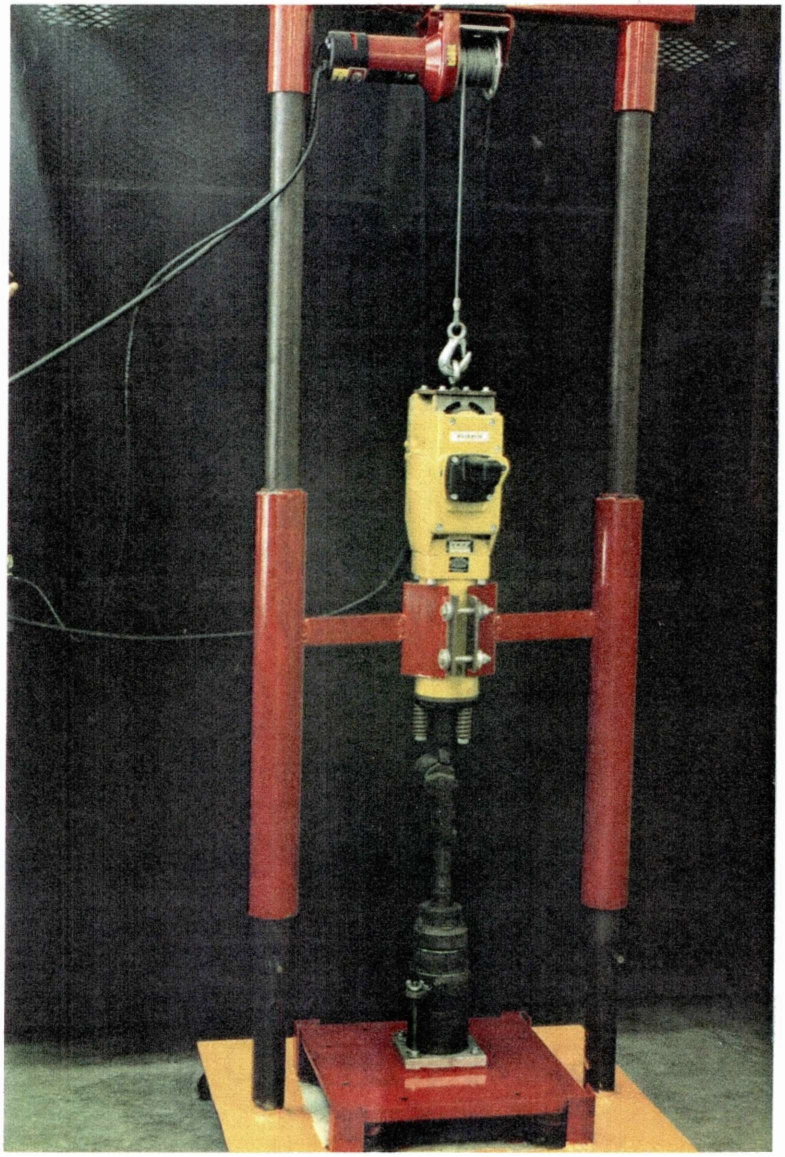


Figure.3. The Dynamic Compaction Apparatus

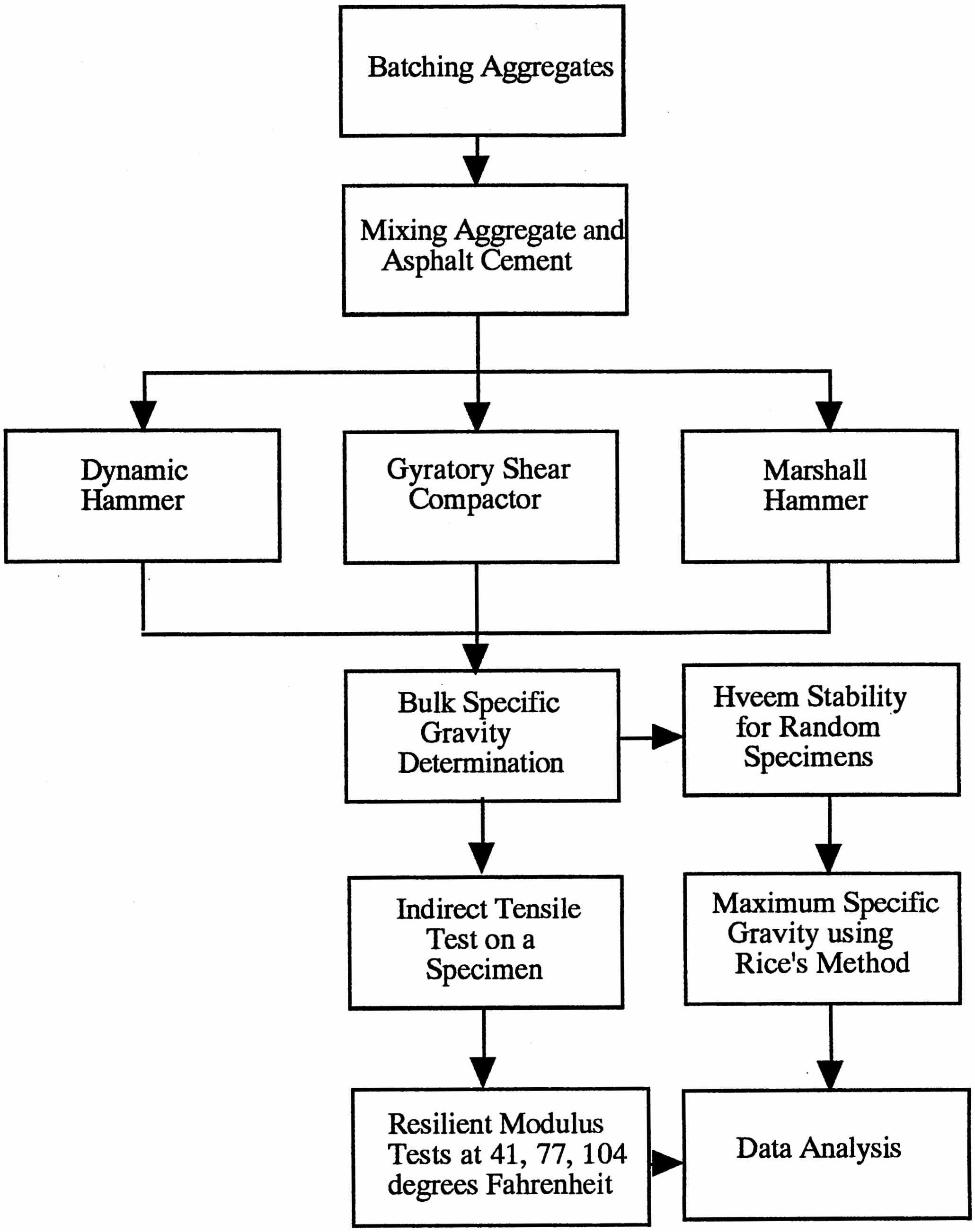


Figure 4. Flow Chart for the Project

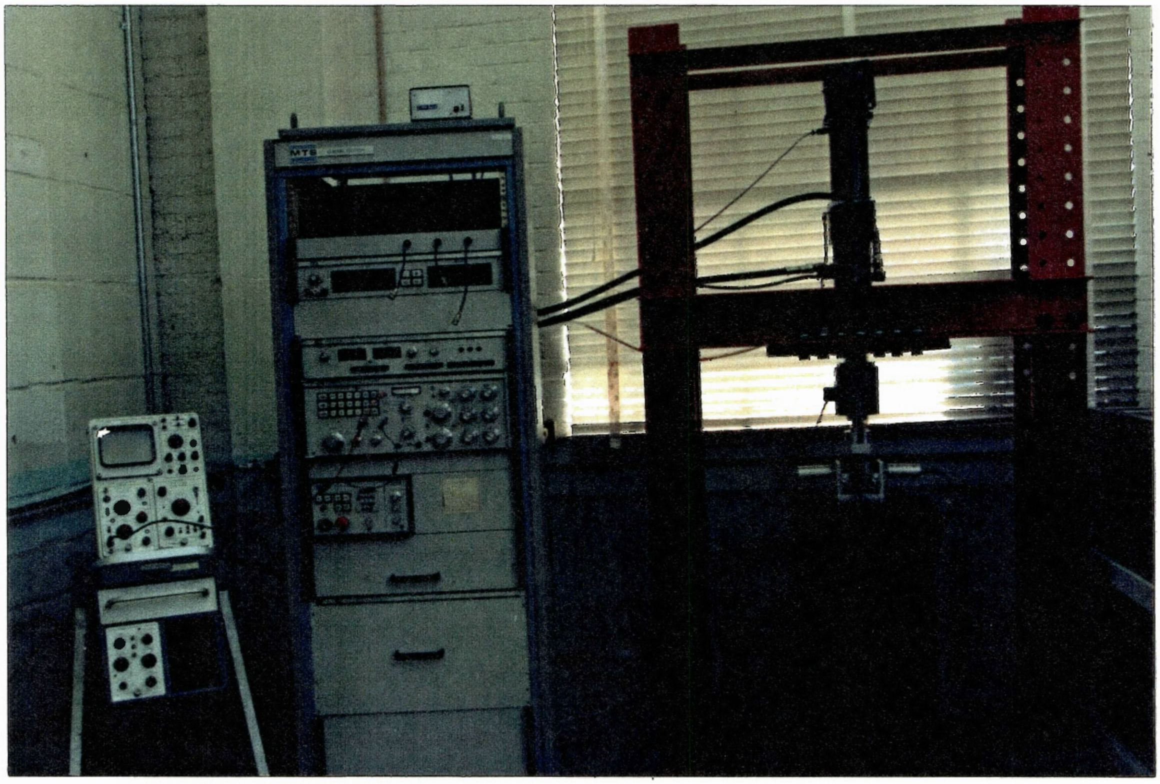
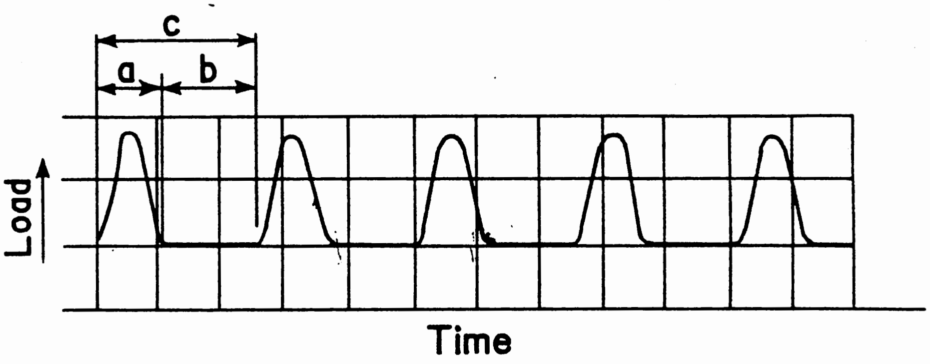
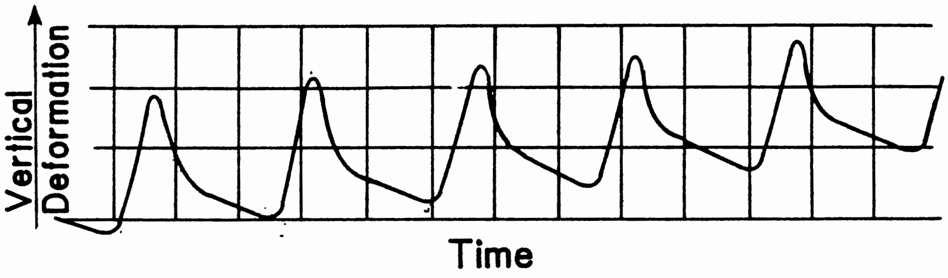


Figure 5. Overall View of Resilient Modulus Testing System



(a) Load-Time Pulse

a = load duration
b = recovery time
c = cycle time



(b) Vertical Deformation Versus Time

Figure 6. Typical Load and Deformation Versus Time Relationships for Resilient Modulus Test

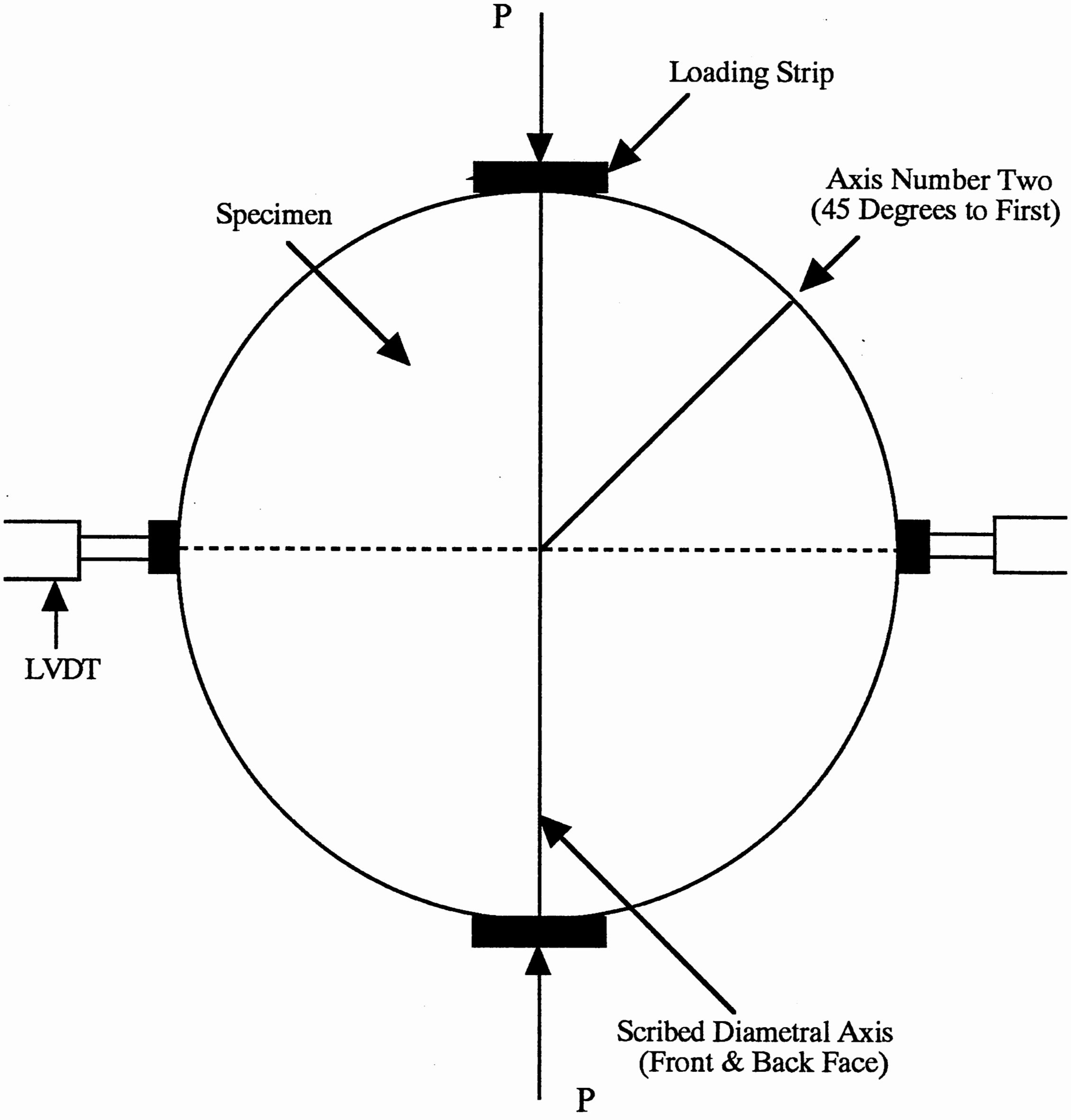


Figure 7. Loading of the Asphalt Concrete Specimen

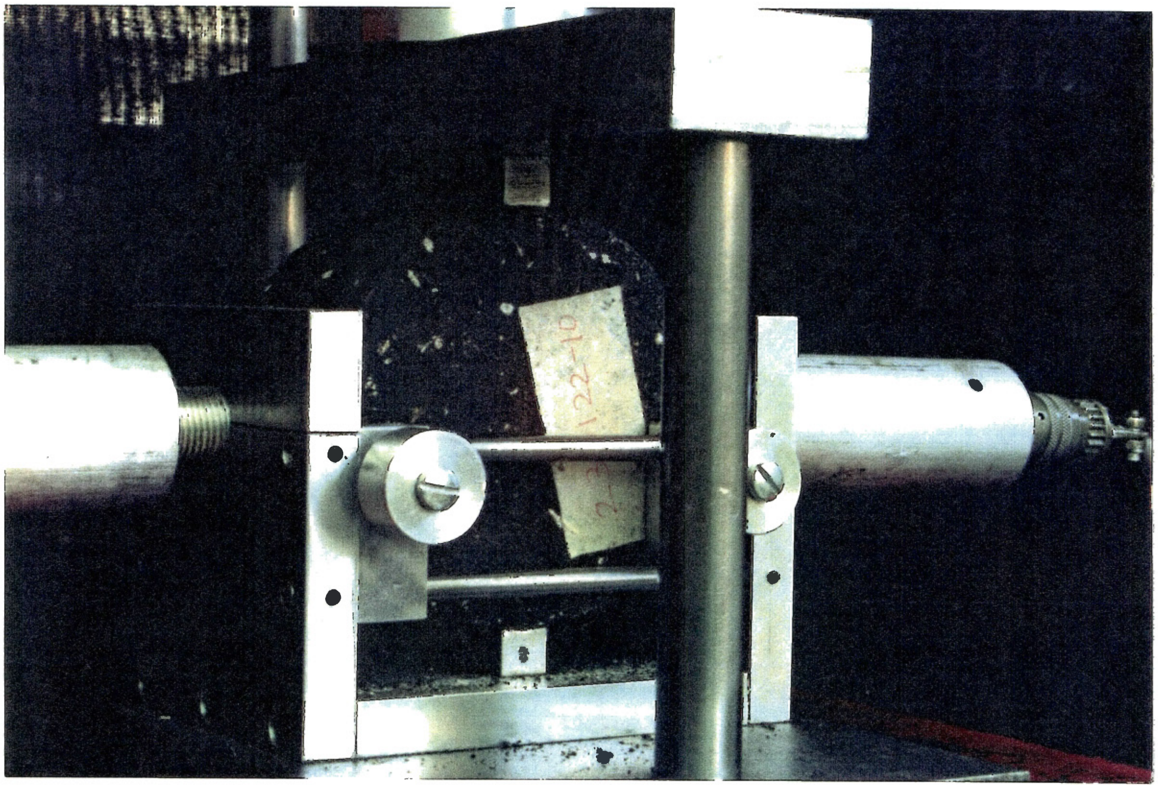


Figure 8. Specimen Setup For Resilient Modulus Testing

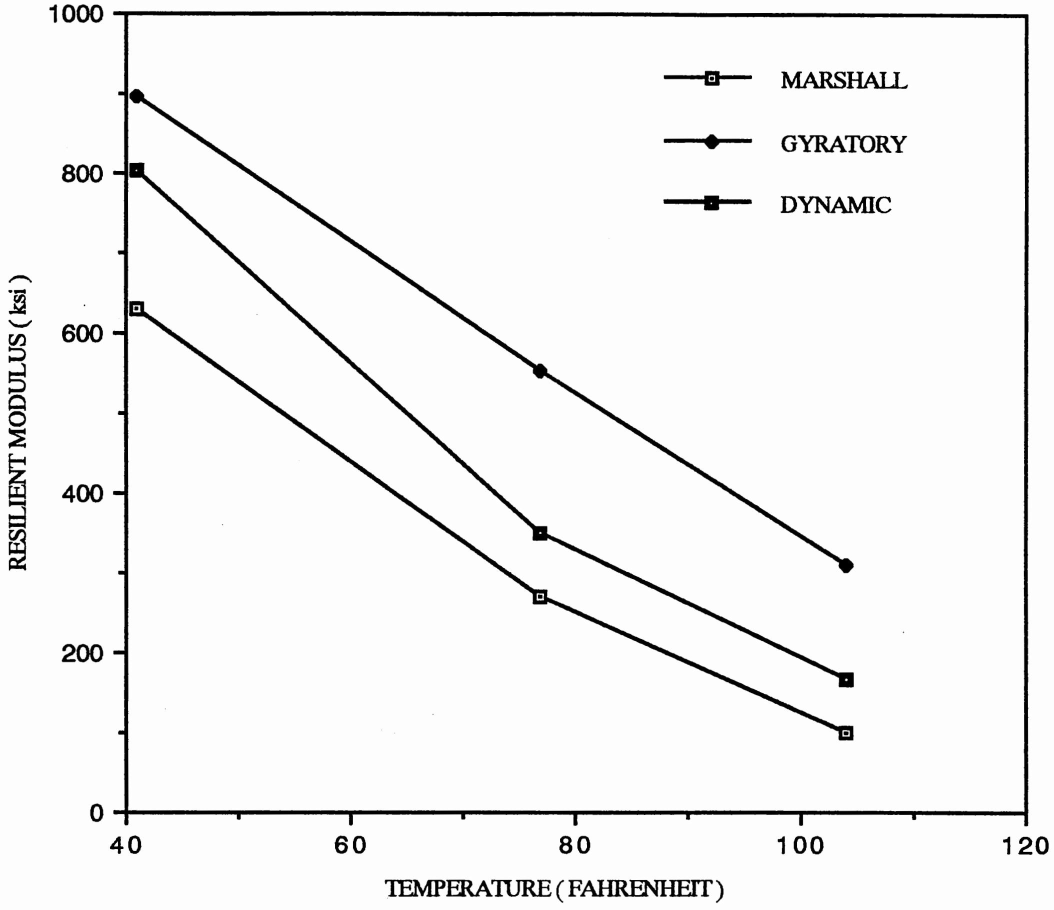


Figure 9 Resilient Modulus at 41, 77, 104 degree Fahrenheit for Source 1

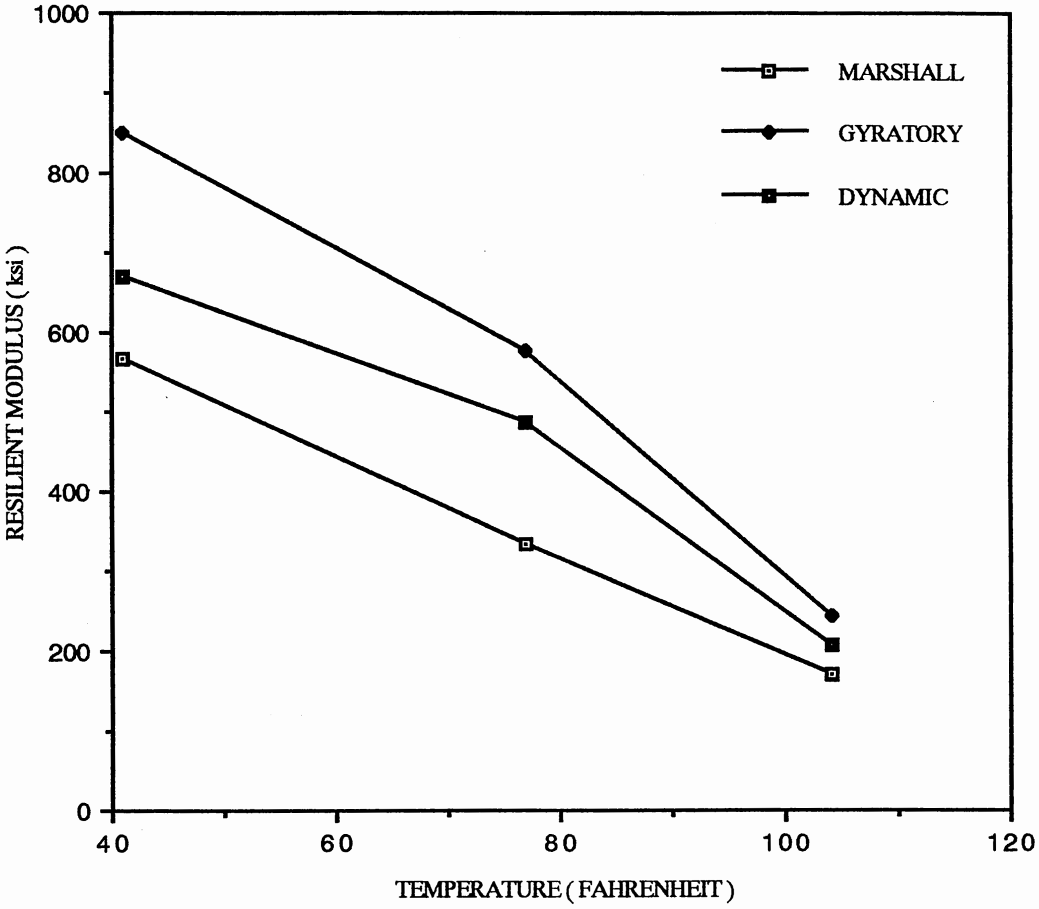


Figure 10 Resilient Modulus at 41, 77, 104 degree Fahrenheit for Source 2

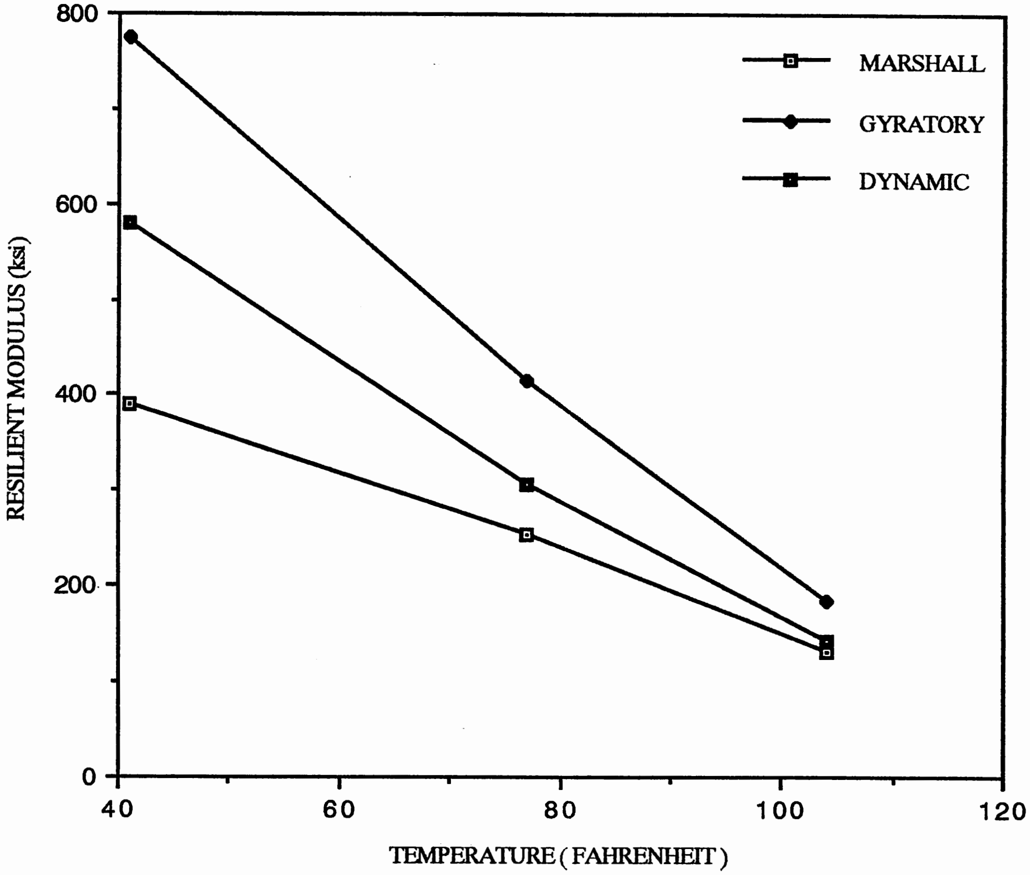


Figure 11 Resilient Modulus at 41, 77, 104 degree Fahrenheit for Source 3

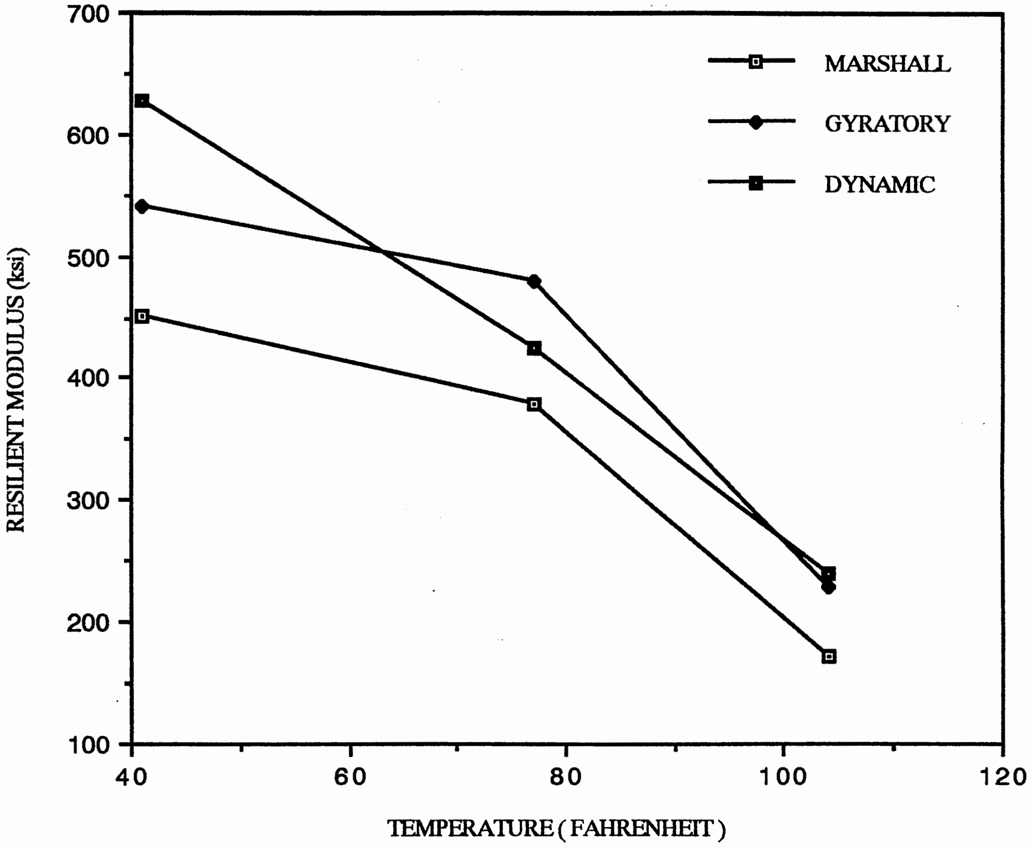


Figure 12. Resilient Modulus at 41, 77, 104 degree Fahrenheit for Source 4

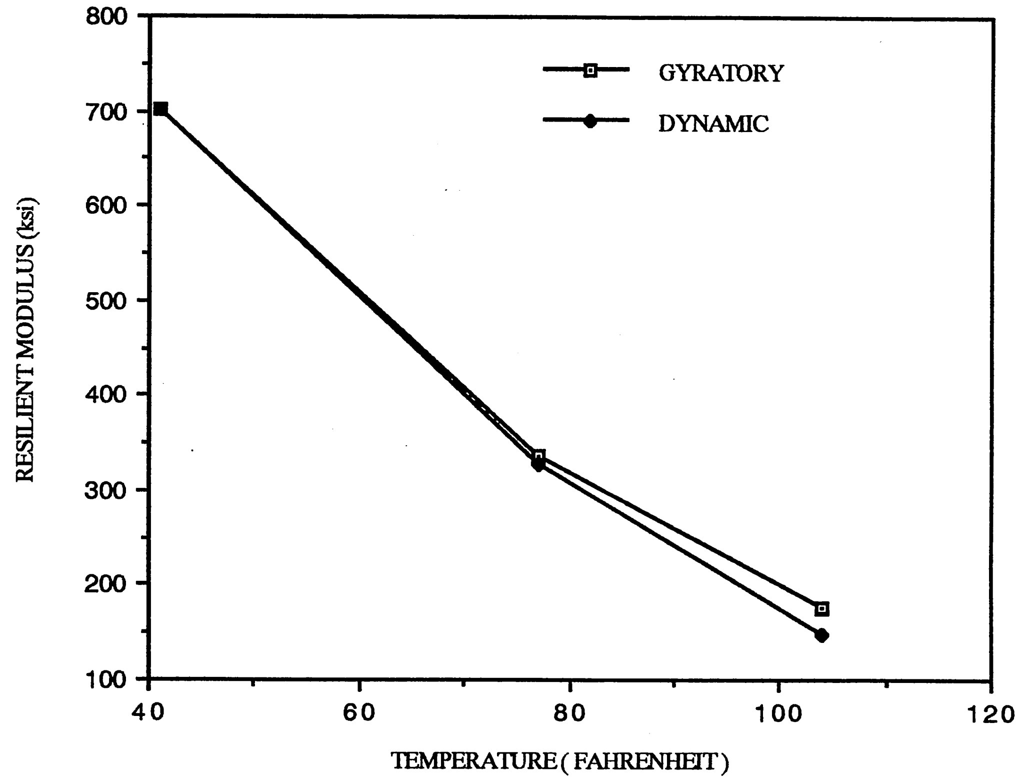


Figure 13. Resilient Modulus at 41, 77, 104 degree Fahrenheit for Source 5

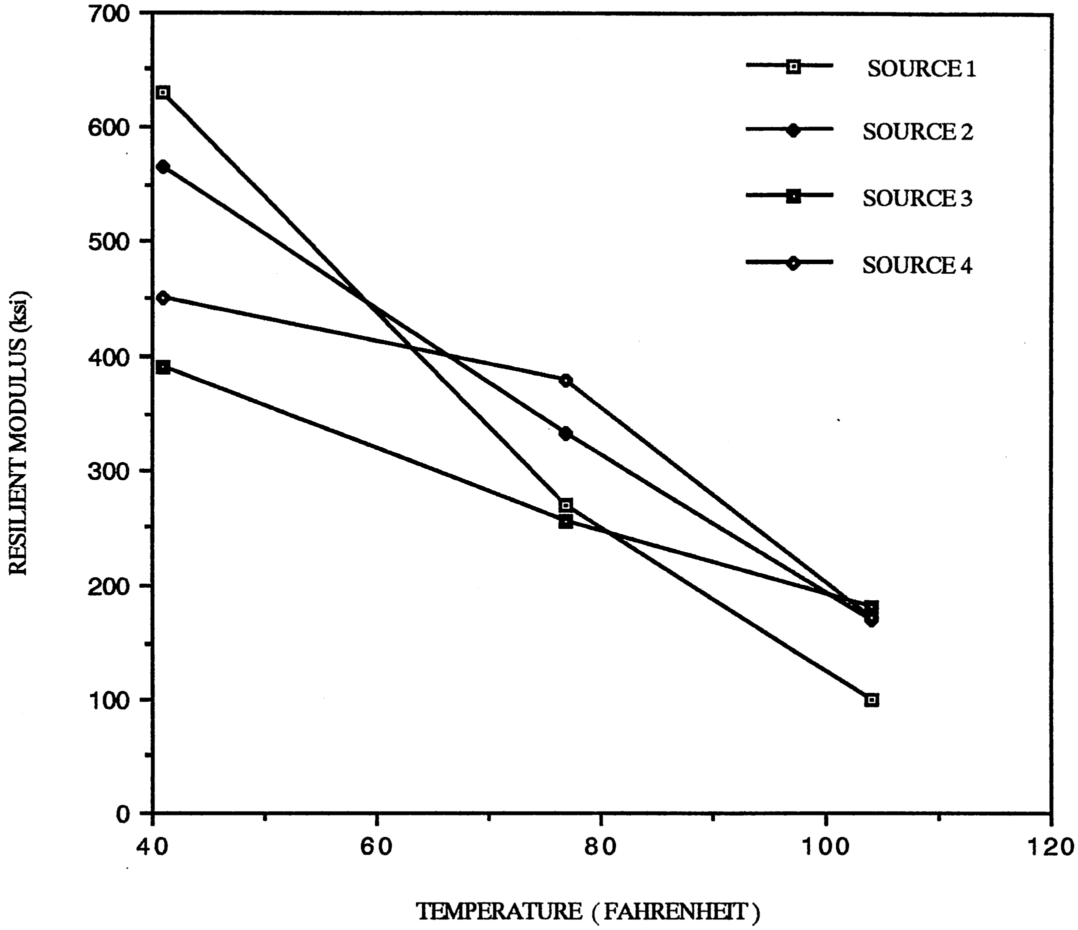


Figure 14. Resilient Modulus for Marshall compacted samples for different sources

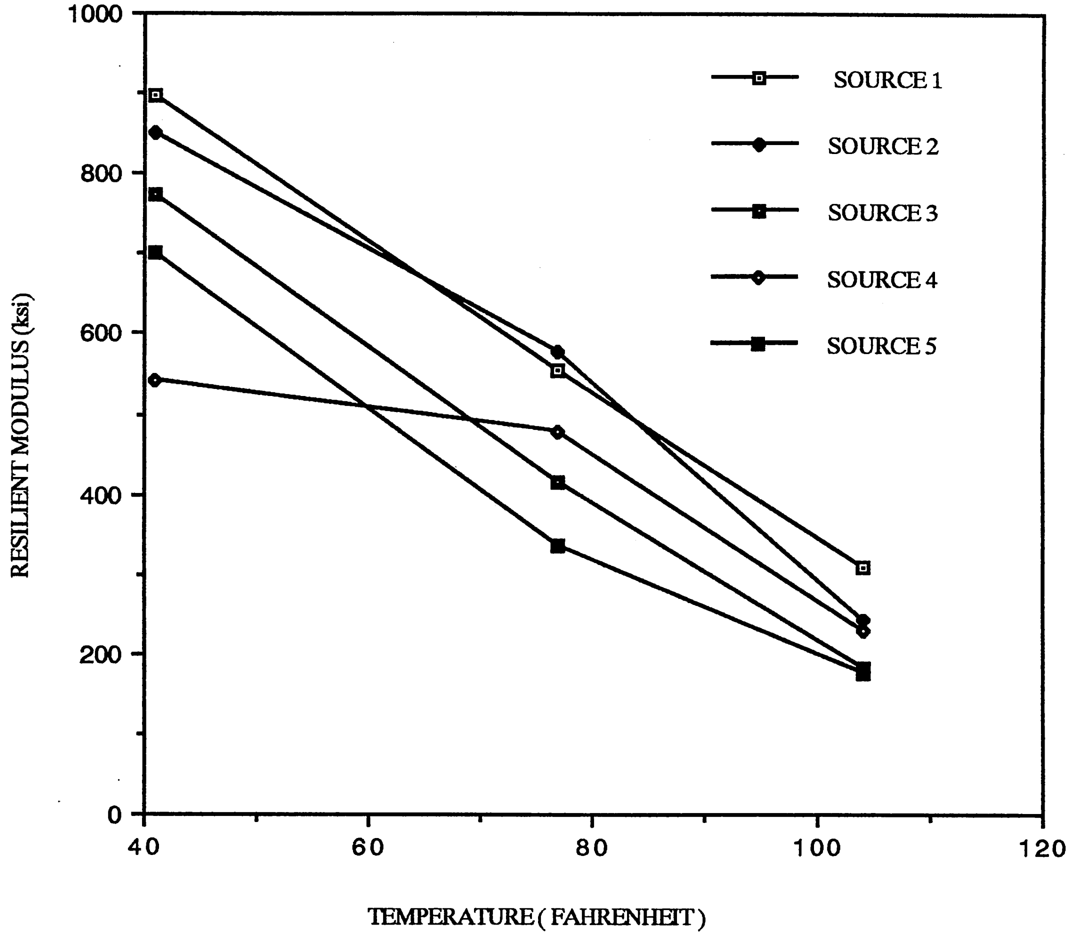


Figure 15. Resilient Modulus for Gyratory compacted samples for different sources

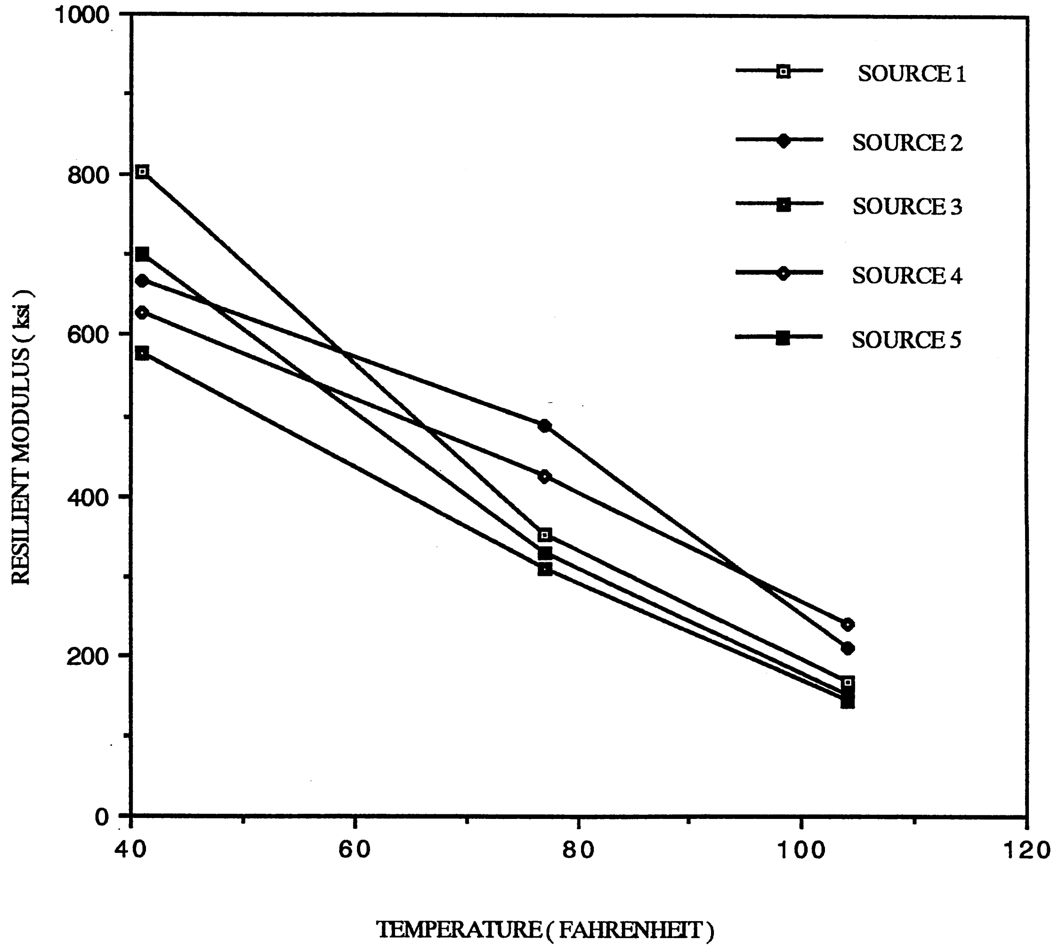


Figure 16. Resilient Modulus for Dynamic compacted samples for different sources

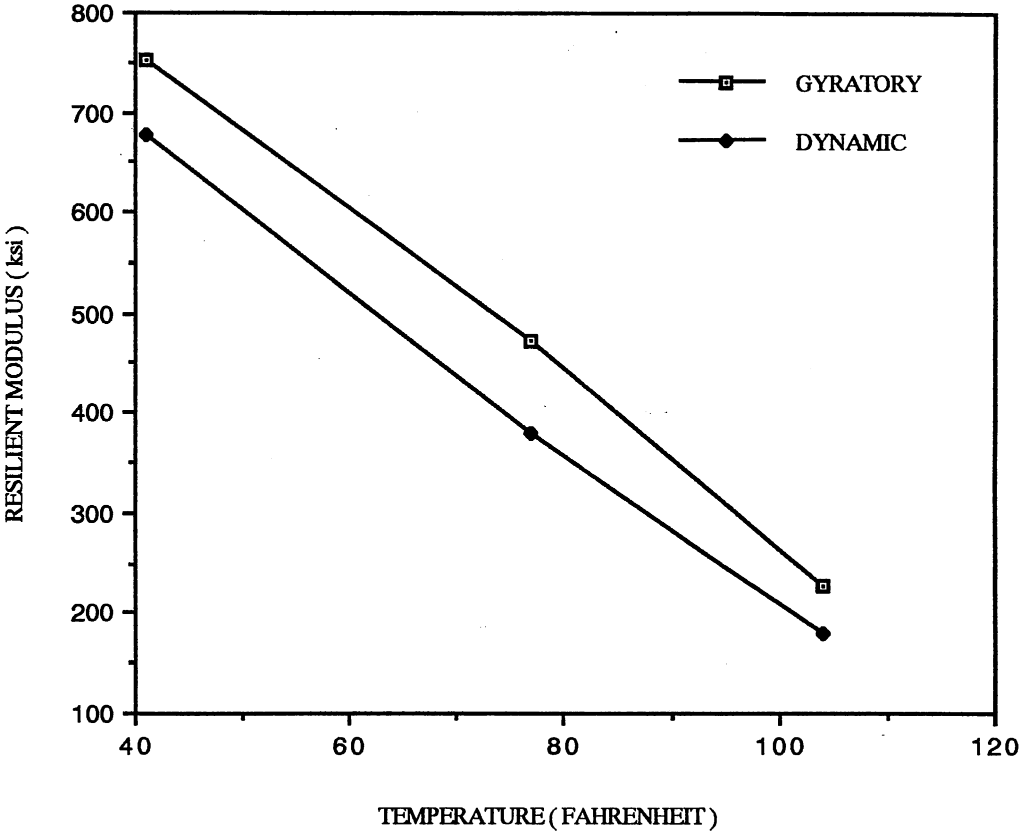


Figure 17 Comparison of Resilient Modulus values for Gyratory and Dynamic compacted specimens

APPENDIX B

LIST OF TABLES

TABLE 1

AGGREGATE GRADATION FOR OKLAHOMA DEPARTMENT OF TRANSPORTATION ASPHALT CONCRETE MIXES

Mixture Type	Asphalt Concrete Mixture Type			
	A	B	C	D
Sieve Size	Percent Passing			
1 1/2"	100	-	-	-
1"	90-100	-	-	-
3/4"	-	100	-	-
1/2"	70-90	90-100	100	-
3/8"	-	70-90	90-100	100
No 4	40-65	45-70	60-80	80-100
No 10	25-45	25-50	35-60	50-90
No 40	10-26	12-30	15-35	20-50
No 80	6-18	7-20	8-22	10-30
No 200	*	*	*	5-15

* For types A, B, C asphalt concrete , 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. The ratio will establish the master range for the job mix on the no. 200 sieve.

TABLE 2

BULK SPECIFIC GRAVITY OF SPECIMENS FROM SOURCE 1

	Type of Compaction		
Sample No.	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 FROM SOURCE 2

	Type of Compaction		
Sample No.	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	2.426	2.436
13	2.334	2.418	2.405
14	2.349	2.420	2.399
15	2.340	2.406	2.416

TABLE 4

BULK SPECIFIC GRAVITY OF SPECIMENS FROM SOURCE 3

	Type of Compaction		
Sample No.	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 FROM SOURCE 4

	Type of Compaction		
Sample No.	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	2.215	2.309	2.253
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 FROM SOURCE 5

	Type of Compaction		
Sample No.	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

AIR VOIDS AND STABILITY TEST RESULTS FOR SOURCE 1 SPECIMENS

[1]SOURCE	AC (%)	[2]BSG	[3]MSG	VOIDS (%)	STABILITY
12-2	5.0	2.412	2.485	3.1	45
12-4	5.0	2.410	2.484	3.3	42
12-8	5.0	2.408	2.479	2.9	44
12-9	5.0	2.405	2.476	3.0	41
12-15	5.0	2.405	2.480	3.1	45

[1] Include Source, Type of Compaction, Sample Number

[2] BSG = Bulk Specific Gravity

[3] MSG = Maximum Specific Gravity

TABLE 8

AIR VOIDS AND STABILITY TEST RESULTS FOR SOURCE 2 SPECIMENS

[1]SOURCE	AC (%)	[2]BSG	[3]MSG	VOIDS (%)	STABILITY
21-2	4.6	2.348	2.527	7.1	-
21-7	4.6	2.312	2.532	8.7	-
21-10	4.6	2.310	2.530	8.7	-
21-12	4.6	2.331	2.531	7.9	-
21-13	4.6	2.334	2.527	7.6	-
22-5	4.6	2.417	2.523	4.2	42
22-9	4.6	2.425	2.520	3.8	43
22-12	4.6	2.426	2.524	3.9	44
22-13	4.6	2.418	2.517	3.9	43
22-14	4.6	2.420	2.520	4.0	42
23-3	4.6	2.394	2.519	5.0	48
23-4	4.6	2.370	2.524	6.1	47
23-6	4.6	2.417	2.528	4.4	58
23-11	4.6	2.412	2.525	4.5	57
23-15	4.6	2.416	2.520	4.1	62

[1] Include Source, Type of Compaction, Sample Number
[2] BSG = Bulk Specific Gravity

[3] MSG = Maximum Specific Gravity
* Marshall Stability not determined

TABLE 9

AIR VOIDS AND STABILITY TEST RESULTS FOR SOURCE 3 SPECIMENS

[1]SOURCE	AC (%)	[2]BSG	[3]MSG	VOIDS (%)	STABILITY
31-2	5.3	2.220	2.461	9.7	-
31-9	5.3	2.223	2.443	8.8	-
31-11	5.3	2.217	2.450	9.5	-
31-12	5.3	2.213	2.446	10.0	-
31-15	5.3	2.216	2.440	9.0	-
32-1	5.3	2.302	2.439	5.6	39
32-3	5.3	2.303	2.440	5.6	40
32-9	5.3	2.301	2.432	5.4	41
32-11	5.3	2.280	2.461	7.3	39
32-13	5.3	2.285	2.451	6.8	39
33-3	5.3	2.254	2.455	8.2	48
33-6	5.3	2.267	2.456	7.7	51
33-8	5.3	2.258	2.449	7.8	49
33-10	5.3	2.249	2.460	8.6	47
33-15	5.3	2.245	2.464	8.9	51

[1] Include Source, Type of Compaction, Sample Number
[2] BSG = Bulk Specific Gravity

[3] MSG = Maximum Specific Gravity
Marshall Stability not determined

TABLE 10

AIR VOIDS AND STABILITY TEST RESULTS FOR SOURCE 4 SPECIMENS

[1]SOURCE	AC (%)	[2]BSG	[3]MSG	VOIDS (%)	STABILITY
42-1	5.2	2.335	2.441	4.3	40
42-2	5.2	2.330	2.448	4.8	45
42-7	5.2	2.265	2.458	7.8	41
42-11	5.2	2.309	2.441	5.4	45
42-13	5.2	2.366	2.442	3.1	45
43-1	5.2	2.337	2.454	4.8	55
43-3	5.2	2.345	2.445	4.1	41
43-8	5.2	2.304	2.446	5.8	50
43-11	5.2	2.253	2.449	8.0	50
43-14	5.2	2.261	2.449	7.7	49

[1] Include Source, Type of Compaction, Sample Number

[2] BSG = Bulk Specific Gravity

[3] MSG = Maximum Specific Gravity

TABLE 11

AIR VOIDS AND STABILITY TEST RESULTS FOR SOURCE 5 SPECIMENS

[1]SOURCE	AC (%)	[2]BSG	[3]MSG	VOIDS (%)	STABILITY
51-2	4.7	2.308	2.483	7.0	-
51-3	4.7	2.314	2.472	6.4	-
51-4	4.7	2.289	2.471	7.4	-
51-7	4.7	2.298	2.478	7.3	-
51-11	4.7	2.307	2.471	6.6	-
52-3	4.7	2.404	2.274	2.8	43
52-5	4.7	2.402	2.476	3.0	44
52-12	4.7	2.406	2.479	2.9	42
52-13	4.7	2.414	2.475	2.5	41
52-14	4.7	2.413	2.476	2.54	38
53-1	4.7	2.363	2.480	4.7	61
53-3	4.7	2.362	2.482	4.8	50
53-6	4.7	2.372	2.480	4.3	57

[1] Include Source, Type of Compaction, Sample Number

[2] BSG = Bulk Specific Gravity

[3] MSG = Maximum Specific Gravity
Marshall Stability not determined

TABLE 12

INDIRECT TENSILE STRENGTH DATA

Sample Code	Indirect Tensile Strength (psi)
B11-07	68.402
B12-05	127.075
B13-03	97.730
B21-14	89.569
B22-08	99.902
B23-07	117.627
B31-14	73.887
B32-08	95.367
B33-02	91.992
B41-12	52.548
B42-04	132.840
B43-12	89.862
B51-06	90.454
B52-04	117.801
B53-12	103.629

TABLE 13

RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING MARSHALL COMPACTION

SOURCE		REST PERIODS					
		0.9s		1.9s		2.9s	
	TEMP	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
1	41°F	630	652	577	649	642	644
		589	519	561	565	553	546
		812	514	802	497	735	781
		568	765	556	714	520	752
2		661	544	639	524	565	502
		741	412	726	404	664	408
		470	570	459	592	423	576
		656	600	645	605	592	580
3		381	571	367	478	355	464
		415	403	431	400	395	384
		425	225	421	230	413	229
		399	318	404	327	387	545
4		451	498	419	417	387	381
		573	295	600	299	575	293
		426	438	413	425	419	499
		361	689	369	630	366	620
5		415	633	440	661	442	630
		539	953	507	877	510	715
		564	564	564	564	564	564
		519	450	504	433	482	439
1	77°F	205	233	200	223	195	241
		320	337	318	329	306	330
		252	251	288	241	333	261
		282	249	285	249	290	255
2		398	314	391	300	387	304
		355	264	370	243	375	235
		394	402	380	389	396	388
		267	286	293	288	294	278
3		194	283	195	283	198	295
		315	260	305	247	301	247
		194	344	200	322	204	313
		256	225	247	222	240	237

TABLE 13 (Continued)

SOURCE		REST PERIODS					
		0.9s		1.9s		2.9s	
	TEMP	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
4		322	259	345	378	323	395
		525	390	465	441	478	440
		363	353	365	351	363	357
		351	360	361	360	388	360
5		339	501	320	513	324	509
		415	408	480	427	512	435
		268	204	276	200	288	196
		251	283	246	283	251	292
1	104°F	106	77	114	72	108	91
		114	86	117	87	110	90
		96	117	91	111	81	107
		99	99	99	99	99	99
2		174	111	168	118	180	131
		172	276	186	288	195	295
		183	150	189	133	199	122
		126	151	140	123	148	117
3		164	146	151	158	153	170
		114	129	121	137	147	129
		182	127	181	150	185	131
		77	100	79	68	82	55
4		202	183	184	189	190	186
		196	118	155	106	182	105
		147	204	142	191	138	167
		143	234	132	265	139	218

TABLE 14

RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING GYRATORY COMPACTION

SOURCE		REST PERIODS					
		0.9s		1.9s		2.9s	
	TEMP	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
1	41°F	1210	1209	1085	1326	1159	1205
		574	572	573	575	548	747
		894	688	918	701	970	680
		972	1008	930	1018	963	1006
2		629	538	634	536	618	584
		919	772	852	776	816	786
		1003	1206	991	1197	866	1387
		928	810	1004	783	996	767
3		869	800	803	950	800	735
		963	845	926	804	883	818
		796	544	795	550	780	524
		902	565	883	567	900	576
4		627	365	567	398	539	341
		573	489	586	490	621	482
		618	766	585	713	577	669
		583	398	577	405	576	399
5		1285	354	1054	371	1004	458
		467	586	496	548	533	565
		556	1350	626	1272	700	1213
		574	531	599	548	602	528
1	77°F	510	589	507	606	498	579
		388	513	380	511	390	488
		545	610	523	607	530	593
		774	593	658	637	637	628
2		479	639	473	663	471	625
		465	698	436	668	395	666
		728	610	645	593	697	574
		588	525	563	533	563	558
3		372	486	374	493	389	497
		487	262	444	250	455	238
		557	451	507	439	520	446
		375	375	391	367	390	359

TABLE 14 (Continued)

SOURCE		REST PERIODS					
		0.9s		1.9s		2.9s	
	TEMP	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
4		567	359	558	345	571	334
		530	605	499	571	512	598
		498	394	476	415	512	428
		550	355	548	347	572	345
5		252	441	243	458	251	458
		309	287	310	291	315	289
		488	417	477	400	473	416
		247	236	265	243	260	253
1	104°F	407	411	408	416	441	409
		329	206	287	204	290	211
		370	217	318	215	357	217
		298	310	289	307	216	294
2		243	275	245	271	262	273
		192	238	210	260	189	247
		212	227	217	217	228	219
		326	217	325	218	321	213
3		213	154	218	152	236	153
		177	201	165	218	157	224
		153	179	159	178	163	165
		226	145	229	151	226	170
4		291	239	316	302	312	292
		261	197	260	202	268	213
		192	147	182	153	169	160
		231	211	223	219	238	222
5		238	122	250	114	261	122
		228	169	208	177	218	173
		177	116	182	124	179	124
		143	179	140	186	144	227

TABLE 15

RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING DYNAMIC COMPACTION

SOURCE		REST PERIODS					
		0.9s		1.9s		2.9s	
	TEMP	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
1	41°F	1020	720	1020	706	1004	722
		804	750	700	720	720	614
		859	886	848	859	876	719
		771	863	724	834	705	817
2		505	547	654	541	692	536
		580	825	684	837	671	700
		560	910	576	865	544	950
		860	466	806	457	803	477
3		491	668	470	690	465	700
		517	721	473	730	445	680
		495	626	516	636	522	608
		525	679	480	687	479	579
4		357	428	374	433	397	426
		931	700	905	699	937	616
		486	922	487	845	500	864
		401	829	452	771	469	836
5		525	767	514	808	548	761
		1230	1015	1013	947	1065	900
		370	697	380	622	404	616
		575	633	550	668	531	700
1	77°F	380	387	434	412	406	423
		276	235	313	310	296	301
		475	421	510	413	485	420
		214	279	217	285	216	306
2		789	491	743	461	743	457
		563	643	530	617	545	604
		620	592	615	580	610	552
		669	486	615	479	590	509
3		275	280	264	267	266	272
		308	308	307	324	329	342
		309	214	304	212	300	206
		397	363	392	355	413	371

TABLE 15 (CONTINUED)

SOURCE		REST PERIODS					
		0.9s		1.9s		2.9s	
	TEMP	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
4		315	466	296	525	300	545
		335	487	330	475	358	496
		509	419	507	396	532	387
		423	387	443	431	436	425
5		334	546	315	561	320	581
		247	187	225	187	249	186
		335	374	353	370	291	363
		284	329	274	315	296	334
1	104°F	144	114	166	130	161	126
		190	142	186	150	201	168
		126	259	154	275	168	279
		140	125	148	122	150	130
2		273	237	233	267	246	264
		182	248	178	239	196	256
		189	145	194	143	195	155
		139	228	157	231	162	227
3		243	149	238	168	256	176
		109	161	113	140	107	143
		178	125	175	123	176	126
		83	87	66	87	73	102
4		223	157	223	140	221	145
		332	223	328	242	367	224
		296	228	269	240	257	236
		246	212	247	224	250	234
5		109	122	113	125	115	129
		141	137	156	143	150	130
		159	99	147	100	149	97
		224	177	223	187	243	173

TABLE 16

OVERALL RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING AGGREGATE SOURCE 1

COMPACTION METHOD		TEMPERATURE 41	77	104
MARSHALL		632	216	95
		556	323	101
		690	271	101
		646	268	99
	TOTAL	2524	1078	396
	TRT. MEAN	631	270	99
GYRATORY		1199	548	415
		598	445	255
		809	568	282
		983	655	286
	TOTAL	3589	2216	1238
	TRT. MEAN	897	554	310
DYNAMIC		865	308	140
		718	233	173
		991	454	210
		1086	253	136
	TOTAL	3210	1403	659
	TRT. MEAN	803	351	165

ANOVA

SOURCE	DF	SS	MS	F	OSL>
TOTAL	35	2830168			
TREATMENT	8	2538067	317258.4	29.325	
METHOD	2	389765.1	194882.5	18.014	
TEMPERATURE	2	2127778	1063889	98.339	
MXT	4	20524.44	5131.111	0.474	0.10
ERROR	27	358335.5	13271.69		

TABLE 17

OVERALL RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING AGGREGATE SOURCE TWO

COMPACTION METHOD		TEMPERATURE 41	77	104
MARSHALL		573	349	147
		559	307	255
		515	392	163
		613	284	134
	TOTAL	2260	1332	679
	TRT. MEAN	565	333	170
GYRATORY		590	558	262
		820	555	223
		1108	641	220
		881	555	270
	TOTAL	3399	2309	975
	TRT. MEAN	850	577	244
DYNAMIC		579	514	253
		716	584	217
		734	495	170
		645	558	191
	TOTAL	2674	2351	831
	TRT. MEAN	669	488	208

ANOVA

SOURCE	DF	SS	MS	F	OSL>
TOTAL	35	1907999			
TREATMENT	8	1726128	215765.9	32.031	
METHOD	2	242430.5	121215.3	17.995	
TEMPERATURE	2	1426823	713411.6	105.91	
MXT	4	56873.83	14218.46	2.110	0.10
ERROR	27	181871.5	6735.981		

TABLE 18

OVERALL RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING AGGREGATE SOURCE 3

COMPACTION METHOD		TEMPERATURE 41	77	104
MARSHALL		436	241	157
		405	279	130
		324	263	159
		397	238	77
	TOTAL	1562	1021	523
	TRT. MEAN	391	255	131
GYRATORY		826	435	188
		873	356	190
		665	487	166
		732	376	191
	TOTAL	3096	1654	735
	TRT. MEAN	774	414	184
DYNAMIC		581	271	205
		594	320	129
		567	258	151
		572	382	83
	TOTAL	2314	1231	568
	TRT. MEAN	579	308	142

ANOVA

SOURCE	DF	SS	MS	F	OSL<
TOTAL	35	1536296			
TREATMENT	8	1469288	183660.9	74.003	
METHOD	2	237668.7	118834.4	47.883	
TEMPERATURE	2	1116891	558445.4	225.02	
MXT	4	114727.9	28681.99	11.557	0.05
ERROR	27	67008	2481.778		

TABLE 19

OVERALL RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING AGGREGATE SOURCE 4

COMPACTION METHOD		TEMPERATURE		
		41	77	104
MARSHALL		426	337	189
		436	457	144
		437	359	165
		506	363	189
	TOTAL	1805	1516	687
	TRT. MEAN	451	379	172
GYRATORY		473	456	292
		540	553	234
		655	454	167
		490	453	224
	TOTAL	2158	1916	917
	TRT. MEAN	540	479	229
DYNAMIC		403	408	185
		798	414	286
		684	458	254
		626	424	236
	TOTAL	2511	1704	961
	TRT. MEAN	628	426	240

ANOVA

SOURCE	DF	SS	MS	F	OSL>
TOTAL	35	889828.8			
TREATMENT	8	750948	93868.5	18.249	
METHOD	2	65687.17	32843.58	6.3852	
TEMPERATURE	2	657793.5	328896.8	63.941	
MXT	4	27467.33	6866.833	1.3350	0.10
ERROR	27	13880.8	5143.731		

TABLE 20

OVERALL RESILIENT MODULUS (KSI) AT 41, 77, 104 DEGREE FAHRENHEIT USING AGGREGATE SOURCE 5

COMPACTION METHOD		TEMPERATURE 41	77	104
GYRATORY		754	351	185
		533	300	196
		953	445	150
		564	251	170
	TOTAL	2804	1347	701
	TRT. MEAN	701	337	175
DYNAMIC		654	443	119
		1028	214	143
		515	348	125
		610	305	205
	TOTAL	2807	1310	592
	TRT. MEAN	702	328	148

ANOVA

SOURCE	DF	SS	MS	F	OSL>
TOTAL	23	1538574			
TREATMENT	5	1219646	243929.3	13.767	
METHOD	1	852.0417	852.0417	0.0481	
TEMPERATURE	2	1217989	608994.5	34.371	
MXT	4	805.3333	402.6667	0.0227	0.10
ERROR	18	318927.3	17718.18		

TABLE 21

F VALUES AT 41, 77, 104 DEGREES FAHRENHEIT

SOURCE	TEMPERATURE	COMPACTION	MEAN	F
1	41	M	631	0.283
1	41	G	897	0.020
1	41	D	803	0.809
1	77	M	270	0.084
1	77	G	554	0.426
1	77	D	351	0.086
1	104	M	99	0.603
1	104	G	309	0.468
1	104	D	165	0.121
2	41	M	565	0.981
2	41	G	850	0.047
2	41	D	669	0.064
2	77	M	333	0.100
2	77	G	577	0.771
2	77	D	488	0.404
2	104	M	170	0.043
2	104	G	244	0.053
2	104	D	208	0.377
3	41	M	390	0.165
3	41	G	774	2.330
3	41	D	578	0.516
3	77	M	255	0.677
3	77	G	414	0.383
3	77	D	307	0.286
3	104	M	131	0.121
3	104	G	184	0.429
3	104	D	142	0.140
4	41	M	451	0.059
4	41	G	539	0.862
4	41	D	628	0.476

TABLE 21 (Continued)

SOURCE	TEMPERATURE	COMPACTION	MEAN	F
4	77	M	379	0.394
4	77	G	479	1.950
4	77	D	426	0.616
4	104	M	172	0.372
4	104	G	229	0.533
4	104	D	240	2.070
5	41	M	564	1.080
5	41	G	701	0.006
5	41	D	702	0.308
5	77	M	343	0.066
5	77	G	337	0.073
5	77	D	327	0.425
5	104	G	175	1.304
5	104	D	148	0.460

M = MARSHALL COMPACTION
G = GYRATORY COMPACTION
D = DYNAMIC COMPACTION

TABLE 22

DESIGN MIX FOR SOURCE 1
PROJECT NO : IR-40-5(171)181 05487(04)

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 23

DESIGN MIX FOR SOURCE 2
PROJECT NO: IR-40-4(340)86 11255(04)

Percent passing	5/8" Chips	Screening	Stone Sand	Fill 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	1.5	10.1	4..3	3.1	5.0

% Asphalt Cement Used : 4.6 %

MATERIAL	SOURCE	% USED
5/8" Chips	The Dolese Co. @ Cooperton, OK.	35
Screenings	The Dolese Co. @ Cooperton, OK.	32
Stone Sand	Dolese Co. @ Richard Spur, OK	18
Fill Sand	The Dolese Co. @ Yukon, OK.	15

TABLE 24

DESIGN MIX FOR SOURCE 3
PROJECT NO: RS-4720(110) 06877(04)

Percent Passing	3/4" Rock	Mine Chat	Mfg Sand	Job Formula
3/4"	100			100
1/2"	76	100		94
3/8"	49	99	100	87
No 4	9	76	78	60
No 10	5	45	36	32
No 40	3	21	13	14
No 80	3	14	7	9
No 200	2.4	10.0	3.2	6.1

% Asphalt Cement Used : 5.3 %

MATERIAL	SOURCE	% USED
3/4" Rock	Cummins Materials @ Tulsa, OK.	25
Mine Chat	Bingham Sand & Gravel @ Treece, Kansas	45
Manufactured Sand	Cummins Materials @ Tulsa, OK.	30

TABLE 25

DESIGN MIX FOR SOURCE 4
PROJECT NO : CMC-66(286) 12247(04)

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	3	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 Sand	Anchor Stone Co. @ Tulsa, OK.	10
Screenings	Anchor Stone Co. @ Tulsa, OK.	34
Sand	Loman Sand Co. @ Bixby, OK.	15

TABLE 26

DESIGN MIX FOR SOURCE 5
PROJECT NO : VARIOUS PURCHASE ORDERS

Percent passing	3/4" Chips	3/8" Chips	Screening	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	2	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" Chips	Bellco Materials Co. @ Snyder, OK.	35
Screenings	Bellco Materials Co. @ Snyder, OK.	40
Sand	CC Sand @ Jenks, OK.	15

VITA

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Master of Science

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