CHARACTERIZATION OF VARIOUS HMA MIXTURES USING RESILIENT MODULUS TEST

MUHAMMAD ZEESHAN

(2011-NUST-MSPhD-Tn-11)

A thesis submitted in partial fulfillment of

the requirements for the degree of

Master of Science

In

Transportation Engineering

NATIONAL INSTITUTE OF TRANSPORTATION (NIT)

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING (SCEE)

NATIONAL UNIVERSITY OF SCIENCES & TECHNOLOGY (NUST)

SECTOR H-12, ISLAMABAD, PAKISTAN.

2014

Certified that the contents and form of thesis titled **“Characterization of Various HMA Mixtures Using Resilient Modulus Test”** submitted by Muhammad Zeeshan have been found satisfactory for the requirement of the degree.

Co-Supervisor: ___________________________

Associate Professor (Dr. Muhammad Irfan, PhD)

Supervisor: ______________________________

Associate Professor (Dr. Tariq Mahmood, PhD)

DEDICATION

To my beloved parents who always supported me morally and financially in all walks of life and to my teachers who nourished me with ample knowledge and wisdom!

ACKNOWLEDGEMENTS

I am thankful to Allah All Mighty, who provided me strength and tolerance to complete my research. I would like to pay debt of thankfulness to Dr. Tariq Mahmood, being supervisor and Dr.Muhammad Irfan, being co-supervisor for this study. Their numerous encouragement and assistance made it possible to complete my research work. In addition, I am grateful to Dr. Sarfraz Ahmed, Dr. Arshad Hussain and Dr. Shahab Khanzada in the capacity of committee member who gave me guidance and opinion throughout the thesis work. I would like to thank my fellows Muhammad Aniq Gull and Yasir Ali for their help in determination of optimum bitumen content for mixtures. I would also like to pay gratitude to the staff of the transportation laboratory of "*National Institute of Transportation (NIT)*" who provided a continuous support during this course of time. In the end, I pay my earnest gratitude with sincere sense of respect to my parents for their encouragement, heartfelt prayers and good wishes for successful completion of my research work.

This research was sponsored by "National Highway Authority (NHA)" through "Highway Training and Research Center (HRTC)" and part of research project titled "Improvement of Asphalt Mix Design Technology for Pakistan" under collaboration agreement with "National University of Sciences and Technology (NUST)". The technical support and financial assistance provided by staff/ officials of NHA, HRTC, and NUST is hereby acknowledged.

(Muhammad Zeeshan)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AASHTO	- American Association of State Highway and Transportation Officials
ARL	- Attock Refinery Limited
ASTM	- American Society for Testing and Materials
AV	- Air Voids
AWC	- Asphalt Wearing Course
BBR	- Bending Beam Rheometer
CBR	- California Bearing Ratio
COC	- Cleveland Open Cup
DTT	- Direct Tension Test
ESAL	- Equivalent Single Axle Load
FWD	- Falling Weight Deflectometer
HMA	- Hot Mix Asphalt
HRB	- Highway Research Board
IDT	- Indirect Tensile
LEA	- Linear Elastic Analysis
LVDT	- Linear Variable Differential Transformer
MEPDG	- Mechanistic Empirical Pavement Design Guide
NCHRP	- National Cooperative Highway Research Program
NRL	- National Refinery Limited
NUST	- National University of Science and Technology
OBC	- Optimum Bitumen Content
OGFC	- Open Graded Friction Course
PAV	- Pressure Aging Vessel
PG	- Performance Grade
PSI	- Pavement Survivability Index
RTFO	- Rotating Thin Film Oven
RV	- Rotational Viscometer
SHRP	- Strategic Highway Research Program
SMA	- Stone Mastic Asphalt
UTM	- Universal Testing Machine
VFA	- Voids Filled with Asphalt
VMA	- Voids in Mineral Aggregate

ABSTRACT

Resilient modulus is an important parameter of hot mix asphalt (HMA) design and analysis of pavement structural response under traffic loading. This research study attempts to characterize different HMA mixtures using resilient modulus test. Four different aggregate gradations of wearing course mixtures including: NHA-A, NHA-B, Superpave and Asphalt Institute's manual series; each prepared with two different penetration grade bitumen (40/50 and 60/70) were considered. Experimental investigation of various factors: test temperature, load pulse duration, binder type, nominal maximum size of aggregate, specimen diameter and their interaction on the resilient modulus of different HMA mixtures was analyzed. Superpave gyratory compacted specimens were subjected to haversine-shaped wave load pulse with load duration of 100 ms and 300 ms at 25°C and 40°C temperatures using repeated-load indirect test setup in Universal Testing Machine (UTM-25). The resilient modulus values of coarser gradation (NHA-A) was relatively higher amongst the tested gradations. Also, the study found that the size of the specimen statistically affected the measured resilient modulus value as the resilient modulus values obtained for 100mm diameter specimens were higher than those obtained for 150 mm diameter specimens at all testing temperatures. The analysis of two-level full factorial design of experiments revealed that the test temperature was the most significant factor affecting the resilient modulus followed by load duration, bitumen type, nominal maximum aggregate size and specimen diameter. A comparison of resilient modulus with dynamic modulus values from the past research on similar experimental design was carried out in which a strong relation was found between the dynamic modulus values at 5 Hz load frequency with the resilient modulus values at 25°C temperature while at 40°C temperature the resilient modulus values showed a close agreement with that of dynamic modulus values at 1 Hz load frequency.

Chapter 1

INTRODUCTION

1.1 BACKGROUND

Transportation is playing an important role in advancement of civilization from ancient times by fulfilling the travel demands of people and goods from one place to another. In developed as well as developing countries, a large number of people travel every day for work, shopping and societal reasons. Among the developing nations, Pakistan is the one, where transportation infrastructure is playing very important part in the movement of people and goods. The total length of road network of Pakistan is approximately 260,000 km and major portion of this network contains hot mix asphalt pavements (Pakistan economic survey 2012-13).

HMA pavements are also known as flexible pavements comprised of several layers of material were initially introduced in 20th century. Hot mix asphalt is a high quality and sensibly produced paving material. Its high performance, sustainability and environmental friendliness with low production cost make it common these days around the globe. Hot mix asphalt comprises of two basic constituents including aggregate and asphalt cement. When aggregate and asphalt cement are combined to prepare a homogeneous mixture then new physical properties will develop related to the physical properties of its constituents. The basic HMA mixture can be characterize by using mechanical laboratory tests.

Hot mix asphalt mixture design is method of determining the suitable aggregate, asphalt cement and the optimal combination of these two components. Several different methods have been developed to fulfill this purpose. Two most common methods, Marshall and Hveem mix design, are used by the highway authorities for the selection of optimum binder content. In both methods, mixture design criteria are based upon the past correlations of laboratory test results with the field performance. It has been understood that these procedures do not foresee field performance with respect to the conditions under which criteria were developed. These approaches are empirical in nature which result pavement failure before completion of its design life.

In order to develop a comprehensive performance based system of asphalt mix design, Strategic Highway Research Program (SHRP) was established in 1987, as an independent unit of National Research Council. Superpave (Superior Performing Asphalt Pavements) is the final product of the Strategic Highway Research Program (SHRP). The mix design system was developed to consider damage and minimize permanent deformation, fatigue cracking and low temperature cracking (Kennedy et al, SHRP-A-410, 1994).

For the hot mix asphalt (HMA) pavement structures, an economical and adequate design is as significant as other engineering structures. An under-designed pavement fails in-advance before completing its design life, needs more money for restoration. The most effective method to decrease the risks of upcoming repair and maintenance problems is accurately selection of materials for construction and using appropriate values of design parameters for the flexible pavements design (MS-4, Asphalt Handbook). Resilient modulus also known as the elastic modulus is one of significant design parameters used for flexible pavement design. Hot mix asphalt (HMA) can either be characterized as visco-elastic material or elastic material. The visco-elastic characterization of HMA involves determination of dynamic modulus whereas; elastic characterization involves measurement of resilient modulus (Katicha, S.W., 2003, MS Thesis Report). Resilient modulus test results are incorporated in the current accepted AASHTO pavement design guideline (AASHTO Design Guide, 1993). However resilient modulus test is replaced by the complex dynamic modulus test, proposed in the mechanistic-empirical design guide (MEPDG), to characterize hot mix asphalt (NCHRP Project 1-37A).

The resilient modulus is the elastic modulus which is used in the layered elastic theory. It is obvious that the most paving materials are not elastic and produce permanent deformation subsequently with each load application. However, if the repeated load is small associated with the strength of the material, the deformation under each load repetition is almost recoverable which can be considered elastic. There is a substantial permanent deformation at the early stage of load applications, characterized as plastic strain. As the number of repetitions increases, the plastic strain due to each load repetition reduces. The strain will be completely recoverable after 100 load repetitions (Huang, 2007).

In the laboratory the resilient modulus of hot mix asphalt can be determined by various forms of repeated load tests. The simplest and the most common method to measure resilient modulus of HMA is the indirect diametral tension test. The diametral tension test provides more appropriate assessment of the stiffness of asphalt layer than the test in the vertical direction (NCHRP Web Doc 14, 1997). In HMA resilient modulus test (ASTM D 4123), a compressive load is applied using haversine waveform through a loading plate in the vertical diametral plane of cylindrical specimen, and the subsequent horizontal recoverable deformation is measured. Usually the loading comprises of 0.1 sec duration followed by 0.9 sec rest period. However, different loading durations can be used to simulate actual vehicle speed on pavement. Following equation is used to calculate resilient modulus.

$$M_R = \frac{P}{Ht} (\upsilon + 0.2734) \tag{1.1}$$

Where,

M_R = Resilient Modulus

P = Cyclic Loading (N)

υ = Poisson's Ratio,

H = Horizontal Recoverable Deformation (mm)

t = Thickness of Specimen. Upward down

Resilient modulus can be used in the assessment of material's quality and serve as an input for pavement design and analysis. For use in pavement design processes and the pavement structural analysis, resilient modulus test results provide a basic association between stiffness and stress state of pavement materials. The resilient modulus test simulates the actual conditions in a pavement due to application of dynamic wheel loading. Conclusively, the test provides an excellent method of relating the performance of pavement construction materials with their stress states under variable conditions like moisture, density, gradation, etc. (NCHRP Project 1-28A).

1.2 PROBLEM STATEMENT

Transportation infrastructure including national highways and motorways is consuming annually massive amount for its overall roads of 260,000 km. Generally, it is experienced that desired level of service is not attained during construction, maintenance and rehabilitation of highways due to the pavement distresses. These distresses provide ground for the premature failure of newly made flexible pavements in shape of fatigue cracking and rutting/permanent deformation. This is because of the empirical design approach in design stage of flexible pavements which do not provide distresses effect in design life of the pavements. If the level of distress severity is included in the design, it will assist pavement design engineers to reduce the effect of distresses by incorporating material properties.

These problems validate the requirement of study which will facilitate the implementation of mechanistic and empirical design approach in Pakistan. To achieve the above stated goal and to establish specifications for flexible pavement design in Pakistan, "National Highway Authority" (NHA) of Pakistan has carried out research project "Improvement of Asphalt Mix Design Technology for Pakistan". Resilient modulus test of various asphalt mixtures, having different wearing course aggregate gradations and bitumen types/sources, is one aspect of that project.

1.3 RESEARCH OBJECTIVES

Following are the objectives for this research work:

1. To characterize various HMA mixtures using resilient modulus test.
2. To investigate the effect of factors including; temperature, load pulse duration, binder type, nominal maximum aggregate size and specimen diameter on resilient modulus of HMA mixtures.
3. To compare the resilient modulus and dynamic modulus values of HMA mixtures.

1.4 SCOPE OF THESIS

To achieve the aforementioned research objectives, a research strategy was made including the following research tasks:

1. Literature review of the earlier research findings on the factors influencing the resilient modulus of HMA mixtures including the test temperature, load pulse duration, specimen's diameter and nominal maximum aggregate size.
2. Laboratory characterization of materials including bitumen and the aggregates.
3. Determination of optimum bitumen content (OBC) for all mix types using Marshall Mix Design method.
4. Preparation of detailed experimental design considering all five factors which effect resilient modulus.
5. Preparation of specimens for eight different wearing course mixtures using two different specimen diameters (4-inch and 6-inch) at 4% air voids by means of Gyratory Compactor.
6. Resilient modulus test using indirect diametral tension test setup by means of Universal Testing Machine (UTM-25) according to ASTM D 4123.
7. Statistical analysis i.e. two-level full factorial design of experiment of the data obtained from resilient modulus tests using MINITAB-15 software.

1.5 ORGANIZATION OF THESIS

This research is organized into five chapters

Chapter 1 Includes a brief introduction of hot mix asphalt design methods, resilient modulus and significance of resilient modulus as an input parameter in the flexible pavement design. Problem statement, research objectives and the scope of the research is also discussed in the chapter.

Chapter 2 Includes detailed explanation of resilient modulus test with its significance and procedure. Literature review on findings of the previous research studies related to the resilient modulus and different factors affecting it.

Chapter 3 Explains the material characterization of aggregate and bitumen by means of extensive laboratory testing. Detailed results of all tests including consistency, property and quality are given in this chapter.

Chapter 4 Illustrates the methodology for the research work including HMA mixture preparation, determination of optimum bitumen content and performance testing of HMA mixtures using stiffness parameter.

Chapter 5 Presents the test results and their statistical analysis, including relative performance plots for given aggregate gradations and two-level full factorial design, to check the significant factors affecting resilient modulus by using MINITAB-15 software. A comparison of resilient modulus with dynamic modulus values from the past research on similar experimental design is also made at the end of the chapter.

Chapter 6 Enlightens the conclusions and recommendations from research findings.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter explains the complete philosophy of resilient modulus which covers the explanation of resilient modulus as an elastic property of HMA mixtures, its significances as an input parameter in pavement structural design and the detailed procedure to find the resilient modulus of HMA mixtures. Several forms of repeated load tests can be used to measure the resilient modulus of hot mix asphalt but indirect diametral tension test is the simplest way to measure the resilient modulus. It has some advantages, related to the stress distribution, over the other methods which are also discussed. The chapter includes the past researches that account different factors influencing resilient modulus of hot mix asphalt mixtures which includes test temperature, load pulse duration, Bitumen type, nominal maximum size of the aggregate and specimen diameter. Each factor and its effect on resilient modulus is discussed separately in the light of past researches.

2.2 RESILIENT MODULUS

Resilient modulus also called the elastic modulus and is defined as the ration of deviator stress and recoverable strain under the repeated loads.

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad (2.1)$$

Where,

M_R = Resilient Modulus

σ_d = Deviator Stress

ε_r = Recoverable Strain

The resilient modulus is the elastic modulus which is used in the layered elastic theory. It is obvious that the most paving materials are not elastic and produce permanent deformation subsequently with each load application. However, if the repeated load is small associated with the strength of the material, the deformation under each load repetition is almost recoverable which can be considered elastic. There is a substantial permanent deformation at the early stage of load applications, characterized as plastic strain. As the number of repetitions increases, the plastic strain due to each load repetition reduces. The strain will be completely recoverable after 100 load repetitions (Huang, 2007). Figure 2.1 shows the straining of a specimen under a repeated load test.

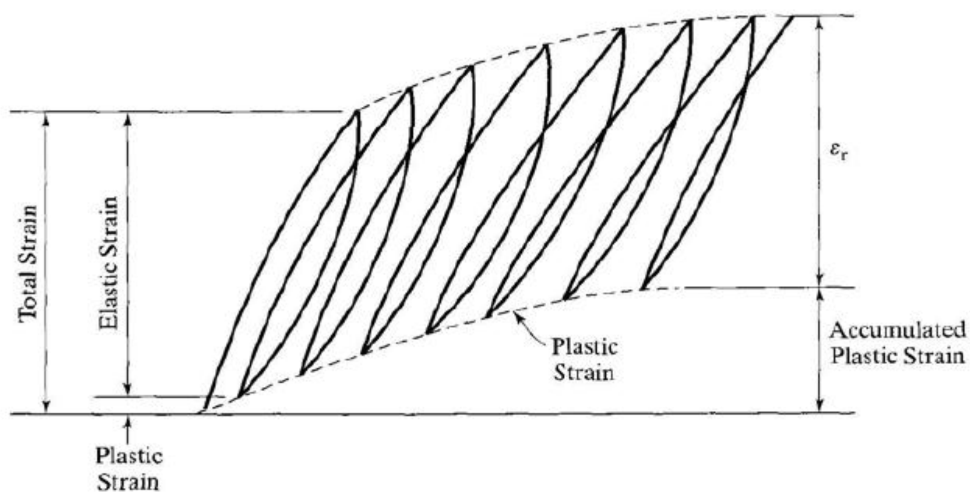


Figure 2.1 Recoverable Strain Under Cyclic Load

In the laboratory the resilient modulus of hot mix asphalt can be determined by various forms of repeated load tests which includes (NCHRP Web Doc 14, 1997);

1. Uniaxial tension test
2. Uniaxial compression test
3. Beam flexure test
4. Indirect diametral tension test
5. Tri-axial compression test.

For a sufficient explanation of the resilient features of asphalt concrete the following five parameters are very important:

1. Vertical strain due to an increment in vertical stress.
2. Radial strain due to an increment in vertical stress.
3. Radial strain due to an increment in radial stress.
4. Vertical strain due to an increment in radial stress.

5. Radial strain due to an increment in radial stress in the direction perpendicular to strain.

In the repeated load indirect diametral tension test a compressive load through a loading strip with a haversine waveform is applied in the vertical diametral plane of a cylindrical specimen, and the successive horizontal recoverable deformation is measured. If an asphalt layer of typical thickness is exposed to a bending action then the radial instead of the vertical stiffness of the asphalt layer will resist the applied stress. So, the diametral test provides a more appropriate assessment of the stiffness of the asphalt layer than tests performed in the vertical direction. Therefore, Diametral test results are mostly attractive for estimating radial tensile strain for a fatigue analysis. The diametral test has additional benefits because thin cores can also be tested which allows more measurements over the depth of thick asphalt layers. The advantages of the indirect tensile test are summarized as follows:

1. The test is comparatively simple and convenient to conduct.
2. The type of equipment and the specimen can be used for other testing.
3. Failure is not seriously affected by surface conditions.
4. Failure is started in a region of comparatively uniform tensile stress.
5. The difference between test results is low compared to other test methods.
6. A specimen can be tested crosswise different diameters, and the results can be used to define whether the sample is homogeneous and undisturbed.
7. The test can provide information on the tensile strength, Poisson’s ratio, fatigue characteristics, and permanent deformation characteristics of asphalt concrete.

Considering the above stated advantages the American society of Testing and Materials (ASTM) has adopted the repetitive indirect tensile test as a standardize method of measuring the resilient modulus of asphalt concrete.

2.2.1 Loading Waveform for Resilient Modulus Test

In the repeated indirect diametral tension test setup the form and period of loading should be comparable with the actual field conditions. When the wheel load is at a substantial distance from a specified point in the pavement, the stress will be zero at that point and the stress will maximum when the load is straight above that specified point.

Therefore, it is acceptable to assume the shape of stress pulse as a triangular or haversine. The time period of that loading depends upon the vehicular speed and the depth of specified point beneath the pavement surface (Huang, 2007).

It is supposed that the amount of load changes with respect to time according to the haversine function which is shown in the figure 2.2. At *t=0*, the load function can be expressed as:

$$L(t) = q\sin^2\left(\frac{\pi}{2} + \frac{\pi t}{d}\right) \quad (2.2)$$

Where,

d = load period (sec)

q = Intensity of load (N)

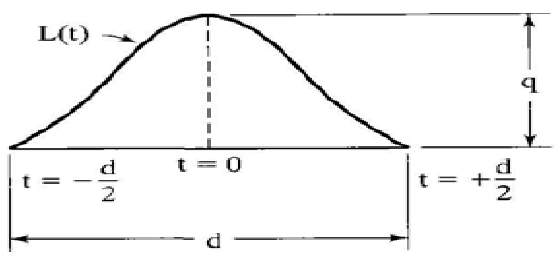


Figure 2.2 Moving Load as a Function of Time

When the load will be at a considerable distance from a definite point where $t = \pm d/2$, the load directly above that point will be zero which can be expressed as $L(t) = 0$. Maximum load intensity (q), when the load is above the specified point, will be used to calculate compressive stress.

The load duration depends upon the vehicular speed "*s*" and the tire contact radius "*a*". It is presumed that the load has practically no effect when it is at a distance of 6*a* from the specified point or,

$$d = \frac{12a}{s} \quad (2.3)$$

Where,

d = duration of load (sec)

s = Vehicle speed (m/s)

a = Tire contact radius (meter)

The vehicle speed varies significantly and the material's depth cannot be considered at the design stage hence, it is suggested to use a haversine load of duration 0.1 s and rest period 0.9s for resilient modulus test in laboratory. It must be considered that load period has very minute effect on the resilient modulus of granular materials, some effect on fine-grained soils depending upon the moisture contents, and a significant effect on bituminous materials. The effect of rest period in the loading cycle is not known and considered insignificant.

2.2.2 Resilient Modulus Significance

Resilient modulus is a basic characterization parameter for hot mix asphalt materials. Resilient modulus of HMA has been used for several years in structural design of flexible pavements. It gives an indication of elastic response of bituminous pavement material. Commonly used technique, to compute pavement reaction under the cyclic load, for pavement structure valuation is Layered Elastic Analysis. Flexible pavement layers are defined by their resilient modulus and Poison's ratios. Although pavement materials are not elastic, LEA is used due to its simplicity comparatively to the other approaches. Also it is appropriate to consider LEA because the magnitude of pavement loading is normally small enough for a linear elastic approximation of pavement material's performance.

In the new mechanistic-empirical pavement design guide (MEPDG) techniques for the design and analysis of flexible pavement, linear elastic analysis is used to determine pavement reaction based on applied traffic loading, environmental conditions and material properties. At two critical positions stiffness can be calculated in the flexible pavement:

1. Bottom strain of the HMA layer
2. Vertical compressive stress at the uppermost position of the sub-grade.

Excessive strain at the bottom of the HMA layer can result in fatigue failure and crack formations which continue upward to the pavement surface. Unnecessary vertical stress at the uppermost position of the compacted sub-grade can result rutting/permanent deformation in the subgrade. After some time period the deformation will be observable at the surface of pavement as a result of loss of support.

2.2.3 Indirect Tensile Strength Test

Hot mix asphalt tensile strength is very essential because it is a good indicator to check the mix potential of cracking. A high tensile strain at failure shows that, a specific HMA is more likely to resist cracking and allow higher strains before failure than HMA with a low tensile strain at failure. The indirect tensile test applies a constant rate of vertical deformation until failure occurs and uses the same testing device as the diametral repeated load test. The test is performed by application of compressive load at deformation rate of 50 mm/min at a temperature of 25 °C, parallel to the vertical diametral plane of 4-inch or 6-inch diameter of a cylindrical specimen. The loading arrangement provides a uniform tensile stress along the vertical diametral plane and perpendicular to the applied load. Splitting of the HMA specimen is the final result of IDT test. The stress distribution on the vertical diametral plane for indirect tension test is shown in Figure 2.3.

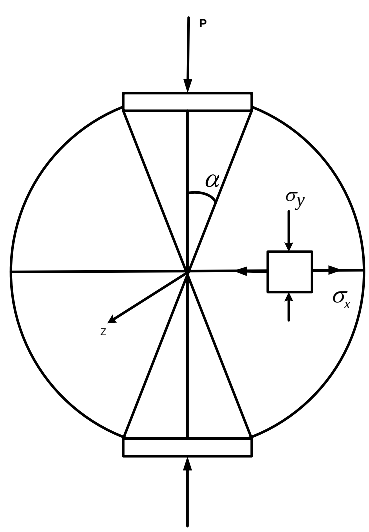


Figure 2.3 Indirect Tension Test Schematic

2.2.4 Resilient Modulus Test Procedure

Resilient modulus test can be performed on laboratory compacted specimens and cores obtained from the field. The resilient modulus of hot mix asphalt mixtures prepared in laboratory depends on the following factors:

1. Type of repeated load test (indirect tension, triaxial or any other)
2. Nature of compaction (Marshall vs. Gyratory compactor).
3. Temperature
4. Loading waveform (triangular or haversine) and duration
5. Specimen’s geometry (diameter and thickness)
6. Strain level

The load pulse is in the form (1-cos θ)/2 with repeated load variation from the contact load $P_{contact}$ to the maximum load $P_{max.}$ The test technique includes three steps i.e. determination of tensile strength, opecimen’s preconditioning with 100 repeated cycles of loaf and determination of resilient modulus.

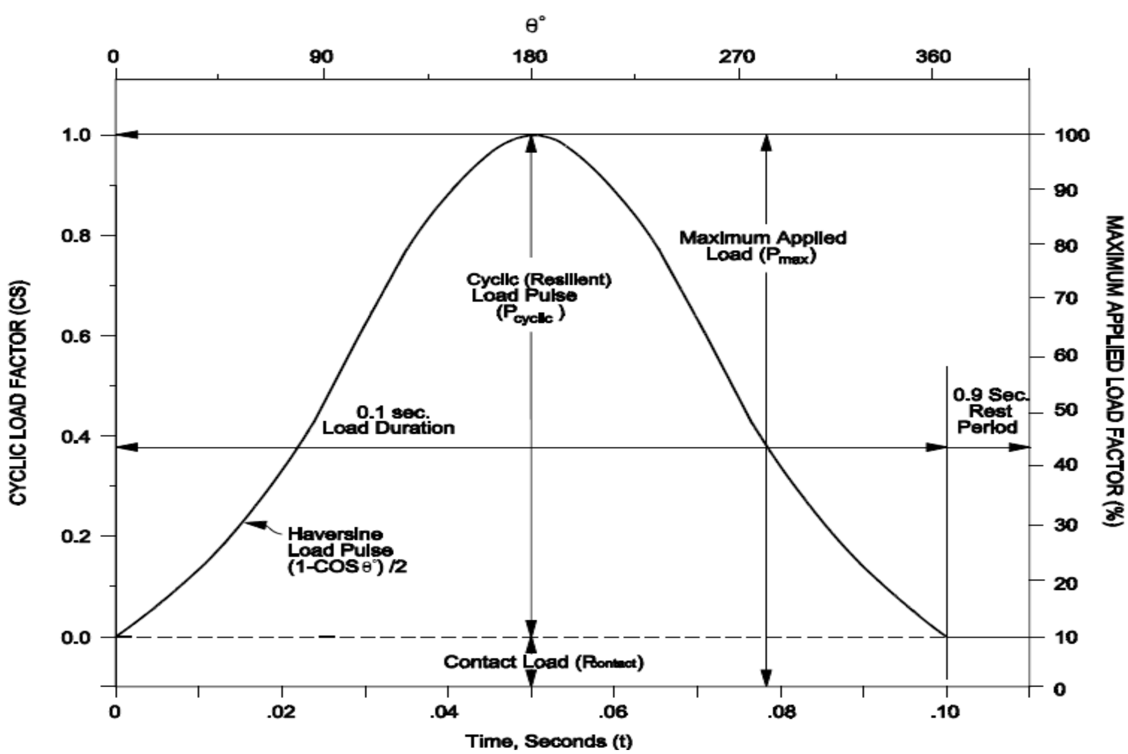


Figure 2.4 Load Pulse Representing the Loading Period of 0.1 sec

Cyclic load (resilient vertical load, P_{cyclic}), is directly used to calculate the resilient modulus.

$$P_{cyclic} = P_{max} - P_{contact} \tag{2.4}$$

Where,

P_{max} = Maximum load including cyclic and contact load.

$P_{contact}$ = Contact load (Seating load) which is 4% of the maximum applied load.

2.2.4.1Determination of Tensile Strength

The indirect tensile strength value for each type of mixture, compacted in the laboratory having the same mix properties, is determined before performing the resilient modulus test. The load levels from 10 to 20 % of the indirect tensile strength value, measured at 25°C, are to be used for each type of mixture in conducting the resilient modulus testing. For determination of indirect tensile strength of HMA mixtures ASTM D 6931 is the standard test specification.

2.2.4.2Preconditioning of Specimens

The preconditioning of specimens shall be conducted while the specimen is located in a temperature controlled cabinet. The specimen contact load or seating load i.e. the vertical load on the specimen to maintain the positive contact between the loading strip and specimen shall be 4% of the maximum load. The number of load applications to be applied for preconditioning cycles shall be 100 to 200. However, the minimum number of load applications for a given situation depends on the stable deformation. It must be noted that the cumulative vertical deformation falls within specified range which is less than 0.001 inch (0.025 mm). If a particular value of Poisson's ration is assumed; as there is an insignificant effect of Poisson's ratio on the resilient modulus value, it is not necessary to measure the vertical deformation.

2.2.4.3Determination of Resilient Modulus

Resulting the stable/constant deformation or after completing the specified conditioning cycles i.e., 100 cycles use first 5 consecutive cycles to determine the mean value of resilient modulus. The resilient modulus is computed from the following equation.

$$M_R = \{P(\upsilon + 0.2734)\}/\delta t \qquad (2.5)$$

Where,

M_R = Resilient modulus of the asphalt concrete specimen (MPa)

P = Magnitude of the dynamic load (N)

υ = Poisson's ratio (assumed 0.4)

δ = Total recoverable deformation (mm)

t = Specimen thickness (mm)

2.3 FACTORS AFFECTING THE RESILIENT MODULUS

There are numerous factors which affect the resilient modulus of hot mix asphalt mixtures, when the resilient modulus test is performed on the specimens using indirect diametral tension test arrangement. These contain temperature, load waveform and pulse duration applied to the specimens, thickness and diameter of specimen and nominal maximum size of aggregate of a particular gradation used in a mixture. Lot of research studies already have been carried on the features influencing the resilient modulus of hot mix asphalt blends. The studies related to this research are discussed below:

Basset et al. (1990) performed a laboratory analysis of the effect of changing the maximum aggregate size of a particular gradation on rut development and on other material properties of asphalt aggregate mixes. They assessed five different asphalt mixture designs with aggregate having dissimilar gradations. The nominal maximum sizes of that gradations were 3/8, 1/2, 3/4, 1, and 1 1/2 in. Compaction through gyratory compactor was exerted on the mixtures to get 4% air voids in each mix. All mixtures formed using five gradations were exposed to a testing program including different tests like Marshall stability and flow test to assess performance parameters of each mixture, indirect tensile strength test, creep test, and resilient modulus to assess stiffness. 4-inch diameter frame was used to prepare/compact the specimens for mix design as well as the assessment of mixture properties. In addition, 6-inch diameter frame was used to prepare/compact specimens at optimal asphalt content for indirect diametral tension test and the creep test. The results of 4-inch and 6-inch diameter specimens for the identical aggregate gradations were compared and analyzed. Test results showed that mixtures having larger aggregate were comparatively stronger than mixtures having smaller aggregate having similar air voids equal to 4%.

Almudaiheem et al. (1991) concluded that the percentage of indirect tensile strength of specific hot mix asphalt mixture used as a cyclic load affects the resilient modulus value. Tests were performed on the specimens having cyclic load ranged from 10 to 30% of indirect tensile strength of similar specimen having identical mixture properties. They concluded that the degree of load in resilient modulus test should be large as it provides a lesser resilient modulus value, to obtain more conventional design. 4% difference in resilient modulus values was found for the samples having 4% asphalt content at load degree of 1000 and 2700 N.

Lim et al. (1995) prepared HMA specimens in the laboratory having three different diameters including 4-inch, 5-inch and 6-inch to examine the sample size influence on the resilient modulus and indirect tensile strength. Four asphalt combinations with dissimilar maximum stone sizes ranging from 15.8 to 31.5 mm were used. The effect of the fractions of the diameter to maximum stone size of the specimen on the resilient modulus as well as indirect tensile strength was studied. Generally, decrease in the resilient modulus and indirect tensile strength was experienced. It was recommended that 5-inch and 6-inch diameter samples would contribute more stiffness and tensile strength for mixtures having large stones. Results achieved from the resilient modulus and the indirect tension test, when large diameter samples were used, were more characteristic to the performance of the mixtures.

Loulizi et al. (2002) find the upright compressive stress pulse produced by a load of moving truck on twelve (12) different flexible pavement segments at changed localities underneath the pavement surface. Pressure cells were used to measure the stress and thermocouples were used to the temperature. These instruments were installed during road construction. Targeted test speeds were 8 km/h, 24 km/h, 40 km/h, and 72 km/h and the considered depths below the pavement surface were 40 mm, 190 mm, 267 mm, 419 mm, and 597 mm. For a moving truck a haversine function was analyzed to be a good depiction of the measured standardized stress pulse. For a truck speed of 70 km/h at 40 mm deepness time duration of 0.02sec and for a truck speed of 10 km/h at 597 mm deepness time duration of 1sec was measured for a haversine wave load pulse. Presently, laboratory dynamic testing on HMA samples is done using a haversine wave having loading duration of 0.1sec. The loading time affects the properties of HMA because it is a viscoelastic material, therefore; it is suggested that the load cycle time of hot mix asphalt dynamic tests should be 0.03 s to simulate loading times found from moving trucks at an average speed.

Pan et al. (2005) measured the resilient modulus for asphalt mixtures to investigate their elastic properties using indirect diametral tension test setup according to ASTM D 4123. They examined the effects of coarse aggregate morphology which was the main factor, and other material properties on the resilient modulus asphalt mixtures. They observed that by using coarse aggregates having uneven morphologies enhanced the resilient modulus values obtained at a temperature of 25°C of different asphalt combinations. Once the data were clustered using binder stiffness, an agreement among the coarse aggregate morphology and the resilient modulus was meaningfully enhanced in each cluster. The variations in aggregate gradation did not considerably affect the association between the coarse aggregate morphology and the resilient modulus. But reducing the nominal maximum size of aggregate from 19 mm to 9.5 mm showed an increased progressive effect of aggregate morphology on the resilient modulus of asphalt mixtures.

Saleh et al. (2006) investigated the different factors influencing the resilient modulus of HMA mixtures. Statistical technique of factorial design was agreed to investigate six influential features each was studied at two levels. These factors were: the compaction methodology, diameter and thickness of specimen, duration and form of load pulse and the nominal maximum size of aggregate. Two kinds of HMA mixtures with unlike maximum aggregate sizes (10 mm and 14 mm) were considered. Marshall and Gyratory compaction methodologies were practiced to make the specimens. Sinusoidal and triangular load pulse arrangements were used to quantify the resilient modulus. This study also involves the examination of different interrelated factors which influenced the resilient modulus. Full factorial design of experiments disclosed that the nominal maximum size of aggregate was the utmost significant factor upsetting the resilient modulus, followed by the load pulse duration, the specimen's geometry including thickness and diameter.

Loulizi et al. (2006) performed stiffness tests at five different temperatures on two representative mixtures. Stiffness tests were resilient modulus and dynamic modulus test. At six different frequencies dynamic modulus was measured at all testing temperatures while the resilient modulus test was done at unique load pulse time. It was examined that entirely at each testing temperature the diameter of the specimen affected the value of resilient modulus and the values acquired using 100-mm-diameter specimens were greater than those found using 150-mm-diameter specimens. A robust relation among the dynamic modulus values obtained at 5 Hz frequency and the resilient modulus values was observed.

Jahromi et al. (2009) examined various factors affecting the resilient modulus of HMA mixtures. Two level factorial analysis of experimentation was carried out incorporating five different factors. These factors include maximum nominal size of aggregate, diameter and thickness of specimen, Type and period of the load pulse. Two kinds of HMA mixtures having dissimilar maximum aggregate sizes were considered and Marshall Compaction technique was adopted for specimen's preparation. Moreover, sinusoidal and triangular types of the load pulse were considered to measure the resilient modulus. Using factorial analysis technique it was concluded that the maximum nominal aggregate size was the chief significant factor influencing the resilient modulus followed by the load pulse duration and the specimen shape (diameter and thickness).

Khan et al. (2012) studied the influence of four factors comprising of percentage bitumen content, specimen's diameter, test temperature and load pulse length on resilient modulus of HMA mixtures. The specimens having 4-inch and 6-inch diameter were made by using Marshall Compaction technique with 4 and 5 percent bitumen content. At two different temperatures including 25°C and 40°C the tests were performed in UTM-25 machine by using indirect diametral tension test arrangement. Load pulse of haversine-shaped having the load time duration of 100ms and 300ms was applied to simulate the actual fast and slow truck traffic speed. The statistical technique of factorial design of experiments was used to analyze the data. It was observed that all four factors have an inverse effect on resilient modulus of HMA mixtures and temperature was the greatest influencing factor affecting the resilient modulus followed by load pulse period and diameter of specimen.

TJAN et al. (2013) compared values found in laboratory testing with the estimated values of the resilient modulus applying Asphalt Institute method, for unique asphalt mixture used in Indonesia. Indirect diametral tension test setup was used to obtain the resilient modulus values. It was observed that for resilient modulus values less than 2000 MPa, values obtained in the laboratory were in-between 0.7 to 1.1 times of the predicted values while for resilient modulus values greater than 2000 MPa, values obtained in the laboratory were in-between 1.19 to 1.6 times of the predicted values. It was determined that the deviation of estimated modulus values from the real obtained values is within an acceptable range and they can be used practically.

Following factors that affect significantly the resilient modulus of HMA mixtures are discussed separately in the light of previous research studies.

2.3.1 Temperature

Temperature is the most important aspect for the performance of the pavement structure as temperature of the asphaltic layer influences the resilient modulus of HMA, fatigue properties of bitumen and the plastic strains. For temperature beyond 20°C, the resilient modulus of HMA decreases quickly and reaches to questionable low values at 40 °C. Therefore, this temperature range is serious for HMA layer (Per Ullidtz 1987). Stroup et al. (1997) conducted wide investigation on the effect of temperature and load duration on HMA resilient modulus. The load ranges of 0.1 and 1.0 sec at various temperatures including -18, 1, 25, and 40°C were inspected. It was found that with intensification of the load duration, the resilient modulus reduced at all temperatures excluding -18°C. At -18°C, marginally increase in the resilient modulus was observed. Ziari et al. (2005) concluded in their investigation that the resilient modulus hurriedly reduces with increasing temperature. This is because of the softening of the asphalt cement at higher temperature. Kamal et al. (2005) investigated the resilient performance of HMA mixture by changing temperature and found that a severe reduction of almost 85% in resilient modulus has been experienced for a rise in temperature from 25 to 40º C.

2.3.2 Load Duration and magnitude

The influential effect of the load pulse length and magnitude on the performance of the hot mix asphalt is comparable with the temperature as the elastic, plastic, and fatigue properties of HMA affects. Almudaiheem et al. (1991) concluded that the percentage of indirect tensile strength of specific hot mix asphalt mixture used as a cyclic load affects the resilient modulus value. Tests were performed on the specimens having cyclic load ranged from 10 to 30% of indirect tensile strength of similar specimen having identical mixture properties. 4% difference in resilient modulus values was found for the samples having 4% asphalt content at load degree of 1000 and 2700 N. Loulizi et al. (2002) concluded that the loading time affects the properties of HMA because it is a viscoelastic material, therefore; it is suggested that the load cycle time of hot mix asphalt dynamic tests should be 0.03 s to simulate loading times found from moving trucks at an average speed. Saleh et al. (2006) found in their research that the load pulse length had substantial effect on resilient modulus values as the resilient modulus reduced with the increase in the load pulse period due to the development of high strain for longer load time whereas the load pulse form and strain level had insignificant effect on the resilient modulus of HMA mixtures.

2.3.3 Specimen Diameter

4-inch or 6-inch diameter specimens having thickness range from 1.5 to 2.5 inch can be used for determination of resilient modulus of HMA mixtures using the indirect diametral tension test arrangement. The test specimens can be equipped in the laboratory or obtained from field coring. The resilient modulus and indirect tension testing (diametral testing) on various diameter specimens were performed by Lim et al. (1995). Specimens of 4, 5 and 6 inch diameter were made, having identical diameter/height ratio of 1.6. It was found that with the similar aggregate gradation and bitumen content, the resilient modulus reduced with the increase of specimen diameter; therefore they concluded that specimen diameter, i.e. geometry of specimen influences the resilient modulus.

2.3.4 Aggregate Gradation

Lim et al. (1995) studied the influential effect of specimen diameter to maximum nominal stone size fraction on the resilient modulus. It was observed that the resilient modulus reduces as the ratio of specimen diameter to maximum nominal aggregate size improved. Therefore, it was concluded that greater resilient modulus values would be obtained using a small diameter specimen with large top stone size. Pan et al. (2005) performed laboratory testing to study the influential effect of material's properties on the resilient modulus of HMA and found that the coarse aggregate morphology is the chief factor that affects the resilient modulus. They observed that by using coarse aggregates having uneven morphologies enhanced the resilient modulus values obtained at a temperature of 25°C of different asphalt combinations. It was also detected that the different aggregate gradation did not considerably affect the correlation between the coarse aggregate morphology and the resilient modulus of hot mix asphalt mixture. Saleh et al. (2006) conducted a research to relate different factors that influences the resilient modulus. Resilient modulus testing was done using 4-inch and 6-inch laboratory compacted specimens. It was found that the most significant factor that influences the resilient modulus was the nominal maximum aggregate size. Higher resilient modulus values of hot mix asphalt mixtures were observed with coarser gradations due to the fact that in coarser aggregate arrangement the large particles have better interlocking. Jahromi et al. (2009) found that the maximum nominal size was the most substantial factor influencing the resilient modulus

2.4 SUMMARY

This chapter includes a comprehensive discussion about the resilient modulus determination through indirect diametral tension test setup. The diametral tension test provides a more appropriate estimate of the stiffness of the asphalt layer than tests performed in the vertical direction. Diametral test results are therefore mostly attractive for estimating radial tensile strain for a fatigue analysis. The diametral test has additional benefits since thin cores can be tested which allows more measurements over the depth of thick asphalt layers. The chapter also includes the literature which explains the effect of different factors affecting resilient modulus of HMA mixtures. Factors like temperature, load pulse duration, specimen diameter and nominal maximum aggregate size are the common factors which are included in different past researches.

Chapter 3

RESEARCH METHODOLOGY AND PERFORMANCE TESTING

3.1 INTRODUCTION

The chapter comprises of the research methodology used to accomplish aforementioned research objectives which are discussed in Chapter 1. Material characterization through laboratory testing and Marshall mix design methods for calculation of optimum binder content for various HMA mixtures, having different aggregate gradations and bitumen type/source, is explained. The technique for specimen preparation through gyratory compactor is described and at the end resilient modulus test on the hot mix asphalt specimens, using indirect tension test setup, is also discussed.

This research includes dynamic load testing (resilient modulus test) on the specimens of various hot mix asphalt mixtures prepared in the laboratory having different aggregate gradations of asphaltic wearing course. This study incorporates four (04) different aggregate gradations of wearing course and two (02) bitumen penetrations grades. Aggregate gradations include NHA-A, NHA-B, Superpave-1 & MS-2 and bitumen penetration grades include NRL 40/50 & ARL 60/70. Specimens have been prepared using Marshall Mix design criteria to determine the optimum binder content (OBC), for eight different hot mix asphalt mixtures, by analyzing volumetric and performance properties of mixtures. On the bases of determined OBC, samples have been prepared for hot mix asphalt mixtures performance testing (resilient modulus test) using gyratory compactor. Specimens of required dimensions have been sliced using core cutting and saw cutting machines. Performance testing i.e., Resilient Modulus testing have been performed on different test conditions using Universal Testing Machine (UTM)-25. Detailed procedures for material characterization, determination of optimum bitumen content, sample preparation and performance testing are described in this chapter. The research methodology is illustrated in Fig. 3.1.

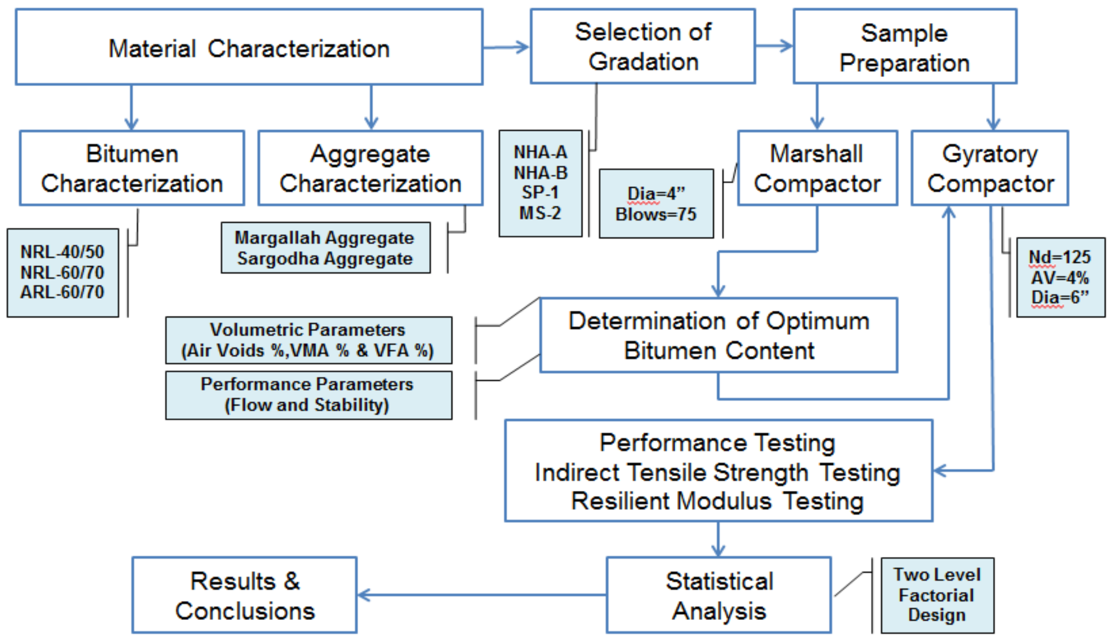


Figure 3.1 Research Methodology

3.2 MATERIAL SELECTION FOR HOT MIX ASPHALT (HMA)

Hot mix asphalt is mainly composed of aggregate and asphalt binder. By weight aggregate normally makes up about 95% of the mixture and asphalt binder makes up remaining 5%. By volume, a typical mixture consists of 85% of aggregate, 10% of asphalt binder and 5% of air voids. For proper selection of materials, including binder and aggregates, laboratory testing is essential to meet the standard requirements for hot mix asphalt mixtures.

3.2.1 Asphalt Binder Grading Systems

The Penetration grade classification was established in the early 1900s to represent the consistency of semi-solid asphalt. In this system, ASTM D 946 specifications classify un-aged asphalt binders into grades according to the penetration value measured at 77°F (25°C). The basic assumption of penetration grading system is that, the less glutinous the asphalt the deeper the needle will penetrate. Asphalt binder performance is empirically linked with the depth of penetration. Therefore, softer (Higher penetration) asphalt binders are used for cold climates and harder (Lesser penetration) are used for warm climates. In Pakistan, a standard 60/70 penetration grade is used for construction of flexible pavements. However, the refineries of Pakistan also produce 40/50 and 80/100 penetration grades. The test only provides the comparative consistency of asphalt binder at a definite temperature, which can be used as a sign of vulnerability of asphalt binder to rutting and fatigue cracking.

A superior asphalt grading system was developed in early 1960s that included coherent scientific viscosity test. This precise test replaced the practical penetration test for the categorization of asphalt binders as the viscosity is the fundamental property of asphalt. ASTM D 3381 specifications established for asphalt binders to test them at 140°F (60°C) and 275°F (135°C) which matches to the representative maximum temperature and temperature at the time of laying of asphalt in the field, respectively. Viscosity grading can be done on original/virgin as well as aged residue samples of asphalt binder. Viscosity grading is not yet established in Pakistan. The test fails to characterize the binder at low temperatures to reduce the cause of thermal cracking. Figure 3.2 is shows the criteria used for both penetration and viscosity grading systems. Two asphalt binders meeting the specifications of penetration and viscosity may behave in a different way at other temperatures.

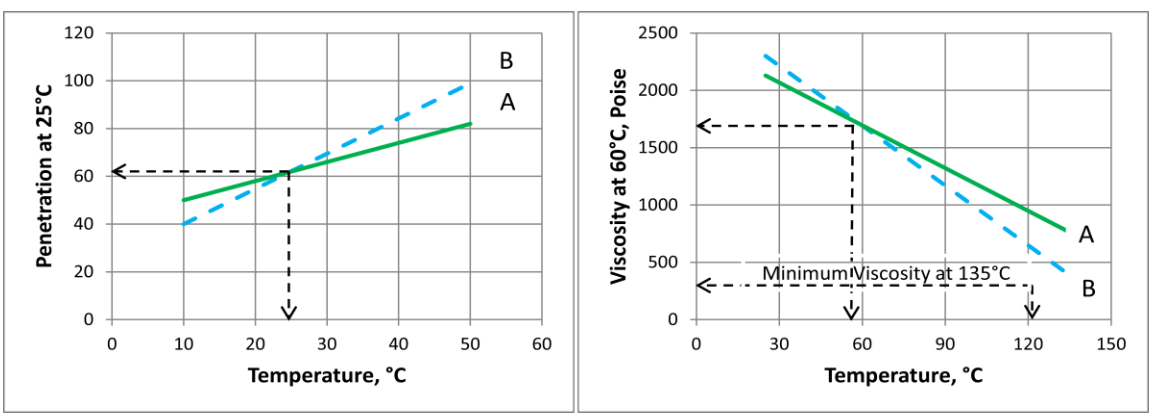


Figure 3.2 Two Binders Meeting Penetration and Viscosity Grading Specifications

3.2.2 Asphalt Binder Selection

It is necessary to perform tests according to the specifications to verify the acceptability of asphalt cement satisfying the desired characteristics including consistency, purity and safety. Different tests including property tests and performance tests must be conducted on the asphalt cement before hot mix asphalt mixture preparation.

3.2.2.1 Penetration Test

For measuring the consistency of the asphalt binder, one of the oldest tests is penetration test for which ASTM D 5 is the standard test specifications. To conduct the penetration test, a sample of asphalt binder is heated to a suitable pouring temperature and poured to a test container. Through a temperature controlled water bath asphalt binder sample is brought to the standard test temperature of 77°F (25°C). The container is then placed in the penetrometer equipment. The total load of 100 grams is released to penetrate the needle in the asphalt binder for 5 seconds. The distance that the needle penetrates into the asphalt binder is stated in units of 0.1 millimeter as the penetration value.

3.2.2.2 Flash and Fire Point Test

The flash point is a temperature indication at which a heated asphalt binder sample instantaneously flashes in the presence of the open flame, while the temperature at which the material supports combustion is called the fire point. To determine the flash point of an asphalt binder the most common test method used is the Cleveland Open Cup (COC) flash point test. ASTM D 92 is the standard test specifications. A brass cup filled with a quantified volume of asphalt binder is heated at a constant rate and at definite intervals a test flare is passed crossways the cup. The temperature, at which passing of the test flare causes the vapors of the sample to ignite, is recorded as the material's flash point. The point at which the test flare causes the sample to burn and continue burning for at least 5 seconds is the fire point of that material.

3.2.2.3Softening Point Test

Softening point of bitumen is the temperature at which a bitumen sample cannot sustain the weight of 3.5 gram steel ball. To determine the softening point of an asphalt binder a Ring and Ball apparatus is used. ASTM D 36 is the standard test specifications. Two horizontal disks of bitumen, cast in a frame of brass rings, are heated at an organized way in a liquid bath while each holds a steel ball. The average temperature at which the two disks of bitumen soften enough to let the balls, enveloped in bitumen, to fall a distance of 25 mm (1.0 inch) is recorded as the softening point of bitumen.

3.2.2.4Ductility Test

Ductility is a physical property of asphalt binder which is considered an important characteristic of asphalt binder. This test measures the ductility of asphalt binder by elongating a standard size briquette of asphalt binder to its breaking point. ASTM D 113 is the standard test specifications. A standard mold shaped like a dog bone is used to make the briquette of asphalt binder. The test is performed in a ductility water bath at a constant temperature of 77°F (25°C). After placing the specimen in the test apparatus one end of the specimen pulled away from the other at a specified rate of speed, normally 5 centimeters per minute until the sample breaks. The distance in centimeters at breaking is then stated as ductility. This test has limited use since it is empirical and conducted at only one temperature. Table 3.1 shows standard test specifications for property tests for asphalt binders.

Table 3.1 Standard Test Specifications for Property Tests for Asphalt Binders

Test Type	Test Standard	Test Specifications
Penetration test @ 25°C, mm	ASTM D 5	40-50, 60-70
Flash and fire point test °C	ASTM D 92	>232
Ductility Test @ 25°C, cm	ASTM D 113	>100
Specific gravity test	ASTM D 70	1.01-1.06

3.2.2.5Rotational Viscometer Test

To determine the viscosity of asphalt binders in the high temperature range of pumping, mixing and construction, the Rotational Viscometer (RV) is used. The RV test can be conducted at various temperatures for specification purpose but usually it is conducted at 275°F (135°C). AASHTO T 316 is the standard test specification. The Rotational Viscometer (RV) can be used to develop temperature-viscosity graphs for assessing mixing and compaction temperatures for use in mixture design. The RV test measures the torque, essential to keep a constant rotational speed of 20 rpm of a cylinder-shaped shaft immersed in an asphalt binder, at a persistent temperature. This torque is then transformed to a viscosity and presented automatically by the RV.

3.2.2.6Bending Beam Rheometer Test

The Bending Beam Rheometer (BBR) test gives low temperature stiffness properties of asphalt binders. This parameter gives a signal of an asphalt binder's capability to resist low temperature cracking. AASHTO T 313 is the standard test specification. Asphalt binder's low temperature PG grade can be measured with BBR test in combination with the Direct Tension Test (DTT). The basic BBR test uses a simply supported small asphalt beam dipped in a cold liquid bath. A load is applied to the midpoint of the beam and its deflection is measured against time. Based on measured deflection and standard beam properties stiffness of the asphalt binder is calculated. The low-temperature thermal cracking act of asphalt pavements is associated to the creep stiffness and the m-value of the asphalt binder used in the mix. BBR tests are conducted on aged asphalt binder samples with the help of pressure aging vessel. For low temperature performance grade of asphalt binder the specifications for BBR test are as under in Table 3.2:

Table 3.2 Standard Test Specifications for BBR Test

Material	Value	Specification	HMA Distress
PAV residue	Creep Stiffness at 60sec	≤300Mpa	Low temperature cracking
PAV residue	m-value at 60sec	≥0.300	Low temperature cracking

3.2.3 Mineral Aggregate Selection

Regarding aggregate for hot mix asphalt, it is essential to determine their acceptability as a sound material. Properties including particle size and grading, toughness, particle shape and angularity, porosity and absorption, specific gravity and cleanliness are important to consider for preparation of hot mix asphalt mixture having adequate performance. Following tests determine the suitability of aggregates for asphalt mixture construction. Table 3.3 & 3.4 are showing the standard test specification for coarse and fine aggregate respectively:

Table 3.3 Standard Test Specifications for Coarse Aggregates

Test Type		Test Standard	Test Specifications
Shape Test	Flakiness Index	ASTM D 4791	≤15
Shape Test	Elongation Index	ASTM D 4791	≤15
Los Angles Abrasion Test		ASTM C 131	≤30
Specific Gravity and Water Absorption Test		ASTM C 127	
Clay Lumps & Friable Particles Test		ASTM C 142	≤3%
Unit Weight Test		ASTM C 29	

Table 3.4 Standard Test Specifications for Fine Aggregates

Test Type	Test Standard	Test Specifications
Sand Equivalent Test	ASTM D 2419	≥50
Specific Gravity and Water Absorption Test	ASTM C 128	
Clay Lumps & Friable Particle Test	ASTM C 142	≤3%
Unit Weight Test	ASTM C 29	
Un-compacted Voids Test	ASTM C 1252	

3.3 ASPHALT/BITUMINOUS MIX PREPARATION

Different methods have been established for the preparation of bituminous paving mixes in which Marshall method is the most favorable method developed by Bruce G. Marshall at the Mississippi Highway Department in 1939. ASTM D 6926 is the standard test specification for preparation of bituminous paving mixes. The standard test specimen for Marshall method has height 64mm (2.5 inch) and diameter 102mm (4 inch). Specimens are prepared using particular procedure for heating, mixing and compacting the asphalt-aggregate mixture. Volumetric analysis and stability-flow tests, on the compacted test specimens of hot mix asphalt, are two principal features of Marshall mix design method. A series of test specimens are prepared, using different asphalt contents for a specific gradation of aggregates, to determine the optimum asphalt content by the Marshall method. Each test specimen usually requires approximately 1200gm (2.7 lb) of aggregate. Steps include for preparing Marshall test specimens are as follows:

1. Number of Specimens
2. Preparation of Aggregates
3. Determination of Mixing and Compacting Temperature
4. Preparation of Mold and Hammer
5. Preparation of Mixtures
6. Packing the Mold
7. Compaction of Specimens

Due to the empirical nature of the Marshall Mix Design method the Strategic Highway Research Program (SHRP) introduced a new method in 1993 for the preparation of bituminous paving mixes in the laboratory, called the Superpave Mix Design method. This method was design to replace the Hveem and Marshall methods of mixing by considering traffic and climate also. Furthermore, the compaction devices from the Hveem and Marshall techniques have been replaced by Gyratory compactor. ASTM D 6925 is the standard test specification for preparation of bituminous paving mixes by means of Superpave Gyratory Compactor. The standard test specimen for this method has diameter 149.5mm (6 inch) with variable heights according to the requirement ranging from 115mm (4.5 inch) to 190.5mm (7.5 inch).

3.3.1 Bituminous Mix Compaction Procedure

Mechanical compactor having compaction hammer of 4.5 kg (10 lb.) is used in the Marshall method for compaction of specimens for which dropping height is 475 mm (18 in.). For heavy traffic Marshall mix design criteria uses 75 number of blows on each side of the sample. In the Gyratory compactor the hydraulically or mechanically operated load is applied on the top of the sample with compaction pressure of 600 kPa (87 psi). The sample rotates at 30 revolutions per minute at an inclination angle of 1.25° under constantly applied load. This helps accomplish a sample particle orientation that achieved in the field after roller compaction. For the traffic loading ≥30 million ESALs design number of gyration are 125 according to the Marshall mix design criteria.

3.4 COMPACTED PAVING MIXTURES VOLUMETRICS

A compacted asphalt paving mixture consists of different volumetric properties which include air voids in the compacted mix, voids in mineral aggregate, Voids filled with asphalt and effective asphalt content. These properties provide some identification of pavement performance during its service life (MS-2 Asphalt Institute).

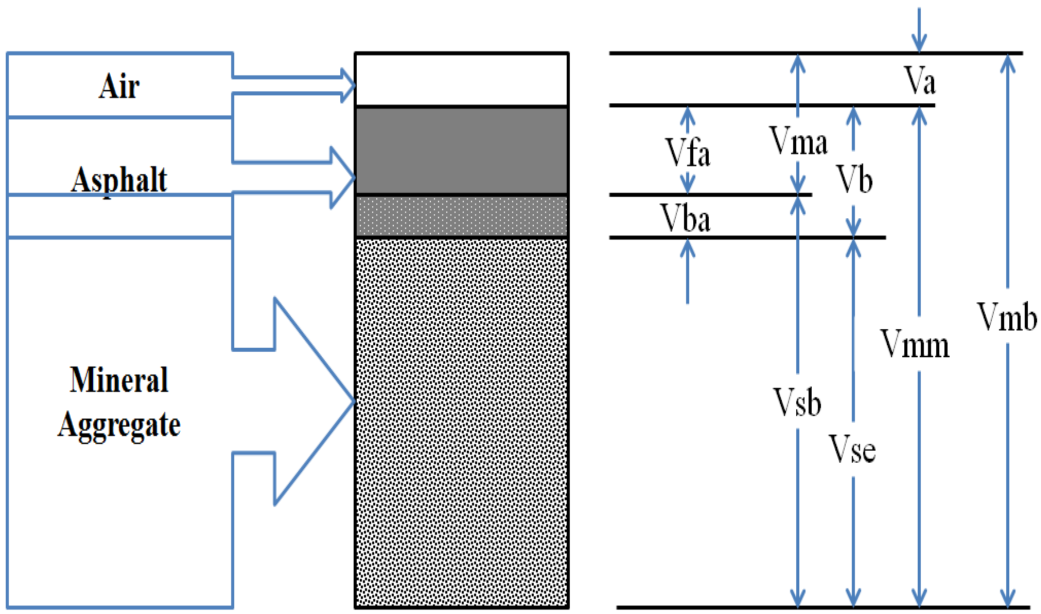


Figure 3.3 Demonstration of Volumes in HMA specimen

3.4.1 Voids in the Mineral Aggregate (VMA)

Voids in mineral aggregate (VMA), are defined as the cavities between the granular particles in a compacted bituminous paving mixture. These spaces include the air voids as well as effective bitumen content, stated as a percentage of total volume of the mixture. Aggregate bulk specific gravity is used to estimate the VMA and is stated as the percentage of bulk volume of compacted asphalt paving blend. Consequently, the VMA can be determined by deducting the aggregate volume from the bulk volume of that compacted mixture. The formula for calculation of VMA is demonstrated as follow:

$$VMA = 100 - \left[\frac{G_{mb} P_s}{G_{sb}} \right] \tag{3.1}$$

Where,

VMA = Voids in mineral aggregate.

P_s = Aggregate content.

G_{mb} = Bulk specific gravity of the compressed mixture (ASTM D 2726)

G_{sb} = Bulk specific gravity of aggregate (ASTM D 127 & ASTM D 128).

3.4.2 Percent Air Voids (Va)

The air voids in compacted asphalt paving blend contain the minor air cavities between the covered aggregate particles. Through the following equation the percentage of air voids in a compacted paving blend can be determined:

$$V_a = 100 \left[\frac{G_{mm} - G_{mb}}{G_{mm}} \right] \tag{3.2}$$

Where,

G_{mb} = Bulk specific gravity (ASTM D 2726).

G_{mm} = Maximum theoretical specific gravity (ASTM D 2041).

V_a = Air voids.

3.4.3 Voids Filled with Asphalt (VFA)

The voids filled with asphalt, VFA, is the fraction of the granular voids in the middle of the aggregate units that are occupied with asphalt. VFA does not include the absorbed asphalt content, and is calculated by using following relation:

$$VFA = 100 \left[\frac{VMA - V_a}{VMA} \right] \tag{3.3}$$

Where,

VFA = Voids filled with asphalt.

VMA = Void is mineral aggregates.

V_a = Air voids.

3.4.4 Effective Asphalt Content (Pbe)

The effective asphalt content represented as Pbe of the asphalt paving mixture is defined as the total asphalt content excluding the amount of asphalt absorbed into the aggregate particles. This portion of asphalt covers the whole particles as a covering layer and governs the performance of an asphalt paving mix.

$$P_{be} = P_b - (P_{ba}/100)P_s \qquad (3.4)$$

Where,

P_{be} = Effective asphalt content.

P_b = Asphalt content.

P_{ba} = Absorbed asphalt.

P_s = Aggregate content.

3.4.5 Specific Gravities

The accuracy of specific gravities measurement for mix design is very important as a small error can cause high variation in the air voids of the mix. Specific gravities which are essential for the calculations of different volumes include:

- Bulk specific gravity of aggregate (G_{sb}), ASTM D 127 & ASTM D 128
- Specific gravity of asphalt (G_b), ASTM D 70
- Bulk specific gravity of compacted mixture (G_{mb}), ASTM D 2726
- Maximum specific gravity of paving mixture (G_{mm})), ASTM D 2041
- Effective specific gravity of aggregate (G_{se})

$$G_{se} = [\{P_{mm} - P_b\}/\{(P_{mm}/G_{mm}) - (P_b/G_b)\}] \qquad (3.5)$$

Where,

G_{se} = Effective specific gravity of aggregate.

P_{mm} = Percent by weight of total mix = 100

P_b = Asphalt content.

G_{mm} = Maximum theoretical specific gravity.

G_b = Specific gravity of asphalt

3.5 STABILITY AND FLOW TESTS

Subsequently determining the bulk specific gravity of the test specimen, stability and flow tests are accomplished. The Marshall stability and flow test gives the performance assessment for the Marshall mix design technique. Before the test, specimens are dipped in water bath for 30 to 40 minutes at 60°C ± 1°C (140°F ± 1.8°F). Marshall stability records the extreme load sustained by the asphalt mix at a loading rate of 50.8 mm/minute. The test load is amplified until it touches extreme. After achieving maximum, when the load just starts to decrease, the load is recorded, called the Marshall stability. During the test, dial gauge is attached which measures the specimen's plastic flow due to the application of load. The flow is the total vertical deformation recorded in the form of 0.25 mm increments at the same time the maximum load is noted.

Marshall stability is related with the resistance of bituminous paving materials to alteration, dislocation, rutting and shearing stresses. The stability of HMA mixture is related primarily from aggregate internal friction and cohesion. Cohesion is the binding force of bituminous material while internal friction is the aggregate interlocking. As bituminous pavement is exposed to severe traffic load, it is essential to select bituminous material with good stability and flow value.

3.6 SELECTION OF GRADATION AND BITUMEN TYPE

The choice and effect of gradation on hot mix asphalt performance has long been a continuous issue. Different agencies indicated different gradations for hot mix asphalt mixtures keeping in view the maximum aggregate size. Asphalt mix prepared from aggregates of same source (quarry) with unvarying physical and chemical properties with same percentage of asphalt content but with changed gradation will result different properties and will perform contrarily under the same loading and environmental conditions.

To observe the effect of gradation on HMA (only for wearing course), four numbers of different gradations were assigned to prepare hot mix asphalt mixtures for performance testing using resilient modulus test. The gradations which were assigned by the HRTC to NUST are included a) NHA-A (NHA gradation), b) NHA-B (NHA gradation), c) Superpave-1 (Superpave Gradation) and d) MS-2 (Asphalt Institute Gradation). NHA-A & NHA-B were coarse gradations having the nominal maximum size of aggregate of 19mm and Superpave-1 & MS-2 were fine gradations having the nominal maximum size of aggregate of 12.5mm. Table 3.5 shows the four asphalt wearing course (AWC) gradations.

Table 3.5 Aggregate Gradations of AWC for Performance Testing

Sieve Size	Asphalt Wearing Course Gradations			
	Cumulative Percentage Passing (%)			
	NHA Gradation	NHA Gradation	Superpave Gradation	Asphalt Institute
	Class-A	Class-B	Class-A (1)	MS-2
37.5 mm (1.5 inch)	100	100	100	100
25.4 mm (1 inch)	100	100	100	100
19 mm (3/4 inch)	95.0	100	100	100
12.5 mm (1/2 inch)	76.0	82.0	94.0	95.0
9.0 mm (3/8 inch)	63.0	70.0	87.0	82.0
6.4 mm (1/4 inch)	51.5	59.0	74.0	69.0
4.75 mm (No. 4)	42.5	50.0	65.0	59.0
2.36 mm (No. 8)	29.0	30.0	37.0	43.0
1.18 mm (No. 16)	20.0	20.0	21.0	30.0
0.6 mm (No. 30)	13.0	15.0	14.0	20.0
0.3 mm (No. 50)	8.5	10.0	9.0	13.0
0.15 mm (No. 100)	6.0	7.0	7.0	8.5
0.075 mm (No. 200)	5.0	5.0	5.0	6.0
Pan	0	0	0	0

Among the four wearing course gradations three of them including NHA-A, NHA-B and Superpave-1 also fulfill the Superpave criteria in which aggregate gradation must pass through the control points. MS-2 gradation passes through the restricted zone but according to the NCHRP Report No. 464 gradations that violate the restricted zone perform likewise to or superior than the mixtures having gradation transient outside the restricted zone. Figs. 3.4 & 3.5 are showing the plots of gradations along with the 0.45 power maximum density curve, control points and restricted zone.

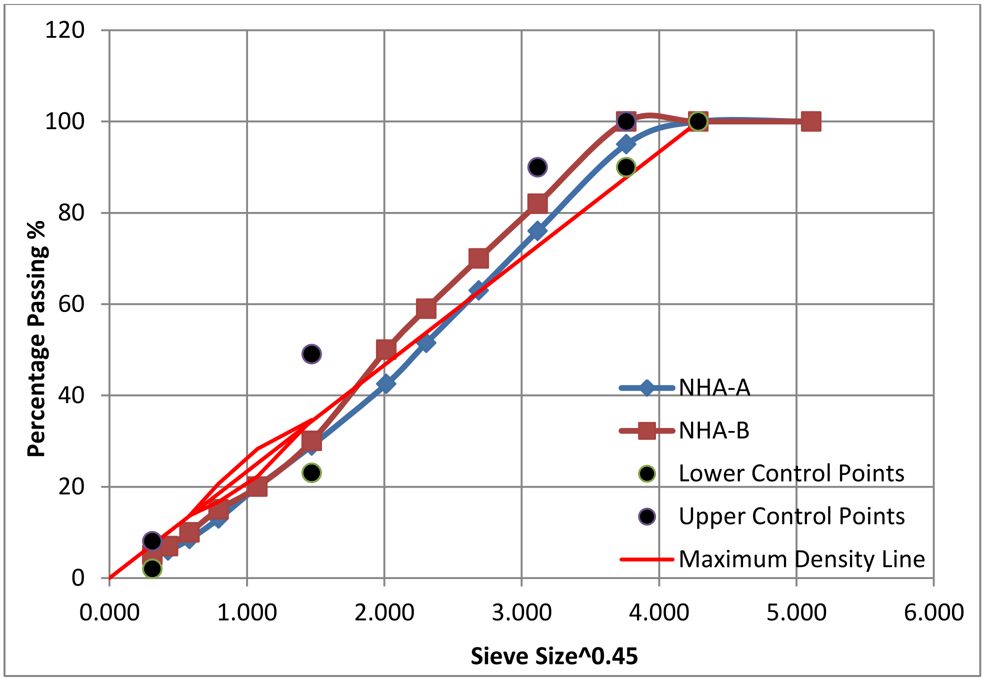


Figure 3.4 Gradation Plot of NHA-A & NHA-B

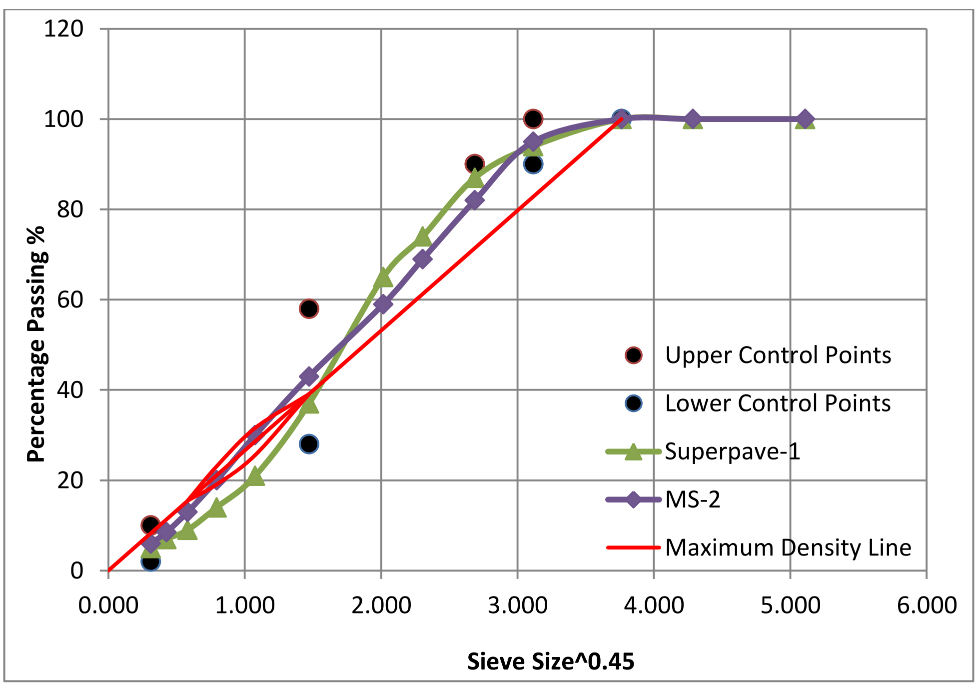


Figure 3.5 Gradation Plot of Superpave-1 & MS-2

Although the amount of binder in the hot mix asphalt is much more less than the aggregate but the type of binder and binder content have the most significant effect on performance of hot mix asphalt. Among the three binder types, two binders were assigned by HRTC to NUST to carry out the performance testing of HMA. NRL

60/70 & ARL 60/70 have the same penetration grade so only ARL 60/70 was included with NRL 40/50 for performance testing.

3.7 DETERMINATION OF OPTIMUM BINDER CONTENT

For determination of optimum bitumen content (OBC) the hot mix asphalt mixture preparation was carried out according to the standard practice for the preparation of bituminous specimens using Marshall Apparatus (ASTM D 6926). Before preparation of specimens for resilient modulus testing, it was required to determine volumetric properties, stability and flow of the hot mix asphalt mixture at optimum asphalt content (OBC) i.e. percent air voids (AV), Voids in mineral aggregates (VMA) and Voids filled with asphalt (VFA).

For this purpose, maximum theoretical specific gravity according to standard test mixtures (ASTM D 2041) and the bulk specific gravity of the compacted mix according to standard test method for the bulk specific gravity and density of non-absorptive compacted bituminous mixtures (ASTM D 2726) were first determined. The steps for preparation of bituminous paving mixes are as follow:

3.7.1 Number of Specimens

For each mix type 15 numbers of samples of 4 inch diameter using 5 trial/experimental bitumen contents (3 specimens each trial bitumen content) were prepared and average values were used to calculate volumetric against each trial bitumen content. Total of seven hot mix asphalt mixtures for wearing course were assigned to calculate the optimum bitumen content (OBC) and to perform resilient modulus testing. Table 3.6 shows the total number of samples prepared for each mix type for calculation of OBC. After calculating the optimum bitumen content through Marshall Mix Design, further 2 samples were prepared for each mixture type to confirm the volumetric.

Table 3.6 Number of Samples for Calculation of OBC (Marshall Compaction)

Sr. No.	Mixture Type	Bitumen Type	Aggregate Gradation	Number of samples for OBC	Number of Samples for Confirmation
1	A	ARL 60/70	NHA-A	15	2
2	B		NHA-B	15	2
3	C		Superpave-1	15	2
4	D		MS-2	15	2
5	E	NRL 40/50	NHA-A	15	2
6	F		NHA-B	15	2
7	G		Superpave-1	15	2
8	H		MS-2	15	2

3.7.2 Preparation of Aggregate and Bitumen

The amount of aggregates required for the preparation of mixture by Marshall Mix Design Method (ASTM D 6926) is 1200gm for 4 inch diameter sample. Amount of aggregates against each sieve size was calculated and after sieving aggregate was dried in oven at temperature 105°C to 110°C. The amount of bitumen required for each sample was taken as the percentage of total weight of mixture obtained from Equation 3.6 and 3.7:

$$W_A + W_B = W_T \tag{3.6}$$

$$W_B = \frac{P}{100} \times W_T \tag{3.7}$$

Where,

P = Percentage of Bitumen

W_A = Weight of the Aggregate

W_B = Weight of the Bitumen

W_T = Weight of the Total Mix

3.7.3 Mixing of Aggregate and Bitumen

The mechanical mixing machine is mentioned by ASTM D 6926 for proper mixing of aggregates and bitumen. The mixing temperature ranged between 160°C and

165°C that match to the temperature during the manufacturing of hot mix asphalt mixture in Pakistan (NHA Specifications).

3.7.4 Compaction and Extraction of Specimens

After mixing the aggregate and bitumen, compaction at temperature 135°C was done using Marshall Method of compaction in which compaction pedestal (mechanical hammer) was used. For compaction of mixture mold kept in the oven at 100°C was used which had an inside diameter of 4-inch and height approximately 3-inch. The mix was placed in the mold in two equal increments with shoveling performed after each increment to avoid honey-combing. The design criterion of heavy traffic was adopted in this research. Hence, to simulate heavy traffic 75 number of blows was delivered on each end of specimen.

After completion of blows on each side the mold was detached from the holder, specimen was then extracted through extraction jack. The specimen was then placed on the flat surface and allowed to cool.

3.7.5 Calculation of Optimum Asphalt Content

In the Marshall Mix Design method, each compacted test specimen was subjected to the following tests and analysis.

- Bulk Specific Gravity Determination
- Stability and Flow Test
- Density and Voids Analysis

After determining the values of above mentioned tests and analysis, separate graphical plots for all values were prepared in such a way that a smooth curve that obtains the “best fit” for all values. Following graphs are used to determine the design/optimum bitumen content of the mixture:

- Stability vs. Asphalt Content
- Flow vs. Asphalt Content
- Unit Weight of Total Mix vs. Asphalt Content
- Percent Air Voids (Va) vs. Asphalt Content

- Percent Voids Filled with Asphalt vs. Asphalt Content
- Percent Voids in Mineral Aggregate (VMA) vs. Asphalt Content

The concluding mix design is generally the most reasonable/cost effective one that will fulfill all the measures for Marshall Mix Design. Normally, the mix design standards produce a narrow range of adequate asphalt contents that accomplishes all requirements. Fig. 3.6 presents the graphs which used to calculate the optimum bitumen content (OBC).

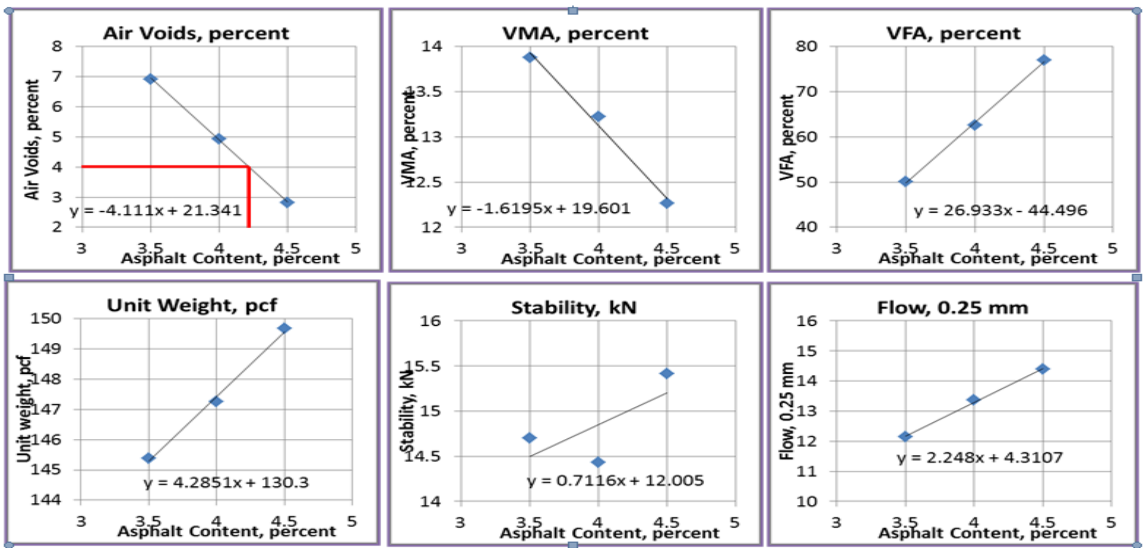


Figure 3.6 Typical Plots to Determine Optimum Bitumen Content at 4% Air Voids

For all mixtures types a criterion of 4% air voids was set to determine the optimum bitumen content (OBC). Against the 4% air voids the bitumen content was determined and then upon that bitumen content other properties of the mixtures were determined by using the graphs shown in Fig. 3.6.

Table 3.7 Marshall Mix Design Criteria

Marshall Mix Design Criteria		**Heavy Traffic**	
		Surface & Base	
		Min	Max
Number of blows each end of specimen		75	
Stability	kg	816	
Flow, 0.25 mm (0.01 inch)		8	14
Percent Air Voids		3	5
Percent Voids Filled With Asphalt (VFA)		65	75

Table 3.7 and 3.8 was used to fulfill the criteria for all the properties of mixtures designed for heavy traffic.

Table 3.8 Minimum Percent Voids in Mineral Aggregate (VMA)

Nominal Maximum Aggregate Size		**Minimum VMA, percent**		
		Design Air Voids, Percent		
mm	inch	3.0	4.0	5.0
12.5	1/2	13.0	14.0	15.0
19	3/4	12.0	13.0	14.0

Ensuing the mentioned criteria in the Table 3.7 & 3.8, optimum bitumen content (OBC) was determined for each mixture type. It was observed that the OBC for fine gradations was more than that of the course ones. This was due to the fact that small particles have more surface area covered with the thin layer of bitumen. Table 3.9 shows the results of optimum bitumen content (OBC) with the volumetric properties of all mixes.

3.8 SAMPLE PREPARATION

After determination of OBC for each mix type samples for performance testing were prepared using Gyratory Compactor. The Superpave gyratory compactor was established to improve mix design’s capability to simulate actual field compaction particle orientation with laboratory apparatus. Samples size of 150 mm (6-inch) in diameter and 190.5 mm (7.5-inch) in height was used to make the samples with 125 numbers of gyrations specified in Superpave mix design for traffic loading ≥ 30 million ESALs. For preparation of samples having the same voids content and volumetric properties as in the Marshall mix design, weight of aggregate was calculated through back calculation. With the help of specimen’s volume and G_{mm} value of mixture the weight of aggregate can be calculated for specimen preparation having the same volumetric properties at 4% air voids.

Table 3.9 Optimum Binder Contents (OBCs) for all Mixture Types

Aggregate Gradation	Bitumen Type/Source	AC	Air Voids	VMA	VFA	Stability	Flow
		%	%	%	%	kg	
NHA-A	ARL 60/70	4.0	4.17	12.30	66.07	1362	12.250
NHA-B		4.1	4.51	12.95	65.16	1291	12.650
SP-1		5.0	4.53	14.70	69.18	1424	13.550
MS-2		4.8	4.68	14.52	67.73	1554	13.120
NHA-A	NRL 40/50	3.9	4.00	13.39	70.16	1496	12.390
NHA-B		4.4	4.89	13.48	63.73	1250	8.720
SP-1		5.6	4.37	15.10	71.06	1383	9.440
MS-2		4.7	4.90	13.62	64.03	1586	10.720

After preparation of gyratory samples, specimens for performance testing were prepared using core cutting and saw cutting machine. Specimens of two diameters (4-inch & 6-inch) were used in the performance testing. For each mix type 5 numbers of specimens were prepared, two specimens for Indirect Tensile Strength Testing and three specimens for Resilient Modulus Testing. The detailed experimental design/test matrix was established including different variables before the performance testing. Table 3.10 shows the detailed test matrix for the performance testing of HMA mixtures.

Table 3.10 Experimental Design/Test Matrix of Performance Testing

Test		**Resilient Modulus Test**							
Diameter & Thickness		4" Diameter (2” Thickness)				6" Diameter (2” Thickness)			
Test Temperature		25°C		40°C		25°C		40°C	
Loading Duration		100 ms	300 ms	100 ms	300 ms	100 ms	300 ms	100 ms	300 ms
Aggregate Gradations	**Bitumen Type**	**Margallah Aggregate**							
NHA-A	ARL 60/70	√	√	√	√	√	√	√	√
NHA-B		√	√	√	√	√	√	√	√
SP-1		√	√	√	√	√	√	√	√
MS-2		√	√	√	√	√	√	√	√
NHA-A	NRL 40/50	√	√	√	√	√	√	√	√
NHA-B		√	√	√	√	√	√	√	√
SP-1		√	√	√	√	√	√	√	√
MS-2		√	√	√	√	√	√	√	√
Total		**192 Specimens with 3 replicates**							

3.9 PERFORMANCE TESTING

In this research, repeated load indirect diametral tension test setup was selected to determine the resilient modules test of hot mix asphalt mixtures due to its simplicity and availability in the laboratory. The tests were conducted in Universal Testing Machine (UTM-25). Indirect tensile strength of hot mix asphalt mixtures was obtained prior to resilient modulus testing. The sequence of the testing is described as follows:

3.9.1 Indirect Tensile Strength Determination

Before determination of actual resilient modulus of hot mix asphalt mixtures, two specimens were subjected to indirect tension test (ASTM D 6931) and average of two values was taken. The specimen was positioned in the test jig above the bottom loading plate and then top loading plate was placed to grip the specimen. The test was conducted by applying compressive load across its vertical diametral plane at controlled deformation rate of 50mm/min at 25°C. The stress at which failure occurred was taken as the indirect tension strength of the specimen. For the resilient modulus test, 20 % of that strength value was taken. Indirect tension test was performed for each mix type with the help of two replicates each using two types of sample diameters (4-inch and 6-inch). Table 3.11 & 3.12 shows the values for indirect tensile strength test for all the wearing course mixtures.

Table 3.11 Results of Indirect Tensile Strength Test for 4-inch Diameter Specimens

Aggregate Gradations	Bitumen Type	Specimen Diameter	Specimen Thickness	Test Temperature	Peak Force (KN)		
		(Inch)	(Inch)	(°C)	Sp. 1	Sp. 2	Average
NHA-A	ARL 60/70	4	2	25	7.465	7.985	7.725
NHA-B		4	2	25	8.238	7.971	8.105
SP-1		4	2	25	6.528	6.914	6.721
MS-2		4	2	25	7.686	7.550	7.618
NHA-A	NRL 40/50	4	2	25	8.016	8.190	8.103
NHA-B		4	2	25	7.742	7.879	7.811
SP-1		4	2	25	7.696	7.281	7.489
MS-2		4	2	25	7.861	7.819	7.840

Table 3.12 Results of Indirect Tensile Strength Test for 6-inch Diameter Specimens

Aggregate Gradations	Bitumen Source & Grade	Specimen Diameter	Specimen Thickness	Test Temperature	Peak Force (KN)		
		(Inch)	(Inch)	(°C)	Sp. 1	Sp. 2	Average
NHA-A	ARL 60/70	6	2	25	8.689	8.788	8.739
NHA-B		6	2	25	8.604	8.750	8.677
SP-1		6	2	25	8.522	8.359	8.441
MS-2		6	2	25	9.293	9.141	9.217
NHA-A	NRL 40/50	6	2	25	8.135	8.245	8.190
NHA-B		6	2	25	8.557	8.697	8.627
SP-1		6	2	25	8.876	8.665	8.771
MS-2		6	2	25	9.113	8.964	9.039

3.9.2 Resilient Modulus Test

Once performing indirect tension test, the actual resilient modulus tests were performed on the remaining three specimens of each mixture. The metallic fixtures for LVDTs (linear variable differential transformer) were installed in the jig. The LVDTs are used for measuring the linear horizontal displacement. The specimen was then fixed into the jig with the help of clamping screws between the loading plates. Afterwards, the jig was shifted for resilient modulus testing into universal testing machine chamber. The LVDTs were installed and adjusted to operate within their range.

As mentioned in ASTM D 4123, the peak loading force was taken as 20% of the failure load and seating force was kept 10% of the peak loading force. Poisson's ratio was assumed as 0.4. By inputting the target temperature (25°C or 40°C), load pulse width (100ms or 300ms), pulse repetition period (1000ms), and conditioning pulse count (100), the test sequence started and specimen was subjected to haversine loading. The indirect tension modulus software recorded and presented the force and displacement as the conditioning stage continued. At the end of the conditioning stage, i.e. after 100 conditioning pulses, the Levels display automatically invoked. The out of range LVDTs were adjusted and by closing the Level display window, automatically 5 pulses of nearly constant deformation were applied to conclude the test.

After completing conditioning pulses deflections and load values were recorded by the software for the last 5 pulses. The values were used to determine the resilient modulus and mean value of resilient modulus was calculated by the software. Three resilient modulus values were determined for each mix type at two different load duration periods, at two different temperatures and for two different diameter specimens, concluding a total of 168 numbers of tests.

3.10 SUMMARY

This chapter includes the material characterization for the HMA mixture preparation. Different laboratory tests are discussed along with the brief procedures. For bitumen characterization consistency tests as well as performance tests are included while for aggregate characterization property tests as well as quality test are included to check the suitability of both the ingredients for hot mix asphalt preparation. Detailed methodology for mixture preparation including mixing, preconditioning, compaction and sample casting is also explained. For determination of optimum bitumen content (OBC) for each mixture volumetric properties of hot mix asphalt mixtures have been calculated along with the Marshall stability and flow tests at different percentages of asphalt binder. Specimens having required dimensions were prepared according to the detailed experimental design with the help of core cutting and saw cutting machine. The testing procedures adopted for the indirect tensile strength testing and resilient modulus testing of hot mix asphalt mixtures has also been explained.

Chapter 4

MATERIAL CHARACTERIZATION

4.1 INTRODUCTION

This chapter includes the material characterization through laboratory testing. Margallah Aggregate and three different bitumen types/sources were characterized in the laboratory and the detail test results are presented in this chapter. Consistency and performance properties were investigated for different bitumen sources as well as property and quality tests were conducted on Margallah aggregate to check the suitability of aggregate for HMA mixture preparation.

4.2 MATERIAL CHARACTERIZATION

For the preparation of hot mix asphalt mixes, it is necessary to check the suitability of both aggregates and bitumen. As this research is the part of the research project "Improvement of asphalt mix design technology for Pakistan" thus, materials which were assigned were characterized using different tests which include a) Quality Tests b) Property Tests and c) Performance Tests. Performance testing was only carried out on the bituminous materials which includes a) Rotational Viscometer Test (RV) and b) Bending Beam Rheometer Test (BBR). Three bitumen grades including a) NRL 40/50, b) NRL 60/70 and ARL 60/70 and single aggregate source (Margallah Aggregates) was characterized using standard test specifications of ASTM and AASHTO.

4.2.1 Bitumen Characterization

Bitumen characterization was carried out in the laboratory using different tests including property tests and performance tests to check the relative behavior of three different bitumen types. Tests which had been carried out include:

1. Penetration Test
2. Flash and Fire Point Test
3. Softening Point Test

4. Ductility Test
5. Rotational Viscometer (RV) Test
6. Bending Beam Rheometer (BBR) Test

4.2.1.1Penetration Test Results

Penetration tests were conducted by using two specimens of each binder type and five values were taken from each specimen. According to the specifications all penetration fulfilled the required criteria of penetration. Grade 40/50 is stiffer than the grade 60/70 as the penetration values are less than 60/70 at 25°C. Table 4.1 shows the results for penetration testing.

Table 4.1 Results of Penetration Test

Binder	**NRL 40/50**		**NRL 60/70**			**ARL 60/70**	
Penetration (0.1mm)	Sp. No. 1	Sp. No. 2	Sp. No. 1	Sp. No. 2	Sp. No. 3	Sp. No. 1	Sp. No. 2
1	40	49	65	65	70	61	65
2	42	46	71	61	70	65	60
3	41	40	67	64	62	60	61
4	40	45	-	67	65	68	68
5	43	40	-	69	64	62	64

4.2.1.2Flash and Fire Test Results

Flash and fire tests were conducted by using three specimens of each binder type. According to the specifications the flash point of bitumen should be greater than 232°C and all observed values fulfilled the required minimum flash point criteria. Table 4.2 shows the results for flash and fire point testing.

Table 4.2 Results of Flash and Fire Test

Binder	**NRL 40/50**			
Flash & Fire Point (°C)	Sp. No. 1	Sp. No. 2	Sp. No. 3	Average
Flash Point	336	334	336	335
Fire Point	360	360	358	359
Binder	**NRL 60/70**			
Flash & Fire Point (°C)	Sp. No. 1	Sp. No. 2	Sp. No. 3	Average
Flash Point	330	328	328	329
Fire Point	356	364	360	360
Binder	**ARL 60/70**			
Flash & Fire Point (°C)	Sp. No. 1	Sp. No. 2	Sp. No. 3	Average
Flash Point	330	326	328	328
Fire Point	364	360	362	362

4.2.1.3Softening Point Test Results

Softening Point tests were conducted by using three specimens of each binder type. Grade 40/50 is stiffer than the grade 60/70 as the average softening point value of NRL 40/50 is 51.6°C compared to the 60/70 grades of the two different binder sources. Table 4.3 shows the results for softening point testing.

Table 4.3 Results of Softening Point Test

Binder	**NRL 40/50**			
Softening Point (°C)	Specimen No. 1	Specimen No. 2	Specimen No. 3	Average
Right	51.5	52.0	52.0	51.8
Left	52.0	51.0	51.0	51.3
Difference	0.5	1.0	1.0	0.8
Average	51.8	51.5	51.5	51.6
Binder	**NRL 60/70**			
Softening Point (°C)	Specimen No. 1	Specimen No. 2	Specimen No. 3	Average
Right	44.5	48.0	45.0	45.8
Left	45.0	47.0	44.5	45.5
Difference	0.5	1.0	0.5	0.7
Average	44.8	47.5	44.8	45.7
Binder	**ARL 60/70**			
Softening Point (°C)	Specimen No. 1	Specimen No. 2	Specimen No. 3	Average
Right	47.5	48.0	48.5	48.0
Left	48.0	49.0	48.0	48.3
Difference	0.5	1.0	0.5	0.7
Average	47.8	48.5	48.3	48.2

4.2.1.4Ductility Test Results

For the design of hot mix asphalt bitumen must have the ductility values greater than the 100 cm when test sample is stretched at 25°C. All bitumen grades had seen satisfying the minimum criteria of ductility as 100cm. Table 4.4 shows the results for ductility testing.

Table 4.4 Results of Ductility Test

Binder	**NRL 40/50**	**NRL 60/70**	**ARL 60/70**
Specimen No.	Ductility (cm)		
1	100	100	100
2	100	100	100
3	100	100	100

4.2.1.5Rotational Viscometer Test Results

Penetration test, flash and fire point test, softening point test and ductility tests are empirical in nature and two performance tests including Rotational Viscometer (RV) test and Bending Beam Rheometer (BBR) test were also conducted in the laboratory on all bitumen grades at different temperatures. Rotation Viscometer (RV) tests were performed on each bitumen grade at two different temperatures using three replicates. Table 4.5 shows the results for Rotational Viscometer (RV) testing. Fig. 4.1 shows the trends for all bitumen grades in which NRL 40/50 shows the higher viscosity as it is stiffer than the other two grades. Moreover, NRL 60/70 has greater viscosity values than ARL 60/70.

Table 4.5 Results of Rotational Viscometer Test

Binder	**NRL 40/50**			
Test Temperature	**135°C**	**160°C**	**135°C**	**160°C**
Specimen No.	Viscosity (cP)		Viscosity (Pa.s)	
1	487.5	87.5	0.488	0.088
2	470.0	75.0	0.470	0.075
3	500.0	87.5	0.500	0.088
Average	485.8	83.3	0.486	0.083
Binder	**NRL 60/70**			
Test Temperature	**135°C**	**150°C**	**135°C**	**160°C**
Specimen No.	Viscosity (cP)		Viscosity (Pa.s)	
1	387.5	95.0	0.388	0.095
2	287.5	85.0	0.288	0.085
3	350.0	90.0	0.350	0.090
4	325.0	80.0	0.325	0.080
Average	337.5	87.5	0.342	0.088
Binder	**ARL 60/70**			
Test Temperature	**135°C**	**160°C**	**135°C**	**160°C**
Specimen No.	Viscosity (cP)		Viscosity (Pa.s)	
1	212.5	62.5	0.213	0.063
2	225.0	75.0	0.225	0.075
3	237.5	82.5	0.238	0.083
Average	225.0	73.3	0.225	0.073

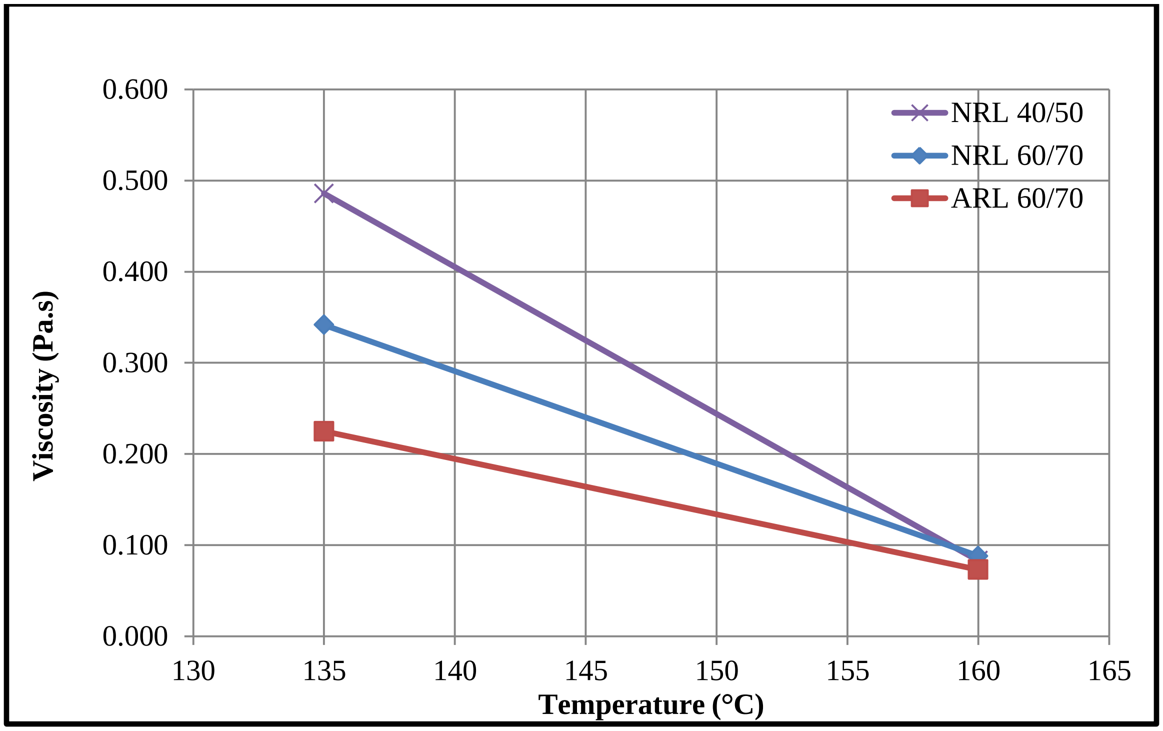


Figure 4.1 Rotational Viscosity Plot for NRL 40/50, NRL 60/70 and ARL 60/70

4.2.1.6Bending Beam Rehometer Test Results

Bending Beam Rheometer (BBR) tests were carried out on each bitumen type at three different temperatures including 0°C, -6°C and -12°C. Tests were carried out on the aged samples of bitumen. Rotating Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) had been used to age the bitumen before testing. Test values can be used to find the low temperature grade of bitumen which is a part of the performance grading (PG) system used in the Superpave mix design. Table 4.6 shows the results for Bending Beam Rheometer (BBR) testing and Fig. 4.2 presents the trends for Bending Beam Rheometer testing.

In addition with the Bending Beam Rheometer (BBR), Dynamic Shear Rheometer (DSR) is a test instrument which measures another part of performance grading (PG) system as high temperature grade of bitumen. In the laboratory only low temperature grades were found while DSR values had been taken from University of Engineering and Technology (UET), Lahore.

Table 4.6 Results of Bending Beam Rheometer (BBR) Test

Sr. No.	Binder Type	Specimen	Temperature (°C)	Time (sec)	Load (mN)	Deflection (mm)	Estimated Stiffness (Mpa)	m-value	Low Temp. Performance Grade (°C)	Comments
1	NRL 40/50	1	0	60.0	982.0	1.2433	64.2558	0.528938	-10	Pass
2		2	0	60.0	983.2	1.4661	54.7179	0.528696	-10	Pass
3		3	0	60.0	974.8	1.3969	56.9541	0.519612	-10	Pass
4		1	-6	60.0	982.7	0.5965	134.4763	0.431605	-16	Pass
5		2	-6	60.0	982.9	0.6845	117.3123	0.397939	-16	Pass
6		3	-6	60.0	987.8	0.7307	110.1738	0.405204	-16	Pass
7		1	-12	60.0	995.8	0.1762	461.0583	0.318140	-22	Direct Tension Test Required
8		2	-12	60.0	987.0	0.1796	448.1442	0.327336	-22	
9		3	-12	60.0	981.7	0.2147	373.0286	0.344917	-22	
1	NRL 60/70	1	0	60.0	984.9	2.4410	32.8618	0.536664	-10	Pass
2		2	0	60.0	990.5	2.6154	30.7371	0.585441	-10	Pass
3		3	0	60.0	978.6	2.6840	29.7508	0.570773	-10	Pass
4		1	-6	60.0	987.2	1.3079	61.8180	0.464934	-16	Pass
5		2	-6	60.0	1004.2	1.1479	71.2826	0.493848	-16	Pass
6		3	-6	60.0	980.4	1.2820	62.6086	0.457239	-16	Pass
7		1	-12	60.0	995.6	0.3402	238.2788	0.494999	-22	Pass
8		2	-12	60.0	983.7	0.3273	245.6438	0.333129	-22	Pass
9		3	-12	60.0	985.0	0.3390	240.0086	0.432891	-22	Pass
4	NRL60/70	1	-6	60.0	978.4	0.9279	86.0527	0.341103	-16	Pass
5		2	-6	60.0	978.4	0.9272	86.0567	0.339101	-16	Pass
7		1	-12	60.0	979.0	0.3828	209.0074	0.306037	-22	Pass
8		2	-12	60.0	979.4	0.3729	256.0035	0.321358	-22	Pass

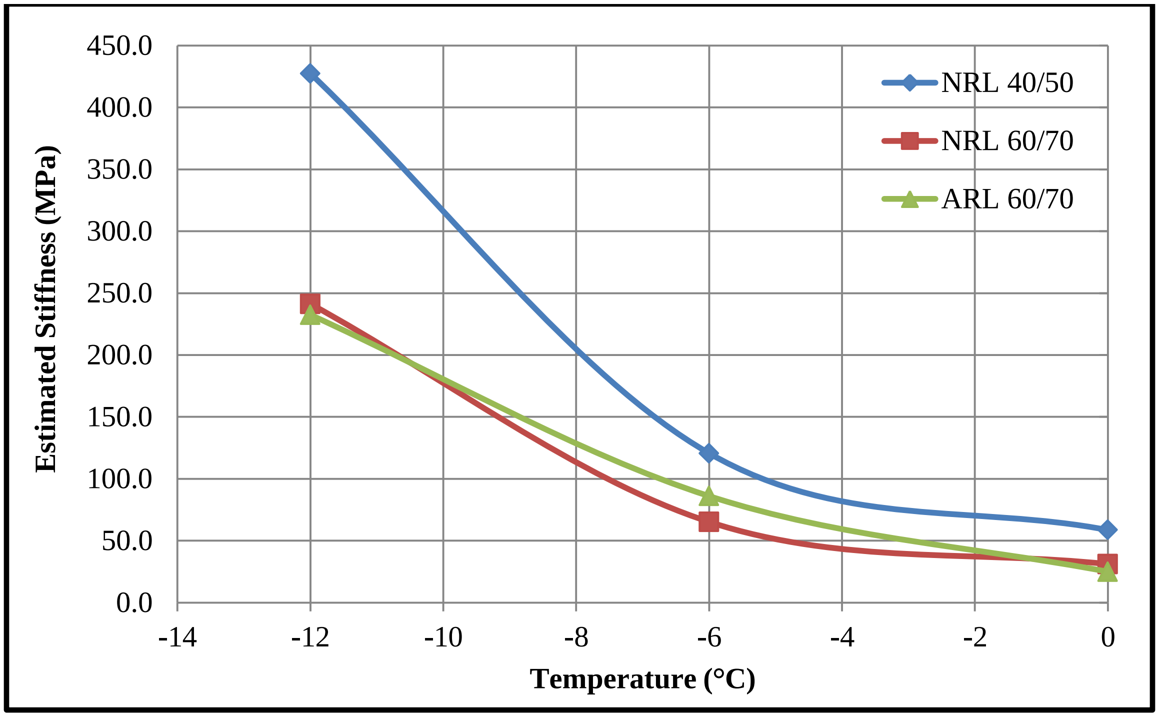


Figure 4.2 Estimated Stiffness Plot for NRL 40/50, NRL 60/70 and ARL 60/70

NRL 60/70 and ARL 60/70 had passed the low temperature criteria of stiffness less than 300 MPa and m-value greater than 0.3 at all the temperatures which define the low temperature grade as -22 by adding -10 in the temperature value at which test passed the required criteria (-12°C). For NRL 40/50 stiffness values at -12°C are greater than 300 Mpa for which Direct Tension Test (DTT) is required to check further criteria of m-value in DTT test. Table 4.7 shows the performance grades along with the penetration grades.

Table 4.7 Performance Grades of Three Bitumen Types

Sr. No.	Bitumen Source	Bitumen Grade	Penetration Grade
1	National Refinery Limited (NRL)	40/50	PG 64-16
2	National Refinery Limited (NRL)	60/70	PG 64-22
3	Attock Refinery Limited (ARL)	60/70	PG 58-22

4.2.1.7Summary of Bitumen Characterization

Table 4.8 presents the summary of all the tests performed on three bitumen types in the laboratory. Out of the three bitumen types two bitumen types including NRL 40/50 and ARL 60/70 were selected to perform Resilient Modulus (M_R) Test.

Table 4.8 Summary of Bitumen Characterization

Type of Test	Asphalt Source & Grade	Test Standard	Specs.	Test Results		
Penetration Test	ARL 60/70	ASTM D5/ AASHTO T49	60-70	63		
	NRL 60/70		60-70	66		
	NRL 40/50		40-50	43		
Flash & Fire Point Test	ARL 60/70	ASTM D92/ AASHTO T48	≥232	328 & 362 ◦C		
	NRL 60/70			329 & 360 ◦C		
	NRL 40/50			335 & 359 ◦C		
Softening Point Test	ARL 60/70	ASTM D36		48.2 ◦C		
	NRL 60/70			45.7 ◦C		
	NRL 40/50			51.6 ◦C		
Ductility Test	ARL 60/70	ASTM D113	≥100 cm	≥100 cm		
	NRL 60/70			≥100 cm		
	NRL 40/50			≥100 cm		
RV Test at 135°C & 160°C	ARL 60/70	AASHTO 316		0.225 pa.s	0.073 Pa.s	
	NRL 60/70			0.338 pa.s	0.204 Pa.s	
	NRL 40/50			0.486 pa.s	0.083 Pa.s	
BBR Test at 0°C -6°C & -12°C	ARL 60/70	ASTM D6648/ AASHTO T313		N/A	86.055 Mpa	232.506 Mpa
	NRL 60/70			31.117 Mpa	65.236 Mpa	241.310 Mpa
	NRL 40/50			58.643 Mpa	120.65 Mpa	427.410 Mpa

4.2.2 Aggregate Characterization

Aggregates are mainly responsible for the load supporting capacity of pavements and the performance of pavements is highly subjective by aggregates. Therefore; it is necessary to use the aggregates, which meet the standard specifications. Aggregate characterization of Margallah and Sargodha aggregates was carried out in the laboratory using different tests including quality tests and property tests to check appropriateness of aggregates for hot mix asphalt design. Only Margallah aggregate was assigned to conduct performance testing of hot mix asphalt mixtures so results for only Margallah aggregate testing are presented in the report. Tests which had been carried out include:

1. Shape Test (Coarse Aggregates Only)
2. Los Angles Abrasion Test (Course Aggregates Only)
3. Specific Gravity and Water Absorption Test (Coarse & Fine Aggregates)
4. Deleterious Test (Coarse & Fine Aggregates)
5. Unit Weight Test (Coarse & Fine Aggregates)
6. Sand Equivalent Test (Fine Aggregates Only)
7. Un-compacted Voids Test (Fine Aggregates Only)

For each aggregate test three replicate samples were used and average is taken. Following tables (Table 4.9 to 4.15) are presenting the detailed testing results on Margallah Aggregate.

4.2.2.1Aggregate Shape Test Results

Shape test tells the amount of flat and elongated particles in the aggregates which are not suitable for hot mix asphalt in higher percentage. According to the specifications percentage flat and elongated particles should be less than equal to 15%. Table 4.9 presents the results of flat and elongated particles amount in aggregate with detailed calculations.

Table 4.9 Results of Flat and Elongated Particles in Aggregates

Seive Sizes	**Wt. of 100 Particles (gm)**			**Wt. of Flate Particles (gm)**			**Wt. of Elongated Particles (gm)**		
(inch)/ Specimen	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1-1/2 -- 1	4771.0	4488	4608	514.5	687	612	301.5	78	112
1 -- 3/4	1859.5	1720	1792	179.5	333	265	110.5	26	96.5
3/4 -- 1/2	593.5	639	614	48.5	32	51.5	11.5	16	13
1/2 -- 3/8	222.5	226	220	53.5	40	46.5	0.0	0	0
3/8 -- No. 4	100.0	100.0	100.0	29.0	12	22	15.5	11	18.5
Total Mass	7546.5	7173.0	7334.0	825.0	1104.0	997.0	439.0	131.0	240.0
				Flat Particles (%)			**Elongated Particles (%)**		
				10.932	14.629	13.211	5.817	1.736	3.180
				Average		**12.924**	**Average**		**3.578**

4.2.2.2Los Angles Abrasion Test Results

Los Angles Abrasion test is the most important test to check the quality/toughness of aggregates. Aggregate abrasion characteristics are important because the aggregate in hot mix asphalt must resist crushing, degradation and disintegration in order to produce high quality HMA. According to NHA specifications abrasion of coarse aggregate for HMA should be less than 30% and the average value calculated in the laboratory for Margallah aggregate is 27.4%. Table 4.10 shows the test results for LA abrasion test.

Table 4.10 Results of Los Angles Abrasion Test

Specimen	Total Mass	Retained #12	Passing # 12	Resistance to Degradation
	(gm)	(gm)	(gm)	(%)
1	5007.5	3635.0	1372.5	27.409
2	5000.0	3672.0	1328.0	26.560
3	5005.0	3598.0	1407.0	28.112
Average	5004.2	3635.0	1369.2	27.360

4.2.2.3Deleterious Materials Test Results

Table 4.11 shows the results of deleterious materials in aggregates. Aggregates must be reasonably clean for HMA. Vegetation, clay particles, excessive dust and soft particles are not appropriate because they usually affect performance by degradation which causes a loss of binder-aggregate bonding.

Table 4.11 Results of Deleterious Materials in Aggregates

Aggregate Type	Coarse Aggregate				Fine Aggregate			
Specimen	**1**	**2**	**3**	**Average**	**1**	**2**	**3**	**Average**
Wt. Before Washing (g)	5000	5000	5000	5000	500	500	500	500
Wt. After Washing (g)	4981.2	4972.7	4974.0	4976.0	487.0	481.0	489.0	485.7
Percentage Clay (%)	0.376	0.546	0.520	0.481	2.600	3.800	2.200	2.867

4.2.2.4Unit Weight of Aggregate Test Results

Unit weight is the property of aggregates which is needed to determine weight to volume relationship and to calculate various volume related quantities such as voids in mineral aggregates (VMA) and voids filled with asphalt (VFA). Also unit weight is very important to determine the packing characteristics of aggregates with the help of Bailey's method. Table 4.12 shows the results for loose and rodded unit weight of coarse and fine aggregates.

Table 4.12 Results of Loose & Rodded Unit Weights of Aggregates

Aggregate Type	Coarse Aggregate				Fine Aggregate			
Specimen's Weight	Weight in Grams				Weight in Grams			
	1	**2**	**3**	**Average**	**1**	**2**	**3**	**Average**
Loose Unit Weight								
Bucket	12011	12011	12011	12011	8227.5	8227.5	8227.5	8227.5
Bucket+ Aggregate	35150	35100	35230	35160	24031.0	23950.0	23808.0	23929.7
Aggregate	23139	23089	23219	23149	15803.5	15722.5	15580.5	15702.2
Unit Weight (Kg/m3)	1543	1539	1548	1543	1580.4	1572.3	1558.1	1570.2
Specimen	**1**	**2**	**3**	**Average**	**1**	**2**	**3**	**Average**
Rodded Unit Weight								
Bucket	12011	12011	12011	12011	8227.5	8227.5	8227.5	8227.5
Bucket+ Aggregate	36320	36450	36390	36387	26003.0	26092.0	25983.0	26026.0
Aggregate	24309	24439	24379	24376	17775.5	17864.5	17755.5	17798.5
Unit Weight (Kg/m3)	1621	1629	1625	1625	1777.6	1786.5	1775.6	1779.9

4.2.2.5Sand Equivalent Test Results

Sand equivalent test is a method of determining the undesirable soil particles in fine aggregates which can coat aggregate particles and prevent proper asphalt binder aggregate bonding. Table 4.13 is representing the sand equivalent test values which should not less than 50% for HMA.

Table 4.13 Results of Sand Equivalent Test

Specimen	Clay Reading	Sand Reading	Difference	Sand Equivalent
	(inch)	(inch)	(inch)	(%)
1	4.25	3.25	1.00	76.5
2	4.30	3.25	1.05	75.6
3	4.25	3.30	0.95	77.6
Average	4.27	3.27	1.00	76.6

4.2.2.6Un-Compacted Air Voids Test Results

Un-compacted voids test is an indirect method of measuring the angularity of fine aggregates which used to certify that the blend of fine aggregate has adequate angularity and texture to resist permanent deformation (rutting) for a given traffic level. A minimum un-compacted void content is generally 40 percent, recommended for the blend of fine aggregates for moderate traffic pavements. Table 4.14 is representing the values of un-compacted voids in the fine aggregate.

Table 4.14 Results of Un-compacted Voids in Fine Aggregate

Specimen	1	2	3	Average
Wt. of Bucket (g)	1488	1488	1488	1488
Bucket + Aggregate (g)	7591.5	7612.0	7585.0	7596.2
Wt. of Aggregate (g)	6103.5	6124.0	6097.0	6108.2
Void Content (%)	39	40	39	39.3

4.2.2.7Summary of Aggregate Characterization

Table 4.15 presents the summary of all the tests performed on Margallah aggregates in the laboratory.

Table 4.15 Summary of Aggregate Characterization

Type Of Test		Aggregate Type	Test Standard	Specifications	Test Results
Shape Test	Flakiness Index	Coarse	ASTM D4791	≤15	12.92%
	Elongation Index	Coarse	ASTM D4791	≤15	3.58%
Deleterious Materials		Coarse	ASTM C142	≤3%	0.48%
		Fine	ASTM C142	≤3%	2.87%
Water Absorption		Coarse	ASTM C127	≤3% (BS 8007)	1.14%
		Fine	ASTM C128	≤3%(BS 8007)	2.27%
Bulk Specific Gravity	20 - 38 mm	Coarse	ASTM C127		2.641
	10 -20 mm	Coarse	ASTM C127		2.636
	5 - 10 mm	Coarse	ASTM C127		2.626
	0 - 5 mm	Fine	ASTM C128		2.590
Unit Weight Test	Unit Weight Loose	Coarse	ASTM C29		1543 Kg/m^3
		Fine	ASTM C29		1570 Kg/m^3
	Unit Weight Rodded	Coarse	ASTM C29		1625 Kg/m^3
		Fine	ASTM C29		1780 Kg/m^3
Los Angeles Abrasion Test		Coarse	ASTM C131	≤30	27.36%
Un-compacted Voids		Fine	ASTM		39.30%
Sand Equivalent		Fine	ASTM	≥50	76.60%

4.3 SUMMARY

In this chapter detailed results of laboratory testing have been presented. Tests were conducted to characterize the two different materials including asphalt and aggregate to check their suitability for HMA mixture preparation. All three bitumen types/sources and single aggregate source (Margalla Aggregate) fulfilled the required criteria for their appropriateness. For each laboratory test three replicate samples have been used and for all replicates results are presented in this chapter.

Chapter 5

ANALYSIS OF EXPERIMENTAL RESULTS

5.1 INTRODUCTION

This chapter contains the detailed analysis of results obtained from the resilient modulus testing. For the analysis Microsoft Excel and the most understandable statistical software recognized as MINITAB-15 was used. Full factorial design of experiment technique was applied to get the significant factors and interactions between the factors. The results obtained from data analysis are presented with graphs such as relative performance plots, normal probability plot, half normal probability plot and factorial plots.

5.2 RESILIENT MODULUS TESTING RESULTS

In this research, five factors were considered in which two factors were material based and three factors were condition based. Material based factors were the aggregate gradation and the bitumen type while the condition/situation based factors were test temperature, load pulse duration and diameter of specimen. Table 5.1 shows the factors considered in the resilient modulus testing which makes total number of 64 combinations with the eight different HMA mixtures. Each experimental condition was replicated three times to obtain a reasonable estimate of experimental error. Therefore; total 192 tests were conducted. Table 5.2, 5.3, 5.4 and 5.5 shows the actual values obtained from resilient modulus testing for each experimental condition.

Table 5.1 Factors Considered in Resilient Modulus Testing

Sr. No.	Factors	Factor Type	Units
1	Nominal Maximum Aggregate Size	Material Based Factors	Mm
2	Bitumen Type/source		0.1mm
3	Temperature	Condition Based Factors	°C
4	Load Pulse Duration		ms
5	Diameter of Specimen		Inch

Table 5.2 Resilient Modulus Test Results for 6-inch Specimens at Temperature 25°C

Aggregate Gradation	Bitumen Type	Sp. Dia.	NMAS	Test Temp.	Load Duration	Resilient Modulus (Mpa)		
		(Inch)	(mm)	(°C)	(ms)	1	2	3
NHA-A	ARL 60/70	6	19.0	25	100	7676	7485	7010
NHA-B		6	19.0	25	100	8746	7724	7256
SP-1		6	12.5	25	100	5401	4875	5040
MS-2		6	12.5	25	100	6875	6583	6950
NHA-A	NRL 40/50	6	19.0	25	100	9164	9053	8659
NHA-B		6	19.0	25	100	9164	9053	8659
SP-1		6	12.5	25	100	7711	7331	6711
MS-2		6	12.5	25	100	8539	7416	6323
NHA-A	ARL 60/70	6	19.0	25	300	4791	4542	4222
NHA-B		6	19.0	25	300	4695	4691	5212
SP-1		6	12.5	25	300	3184	3110	3254
MS-2		6	12.5	25	300	4268	3147	3005
NHA-A	NRL 40/50	6	19.0	25	300	6444	6230	6093
NHA-B		6	19.0	25	300	5794	5783	5919
SP-1		6	12.5	25	300	4792	4741	4214
MS-2		6	12.5	25	300	5699	5464	5175

Table 5.3 Resilient Modulus Test Results for 6-inch Specimens at Temperature 40°C

Aggregate Gradation	Bitumen Type	Sp. Dia.	NMAS	Test Temp.	Load Duration	Resilient Modulus (Mpa)		
		(Inch)	(mm)	(°C)	(ms)	1	2	3
NHA-A	ARL 60/70	6	19.0	40	100	1956	1618	1737
NHA-B		6	19.0	40	100	2068	1894	2455
SP-1		6	12.5	40	100	1130	911	1011
MS-2		6	12.5	40	100	1546	1190	1230
NHA-A	NRL 40/50	6	19.0	40	100	3504	3395	3194
NHA-B		6	19.0	40	100	3892	3296	2812
SP-1		6	12.5	40	100	2332	2077	2171
MS-2		6	12.5	40	100	2583	2400	2310
NHA-A	ARL 60/70	6	19.0	40	300	1049	Fail	1114
NHA-B		6	19.0	40	300	1155	896	877
SP-1		6	12.5	40	300	Fail	588	536
MS-2		6	12.5	40	300	888	840	803
NHA-A	NRL 40/50	6	19.0	40	300	2133	2002	1820
NHA-B		6	19.0	40	300	1842	1751	2092
SP-1		6	12.5	40	300	1379	1261	1142
MS-2		6	12.5	40	300	1340	1318	1454

Table 5.4 Resilient Modulus Test Results for 4-inch Specimens at Temperature 25°C

Aggregate Gradation	Bitumen Type	Sp. Dia.	NMAS	Test Temp.	Load Duration	Resilient Modulus (Mpa)		
		(Inch)	(mm)	(°C)	(ms)	1	2	3
NHA-A	ARL 60/70	4	19.0	25	100	9492	7947	8835
NHA-B		4	19.0	25	100	8801	8666	7680
SP-1		4	12.5	25	100	5650	5572	5402
MS-2		4	12.5	25	100	8530	8269	7510
NHA-A	NRL 40/50	4	19.0	25	100	11711	11475	11107
NHA-B		4	19.0	25	100	11624	10109	9474
SP-1		4	12.5	25	100	9797	9180	7980
MS-2		4	12.5	25	100	9696	9493	9376
NHA-A	ARL 60/70	4	19.0	25	300	6657	5581	6003
NHA-B		4	19.0	25	300	6164	5995	5346
SP-1		4	12.5	25	300	3402	3272	3340
MS-2		4	12.5	25	300	5906	5567	5220
NHA-A	NRL 40/50	4	19.0	25	300	7341	7269	6919
NHA-B		4	19.0	25	300	7937	6906	6215
SP-1		4	12.5	25	300	6371	6265	6152
MS-2		4	12.5	25	300	7045	6404	5986

Table 5.5 Resilient Modulus Test Results for 4-inch Specimens at Temperature 40°C

Aggregate Gradation	Bitumen Type	Sp. Dia.	NMAS	Test Temp.	Load Duration	Resilient Modulus (Mpa)		
		(Inch)	(mm)	(°C)	(ms)	1	2	3
NHA-A	ARL 60/70	4	19.0	40	100	2150	2811	2717
NHA-B		4	19.0	40	100	2575	2397	1969
SP-1		4	12.5	40	100	1390	1085	1079
MS-2		4	12.5	40	100	1862	1498	1723
NHA-A	NRL 40/50	4	19.0	40	100	5522	4158	3680
NHA-B		4	19.0	40	100	4879	4854	4743
SP-1		4	12.5	40	100	2880	2678	2989
MS-2		4	12.5	40	100	3001	2621	2633
NHA-A	ARL 60/70	4	19.0	40	300	1583	1291	2097
NHA-B		4	19.0	40	300	1331	1171	1020
SP-1		4	12.5	40	300	720	647	593
MS-2		4	12.5	40	300	1026	880	1026
NHA-A	NRL 40/50	4	19.0	40	300	2182	2252	2073
NHA-B		4	19.0	40	300	2375	2043	2402
SP-1		4	12.5	40	300	1579	1307	1542
MS-2		4	12.5	40	300	1627	1392	1601

5.3 RELATIVE PERFORMANCE PLOTS

The main objective of this research was to characterize the various HMA mixtures, to analyze the relative performance of the mixtures using different wearing course gradations and different binder types/sources. Among the mixtures with NRL 40/50 binder; NHA-A relatively performed well followed by NHA-B, MS-2 and Superpave-1 consistently in all test conditions. Moreover, 39% decrease in the resilient modulus values was observed due to the load pulse duration change from 100ms to 300ms simulating the fast and slow vehicle speeds of 64 Km/h and 22 Km/h respectively. Almost 68% decrease in the resilient modulus values was observed due to the temperature change from 25°C to 40°C. Resilient modulus values of specimens having diameter 150 mm were found comparatively lower than that of diameter 100 mm and percentage decrease was 17%. Figure 5.1 shows the charts for relative performance of mixtures with NRL 40/50 binder.

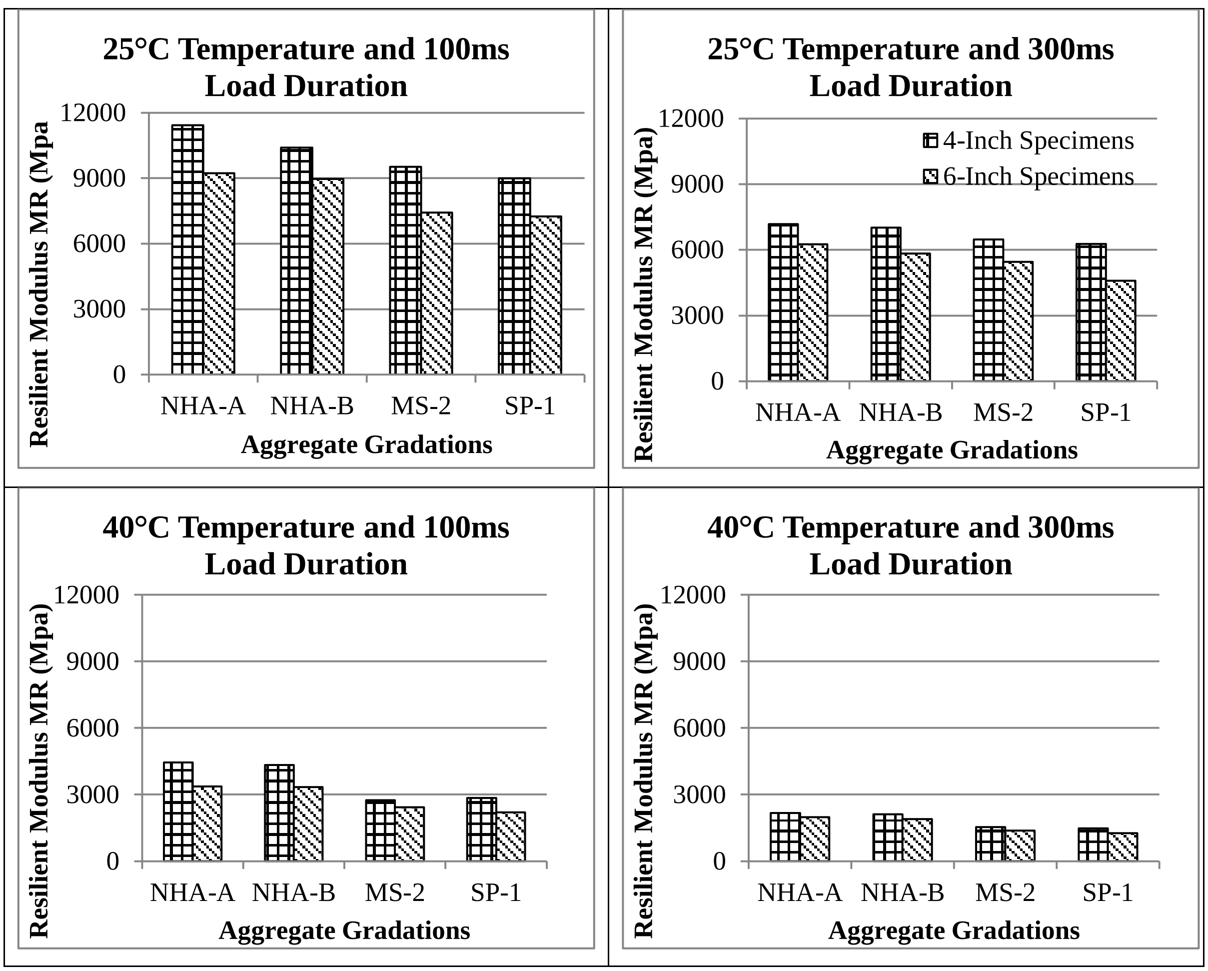


Figure 5.1 Charts Showing Relative Performance of Mixtures with NRL 40/50

Among the mixtures with ARL 60/70 binder; again NHA-A relatively performed well followed by NHA-B, MS-2 and Superpave-1 consistently in all test conditions. Moreover, 40% decrease in the resilient modulus values was observed due to the load pulse duration change from 100ms to 300ms simulating the fast and slow vehicle speeds of 64 Km/h and 22 Km/h respectively. Almost 78% decrease in the resilient modulus values was observed due to the temperature change from 25°C to 40°C. Resilient modulus values of specimens having diameter 150 mm were found comparatively lower than that of diameter 100 mm and percentage decrease was 18%. Figure 5.2 shows the charts for relative performance of mixtures with NRL 40/50 binder.

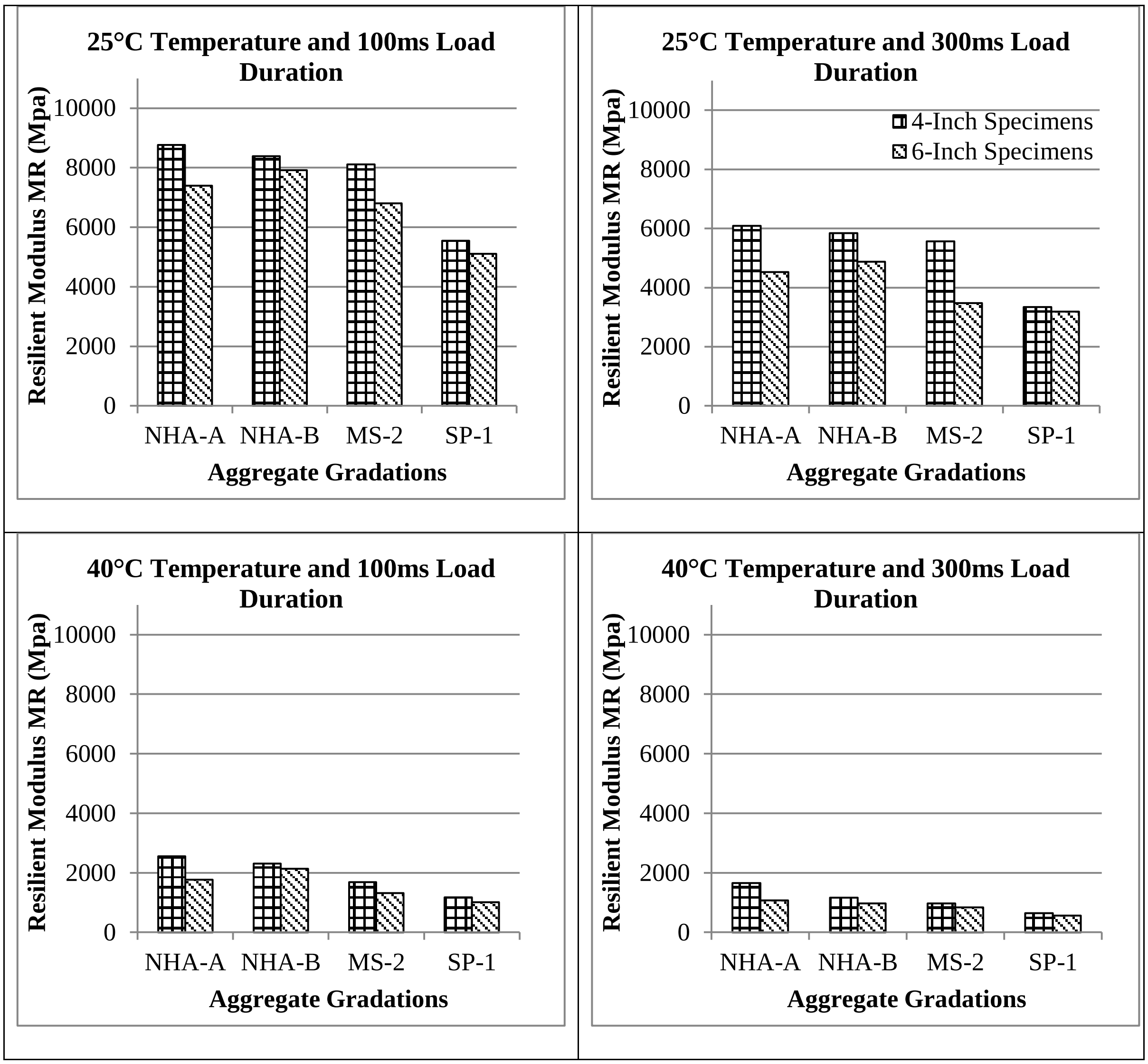


Figure 5.2 Charts Showing Relative Performance of Mixtures with ARL 60/70

Among the two asphalt binders; NRL 40/50 relatively performed well alongside ARL 60/70 repetitively in all test conditions. NRL 40/50 is relatively stiffer binder which was also observed in the binder characterization explained in chapter 3. The rotational viscosity as well as the estimated stiffness of NRL 40/50 in Bending Beam Rehometer was relatively higher among the three binders. In resilient modulus testing same effect was observed. Figure 5.3 and 5.4 clearly shoes that the samples prepared with NRL 40/50 have higher resilient modulus values than ARL 60/70.

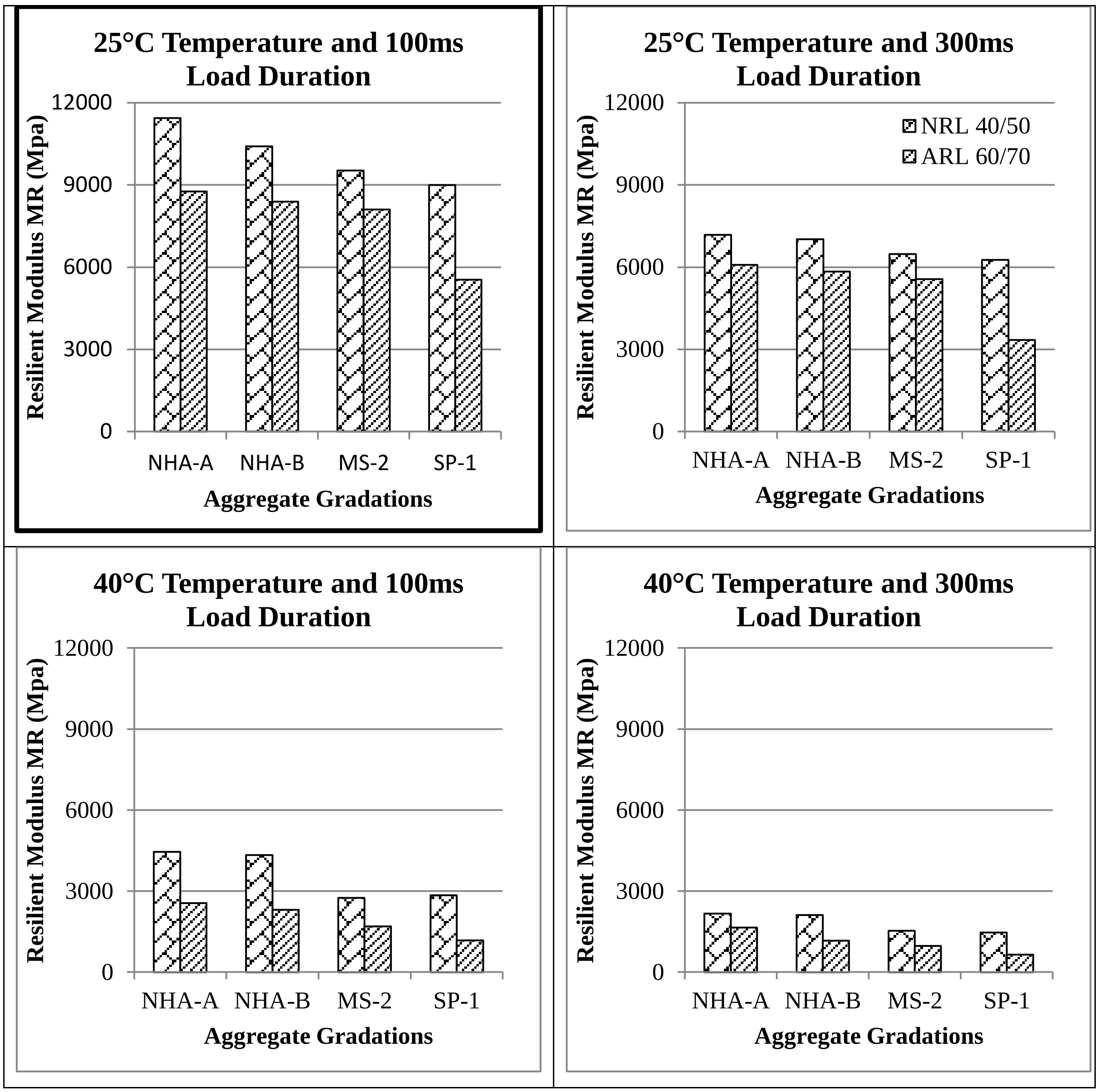


Figure 5.3 Charts Showing Relative Performance of Binders in 4-Inch Diameter Samples

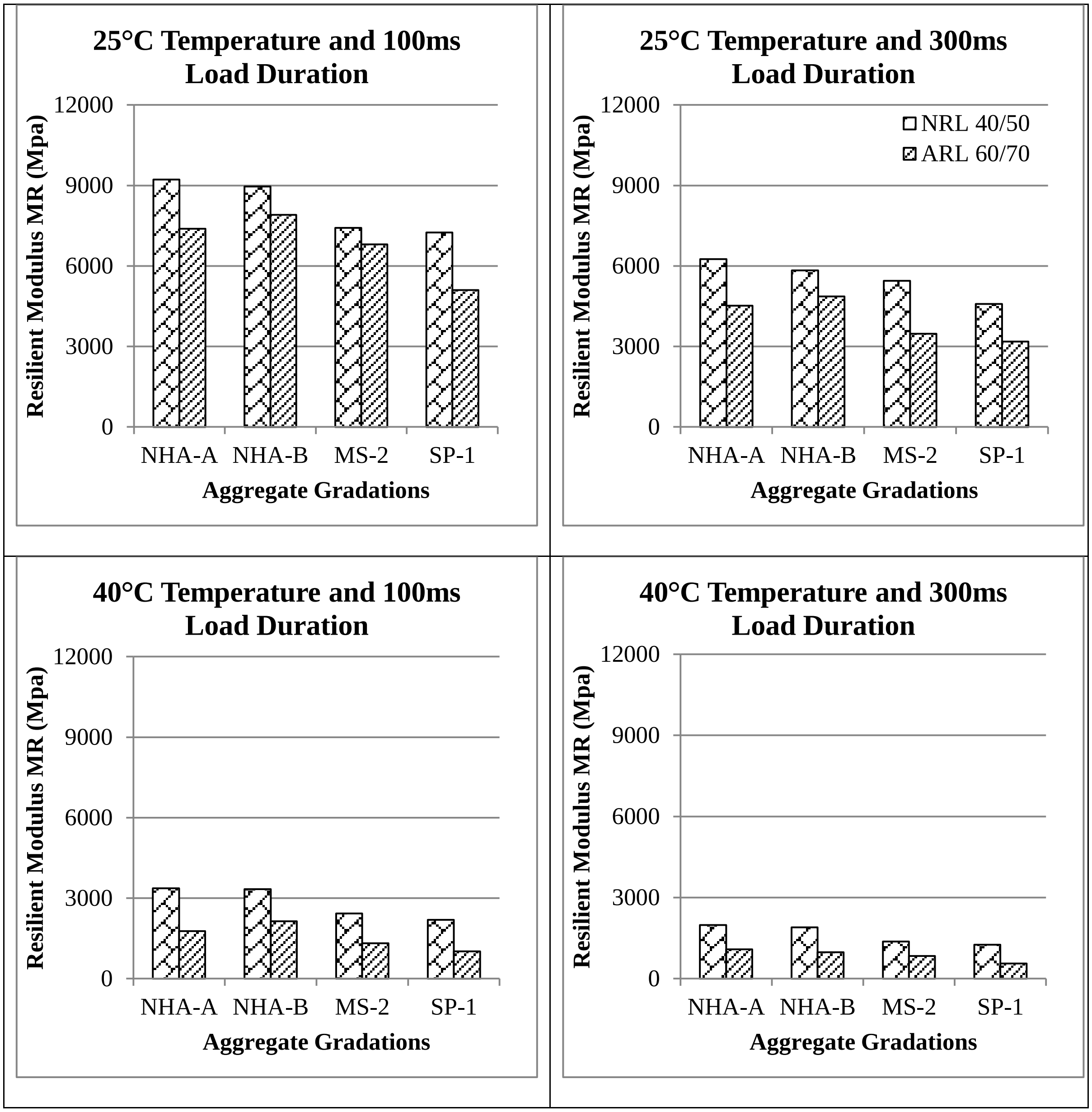


Figure 5.4 Charts Showing Relative Performance of Binders in 6-Inch Diameter Samples

Figure 5.5 shows the comparison between low and high temperature on which change in the resilient modulus values due to different specimen's diameter was observed. The change in resilient modulus values from 6-inch specimens to 4-inch specimens was observed relatively similar at 40°C temperature than 25°C as the slopes of both lines are same. So, it is concluded that both the specimen diameters have almost same sensitivity at the temperature change and percentage decrease in the resilient modulus values due to temperature change is similar for both 4-inch and 6-inch diameter specimens.

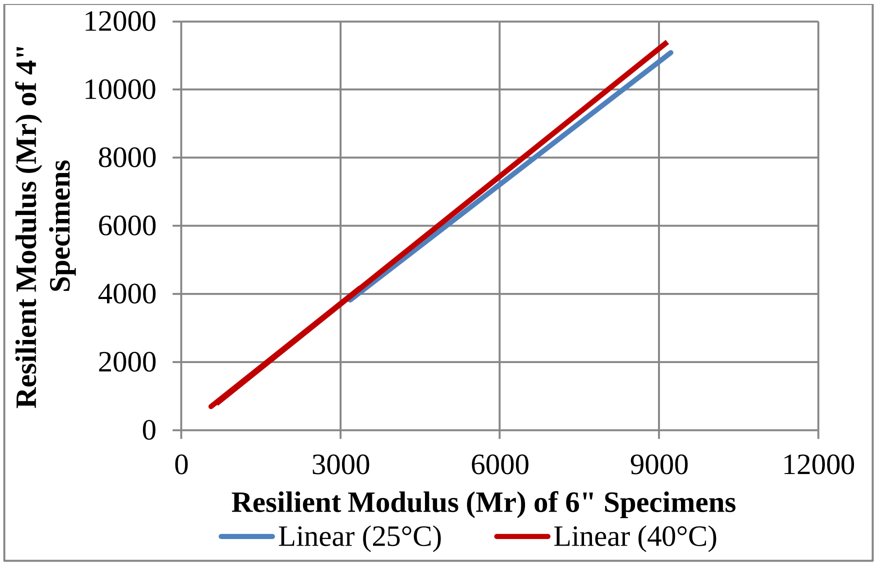


Figure 5. 5 Effect of Specimen Diameter Change at Low and High Temperature

Figure 5.6 shows the comparison between 40/50 and 60/70 binders for which change in the resilient modulus values due to different temperature was observed. The change in resilient modulus values from 25°C temperature to 40°C temperature was observed relatively higher with ARL 60/70 than NRL 40/50. So, it is concluded that both the specimen diameters have almost same sensitivity at the temperature change and percentage decrease in the resilient modulus values due to temperature change is similar for both 4-inch and 6-inch diameter specimens.

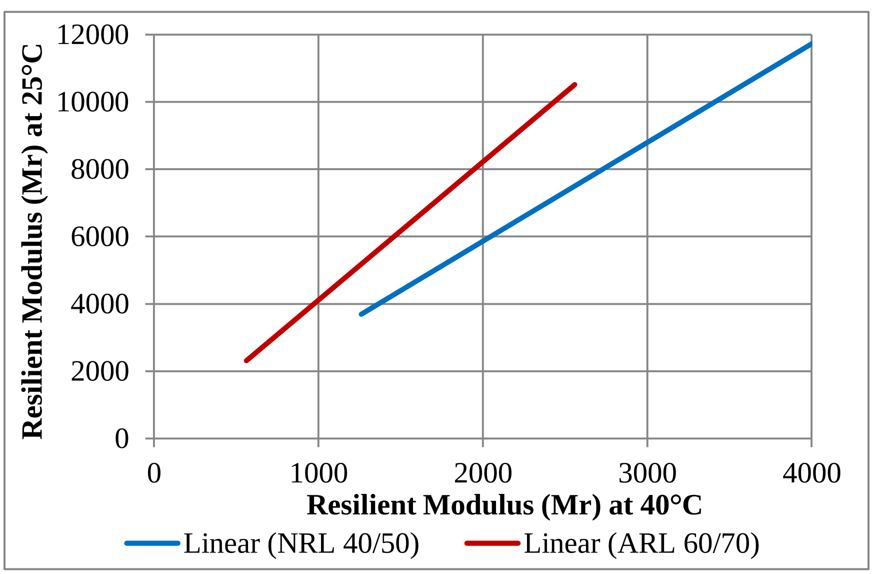


Figure 5.6 Effect of Temperature Change on Bitumen Type/Source

5.4 FACTORIAL DESIGN OF EXPERIMENTS

Factorial design of experiments is a statistical technique to study the effect of factors on the response variable. It is very difficult to study effect of factors when number of factors will be more against a single response variable. This technique is very useful to study the effect of individual factors and their combined effect on the response variable. In this research two-level factorial design using statistical software MINITAB. The response variable was the resilient modulus value and five different factors were considered to check their effect on resilient modulus value. Each factor had two levels, low level and higher level. Table 5.6 shows the factors considered in the resilient modulus testing with their respective abbreviations and high and low levels.

Table 5.6 Considered Factors along Their Low and High Levels

Abbreviation	Factors	Levels		Units
A	Temperature	25	40	°C
B	Load Pulse Duration	100	300	ms
C	Bitumen Type	45	67	mm^{-10}
D	Nominal Maximum Aggregate Size	19.0	12.5	Mm
E	Diameter of Specimen	4	6	Inch

Table 5.7 shows the estimates of main factor effects as well as their combined effect (2-way interactions). The effect can be defined as it is the difference in response values due to any factor at the two levels (low & high) while the interaction effect can be defined as the mean difference between effect of one factor at high and low level values of other factor. The design of experiments was conducted at 95% confidence interval with significance level of $\alpha=0.05$. The significance of any factor can be judged through its p-value against the significance level. If p-value is less than the 0.05 then the factor will be considered as significant. Table 5.7 shows the p-values of all individual factors as well as their two way interaction. All five individual factors have p-value 0.000 which shows that all individual factors are significant. All 2-way interaction of factors are also significant except Load Duration*Diameter, Bitumen Type*Nominal Maximum Aggregate Size and Nominal Maximum Aggregate Size*Diameter.

Table 5.7 Effects and P-values of Individual Factors and Their Interactions

Factors	Effect	P-value
Temperature	-4850	0.000
Load Duration	-1979	0.000
Bitumen Type	-1268	0.000
Nominal Maximum Aggregate Size	1996	0.000
Diameter	-852	0.000
Temperature*Load Duration	837	0.000
Temperature*Bitumen Type	297	0.001
Temperature*Nominal Maximum Aggregate Size	-226	0.021
Temperature*Diameter	468	0.000
Load Duration*Bitumen Type	202	0.019
Load Duration*Nominal Maximum Aggregate Size	-263	0.007
Load Duration*Diameter	86	0.309
Bitumen Type*Nominal Maximum Aggregate Size	86	0.387
Bitumen Type*Diameter	177	0.039
Nominal Maximum Aggregate Size*Diameter	-35	0.716

Table 5.8 represents the analysis of variance (ANOVA) of the data including main effects and 2-way interaction effects for resilient modulus of HMA mixtures. Degree of freedom (DF) for main effects is 5 and 2-way interacting effects is 10 which means that total 5 main factors and 10 interacting factors explain the variation in the resilient modulus values. Significance of the factors can be judged through the p-value which is 0.000 for main factors as well as 2-way interacting factors. F value generally greater than 10 also shows the significance of the factors.

Table 5.8 ANOVA for Resilient Modulus Testing

Source	DF	Sum of Sq	Mean Sum of Sq	F	P
Main Effects	5	3254346781	529877607	654.74	0.000
2-Way Interaction	10	128483662	12848366	15.88	0.000
Residual Error	149	120585087	809296		
Pure Error	110	48543981	441309		
Total	165	3523087243			

5.4.1 Significant Effects and Interaction Plots

Figure 5.7 shows the significance of the individual and combined on resilient modulus of HMA mixtures. T-critical reference line is drawn on the chart which indicates the bars crossing the reference line are significant. Bars are showing the significant as well as insignificant factors. Last three bars on the left side of T-critical line are showing insignificant factors. It is very clear that, among all individual factors, temperature (A) was the most significant factor affecting the resilient modulus followed by load duration (B), bitumen type (C), Nominal maximum aggregate size (D) and diameter of specimen (E). Moreover, 2-way interactions of all factors were critical except load duration*Diameter (BE), bitumen type*nominal maximum aggregate size (CD) and nominal maximum aggregate size*diameter (DE).

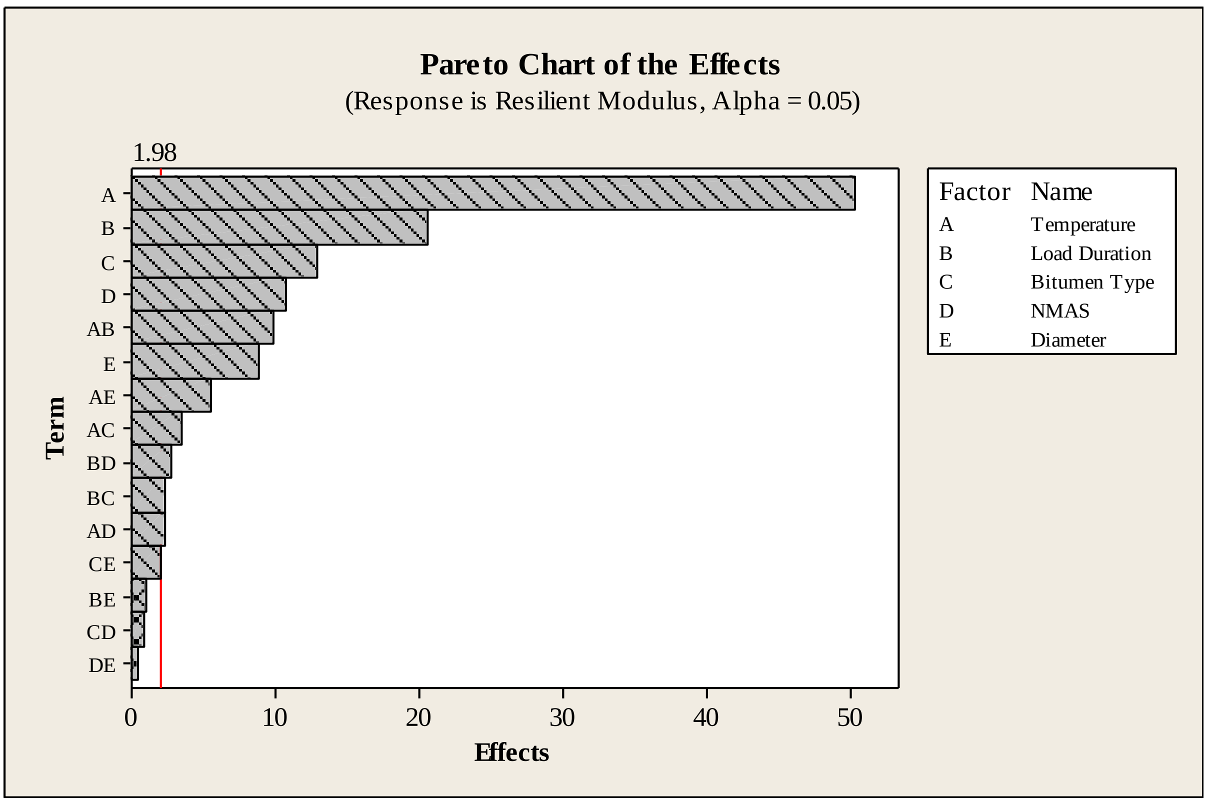


Figure 5.7 Pareto Chart Showing Significant Factors for Resilient Modulus

Figure 5.8 and 5.9 shows the cumulative half normal and normal probability plots of standardized effects for resilient modulus of HMA mixtures at 95% confidence interval. Plots are also showing significant and insignificant factors with the help of red and black markers respectively.

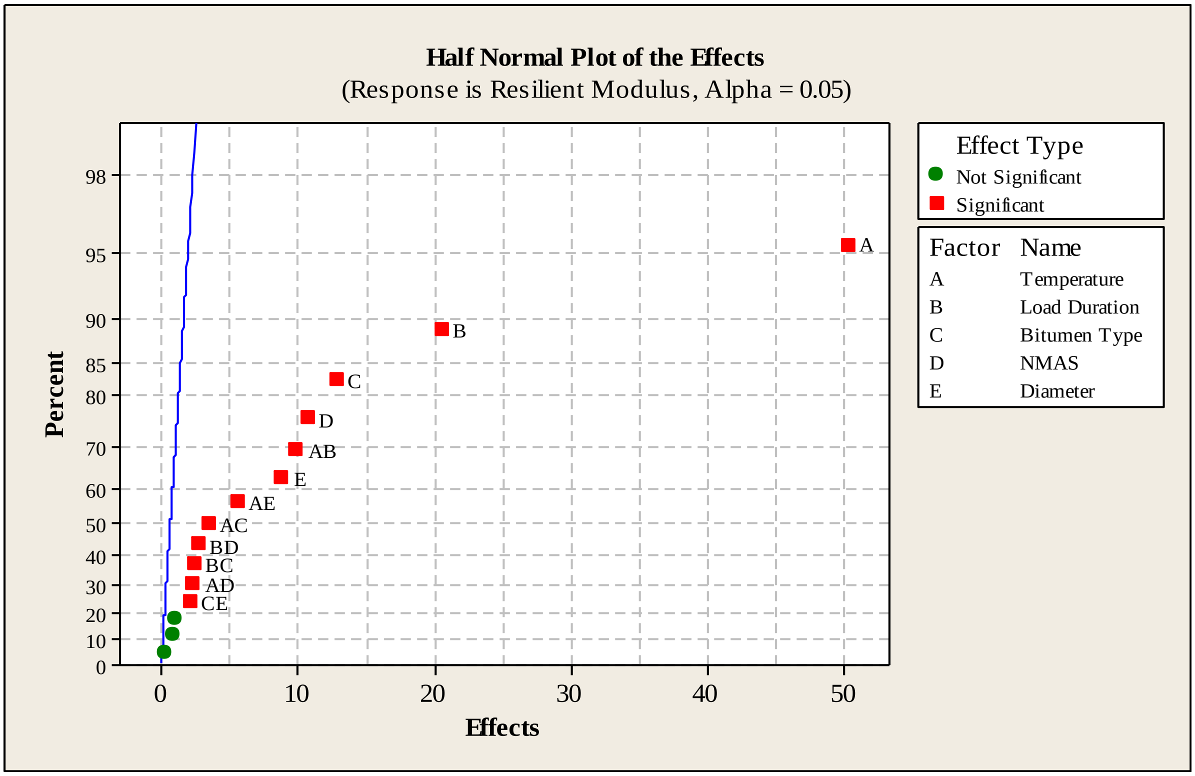


Figure 5.8 Half Normal Plot of Standardized Effect

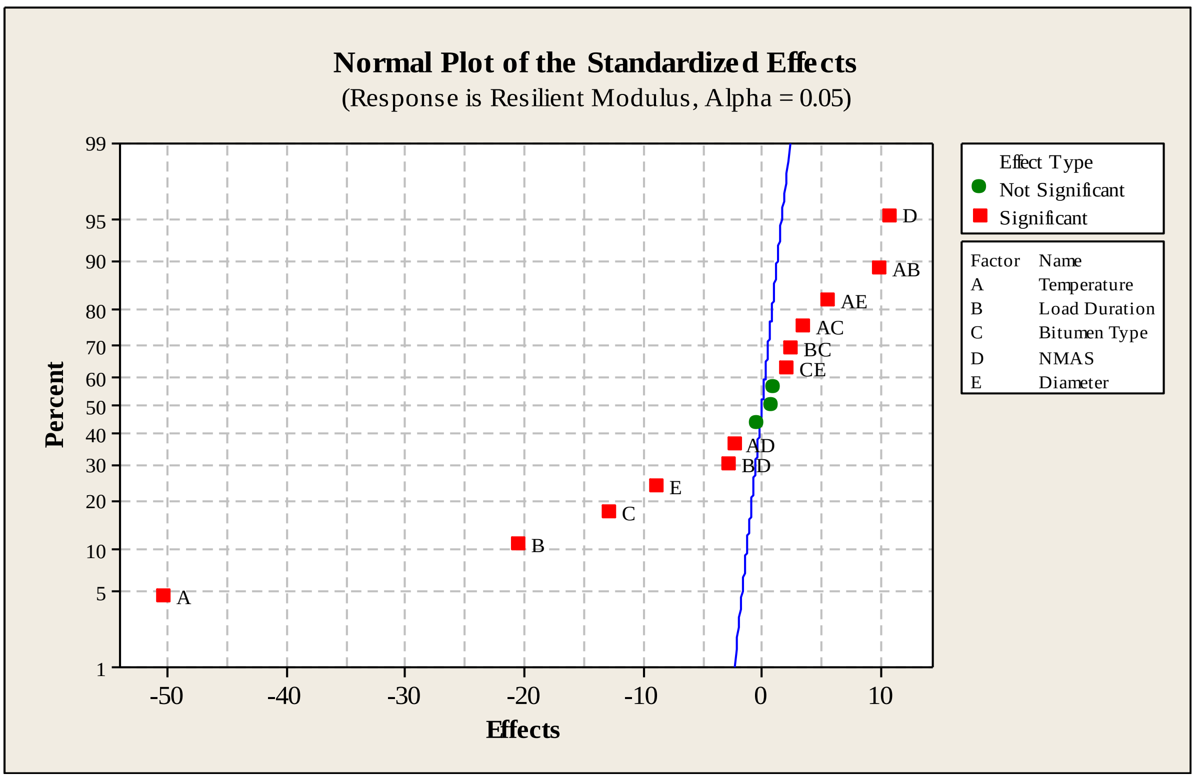


Figure 5.9 Normal Plot of Standardized Effect

5.4.2 Factorial Plots

Factorial plots tell the effect of main factors and their combined effect on the response variable. Figure 5.10 shows the main factors affecting the resilient modulus value of HMA mixtures. Slope of line is shows how much strong the effect is or how much the factor is significant. All five main factors have inverse relationship with the resilient modulus value except nominal maximum aggregate size which has direct relationship with resilient modulus value.

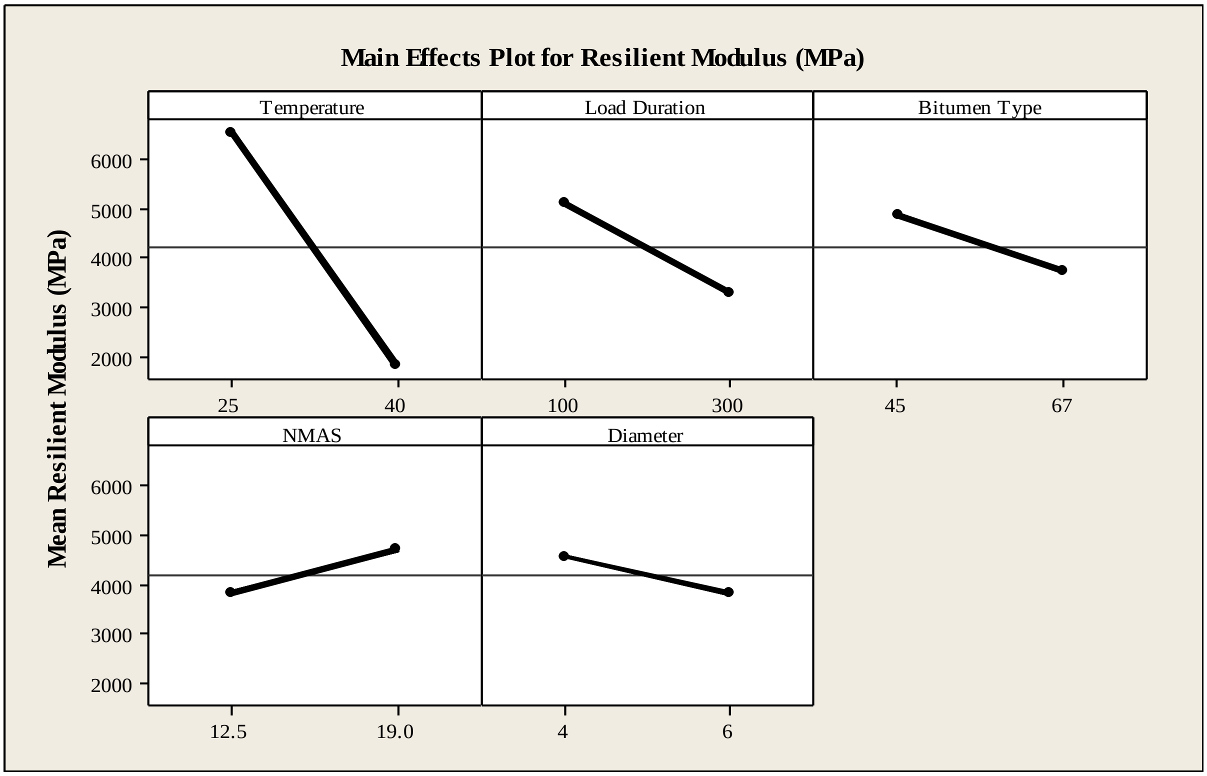


Figure 5.10 Main Effects Plot for Resilient Modulus

Figure 5.11 illustrates the interaction plots for all five factors in which 2-way interaction of factors is plotted. Interaction of temperature with all other four factors is significant as the distance between the lines is more while in the case of nominal maximum aggregate size with specimen diameter lines are parallel and are closed to each other showing insignificance.

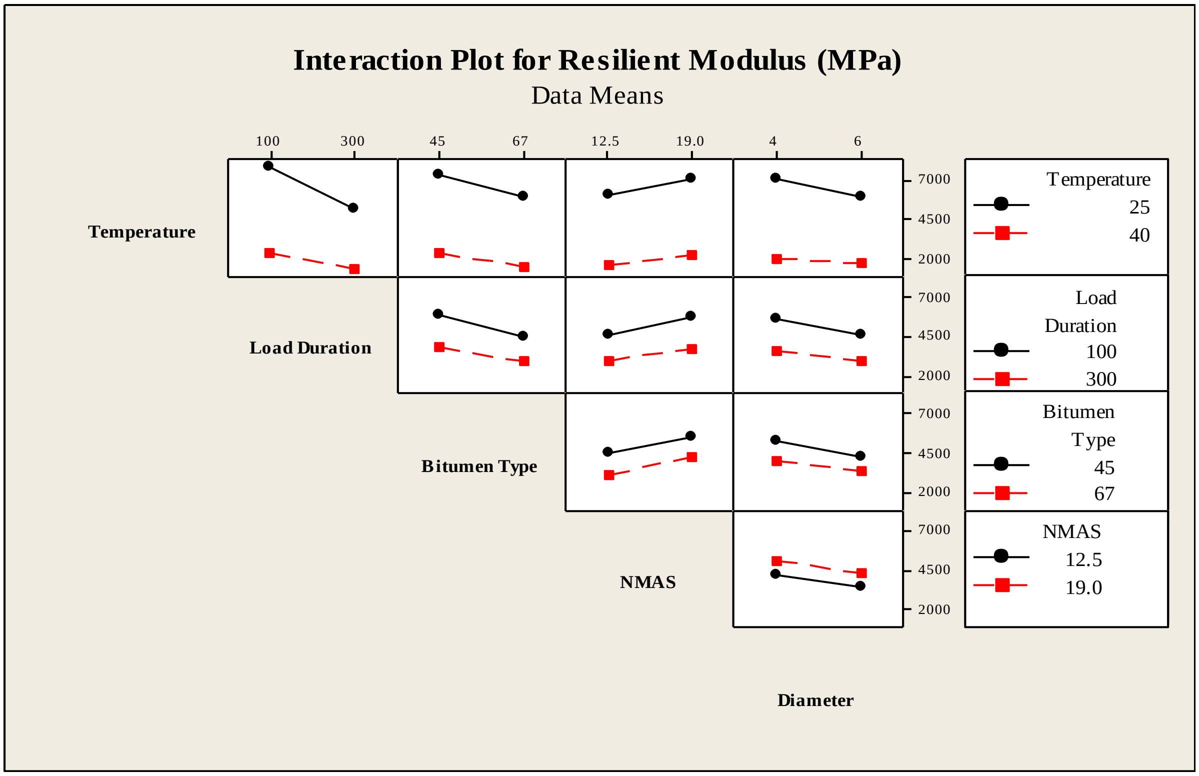


Figure 5.11 Interaction Effects Plot for Resilient Modulus

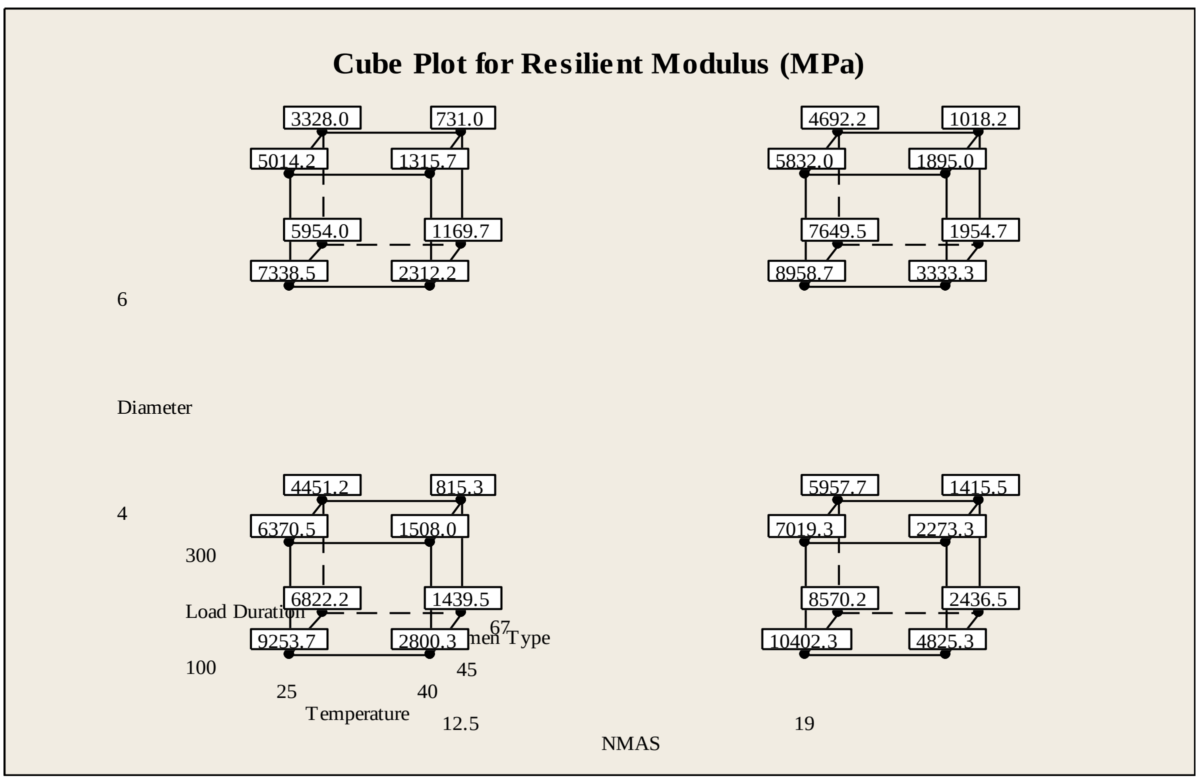


Figure 5.12 Cubic Plots Showing the Resilient Modulus Values

Figure 5.12 shows the resilient modulus values in the form of cubic plots. Each cubic plot has three dimensions “x”, “y” and “z” which are showing the most significant factors respectively on “x”, “y” and ”z” dimensions. Test temperature, load duration and bitumen type was three most significant factors for which, low and high, mean resilient modulus values on the corners of each cubic plot are shown. Other two significant factors including nominal maximum aggregate size and specimen diameter are shown on “x” and “y” axis respectively. So, the minimum value of resilient modulus is shown at the upper right corner at z-axis of upper left cubic block which is 731 MPa and the maximum value of resilient modulus is shown at the lower left corner at z-axis of lower right cubic block which is 10402.3 MPa.

5.5 COMPARISON OF M_R AND E* VALUES

This research study is the part of the research project titled “Improvement of asphalt mix design technology for Pakistan”. A similar study, “Laboratory Characterization of Asphalt Concrete Mixtures Using Dynamic Modulus Test” was carried out at “National Institute of Transportation (NIT), NUST” having the same experimental design, in which dynamic modulus test was performed on the same wearing course gradations along with ARL 60/70 bitumen. A comparison was carried out at temperature 25°C and 40°C, using the dynamic modulus values and resilient modulus values at 100 ms load duration, based upon a previous research study “Comparing Resilient Modulus and Dynamic Modulus of Hot-Mix Asphalt as Material Properties for Flexible Pavement Design” (Loulizi et al. in 2006).

A strong relation was found between the dynamic modulus values at 5 Hz load frequency with the resilient modulus values at 25°C temperature and 100ms load duration while at 40°C temperature the resilient modulus values at 100ms load duration showed a close agreement with that of dynamic modulus values at 1 Hz load frequency. Figure 5.13, 5.14, 5.15 and 5.16 shows the comparison of resilient modulus values and dynamic modulus values for aggregate gradations NHA-A, NHA-B, MS-2 and Superpave-1 respectively. Diagonal black line is showing the line of equality and blue and green markers showing the relationship of values against temperature 25°C and 40°C respectively.

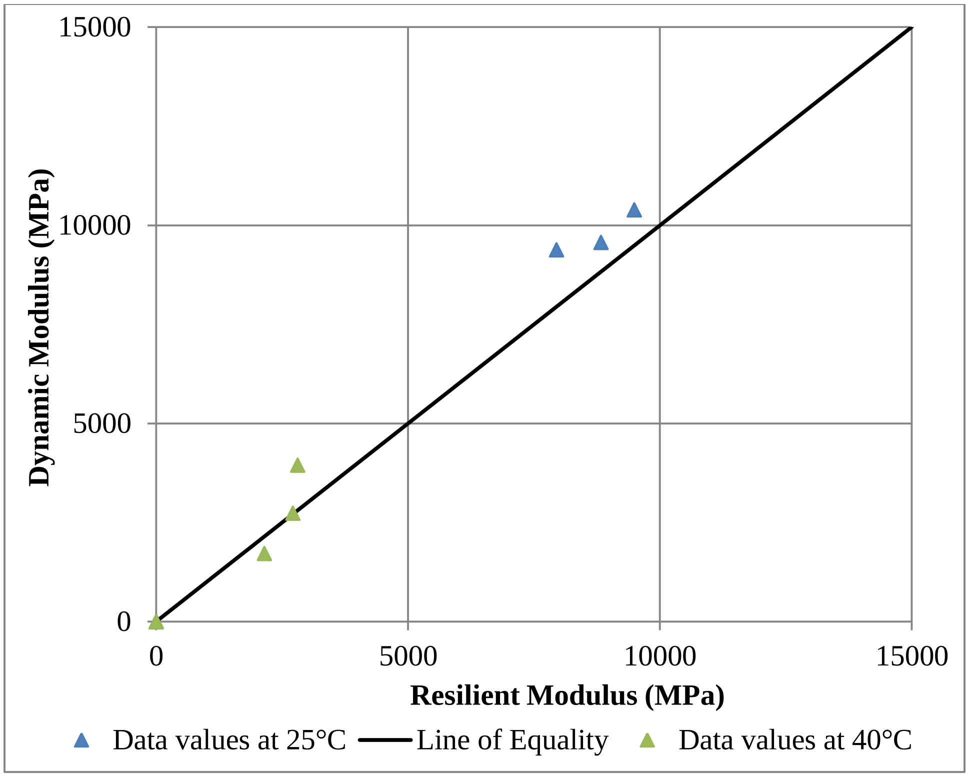


Figure 5.13 Comparison of MR and E* Values of NHA-A Gradation

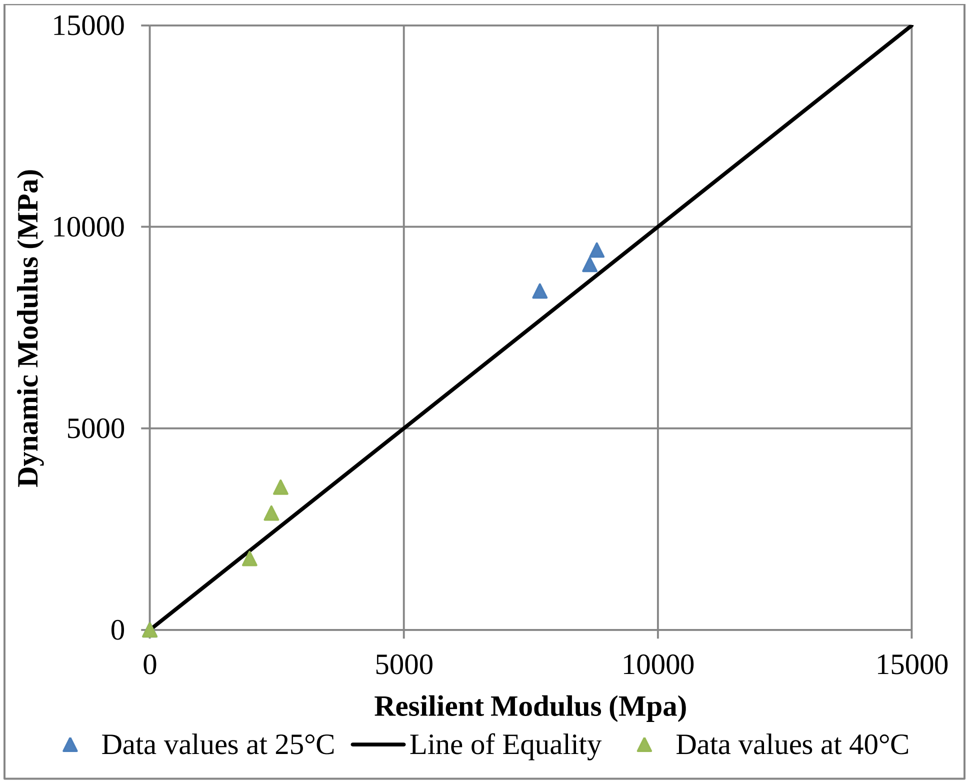


Figure 5.14 Comparison of MR and E* Values of NHA-B Gradation

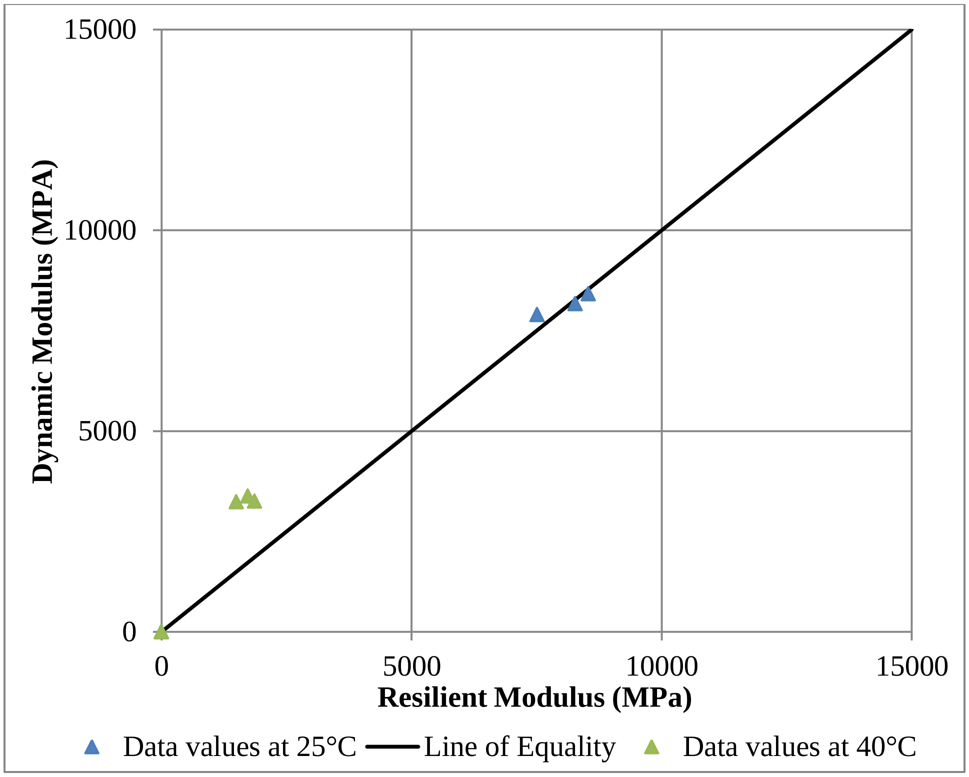


Figure 5.15 Comparison of MR and E* Values of MS-2 Gradation

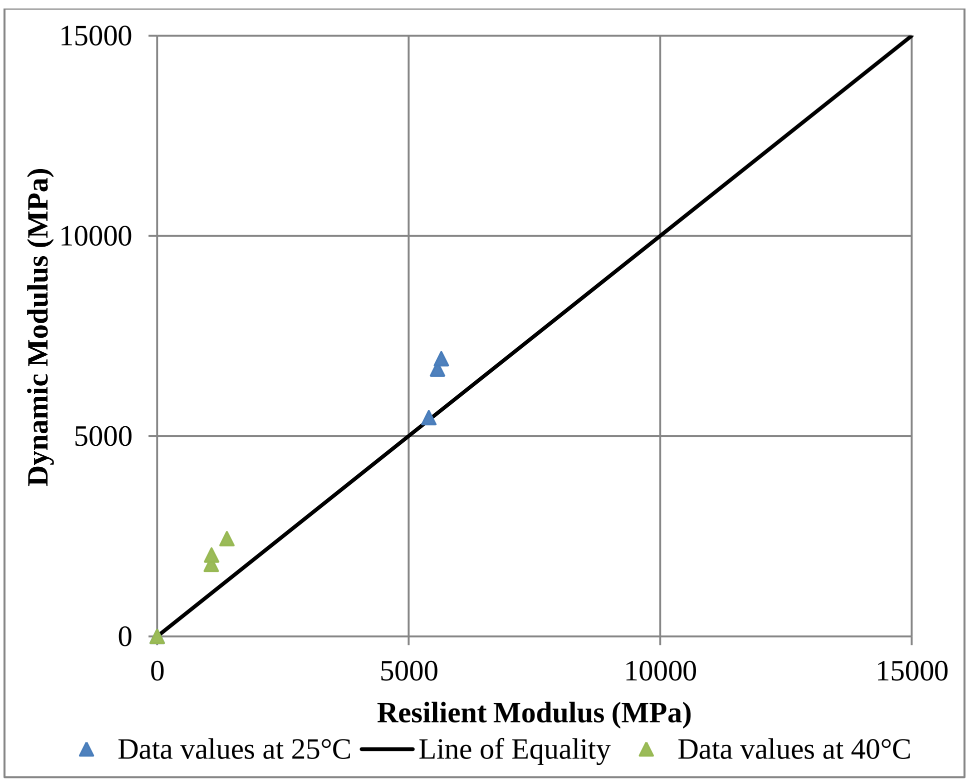


Figure 5.16 Comparison of MR and E* Values of Superpave-1 Gradation

5.6 SUMMARY

Chapter illustrates the complete analysis of the results obtain from performance testing of various HMA mixtures. Eight different mixes, having four wearing course gradations and two asphalt binders, were analyzed. Relative performance of gradations were examined in which NHA-A gradation relatively performed good among four gradations i.e., NHA-A, NHA-B, MS-2 & Superpave-1 with asphalt binder NRL 40/50 & ARL 60/70 consistently in all test conditions. Moreover, relative performance of two binders was also examined in which NRL 40/50 comparatively performed well against ARL 60/70 repetitively in all test conditions.

Two-level factorial design was conducted to check the effect of factors (individually and in 2-way interaction). Temperature was found most significant factor affecting resilient modulus of HMA mixtures followed by load duration, bitumen type, nominal maximum aggregate size and specimen diameter. In 2-way interaction of factors, total 7 interactions out of 10 were significant and 3 were insignificant.

A comparison between resilient modulus values and dynamic modulus values from the past study having similar experimental design was also carried out. A strong relation was found between the dynamic modulus values at 5 Hz load frequency with the resilient modulus values at 25°C temperature while at 40°C temperature the resilient modulus values showed a close agreement with that of dynamic modulus values at 1 Hz load frequency.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

This research study attempts to characterize different HMA mixtures using resilient modulus test. Four different aggregate gradations of wearing course mixtures including: NHA-A, NHA-B, Superpave and Asphalt Institute's manual series; each prepared with two different penetration grade bitumen (40/50 and 60/70) were considered. Experimental investigation of various factors: test temperature, load pulse duration, binder type, nominal maximum size of aggregate, specimen diameter and their interaction on the resilient modulus of different HMA mixtures was analyzed. Superpave gyratory compacted specimens were subjected to haversine-shaped wave load pulse with load duration of 100 ms and 300 ms at 25°C and 40°C temperatures using repeated-load indirect tension test setup in Universal Testing Machine (UTM-25).

6.2 CONCLUSIONS

Given the tested gradations/mixes with ARL 60/70 & NRL 40/50 bitumen using Margallah aggregates and based upon Resilient Modulus Test Results following conclusions have been drawn:

1. With asphalt binder NRL 40/50, NHA-A relatively performed well followed by NHA-B, MS-2 and Superpsve-1 consistently in all test conditions.

2. Similarly, with asphalt binder ARL 60/70, NHA-A relatively performed well followed by NHA-B, MS-2 and Superpsve-1 consistently in all test conditions.

3. Among the two bitumen sources, NRL 40/50 performed better than ARL 60/70 repetitively in all test conditions.

4. Percentage decrease in resilient modulus values due to increase in load pulse duration was observed almost same 39% and 40% in the mixtures prepared with NRL 40/50 and ARL 60/70 respectively.

5. Percentage decrease in resilient modulus values due to increase in temperature was relatively more in the mixtures prepared with NRL 40/50 than ARL 60/70. 78% decrease in the resilient modulus values was observed for samples prepared with ARL 60/70 and 68% decrease in the resilient modulus values was observed for samples prepared with NRL 40/50. So, it is concluded that specimen prepared using bitumen penetration grade ARL 60/70 were found more sensitive in temperature change.

6. Effect of diameter change on the resilient modulus values of different mixtures was found relatively similar at temperature 25°C and 40°C. So, it is concluded that specimens with different diameters have shown almost same percentage decrease in resilient modulus values due to temperature change.

7. Among the five main factors temperature was the most significant factor affecting the resilient modulus followed by load duration, bitumen type, nominal maximum size of aggregate and specimen diameter.

8. Among the ten (10) interacting factors, interaction of temperature with all other four factors was significant. However, three interactions were insignificant including Load Duration*Diameter, Bitumen Type*Nominal Maximum Aggregate Size and Nominal Maximum Aggregate Size*Diameter.

9. At temperature 25°C a strong relation was observed between the dynamic modulus test performed at 5 Hz in past research and the resilient modulus test performed at a loading time of 0.1 sec.

10. At temperature 40°C similar relation was observed between the dynamic modulus test performed at 1 Hz in past research and the resilient modulus test performed at a loading time of 0.1 sec.

6.3 RECOMMENDATIONS

Based upon the resilient modulus testing results and the environmental conditions of Pakistan following recommendations have been drawn:

1. To improve the stiffness and prevent premature failure of pavements, in the preparation of hot mix asphalt mixture, penetration grade 40/50 should be used instead of 60/70 for hot climate areas of Punjab and Sindh provinces of Pakistan.
2. HMA mixtures with course gradations, including NHA-A and NHA-B, should be used in hot climate areas of Pakistan due to higher stiffness values at high temperatures.
3. HMA mixtures with fine gradations, including MS-2 and Superpave-1, should be used in cold climate areas of Pakistan due to lower stiffness values at high temperatures to prevent fatigue failure.
4. Temperature and load duration are the most influential factors in determining the resilient modulus HMA mixtures. Therefore; these factors should be considered in the resilient modulus testing as per in-situ conditions.

REFERENCES

AASHTO (1993). *"Guide for the Design of Pavement Structures"*, American Association of State Highway and Transpiration Officials (AASHTO), Washington, D.C.

AASHTO (2002). *"Guide for the Design of Pavement Structures"*, American Association of State Highway and Transpiration Officials (AASHTO), Washington, D.C.

AASHTO T 313 (2008). "Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer", American Association of State Highway and Transpiration Officials (AASHTO), Washington, D.C.

AASHTO T 316 (2010). "Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer", American Association of State Highway and Transpiration Officials (AASHTO), Washington, D.C.

Ali, Y., (2014). "Laboratory Characterization of Asphalt Concrete Mixtures Using Dynamic Modulus Test", *MS Thesis Report*, National Institute of Transportation, (SCEE), National University of Science and Technology, Islamabad, Pakistan.

Almudaiheem, J.A. and Al-sugair, F.H. (1991). "Effect of Loading Magnitude on Measured Resilient Modulus of Asphalt Concrete Mixes", *Journal of Transportation Research Board*, No. 1317, pp. 139-144.

Asphalt Institute (1981). *"Thickness Design--Asphalt Pavements for Highways and Streets"*, Manual Series No.1 (MS-1), Pennsylvania State University.

Asphalt Institute (1989). *"Mix Design Methods"*, Manual Series No.1 (MS-2), Pennsylvania State University.

Asphalt Institute (2007). *"The Asphalt Handbook"*, Manual Series No.1 (MS-4), Pennsylvania State University.

Asphalt Research Program (1994). "Superior Performing Asphalt Pavement", Strategic Highway Research Program (SHRP), SHRP-A-10, National Research Council, Washington, DC.

ASTM C 29 (2009). "Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM C 127 (2012). "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM C 128 (2012). "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM C 131 (2006). "Standard Test Method for Resistance of Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM C 142 (2010). "Standard Test Method for Clay Lumps and Friable Particles in Aggregate", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM C 1252 (2006). "Standard Test Method for Un-compacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 5 (2013). "Standard Test Method for Penetration of Bituminous Materials", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 36 (1995). "Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 70 (2009). "Standard Test Method for Density of Semi-Solid Bituminous Materials (Pycnometer Method)", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 92 (2012). “Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 113 (2007). “Standard Test Method for Ductility of Bituminous Materials”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 946 (2009). “Standard Specification for Penetration-Graded Asphalt Cement for Use in Pavement Construction”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 2041 (2011). “Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 2419 (2009). “Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 2726 (2011). “Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 3381 (2013). “Standard Specification for Viscosity-Graded Asphalt Cement Use in Pavement Construction”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 4123 (1995). “Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 4791 (2010). “Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate”, American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 6925 (2009). “Standard Test Method for Preparation and Determination of the Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave

Compactor", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 6926 (2010). "Standard Practice for Preparation of Bituminous Specimens Using Marshall Apparatus", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

ASTM D 6931 (2012). "Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures", American Society for Testing and Materials (ASTM) International, West Conshohocken, PA.

Bassett, C.E., (1990). "Effects Of Maximum Aggregate Size on Rutting Potential And Other Properties Of Asphalt-Aggregate Mixtures", *Journal of Transportation Research Board*, No. 1259, pp. 107-119.

FHWA (1998). *"Strategic Highway Research Program",* Federal Highway Administration (FHWA), Washington, D.C. USA.

General Specifications (1998). National Highway Authority (NHA), NHA Headquarters, 27-Mauve Area, G-9/1, Islamabad, Pakistan.

Huang, Y.H., (2004). *"Pavement Analysis and Design"*, Pearson Education, Inc.

Jahromi, S.G. and Khodaii, A., (2009). "Compairing Factors Affecting Resilient Modulus in Asphalt Mixtures", *Journal of Scientia Iranic*, Vol. 6, pp. 1302-1312.

Katicha, S.W., (2003). "Development of Laboratory to Field Shift Factors for Hot-Mix Asphalt Resilient Modulus", *MS Thesis Report*, Blacksburg, Virginia.

Kamal, M.A., Shazib, F. and Yasin, B., (2005). "*Resilient Behaviour of Asphalt Concrete under Repeated Loading & Effects of Temperature*." Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 1329-1343.

Khan, M. B., Khattak, A., Irfan, M. and Ahmed S., (2012). "Factorial Design Approach to Investigate the Effect of Different Factors on the Resilient Modulus of Bitumenous Paving Mixes." *ARPN Journal of Science and Technolology*, Vol. 2, No.11.

Lim, C.T., Tan, S.A., and Fwa, T.F., (1995). "Specimen Size Effects on the Diametrical Mechanical Testing of Cylindrical Asphalt Mixes", *Journal of Testing and Evaluation (JTE)*, Vol. 23, pp. 436-441.

Loulizi, A., Al-Qadi, I.L., Lahouar, S. and Freeman, T.E., (2002). "Measurement of Vertical Compressive Stress Pulse in Flexible Pavements: Representation of Dynamic Loading Tests", *Journal of Transportation Research Board*, No. 1816, pp. 125-136.

Loulizi, A., Flintsch, G.W., Al-Qadi, I.L. and Mokarem, D., (2006). "Compairing Resilient Modulus and Dynamic Modulus of Hot-Mix Asphalt as Material Properties for Flexible Pavement Design", *Journal of Transportation Research Board*, No. 1970, pp. 161-170.

NCHRP (1997). "Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design", National Cooperative Highway Research Program (NCHRP), Project 1-28A, *Transportation Research Board of the National Academics*, Washington, D.C., 2004.

NCHRP (1997). "Laboratory Determination of Resilient Modulus of Flexible Pavement Design". National Cooperative Highway Research Program (NCHRP), Web Doc 14, *Transportation Research Board of the National Academics*, Washington, D.C., 2004.

NCHRP (2001). "The Restricted Zone in the Superpave Aggregate Gradation Specification", National Cooperative Highway Research Program (NCHRP), Report No. 285, *Transportation Research Board* of the National Academics, Washington, D.C.

NCHRP (2004). "Guide for Mechanistic Empirical Design of New and Rehabilitated Pavement Structures", National Cooperative Highway Research Program (NCHRP), Project 1-37A, *Transportation Research Board of the National Academics*, Washington, D.C., 2004.

NCHRP (2004). "Laboratory Determination of Resilient Modulus for Flexible Pavement Design", National Cooperative Highway Research Program (NCHRP), Research Results Digest No. 285, *Transportation Research Board* of the National Academics, Washington, D.C.

Pakistan Economic Survey (2012-13). Ministry of Finance, Government of Pakistan.

Pan, T., Tutumluer, E. and Carpenter, S.H., (2005). "Effect of Coarse Aggregate Morphology on the Resilient Modulus of Hot Mix Asphalt", *Journal of Transportation Research Board*, No. 1929, pp. 1-9.

Saleh, M. F. and Jian, S.J., (2006). "Investigation of factors affecting resilient modulus for hot mix asphalt", University of Canterbury, Civil Engineering.

Saleh, M. F. and Ji, S.J., (2006). "Experimental Analysis of Factors Affecting Resilient Modulus of the Hot Mix Asphalt." *Australian Road Research Board*, 12p.

TJAN, A. and NAPITUPULU, R., (2013) "Verification of Resilient Modulus Prediction of Asphalt Mixtures", *Proceeding of the Eastern Asian Society for Transportation Studies*, Vol. 9.

Ullidtz, P., (1987). "Pavement Analysis", *Elsevier*, New York, N.Y, USA.

Ziari, H. and Khabiri, M.M., (2005). "Effect of Bitumen Content on Resilient Modulus of Asphalt Concrete", Proceedings of the International Symposium on Pavement Recycling. Sao Paulo, Brazil.

APPENDICES

APPENDIX: I UTM-25 TEST RESULTS

Indirect Tension Test

Stress Strain Test

Data file name: D:\Z Thesis Work\Thesis\Resilient Modulus & Indirect Tensile Test Reports\IDT Test Reports\4 inch IDT\NHA-A 6070 4 inch 2.D
Template file name:
Test date & time: 30/10/2013 10:43:05 AM
Project: MS Thesis
Operator: ZEESHAN
Comments:

Specimen Information
Identification: NHA-A-2
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	50.0	50.1	50.2				50.1	0.1
Diameter (mm)	100.0	100.0	100.0				100.0	

Cross-sectional area (mm²): 7854.0

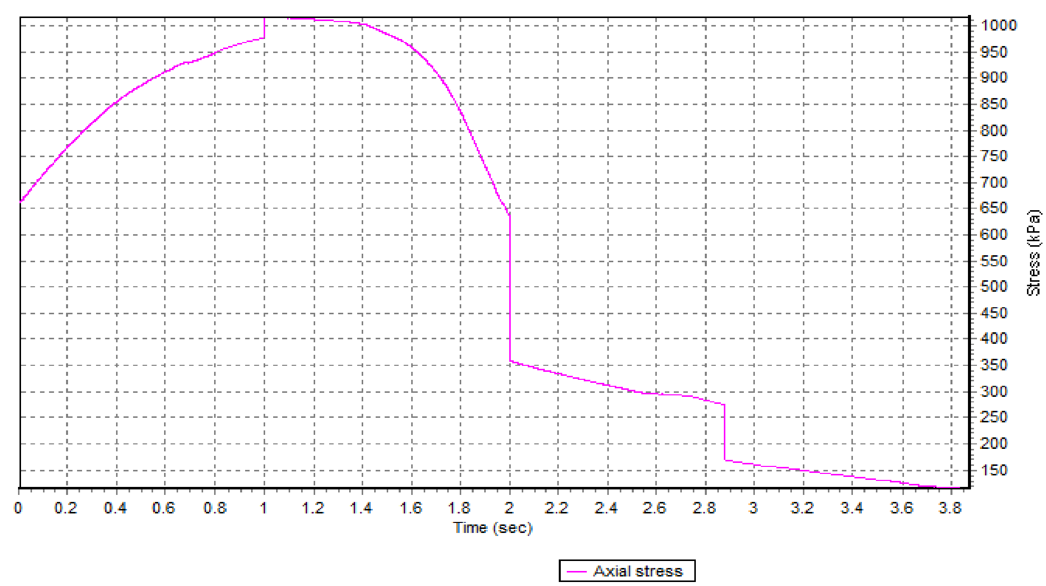
Setup Parameters
Axial loading control: Actuator displ.
Rate (mm/min): 50
Force (kN): 0.05
Pre-load time (s): 5

Strain conversion parameters
Actuator gauge length (mm): 200.0

Stress conversion parameters
Actuator area (mm²): 7854.0

Test Results
Total time (hhmmss): 00:00:03
Displayed time (hhmmss): 00:00:03
Displayed seconds: 3
Actuator displ. (mm): 5.916
Actuator microstrain: 29,580.000
Actuator position (mm): -17.992

Axial force (kN): 0.893
Axial stress (kPa): 113.750
Maximum axial force (kN): 7.985
Minimum axial force (kN): 0.893



Industrial Process Controls Global Ltd UTS002 Ver:3.12 (3.13b) Page: 1 Printed 9/1/2014 1:01:27 PM

Resilient Modulus Test

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: D:\Z Thesis Work\Thesis\Resilient Modulus & Indirect Tensile Test Reports\MR Results 4 inch 25 degree 300 ms\NHA-A 60
Template file name: 122
Test date & time: 26/12/2013 2:37:56 PM
Project: MS Thesis
Operator: Zeeshan
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 300
Pulse repetition period (ms): 1000
Conditioning pulse count: 100
Peak loading force (N): 1545
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: NHA-A 6070 300 1
Remarks...

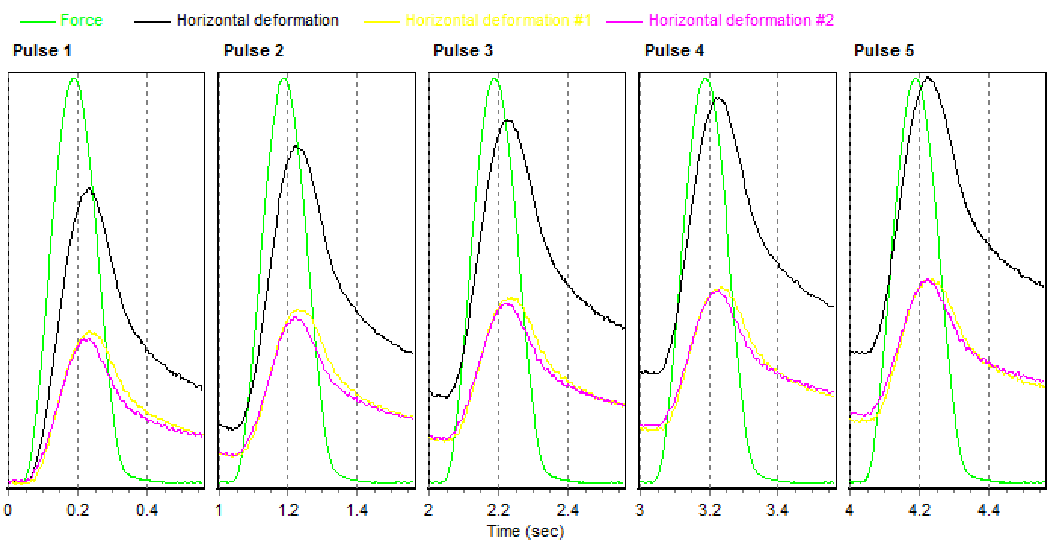
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	49.9	50.0	49.9				49.9	0.1
Diameter (mm)	100.0	100.0	100.0				100.0	

Cross-sectional area (mm²): 7854.0

Test Results

Conditioning pulses: 100
Core temperature (°C): 0.0
Skin temperature (°C): 0.0
Perm't horiz'l defn/pulse (µm): 0.892000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5842	5642	5510	5488	5424	5581	148.77	2.67
Total recoverable horiz. deform. (µm)	3.55	3.68	3.76	3.78	3.82	3.72	0.10	2.63
Peak loading force (N)	1544	1546	1544	1545	1545	1545	0.88	0.06
Recoverable horiz. deform. #1 (µm)	1.84	1.90	1.94	1.94	1.96	1.92	0.04	2.24
Recoverable horiz. deform. #2 (µm)	1.71	1.78	1.82	1.84	1.86	1.80	0.05	3.04
Seating force (N)	155	154	155	155	154	155	0.44	0.29



Industrial Process Controls Global Ltd UTS003 Ver:1.41 (1.41)
Printed 9/1/2014 1:09:40 PM

APPENDIX: II FULL FACTORIAL ANALYSIS USING MINITAB-15

Estimated Effects and Coefficients for MR (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		2896	252.44	11.47	0.000
Gradation Type		541	91.48	5.92	0.000
Temperature	-4850	-2425	48.21	-50.30	0.000
Load Duration	-1979	-990	48.21	-20.53	0.000
Bitumen Type	-1268	-634	49.25	-12.88	0.000
NMAS	1996	998	93.27	10.70	0.000
Diameter	-852	-426	48.21	-8.83	0.000
Temperature*Load Duration	837	418	42.33	9.88	0.000
Temperature*Bitumen Type	297	149	42.54	3.50	0.001
Temperature*NMAS	-226	-113	48.24	-2.34	0.021
Temperature*Diameter	468	234	42.33	5.53	0.000
Load Duration*Bitumen Type	202	101	42.54	2.38	0.019
Load Duration*NMAS	-263	-131	48.24	-2.72	0.007
Load Duration*Diameter	86	43	42.33	1.02	0.309
Bitumen Type*NMAS	86	43	49.32	0.87	0.387
Bitumen Type*Diameter	177	88	42.54	2.08	0.039
NMAS*Diameter	-35	-18	48.24	-0.36	0.716

S = 899.609 PRESS = 49753759
R-Sq = 96.58% R-Sq(pred) = 98.59% R-Sq(adj) = 96.21%

Analysis of Variance for MR (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Covariates	1	19671713	28323358	28323358	35.00	0.000
Main Effects	5	3254346781	2649388037	529877607	654.74	0.000
2-Way Interactions	10	128483662	128483662	12848366	15.88	0.000
Residual Error	149	120585087	120585087	809296		
Lack of Fit	39	72041107	72041107	1847208	4.19	0.000
Pure Error	110	48543981	48543981	441309		
Total	165	3523087243				

Estimated Coefficients for MR using data in uncoded units

Term	Coef
Constant	28584.3
Gradation Type	541.156
Temperature	-618.920
Load Duration	-28.9603
Bitumen Type	-193.698
NMAS	498.323
Diameter	-1892.14
Temperature*Load Duration	0.557713
Temperature*Bitumen Type	1.80234
Temperature*NMAS	-4.63310
Temperature*Diameter	31.2152
Load Duration*Bitumen Type	0.0918580
Load Duration*NMAS	-0.404063
Load Duration*Diameter	0.431709
Bitumen Type*NMAS	1.19805
Bitumen Type*Diameter	8.04516
NMAS*Diameter	-5.4036

```
Least Squares Means for MR

                             Mean  SE Mean
Temperature
 25                          6795    68.33
 40                          1944    68.81
Load Duration
 100                         5359    68.33
 300                         3380    68.81
Bitumen Type
 45                          5004    73.84
 67                          3735    64.44
NMAS
 12.50                       3372    92.40
 19.00                       5367   116.67
Diameter
 4                           4795    68.33
 6                           3944    68.81
Temperature*Load Duration
 25 100                      8202    93.58
 40 100                      2516    93.55
 25 300                      5387    93.55
 40 300                      1373    94.93
Temperature*Bitumen Type
 25 45                       7577    99.59
 40 45                       2430    99.58
 25 67                       6012    88.59
 40 67                       1459    89.81
Temperature*NMAS
 25 12.50                    5684   104.13
 40 12.50                    1060   105.35
 25 19.00                    7905   143.05
 40 19.00                    2829   143.19
Temperature*Diameter
 25 4                        7455    93.58
 40 4                        2136    93.55
 25 6                        6135    93.55
 40 6                        1753    94.93
Load Duration*Bitumen Type
 100 45                      6094    99.59
 300 45                      3913    99.58
 100 67                      4624    88.59
 300 67                      2847    89.81
Load Duration*NMAS
 100 12.50                   4230   104.13
 300 12.50                   2513   105.35
 100 19.00                   6488   143.05
 300 19.00                   4246   143.19
Load Duration*Diameter
 100 4                       5828    93.58
 300 4                       3763    93.55
 100 6                       4890    93.55
 300 6                       2997    94.93
Bitumen Type*NMAS
 45 12.50                    4049   104.13
 67 12.50                    2695   105.35
 45 19.00                    5959   145.72
 67 19.00                    4776   143.40
Bitumen Type*Diameter
 45 4                        5518    99.59
 67 4                        4073    88.59
```

```
 45 6                        4489    99.58
 67 6                        3398    89.81
NMAS*Diameter
 12.50 4                     3780   104.13
 19.00 4                     5811   143.05
 12.50 6                     2963   105.35
 19.00 6                     4924   143.19
```