PERFORMANCE EVALUATION OF ASPHALTIC MIXTURES USING BAKELITE

ADNAN YOUSAF
(2011 – NUST – MS PhD – Tn – 02)

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)

ISLAMABAD, PAKISTAN.

(2014)

Certified that the contents and form of thesis titled **"Performance Evaluation of Asphaltic Mixtures Using Bakelite"**, submitted by Adnan Yousaf, have been found satisfactory for the requirement of the degree.

Supervisor: ______________________________

Assistant Professor (Dr. Arshad Hussain, PhD)

DEDICATED TO MY TEACHERS AND MY PARENTS

ACKNOWLEDGEMENTS

I am thankful to Allah, who gave me strength and patience to complete my research. I would like to pay debt of gratitude to Dr. Arshad Hussain, being the advisor for this study, whose countless inspiration and guidance made it possible to complete my research work. In addition, Dr. Muhammad Irfan, Dr. Muhammad Babar Khan and Dr. Anwaar Ahmed, in the capacity of committee members, gave me guidance and feedback throughout the thesis process.

I would like to pay gratitude to the academic members of the National Institute of Transportation who provided a lot of knowledge during academic session in the postgraduate program. In the end, I pay my earnest gratitude with sincere sense of respect to my parents for their encouragement, sincere prayers and good wishes for successful completion of my research work.

(Adnan Yousaf)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AASHTO	- American Association of State Highway and Transportation Officials
AC	- Asphalt Concrete
AMPT	- Asphalt Mixture Performance Tester
ANOVA	- Analysis of Variance
ASTM	- American Society for Testing and Materials
BS	- British Standard
DFITS	- Difference in the Fitted Values
ESALs	- Equivalent Single Axle Loads
HMA	- Hot Mix Asphalt
LVDT	- Linear Variable Differential Transformer
NCHRP	- National Corporative Highway Research Program
SGC	- Superpave Gyratory Compactor
SPT	- Simple Performance Tester / Simple Performance Tests
VA	- Air Voids
VFA	- Voids Filled with Asphalt
VMA	- Voids in Mineral Aggregates

ABSTRACT

Flexible pavements mainly consists of two basic components that are aggregate and asphalt binder. These two components (aggregate and asphalt) in HMA mixtures are optimally mixed in quantity to produce an economical mix design. Flexible pavements are facing serious problem of developing ruts particularly in areas of Pakistan where temperature is high. This is mainly due to the drastic increase in road traffic during the last two decades. This study targets upon the performance evaluation of modified and controlled laboratory prepared HMA mixtures. Wheel tracking and dynamic modulus tests are used to evaluate the performance of HMA mixtures. Two gradations (NHA class-A and NHA class-B) of wearing course, a bitumen penetration grade of ARL 60/70 and an aggregate source of Margalla were used for preparation of mixtures. Bakelite was introduced as modifier for performance characterization of asphaltic mixtures prepared for this study.

The test results indicated that with the addition of bakelite, the performance of mixtures improved significantly. The percentage reduction in rut depth at 6% optimum bakelite content was observed to be 29% for HMA mixtures of class-A gradation, while that was 38% for HMA mixtures of NHA class-B, when compared to controlled mixtures. Likewise, the percentage increase in dynamic modulus values was found to be 36% for HMA mixtures of NHA class-A, while that was 46% for HMA mixtures of NHA class-B at temperature of 50°C. The analysis technique of 2n Full Factorial Design of Experiments was used to carry out analysis. Loading frequency was found to be the most effectual factor on the values of dynamic modulus, followed by temperature and percentage of bakelite.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The roadway network plays a very important role in economic as well as social growth of any country. It provides more economic and social opportunities that result in better accessibility to markets, employments and additional investments. Pakistan's roadway network mainly consists of flexible pavements. Hot mix asphalt (HMA) is used as a primary paving material for construction of roads all over the world for more than a century (Hafeez, 2012). In Pakistan, most of the flexible pavements undergo premature failure, i.e. is rutting. This is mainly due to the drastic increase in road traffic during the last two decades. Rutting in the shape of shear flow is a particular pavement failure that mainly contributes to the increased tire pressure, high temperature and heavy axle loads. National Highway Authority (NHA) Pakistan is facing problems due to predominant pavement failures, high costs of repair and maintenance and very poor riding quality of pavements (Hafeez, 2010).

Rutting, also called as permanent deformation or creep in flexible pavements, usually consists of longitudinal depressions in the wheel paths, which are an accumulation of small amounts of unrecoverable deformation caused by each load application. It is a phenomenon that is developed in all layers of flexible pavements, under the application of repeated traffic loading, by the accumulation of permanent strains (Hafeez, 2010). The cumulative permanent strains in the wearing course of a asphaltic pavements is known to be accountable, for the final rut depth measured on the pavement surface, among the contributions of rut depth by the various pavement layers. Rutting occurs only on flexible pavements, as indicated by the permanent strains or rut depth along the wheel paths. Flexible pavement's rutting susceptibility can be best predicted by Wheel tracker test.

"The complex modulus is defined as the complex number that relates stress and strain for a linear viscoelastic material subjected to sinusoidal loading, the absolute value of complex modulus is commonly called as dynamic modulus". The two properties determined from complex modulus testing are dynamic modulus (E*), and phase angle (Ø). The dynamic modulus is the main input parameter for mechanistic empirical pavement design guide (MEPDG) of hot mix asphalt (HMA) due to which it has gained more attention recently. Dynamic modulus can be determined by temperature and loading rate-dependent actions of Hot mix asphalt in MEPDG. In dynamic modulus test deformation are measured by application of sinusoidal loads. The ratio of stress to the strain amplitude is called as dynamic modulus (AASHTO TP 62-07, 2007). The dynamic modulus test is conducted according to AASHTO TP 62-07 on Asphalt Mixture Performance Tester (AMPT).

Different laboratory test methods are being utilized to predict the rutting in flexible pavements. One of the method currently in common practice is wheel tracking. Wheel tracking device estimates the permanent deformation in flexible pavements by subjecting the specimens to repeated loading under a moving wheel. The pressure on the steel wheel produces the same effect as produced by a rear tire of a double-axle truck.

1.2 PROBLEM STATEMENT

In recent years, the capacity on road increase since the increasing of vehicle ownership and development of world transportation. This kind of situation may lead to higher traffic volumes, traffic loads and tire pressure. These factors will increase pavement deformation such as the rutting. In Pakistan, permanent deformation or rutting is a failure that usually happens on flexible pavement. Rutting exists when the interlocking between aggregate and bitumen not really strong and happen in the form of longitudinal depression in wheel path. Another possible factor that causes rutting is improper mix design like the excessive asphalt content and an insufficient amount of aggregate particles in mixtures. The presence of rutting could reduce the serviceability life of the flexible HMA pavement and lead to certain safety risks as well. Furthermore, rut can lead to car accidents because it tends to pull a vehicle towards the rutted track as it is steered across the rut and it is also may cause the hydroplaning of the vehicle during rainy day as water filled up the rut.

As road consumer, this study is significant in the sense of obtaining good quality of pavement which provided long term road serviceability. It is necessary to provide pavement which has good characteristics in term of durability, strength, moisture content and air void that can resist the formation of surface deformation. There are two principle solutions to construct a more durable pavement; first by applying a thicker asphalt pavement which will increases the construction cost and secondly making an asphalt mixture with modified characteristics (Moghaddam, 2011). There are several actions can be done in improving the HMA mixtures. One of action is using additives such as polymer modified binder in hot mix asphalt to increase durability of pavement structures because additives have abilities to captivate amount of distress imposed by a continuous heavy traffic load.

The aim of this study is to evaluate the rutting performance on the HMA mix design using Bakelite thus, to determine its effectiveness to be used in order to minimize the rutting resistance on HMA pavement. This study shows comparisons between two types of polymer modified binder on Hot Mix Asphalt by using Superpave Design Method and evaluation of rutting performance and dynamic modulus values on those mixes. The effects of main factors and their interactions on the dynamic modulus were analyzed using 2^3 full factorial design of experiment with the help of MINITAB-16 software. From the analysis of experimental results, we obtained the factors that have significant effect on the resilient modulus values as well as the significant interactions among the factors.

1.3 RESEARCH OBJECTIVES

The objectives proposed for this study are briefed as follows:

- To determine rutting susceptibility of HMA mixtures using Wheel Tracker.
- To determine the dynamic modulus values of mixtures using asphalt mixture performance tester.
- To determine the effectiveness of Bakelite on performance of asphaltic mixtures.
- To investigate individual and joint effect of factors on dynamic modulus.

1.4 SCOPE OF THE THESIS

To achieve the research objective described above, a comprehensive research plan was prepared and following research tasks were outlined:

- Literature review of the previous researches carried out on flexible pavement's permanent deformation evaluation.
- Laboratory characterization of material to be used in this research work, i.e. determination of various properties of aggregates and the asphalt binder.
- Preparation of specimens at optimum asphalt content using superpave gyratory compactor.
- Performing dynamic modulus test by Asphalt Mixture Performance Tester (AMPT) according to AASHTO TP-62-07 and wheel tracker test using Hamburg Wheel Tracking Device for measuring the rutting according to AASHTO T-324-04.
- The test matrix for dynamic modulus test and wheel tracker test is given below in table 1.1 and 1.2 respectively.

Table 1.1: Test Matrix for Dynamic Modulus and Wheel Tracker Test

Gradation	Mix	Binder Type	Wheel Tracker Test	Dynamic Modulus Test	Total Specimens
NHA class A	Wearing Course	ARL 60/70	3	3	6
		Modified ARL 60/70	3	3	6
NHA class B	Wearing Course	ARL 60/70	3	3	6
		Modified ARL 60/70	3	3	6
Total Specimens			**12**	**12**	**24**

1.5 ORGANIZATION OF THESIS

This research is organized in five chapters; brief description of each is as follows:

- Chapter 1 includes a brief but comprehensive introduction to the influence of premature failure of flexible pavements on its performance, the objectives and scope of the study.
- Chapter 2 describes the literature review on the flexible pavements, their distresses, review of the findings of previous researches related to evaluation of flexible pavements premature failure, i.e. rutting.
- Chapter 3 explains the research methodology used to achieve the objectives of this study. It explains in detail the source, specifications of materials and procedure used for determining the volumetric parameters of HMA mixes. This chapter also explains in detail the about the Hamburg Wheel Tracking (HWT) device and Superpave Performance Tester (SPT) and their test procedures.
- Chapter 4 presents the details of test results obtained by conducting rutting propensity test using wheel tracker, dynamic modulus test using Simple performance tester and the analysis performed.
- Chapter 5 includes the conclusions and recommendations for future work. Conclusions and recommendations are drawn from the research findings.

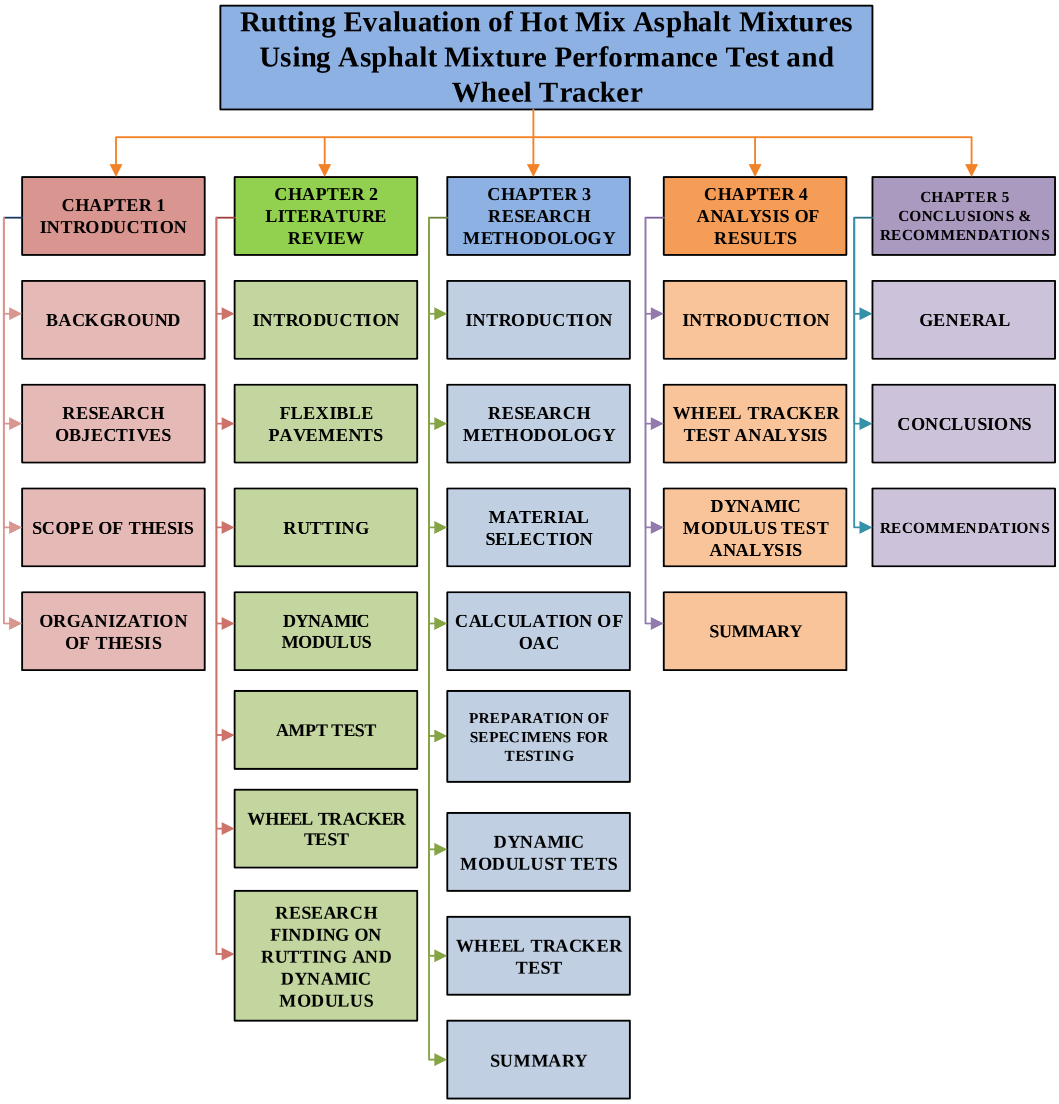


Figure 1.1: Organization of Research Thesis

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter includes a brief and appropriate review of the literature and theory related to the response of hot mix asphalt mixes (HMA) to the Hamburg wheel tracker tests (for Rutting) and Dynamic Modulus tests. This chapter deals with hot mix asphalt rutting, types of rutting and researches carried out previously to predict HMA rutting using wheel tracker test and Dynamic modulus tests. The detail of Hamburg Wheel tracker and Dynamic Modulus tests on HMA mixtures is also explained.

2.2 HOT-MIX ASPHALT (HMA) PAVEMENTS

A true HMA pavement (flexible pavement) yields “elastically” to traffic loading. Flexible pavements are constructed with an asphalt treated surface or a relatively thin surface of Hot-Mix Asphalt (HMA) over one or more unbound base courses resting on a compacted or stabilized subgrade. The strength of HMA pavements is obtained from the characteristics of load distribution of a layered system that is designed to eventually protect each underlying layer and yet including the subgrade from compressive shear failure. The flexible pavements structures should be designed in such a way that it has a successful performance and serve many functions including load carrying capacity, skid resistance, riding comfort, safety, surface and subsurface drainage throughout its design life.

Application of traffic loading on the top of pavement layer stimulates different kind of stresses in all the layers. These stresses decrease from top layer toward bottom. Therefore, for an economical design of pavements, material of good quality and higher strength is always placed on the top of the pavement structure to carry the stresses of high magnitude while the material of low strength and inferior quality is always placed at the bottom, due to which the stress or load distributions gets wider and eventually the stress magnitude becomes low. A typical flexible pavement structure normally consists of the following layers;

- Surface course or wearing surface
- Base course
- Sub base course
- Compacted or treated Subgrade / Natural Subgrade

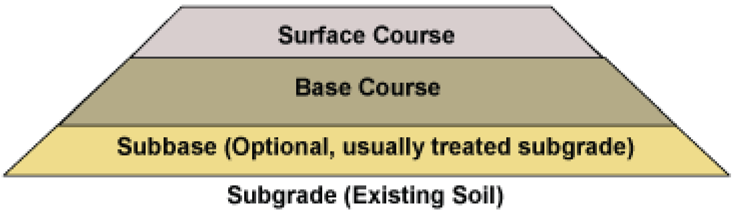


Figure 2.1: Pavement Structural Layers

Figure 2.1 illustrates that the surface course is the top most layer of pavement structure. It should be sufficiently strong enough to resist the applied stresses on it, while providing a smooth riding surface. The dense graded bituminous mixture is general mix design for wearing surface. The layer below surface course is base course. It consists of crushed materials or the materials stabilized by asphalt, Portland cement or lime. The layer under the base course is the subbase course and it is composed of low quality, inexpensive material because, of its low quality and its porosity, it acts like a filter for drainage between subgrade and base course. The subgrade is on site prepared soil and it is normally compacted to the optimum moisture content.

2.3 HMA RUTTING PROPENSITY

Rutting is one of the primary distress in flexible pavement that reduces the performance of pavements. It can be defined as, "the load induced permanent deformation of a flexible pavement that can be attributed to excessive consolidation caused by repeated heavy loads or lateral movement of the pavement material due to shear failure of asphalt concrete layer under the effects of high temperature and loading or both".

The Distress Identification Manual for the Long-Term Pavement Performance Project defines rut as "a longitudinal surface depression in the wheel path [that] may have associated transverse displacement" (FHWA, 2003). Some amount of permanent deformation occurs in merely all flexible pavements. Rutting can be identified visually by a continuous depression parallel to the traffic direction in wheel path. It is usually observed in the outer most lanes which are solely occupied by heavy traffic.

t2.3.1 CLASSIFICATION OF RUTTING

Rutting can be classified into three types. These types are defined by the cause and layers in which rutting occurs, and it can be characterized by two components of the original (initial) pavement profile change which are direct consequences of permanent deformation: uplift and downward deformation as shown in figure2.2 (Kandhal, 2003).

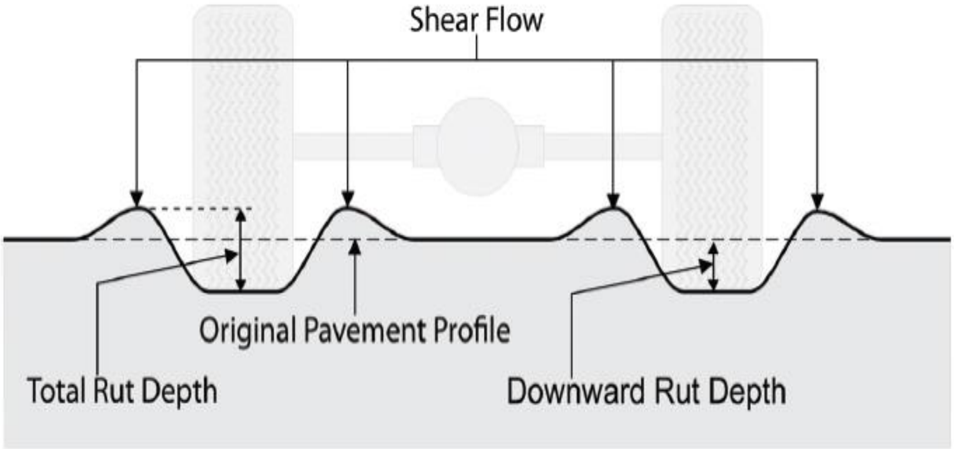


Figure 2.2: Characterization of Downward and Total Rutting (Williams, 2013)

2.3.1.1 Structural rutting

If rutting occurs in the layers under the surface layer, it is known as structural rutting (consolidation rutting or compaction). Its main cause is weak underlying layers because of which pavement structure settles as a whole. The surface layer itself does not fail but surface depression or deflection is observed due to lack of load carrying capacity of underlying layers.

Structural rutting can be easily differentiated from other types of rutting by visual observation of pavement surface. In structural rutting, rut basins have greater depth and no hump is formed due to overflowed material on the sides of rut basin.

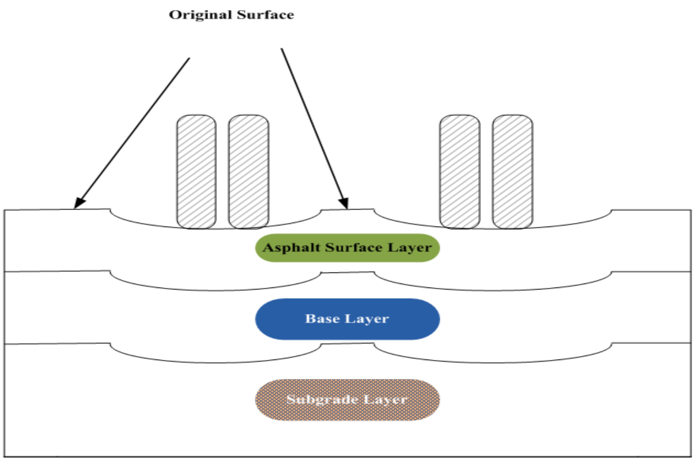


Figure 2.3: Structural Rutting in Flexible Pavements (Hussain, 2012)

The shape of surface clearly indicates that which layer below HMA Layer has failed. In case of subgrade failure, no hump is formed and wide rut basin is observed but in case of base failure, a small hump in centre is observed. Problems in the material design, uncontrolled loading conditions, poor surface or sub-surface drainage are commonly the main cause of structural rutting. (Miljkovic, 2011)

2.3.1.2 Instability rutting

Instability rutting also known as shear deformation or plastic flow is one of common type of rutting observed in flexible pavements. It is known as instability rutting because it occurs due to failure of HMA layer instead of failure of complete structure. Epps [1990] concluded that if the rigidity of base/ subbase and subgrade layers is sufficient instability rutting could occur. Because in such condition, the governing factor is shear deformation. This type of rutting can be identified visually by formation of humps along with rut basin as shown in figure 2.4 below.

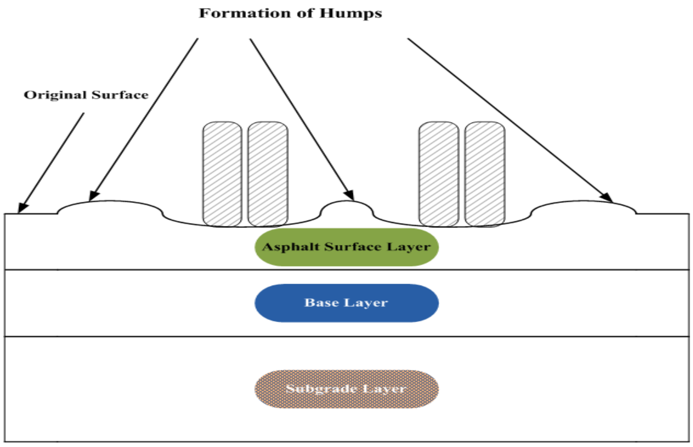


Figure 2.4: Instability Rutting in Flexible Pavements (Hussain, 2012)

It is an important observation that this type of rutting is commonly observed at intersections, horizontal curves etc. The reason behind above fact is that when vehicle slows down loading time increases, which is one of the major factors responsible for causing rutting. Pavement temperature is also an important factor, which causes this type of permanent deformation. It has been observed that in summer season pavement temperature increases due to which the stiffness asphalt layer is reduced thus, the pavement becomes more prone to instability rutting. The use of rounded aggregates instead of angular ones in hot mix asphalt reduces its shear resistance and may cause instability rutting. Use of excessive quantity of binder and presence of insufficient air voids in HMA can also cause this type of rutting (Miljkovic, 2011).

2.3.1.3 Wear rutting

The consolidation in the wheel paths of the HMA layer due to insufficient compaction effort is known as Wear rutting. Due to insufficient compaction the desired density is not achieved so, the HMA layer continues to compact or settle under the traffic loading. This type of rutting rarely occurs as shown in figure 2.5 below.

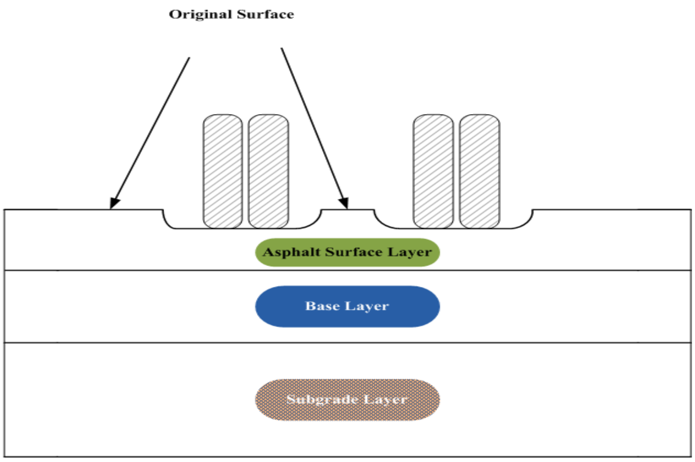


Figure 2.5: Wear Rutting in Flexible Pavements (Hussain, 2012)

One of the various causes of wear rutting is the lack of compaction effort applied at surface layer. Cooling or hardening of HMA before achieving required density is also an important factor. It is especially significant in winter season. Similarly, problems with mix gradations, lack of asphalt content, and presence of moisture in asphalt may cause surface/wear rutting (Miljkovic, 2011).

2.3.2 DESIGN FACTORS CONTRIBUTING TO HMA RUTTING

It is essential to note that quality of material used in pavement layers should be well designed because if, the material properties are not properly designed, it is impossible to reduce rutting susceptibility no matter how much layer thickness is provided or how much quality controlled construction is carried out. It can be derived from the above statement that proper structural design of pavement layers, the material properties of individual layers and construction quality control are equally important for a good and satisfactory performance of flexible pavements.

Permanent deformation in flexible pavements generally depends on several factors such as hot mix asphalt properties, which further include gradation and types of aggregates, type of binder and its properties and finally the extent of applied compaction effort. Factors related to loading pattern includes vehicle types, tire types and pressure, vehicle speeds and axle load. Similarly, environmental factors such as climatic conditions and pavement temperature also affect the type and intensity of rutting. Likewise, layer thicknesses, material properties of base and subbase layers and bearing capacity of subgrade also play a vital role.

2.3.3 NEGATIVE EFFECTS OF RUTTING

Various reasons enforce the distress rutting to be considered as a phenomenon not desired in flexible pavements. It has numerous disadvantages, which affect the road users as well as highway agencies. Some of these are discussed below;

- Rutting is a major contributing factor in causing hydroplaning because, water accumulates in rut depressions. This accumulation of water can be dangerous in rainy season, as it reduces the skid resistance when brakes are applied.
- Rutting is responsible for causing functional failure of pavements by reducing the driver comfort. Driver comfort is reduced because rut depressions are not uniform throughout the length of road. This non-uniformity in rut depressions is a major cause of driver discomfort.
- Rutting in flexible pavements is also responsible for the increase in vehicle operating costs. As when a tire operates in a rutted section, there is more wear and tear of tire. Secondly contact area of tire with the pavement increases, thus tire friction increases and as a result fuel consumption increases. There is increase in the fuel expenditure because vehicle has to do extra effort to overcome additional frictional resistance due to rutted surface.
- Rutting also encourages the water to accumulate in the subgrade layer instead of draining out. Due to which the base or subgrade layer becomes weak and their load carrying capacity is reduced. The weakening of these base layer increases stress concentration on top surface layers because of all this phenomenon early deterioration of pavement occurs.
- Rutting also causes safety concerns when vehicles travelling at high speed maneuver from one lane to the other. This observation is supported by the fact that accident rate increases as the rut of pavement increases (Miljkovic, 2011).

2.3.4 RUT DEPTH

Rut depth is a measure of functional discomfort imparted by rutting to the road user. According to general point of view, it seems that rut depth can be measured conveniently. The rut depth is defined as the maximum distance perpendicular to the wire line constructed by joining the high points of the transverse profile of a rutted flexible pavement (Agardh, 2005).

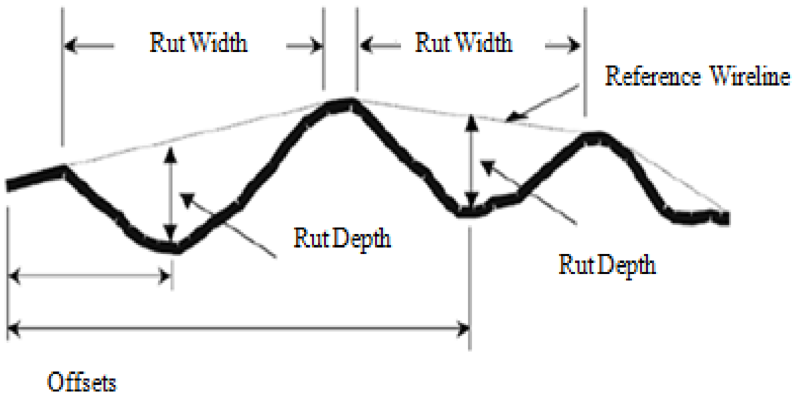


Figure 2.6: Definition of Rut Depth (Elkins, 2003)

2.4 SUPERPAVE MIX DESIGN

One of the principal results from the Strategic Highway Research Program (SHRP) was the Superpave mix design method. The Superpave mix design method was designed to replace the Haveem and Marshall methods. The volumetric analysis common to the Haveem and Marshall methods provides the basis for the Superpave mix design method. The Superpave system ties asphalt binder and aggregate selection into the mix design process, and considers traffic and climate as well. The compaction devices from the Haveem and Marshall procedures have been replaced by a gyratory compactor and the compaction effort in mix design is tied to expected traffic.

2.4.1 SUPERPAVE HISTORY

Under the Strategic Highway Research Program (SHRP), an initiative was undertaken to improve materials selection and mixture design by developing:

- A new mix design method that accounts for traffic loading and environmental conditions.
- A new method of asphalt binder evaluation.
- New methods of mixture analysis.

When SHRP was completed in 1993 it introduced these three developments and called them the Superior Performing Asphalt Pavement System (Superpave). Although the new methods of mixture performance testing have not yet been established, the mix design method is well-established (Asphalt institute Sp-2, 2001).

2.4.2 SUPERPAVE MIX DESIGN PROCEDURE

The Superpave mix design method consists of 4 steps:

- Selection of materials.
- Selection of design aggregate structure.
- Selection of design asphalt binder content.
- Evaluation of moisture susceptibility.

2.4.2.1 Selection of materials

This step is accomplished by first selecting a Performance Grade asphalt binder for the project climate and traffic conditions. Superpave binders are designated with a high and low temperature grade, such as PG 64-22. For this binder, "64" is the high temperature grade and is the 7-day maximum pavement design temperature in degrees centigrade for the project. The low temperature grade, "-22," is the minimum pavement design temperature in degrees centigrade. Both high and low temperature grades are established in 6-degree increments. Thus, the binder grade is an indication of the project-specific temperature extremes for which the asphalt mixture is being designed.

In addition to climate, traffic speed and traffic level may also influence Superpave binder selection. A project with slow moving or stationary traffic would require a binder with one or two higher temperature grades than would otherwise be selected on the basis of climate alone. Projects with very high traffic levels in excess of 30 million 80 KN equivalent single axle loads would also require an increase in high temperature binder grade.

Five asphalt mixture types are specified in Superpave according to nominal maximum aggregate size: 9.5 mm, 12.5 mm, 19 mm, 25 mm, and 37.5 mm. To specify mineral aggregate, Superpave uses two approaches. First, it places restrictions on aggregate gradation by means of broad control points and a restricted zone. Second, it places consensus requirements on coarse and fine aggregate angularity, flat and elongated particles, and clay content (Asphalt institute Sp-2, 2001).

2.4.2.2 Selection of design aggregate structure

Once binder and aggregate materials have been selected, various combinations of these materials are evaluated using the Superpave gyratory compactor. Three, and sometimes more, trial blends are evaluated. Once the trial blends are established, a trial asphalt binder content is selected for each blend. The trial asphalt binder content is selected using an estimation procedure contained in Superpave or on the basis of the designer's experience.

Two specimens of each trial blend are batched and compacted in the Superpave gyratory compactor. In addition, two loose specimens of each trial blend are produced and used to measure maximum theoretical specific gravity. The volumetric and densification characteristics of the trial blends are analyzed and compared with Superpave mix design criteria. Any trial blend that meets these criteria can be selected as the design aggregate structure (Asphalt institute Sp-2, 2001).

2.4.2.3 Selection of design asphalt binder content

The next step involves selection of the design asphalt binder content for the design aggregate structure. This step is necessary to verify the approximate binder content used in the preceding step. The Superpave gyratory compactor is used to fabricate test specimens composed of the selected design aggregate structure, but at four different asphalt contents. The asphalt content that results in 4 percent air voids at the design number of gyrations is the design asphalt binder content. The design aggregate structure containing the design asphalt binder content becomes the design asphalt mixture (Asphalt institute Sp-2, 2001).

2.4.2.4 Evaluation of moisture susceptibility

This final step requires that the design asphalt mixture be evaluated using a test procedure called, AASHTO T283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage." This test method was already in wide use prior to the development of Superpave. Six test specimens are fabricated using the Superpave gyratory compactor. Three of the six are moisture conditioned. The remaining three specimens remain unconditioned. All of the test specimens are evaluated for their indirect tensile strength. The ratio of conditioned to unconditioned tensile strength is called tensile strength ratio or TSR. The design asphalt mixture is judged to be non-moisture susceptible if it has a TSR greater than 80 percent (Asphalt institute Sp-2, 2001).

2.4.3 SUPERPAVE VOLUMETRICS

Volumetric analysis of the compacted paving mix gives an idea of the probable durability and service performance can be determined. Information about ingredients of asphalt mixture must be known before any calculation of weight and volume. This information includes the specific gravity of the asphalt, bulk specific gravity of aggregates, ratio of each ingredient of the mixture, air voids (Va), void in mineral aggregates (VMA), voids filled with asphalt (VFA), Gmb and Gmm. The important properties generally considered for volumetric analysis are as follows: (Asphalt institute Sp-2, 2001)

2.4.3.1 Bulk specific gravity of aggregates (G_{sb})

"It is the ratio of the mass in air of a unit volume of a permeable material (including both permeable and impermeable voids normal to material) at a standard temperature to the mass in air of equal density of an equal volume of gas-free distilled water at stated temperature". When the total mass of aggregate consists of separate fractions of coarse aggregate, fine aggregate and mineral filler, all having different measured specific gravities, equation 2.1 is used to calculate the bulk specific gravity for total aggregate.

$$G_{sb} = \frac{P1+P2+P3+\cdots+Pn}{\frac{P1}{G1}+\frac{P2}{G2}+\cdots+\frac{Pn}{Gn}} \qquad (2.1)$$

Where,

G_{sb} = Bulk specific gravity for total aggregate

P_1, P_2, P_n = Individual percentages by mass of aggregate

G_1, G_2, G_n = Individual bulk specific gravity (coarse, fine) of the aggregate

2.4.3.2 Effective specific gravity of aggregates (G_{se})

"It is the ratio of the mass in air of a unit volume of a permeable material (excluding voids permeable to asphalt) at a standard temperature to the mass in air of equal density of an equal volume of gas-free distilled water at stated temperature". When based on the maximum specific gravity of a paving mixture, G_{mm}, the effective specific gravity of the aggregate, G_{se}, includes all void spaces in the aggregate particles except those that absorb asphalt. Equation 2.2 shows the formula used for calculating G_{se}.

$$G_{se} = \frac{Pmm - Pn}{\frac{Pmm}{Gmm}+\frac{Pb}{Gb}} \qquad (2.2)$$

Where,

G_{se} = Effective specific gravity of aggregate

G_{mm} = Maximum specific gravity of paving mixture

P_{mm} = Percent by mass of total loose mixture (100)

P_b = Asphalt content, percent by mass of total loose mixture

G_b = Specific gravity of asphalt

2.4.3.3 Maximum specific gravity of mix (G_{mm})

"It is the ratio of weight in air of a unit volume of an uncompacted bituminous mixture at a stated temperature to the weight of equal volume of gas-free distilled water at a stated temperature". This test procedure was developed by James Rice, afterwards it is referred as "Rice Specific Gravity". The air voids percentage for each asphalt contents is calculated from Gmm which is necessary to calculate at every asphalt contents in the design of bituminous paving mix. The standard method used for the determination of Gmm is ASTM D 2041 and the following equation 2.3 is used for its calculation:

$$G_{mm} = \frac{Pmm}{\frac{Ps}{Gs}+\frac{Pb}{Gb}} \quad (2.3)$$

Where,

Gmm = maximum specific gravity of bituminous paving mixture

Pmm = total loose mixture

Ps = percent aggregate by total weight of the mixture

Pb = Percent asphalt by total weight of the mixture

Gse = effective specific gravity of the aggregate

Gb = specific gravity of asphalt

2.4.3.4 Bulk specific gravity of the mixture (G_{mb})

"The bulk specific gravity is defined as the ratio of the weight in air of a unit volume of a compacted mixture of HMA at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature". The standard ASTM D2726 is used to determine Gmb of asphalt concrete and the following equation 2.4 is used for its calculation:

$$Gmb = \frac{Wd}{Wssd - Wsub} \quad (2.4)$$

Where,

Gmb = bulk specific gravity of mixture

Wd = dry weight, grams

Wssd = saturated surface dry weight, grams

Wsub = saturated surface dry weight submerged in water, grams

2.4.3.5 Voids in mineral aggregates (VMA)

"The amount of intergranular voids between the aggregate particles in a compacted paving mixture is defined as voids in mineral aggregates that include the effective bitumen content and the air voids, stated as the percent of total volume of the mix". VMA calculated based on the bulk specific gravity of the aggregate and is expressed as percentage of the bulk volume of compacted paving mixture. Thus, VMA can be calculated by subtracting the volume of aggregate determined by its bulk specific gravity from the bulk volume of the compacted paving mixture. Method of calculation illustrated as equation 2.5.

$$VMA = 100 - \frac{Gmb * Ps}{Gsb} \tag{2.5}$$

Where,

VMA = voids in mineral aggregate, percent of bulk volume

Gmb = bulk specific gravity of the mixture

Ps = aggregate content percent by total weight of the mixture

Gsb = bulk specific gravity of the total aggregate

2.4.3.6 Percent air voids (V_a)

The air voids in compacted paving mixture consist of the small air spaces between the coated aggregate particles. The following equation 2.6 can be used for the determination of percent air voids in a compacted paving mix:

$$V_a = 100 * \frac{Gmm - Gmb}{Gmm} \tag{2.6}$$

Where,

V_a = air voids in compacted mixture, percent of the total volume

Gmm = maximum specific gravity of the mixture

Gmb = bulk specific gravity of the mixture

2.4.3.7 Voids filled with asphalt (VFA)

"The voids filled with asphalt, is the percentage of the intergranular void spaces between the aggregate particles (VMA) that are filled with asphalt". Absorbed asphalt is not the part of VFA, it is calculated using the following equation 2.7.

$$VFA = \frac{100\ (VMV - Va)}{VMA} \tag{2.7}$$

Where,

VFA = Voids filled with asphalt, percent of VMA

VMA = Voids in mineral aggregate, percent of bulk volume

V_a = Air voids in compacted mixture, percent of total volume.

2.4.3.8 Asphalt absorption

Absorption is expressed as a percentage by mass of aggregate rather than as a percentage by total mass of mixture. Equation 2.8 is used to determine the asphalt absorption, P_{ba}.

$$P_{ba} = 100 \; x \; \frac{Gse - Gsb}{Gsb \; x \; Gse} \; x \; Gb \quad (2.8)$$

Where,

P_{ba} = Absorbed asphalt, percent by mass of aggregate

G_{se} = Effective specific gravity of aggregate

G_{sb} = Bulk specific gravity of aggregate

G_{b} = Specific gravity of asphalt

2.5 POLYMER MODIFIED ASPHALT

Polymer modified Asphalt is asphalt which has undergone modification by addition of modified binder such as elvaloy, latex, sasobit, sbs and polyacrylates into the mix. The advantages of using polymer modified asphalt are it has better performance in durability, resistance and strength. Besides the physical properties of the asphalt when added modified binder does not change the chemical nature of the asphalt. Research done also stated that modified asphalt binders make the texture of the mixture become soft and smooth at lower temperature which resulting in reduction of thermal cracking. In addition to fatigue resistance of the asphalt mixes is being improved with the polymer modified asphalt usage and since the fatigue resistance of asphalt improves the pavement can resist more traffic load and extreme climate temperature changes. (Bahia, 2001)

2.5.1 TYPE OF ASPHALT MODIFIERS

Asphalt modifiers can be categorized in several ways which depends on the mechanism where the modifier alters the asphalt properties, on the composition and physical nature of the modifier itself, or on the properties of the target asphalt that needs improvement or enhancement. A list of the types of modifiers commonly used in the asphalt industry is given in Table 2.1. The modifiers are classified based on the nature of the modifier and the generic types of asphalt modifiers (National Cooperative Highway Research Program, 2001). The target distress shown in the table corresponds to the main distress the additive is expected, or claimed, to reduce. The information is based on an interpretation of the published information for brands of modifiers that belong to the modifier classes shown. The information in Table 2.1 indicates that asphalt modifiers vary in many respects. They can be particulate matter or additives that will disperse completely or dissolve in the asphalt. They range from organic to inorganic materials, some of which react with the asphalt, while others are added as inert fillers. The modifiers generically vary in their specific gravity as well as other physical characteristics. They are expected to react differently to environmental conditions such as oxidation and moisture effects. (Bahia, 2001)

Table 2.1: General Types of Asphalt Modifiers used for Paving Applications (Bahia, 2001)

Modifier Type	Class	Effects on Distress				
		[a]PD	[b]FC	[c]LTC	[d]MD	[e]OA
Fillers	Carbon black	x				x
	Mineral: Hydrated lime	x				x
	Fly ash	x				
	Portland Cement	x				
	Bag house fines	x				
Extenders	Sulphur	x	x	x		
	Wood lignin				x	
Polymers-Elastomers	Styrene butadiene di-block SB	x		x	x	
	Styrene butadiene triblock/ radial block (SBS)	x	x	x		
	Styrene isoprene (SIS)	x				
	Styrene ethyl butylene (SEBS)					
	Styrene butadiene rubber latex SBR	x		x		
	Polychloroprene latex	x	x			
	Natural rubber	x				
	Acrylorite butadiene styrene (ABS)	x				
Polymers-Plastomers	Ethylene vinyl acetate (EVA)	x	x			
	Ethylene propylene diene monomer (EDPM)	x				
	Ethylene acrylate (EA)	x				
	Polyisobutylene	x				
	Polyethylene (low density and high density)	x		x		
	Polypropylene	x				
Crumb rubber	Different sizes, treatment and process	x	x	x		

Oxidants	Manganese compounds	x				
Hydrocarbons	Aromatics			x		
	Naphthenic					
	Paraffinic/ wax			x		
	Vacuum gas oil			x		
	Asphaltenes: ROSE process resins	x				
	SDA asphalteners	x				
	Shale oil				x	x
	Tall oil					
Antistrips	Polyamides				x	
	Hydrated lime				x	
	Organometallics				x	
Fiber	Polypropylene	x	x	x		
	Polyester	x		x		
	Fiberglass					
	Steel	x	x	x		
	Reinforcement	x	x	x		
Antioxidants	Carbon black	x				x
	Calcium Salts					x
	Hydrated lime				x	x
	Phenols					x
	Amines				x	x
a = Permanent Deformation						
b = Fatigue Cracking						
c = Low Temperature Cracking						
d = Moisture Damage						
e = Oxidative Aging						

2.6 BAKELITE

Bakelite (poly-oxy-benzyl-methylene-glycol-anhydride) is an old plastic. Bakelite is a thermosetting resin of phenol formaldehyde. It is produced as a result of an elimination reaction between phenol and formaldehyde. Bakelite was developed by chemist Leo

Baekeland in New York in 1907. Bakelite due to its non-conductivity and heat resistant characteristics i.e. thermosetting property, it is widely used in manufacturing cases of electrical appliances such as radio, irons, switches etc. The chemical formula of bakelite can be expressed with the help of figure 2.7 respectively.

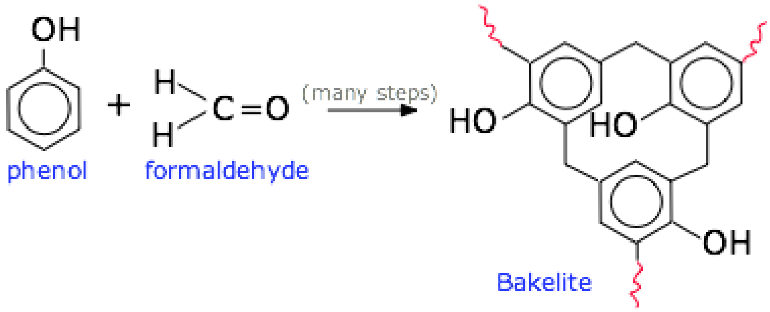


Figure 2.7: Chemical formula of Bakelite

It is thermosetting in nature due to which bakelite cannot be remolded under heat once it attains a particular shape. It is also widely used in automobile industries because of its remarkably high resistance, to electricity, heat and to chemical action. It is also used for insulating the wires and brake pads. It is available in different colors and in powder form. In Pakistan, it is also used in plastic industry for making different products of plastics such as toys, handles of kitchenware, jewelry etc. Figure 2.9 shows the bakelite in powder form, which was used in this research work. In early 70's bakelite was reported to be used in asphalt pavements but after that its use in flexible pavements has never been reported.

Figure 2.8: Bakelite in Powdered form

2.7 DYNAMIC MODULUS

"The complex modulus is defined as the complex number that relates stress and strain for a linear viscoelastic material subjected to sinusoidal loading, the absolute value of complex modulus is commonly called as dynamic modulus". The two properties determined from complex modulus testing are dynamic modulus (E*), and phase angle (Ø).

The dynamic modulus is a main input parameter for mechanistic empirical pavement design guide (MEPDG) of hot mix asphalt (HMA) due to which this property has gained more attention recently. Dynamic modulus can be determined by temperature and loading rate-dependent actions of Hot mix asphalt in MEPDG. In dynamic modulus test deformation are measured by application of sinusoidal loads. The ratio of stress to the strain amplitude is termed as dynamic modulus. Equation 2.1 is cast off for calculating dynamic modulus.

$$|E^*| = \frac{\sigma_\circ}{\epsilon_\circ} \qquad (2.1)$$

Where,

$|E^*|$ = Dynamic modulus in psi

$\sigma_\circ$ = Peak-to-peak stress amplitude in psi

$\epsilon_\circ$ = Peak to peak strain amplitude in inches/inch.

The phase angle is determined from equation 2.2

$$\varnothing = 2\pi f \Delta t \qquad (2.2)$$

Where,

$\varnothing$ = Phase angle in radians

f = Frequency in Hz

Δt = Time lag between stress & strain in seconds

Dynamic modulus and phase angle of hot mix asphalt depends on loading frequency and temperature. In laboratory, three test methods are used to determine the dynamic modulus of asphalt concrete. Two test methods among these are designed to test the cylindrical specimens in axial compression. These methods are Simple Performance tester (SPT) and AASHTO TP-62. Identical specimens are use in these test protocols; however, the analysis method and testing conditions are slightly different. The dynamic modulus from third method is determined by IDT test specimen that is more relevant to field cores rather than laboratory compacted specimens.

2.8 HAMBURG WHEEL TRACKER DEVICE

Different laboratory test methods are being utilized to predict the rutting in flexible pavements. One of the method currently in common practice is wheel tracking. Wheel tracking device estimates the permanent deformation in flexible pavements by subjecting the specimens to repeated loading under a moving wheel. The first wheel-tracking device was developed in the city of Hamburg, Germany in 1970s. Helmut-wind incorporated, of Hamburg developed the test method and specifications to estimate the rutting and stripping susceptibility.

The device used in this study was wheel tracker manufactured by Precision Machine Welding (PMW). It consists of only one wheel, which is recognized as left wheel in the software. Wheel tracker is an electrically powered device, which is capable of moving a 203.2mm diameter, 47-mm wide steel wheel over a test specimen. The load on the steel wheel is 158±1.0 lb. and the average contact stress produced by the contact of wheel is approximately 0.73 MPa with a contact area around 970 mm^2. The contact pressure induced by the steel wheel produces the same effect as produced by the rear tire of a double-axle truck. With increase in rut depth the contact area increase as result of which the contact stress becomes variable. The steel wheel moves over the specimen in forward and backward direction. The steel wheel should complete approximately 50 passes over the specimen per minute. Its maximum speed is approximately 1 ft. /sec, which is reached at the midpoint of the specimen. Using this device rutting test can be performed on Air, Wet and Dry modes. These modes can be used by adjusting the device at desired test conditions (AASHTO T 324-04, 2007).

Figure 2.9: PMW Wheel Tracking Device

2.8.1 PARTS OF WHEEL-TRACKING MACHINE

- ***Temperature Control System:*** it consists of a water bath, which can control the temperatures over a range of 25 to 70°C.
- ***Impression Measuring System (LVDT):*** LVDT stands for Linear Variable Displacement Transformers. It is used for measuring the depth of wheel impression within 0.01mm (0.0004in.) over a minimum range of 0 to 20 mm (0.8 in.). For counting the wheel passes, a counter is also attached. It is a non-conducting solenoid, which counts each wheel pass over the specimen. Signals

from this counter are coupled to the wheel impression measurement, due to which rut depth is expressed as a function of the wheel passes.

- ***Specimen Mounting System:*** This system contains a stainless steel tray, which is mounted rigidly to the machine. It restricts shifting of the specimen to within 0.5 mm (0.02in.) during testing, (AASHTO T 324-04, 2007).

2.9 ASPHALT MIXTURE PERFORMANCE TESTER (AMPT)

Superpave mix design and analysis method has been developed for more than a decade ago under Strategic Highways Research Program (SHRP) to accurately predict in situ performance of the HMA. Bonaquist et al. has recommended three candidates of performance tests in NCHRP Report 513 that are Dynamic Modulus, Flow Number and Flow Time tests for Superpave mix design procedure to predict the performance of HMA mixtures designed. The dynamic modulus test is being used to predict in situ performance of HMA mixes against rutting. Dynamic Modulus tests can be performed with IPC Global Servo Pac SPT device as shown in figure 2.11 below.

Figure 2.10: Asphalt Mixture Performance Tester (AMPT)

It consists of an environmental chamber, a tri-axial cell, a pump, a hydraulic actuator a refrigeration and heating unit with heat exchanger and a data acquisition system. The environmental chamber is capable of controlling temperature ranging from -4 to 60˚C and confining pressure unit is capable of providing pressure up to 210 kPa. The specimen is left to equilibrate for required test temperature in environmental chamber. After accomplishing desired temperature, tuning is done which yields initial modulus value which is to be input before running test. The UTS 6 software of SPT is used to run the test which automatically measure and record the test data. (AASHTO TP 62-07, 2007)

2.10 RESEARCH FINDINGS

2.10.1 RESEARCH FINDINGS ON HMA RUTTING

Reddy et al. (2013) has evaluated the rutting resistance of waste tire rubber modified flexible pavement surface test sections with laboratory wheel tracking test and an accelerated pavement rut tester (MAPRT). The objective of this research was to highlight the improvement in performance of the conventional bitumen surfaces with respect to rut resistance with addition of waste tire rubber using both laboratory wheel tracking test and field testing with medium scale accelerate pavement rut tester. Test track with waste tire rubber modified surface course on a clay subgrade along with conventional materials was considered for testing. The results were encouraging indicating a 35% improvement in rut resistance in case of waste tire rubber modified surfaces.

Ahmed et al. (2013) has studied the impact of aggregate gradation and type on hot mix asphalt rutting in Egypt. The main objectives of this research were to evaluate the impact of aggregate gradation and type on hot mix asphalt (HMA) rutting potential in Egypt, understand the effect of aggregate properties on Marshall mix properties and evaluate the relation between mix properties and rutting potential of HMA. Samples prepared at optimum asphalt content, as defined by Marshall method, were tested using wheel track test and permanent deformation was measured. Study results showed that rutting resistance of asphalt paving mixes is affected by the mix gradation and type of aggregate. Coarser gradation had the highest resistance to rutting for all types of aggregate, while open graded mixes had the lowest resistance. Dolomite had the highest resistance for all types of gradations. Marshall flow had the highest linear correlation with rutting, with coefficient of determination (R^2) of 0.74.

Al-Khateeb et al. (2013) has carried out a rutting performance - based comparison between limestone and basalt superpave mixes. The specific objective of this study was to compare basalt and limestone mixtures in terms of rutting performance. Dynamic creep rutting test was performed on basalt and limestone mixtures prepared using PG 64-10 binder. Rutting performance of both mixtures was evaluated at one loading frequency of 8Hz and four different temperatures i.e. 40, 50, 60 and 65˚C. This study concludes that basalt superpave asphalt mixtures showed higher resistance to rutting as compared to the limestone superpave asphalt mixtures. Also the difference in number of loading cycles to rutting failure between limestone and basalt asphalt mixtures was statistically significant at a level of $\alpha = 0.1\%$ for all temperatures.

Hafez et al. (2010) has determined the effect of Maximum Size of Aggregate on Rutting Potential of Stone Mastic Asphalt. This objective of study was limited to investigate higher temperature susceptibility to permanent deformation with influence of aggregate size used in stone mastic asphalt. The aggregate size includes 9.5, 12, 19 and 25.4 mm and wheel tracker test was carried out at 25, 40 and 60 ˚C. This study also proposes the regression model for rut depth. This study concluded that rutting is function of temperature and aggregate size. Rutting has direct relation with temperature and inverse with aggregate size.

Kim et al. (2009) has determined the performance of polymer modified asphalt mixture with reclaimed asphalt pavements (RAP). The objective of this study was to evaluate the rutting and cracking performance of SBS (Styrene-Butadiene-Styrene) polymer modified mixtures with addition of RAP materials. Asphalt pavement analyzer (APA) test, indirect tensile (IDT) test and multiple stress and creep recovery (MSCR) test were performed for laboratory evaluation. RAP mixtures with SBS polymer modified binder were fabricated using 0, 15, 25 and 35% of RAP materials. This study concluded that RAP mixtures with modified binders have shown good resistance to rutting irrespective of the amount of RAP materials in HMA.

Khan et al. (2008) has carried out a research study in Pakistan, which highlights the impact of SuperPave mix design method on rutting behavior of flexible pavements. The objective of this study was to compare the Superpave and Marshall Mix design method used in asphalt concrete designs. Moisture Sensitivity, Creep Performance and IDT tests were performed. The guidelines for implementation of Superpave mix design method in Pakistan have been proposed. This study concluded that rut depth has a direct relation with no of passes and temperature. Superpave mix showed better performance in terms of low accumulated strains (%) (Permanent deformation) as compared to Marshall and SMA mixes.

Weidong et al. (2006) has investigated the rutting resistance of multilayer asphalt wheel tracker test. The objective of this study was to evaluate the rutting resistance of multilayer asphalt overlay structures by means of multilayer specimens and to compare the rutting resistance of multilayer specimens with standard specimens of various layers. The experimental results indicated that test temperature and applied load have a significant effect on rutting resistance of asphalt concrete. Rutting in multilayer specimens has an indirect relation with temperature and applied loading.

Gardete et al. (2005) has done work on Wheel Tracking test, the Cyclic Compression Test (Uniaxial and Triaxial) and the Repetitive Shear at Constant Height (RSCH) test for determining permanent deformation in Portugal. They concluded that the use of tests like the Wheel tracking test or the Uniaxial Cyclic Compression test seem to be more interesting, as they are capable of characterizing the behavior of bituminous mixtures to permanent deformation and have simpler procedures and equipment. For the conditions used in this study the Wheel-Tracking Test and the Uniaxial Cyclic Compression test had better results in differentiating the mixtures and the classification was clearer. The deformation rate obtained in the Wheel-Tracking Test and the creep rate obtained in the Uniaxial Cyclic Compression test are suitable values to characterize bituminous mixtures to permanent deformation.

2.10.2 RESEARCH FINDINGS ON DYNAMIC MODULUS

Hafeez et al. (2012) investigated the performance of asphalt mixture predicted from the asphalt binder. The objective of this study was to characterize the rheological behavior of asphalt cement and investigate the influence of virgin binder and polymer on asphalt mixtures. Development of master curves and relationship of phase angle with parameters like complex modulus etc. Horizontal shift factors were also generated. This research concluded that load frequency and temperature is function of stiffness of both binder and mixes. The susceptible of Virgin asphalt cement is high as compared to polymer modified.

Hassan et al. (2011) has investigated the use of granulated copper slag as fine aggregate in hot mix asphalt mixtures. Marshall Mix design was performed at different blends of aggregates containing up to 40% copper slag. Dynamic modulus test was performed at different temperatures (25 to 60˚C) and different frequencies (0.1 to 16 Hz). |E*| master curves and shift factors were reported to be developed for control and slag mixes. The developed master curves were compared with Witczak predictive model. This study concludes that the use of copper slag as a fine aggregate substitute in asphalt concrete mix provides a viable alternative to disposal of material. Satisfactory mix results can be obtained using up to 10% copper slag.

Contreras et al. (2010) has determined the dynamic modulus of dense and porous asphalt mixtures manufacture with dolerite and limestone aggregates. The objective of this study was to determine the dynamic modulus using ultrasonic direct test and to compare with the standard dynamic modulus test results. Using ultrasonic transmission dynamic modulus was calculated at a frequency of 65 kHz and standard dynamic modulus test was conducted at 2, 5, 8 and 10 Hz frequency. This study concluded that for asphalt mixtures tested ultrasonically the increase in magnitude of dynamic modulus can be associated with an increase in the frequency used but it may be due to different testing method.

Hafeez et al. (2012) has carried out a research study in Pakistan to investigate the rutting potential of asphalt concretes using dynamic modulus and wheel tracker test. The objective of this study was to evaluate the rutting propensity of HMA mixtures using virgin and lime modified performance grades. Wheel tracker rut depth factor and dynamic modulus rutting factor are related to each other. This study concludes that polymer modified asphalt mixtures yielded in low rutting and high dynamic modulus values.

Kim et al. (2012) has evaluated the performance of Warm- and Hot-Mix Asphalt mixtures. The specific objective of this study was to evaluate the resistance to rutting, cracking and to determine viscoelastic properties of innovative wax-based LEADCAP WMA additive used in HMA mixtures mixed and compacted at low temperatures. Dynamic modulus test, indirect tensile strength test and indoor accelerated pavement test were performed to achieve the objective. This study concludes that LEADCAP additive is effective in producing and paving asphalt mixtures at approximately 30˚C lower temperature than a controlled HMA mixture.

Ahmad et al. (2011) has determined the rutting resistance of dense graded hot mix asphalt mixtures. The objective of this study was to evaluate the rutting susceptibility of dense graded asphalt mixtures. Wheel tracker test and dynamic modulus test were performed at 40, 45 and 50˚C and 5, 2, 1 and 0.5 Hz loading frequencies. A correlation was developed between rut stiffness factor from AMPT dynamic modulus test at 5Hz frequency and rut depth from wheel tracker at 40, 45 and 50˚C.

2.11 SUMMARY

This chapter discusses the flexible pavements and methods for design and analysis of flexible pavements. Then the focus is towards the distress mostly encountered on pavements of Pakistan that is rutting also known as permanent deformation. The types of rutting and its developing phenomenon are also discussed. Afterwards, related research findings, to this study, over a decade has been quoted about the Hamburg wheel tracking test and Dynamic Modulus tests is explained with all references.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter explains in detail the methodology used in this research work to achieve the objectives of this research work. Testing on laboratory prepared samples was conducted in three stages. In first stage, superpave mix design method was utilized to determine the volumetric properties of bituminous mixes. In the second stage, wheel tracker test was performed on gyratory compacted HMA mixes to determine their rutting resistance. In the third and final stage, dynamic modulus test was performed on gyratory compacted HMA mixes using AMPT.

For the first stage of testing two different aggregate gradations of wearing coarse and two binders i.e. virgin and modified, were used to determine the volumetric properties of laboratory prepared HMA specimens. The reason for selecting two different gradations and binders was to check the behavior of HMA mixes using Superpave mix design method against various properties. For performance evaluation of laboratory specimens compacted at 135 ^{o} C, rutting and dynamic modulus tests were carried out.

3.2 FRAMEWORK OF RESEARCH METHODOLOGY

The complete testing procedure adopted in this research work is described in figure 3.1. First material selection was done. Then the material characterization was done, in which different properties of aggregate and bitumen were determined in accordance with applicable standards. In the next step, aggregate gradations to be used were selected according to NHA (1998) specifications for wearing course. In the next step, mix volumetric properties were determined and samples were prepared for tests. After this step tests were conducted using Wheel tracker and AMPT to find rutting propensity and dynamic modulus. At last the test results were tabulated and statistical analysis was performed on the test results.

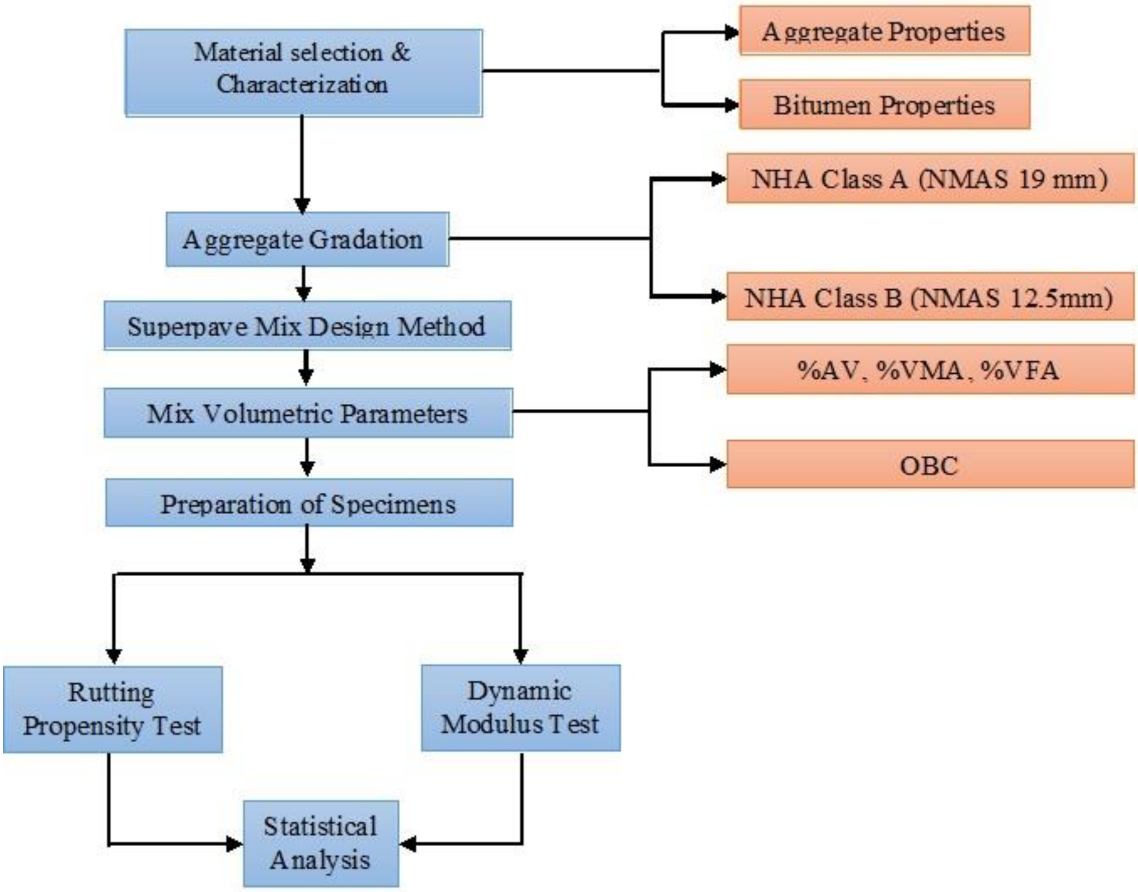


Figure 3.1: Procedure Adopted for Research Work

3.3 MATERIAL SELECTION

Selection of material to be used in this research work was the first task, which was successfully achieved. The source for aggregates (both coarse and fine) was the Margalla quarry. The source of bitumen was Attock Refinery Limited (ARL) and penetration grade 60/70 was selected to be used. The reason for selecting the penetration grade 60/70 is that it is the commonly used bitumen grade across Pakistan and is suitable for colder to moderate temperature regions.

3.3.1 LABORATORY CHARACTERIZATION OF MATERIAL

After selection of material, next task was to characterize the material according to reference specifications. Researchers have proven that aggregate structure provides greater resistance to permanent deformation in bituminous paving mixes. It has also been observed that aggregate gradation, shape and surface texture have a great influence on hot mix asphalt properties. The suitability of selected aggregates and bitumen for use in preparing bituminous paving mixes is necessary to be checked. Tests were conducted on bitumen and aggregate in accordance with ASTM and AASHTO standard specifications. The results of tests performed are shown in table 3.1 and 3.2 respectively.

Table 3.1: Physical Properties of Aggregates

Test Name	Designation	Recommended value (NHA Specs)	Result
Flakiness Index (FI)	BS 812	15 (maximum)	14.5%
Elongation Index (EI)			12.6%
Aggregate absorption	AASHTO T-166	------	0.8%
Soundness	AASHTO T-104	12 (maximum)	3.32%
Los Angeles Abrasion	AASHTO T-96	30 (maximum)	22%
Specific Gravity(coarse)	AASHTO T 85-91		2.68
Specific Gravity (fine)	AASHTO T 84-6		2.61

Table 3.2: Properties of Bitumen

Test Name	Designation	Recommended Value (NHA Specs)	Result
Penetration @ 25ºC, (mm)	ASTM D 5-97	60-70	64
Flash Point (ºC)	AASHTO T 48-89	232	232
Specific Gravity	AASHTO T 228-06	(ASTM) 1.02-1.05	1.04
Ductility (cm)	ASTM D 113-86	>100	103

3.3.2 AGGREGATE GRADATION

For obtaining the required gradation, the combination of aggregates is the most important step of hot mix asphalt design. Maximum size of aggregate is related with the typical lift thickness used on highways in Pakistan. Pakistan's National Highway Authority in its general specifications has specified two aggregate gradation namely class A and B respectively for wearing coarse and base coarse. Therefore in this research work NHA's both gradations (i.e. Class A and B) for wearing course have been selected. The selected gradations are shown in table 3.3 and 3.4 and figure 3.2 and 3.3 shows that both gradations are plotted with percentage passing verses sieve sizes. The nominal maximum aggregate size selected for class A wearing coarse gradation was 19.0 mm and for class B it was 12.5 mm respectively. Both the selected gradations were further plotted against the NHA's specified limits and Superpave's specified control points for the selected NMAS of both gradations as shown in figure 3.3 and 3.5 respectively.

Table 3.3: Class-A Gradation Selected for Testing

Sieve Size		sieve power 0.45 gradation	NHA limits		**Selected % Passing**
(mm)	(U.S.)		Upper	Lower	
25	1 in	4.26	100	100	**100**
19	3/4 in	3.76	100	90	**90**
9.5	3/8 in	2.75	70	56	**68**
4.75	No. 4	2.02	50	35	**48**
2.36	No. 8	1.47	35	23	**27**
0.3	No. 50	0.58	12	5	**12**
0.075	No. 200	0.31	8	2	**8**

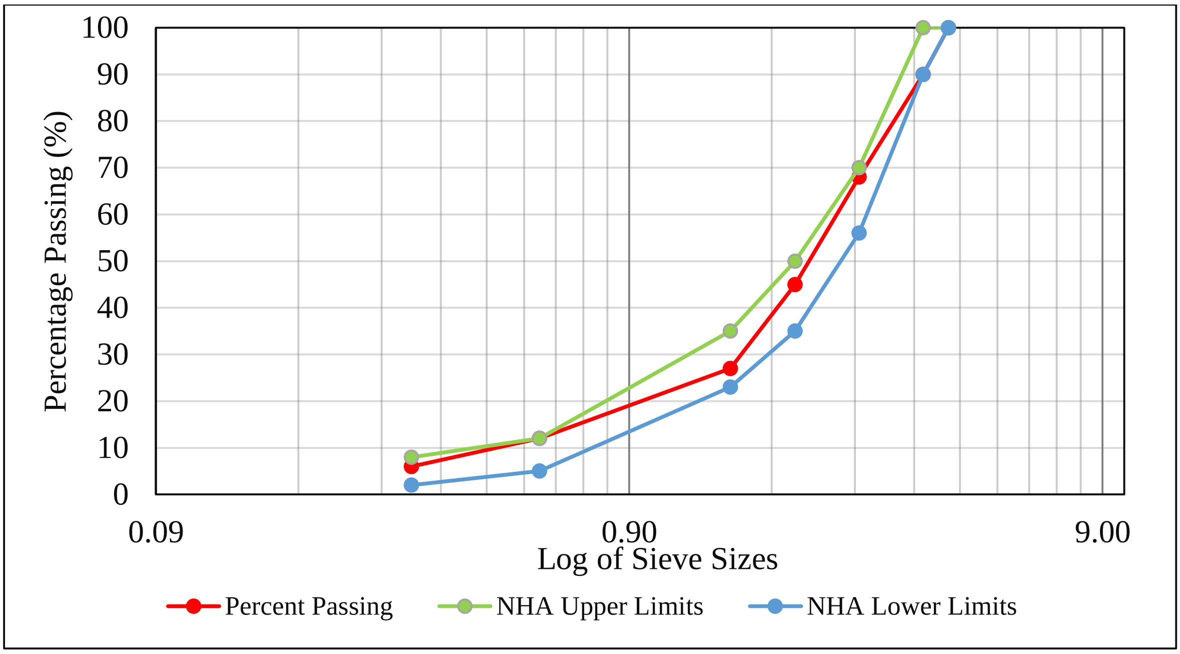


Figure 3.2: Class-A Gradation Plot with NHA Specified limit

3.4 PREPARATION OF BITUMINOUS MIXES

For determining the optimum asphalt content bituminous paving mixes were prepared according to the method explained in Asphalt Institute's Superpave mix design manual (SP-2). As there were two gradations and two binder contents (i.e. virgin 60/70 and modified 60/70), the optimum asphalt content for each was determined by repeating the Superpave mix design procedure four times. The volumetric parameters theoretical maximum specific gravity G_{mm}, effective specific gravity G_{se}, Bulk specific gravity G_{mb}

and $\%G_{mm}$ of prepared specimens were measured, verified in light of Superpave mix design criteria and finally optimum asphalt contents were determined. Superpave mix design was carried out as follows:

Table 3.4: Class-B Gradation Selected for Testing

Sieve Size		sieve power 0.45 gradation	NHA limits		**Selected % Passing**
(mm)	(U.S.)		Upper	Lower	
19	3/4 in	3.76	100	100	**100**
12.5	1/2 in	3.12	90	75	**90**
9.5	3/8 in	2.75	80	60	**80**
4.75	No. 4	2.02	60	40	**50**
2.36	No. 8	1.47	40	20	**30**
0.3	No. 50	0.58	15	5	**11**
0.075	No. 200	0.31	8	3	**5.5**

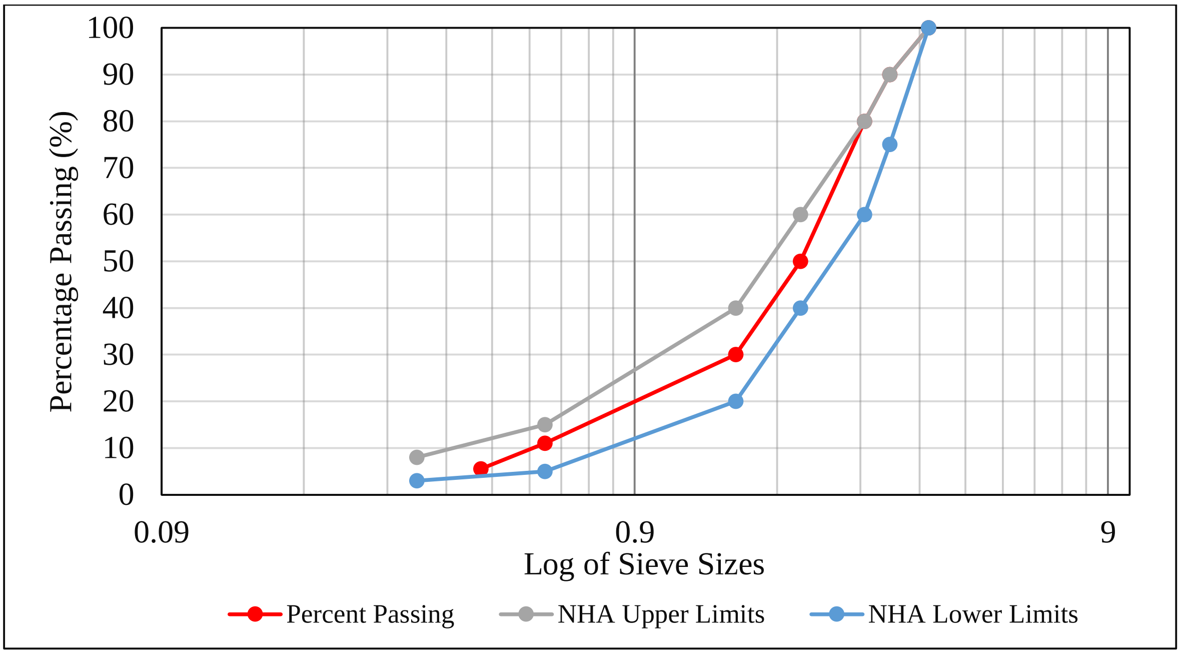


Figure 3.3: Class-B Gradation with NHA Specified limit

3.4.1 NUMBER OF SAMPLES FOR EACH JOB MIX FORMULA

For each combination of aggregate and binder three samples were prepared. As there were two gradations i.e. NHA class A and class B for wearing coarse and two binders i.e. ARL virgin 60/70 and ARL 60/70 modified with Bakelite, 12 specimens for each type were prepared. So, a total of 48 specimens were prepared for determining the optimum binder content at three different binder contents (3.5, 4.0 and 4.5%).

3.4.2 PREPARATION OF MATERIALS FOR MIX DESIGN

After sieving the aggregates were dried to constant weight at 105ºC to 110ºC. The quantity of aggregates used for preparing the compacted 6 inch diameter each specimen by Superpave mix design method was 4500 gm. The amount of binder content used for preparing each specimen was taken as the percentage of total weight of mix obtained from equation 3.2:

$$M_T = M_a + M_b \tag{3.1}$$

$$M_b = \frac{X}{100}(M_a) \tag{3.2}$$

Where,

M_T = Mass of Total mix

M_a = Mass of Aggregates

M_b = Mass of Bitumen

X = Percentage of Bitumen

3.4.3 MIXING OF AGGREGATE AND BITUMEN

The Superpave mix design manual (SP-2) recommends the use of mechanical mixer for mixing the aggregate and bitumen as shown in figure 3.4. The reason for using the mechanical mixer is that it ensures the proper mixing of aggregates and bitumen. The heated dry aggregates and heated bitumen were charged immediately into the mechanical mixer and mixed thoroughly for 10 to 15 minutes at a temperature ranging from 160ºC to 165ºC respectively. This mixing temperature corresponds to the temperature during manufacturing hot mix asphalt mixes in Pakistan as specified by NHA. Moreover this mixing temperature corresponds to the binder viscosity range of 0.17±0.02 Pa. as specified by Superpave mix design (SP-2).

Figure 3.4: Asphalt Mixing Machine

Figure 3.5: Mix Placed in Tray for Conditioning

3.4.4 CONDITIONING OF MIXTURES

The Superpave mix design manual (SP-2) recommends that hot mix asphalt mixes should be conditioned for approximately 2 hours ± 5 minutes at a temperature equal to the mixture's specified compaction ± 3ºC. Therefore, each bituminous mix obtained from mixer was placed in steel tray and placed in oven for about 2 hours at 135ºC as shown in figure 3.5 respectively.

3.4.5 COMPACTION OF MIXES

After conditioning, the prepared mixes were compacted using Superpave Gyratory Compactor (SGC) at 135ºC. But before compacting the specimen, the mold in which the sample was to be poured was cleaned and placed in oven at 100ºC for 30 minutes. The SGC mold is cylindrical wall (having 150 mm inside diameter) with a base plate at the bottom to provide confinement during compaction. Once the packed mold is placed in the SGC its base rotates at a constant speed of 30 revolutions per minute during compaction, while the mold is positioned at an angle of 1.25 degrees. A loading system applies a load to the loading ram, which imparts a 600 KPa compaction pressure to the specimen. The entire batch of mix was transferred to the mold also a filter paper was placed on both sides of mold i.e. top and bottom.

In this research, the design criteria of heavy traffic or design ESAL $\geq$ 30 was adopted. Therefore, to simulate the effect of heavy traffic the number of gyrations required were 125 as specified by SP-2 manual. For compaction, the mold was placed in the superpave gyratory compactor and the required number of gyrations were provided to the specimen. After the required gyrations and compaction was achieved, the mold was removed from compactor and the specimen was extracted from mold by means of mechanical sample extruder. The complete procedure adopted for compaction of specimens is shown through figure 3.6 to 3.9.

3.4.6 DETRMINATION OF VOLUMETRICS

The volumetric properties of mix including, air voids (V_a), voids in mineral aggregates (VMA) and voids filled with asphalt (VFA) were determined using their respective formulae after determination of theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}). Theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}) were determined in accordance with AASHTO T209 and AASHTO T166 respectively. Figure 3.9 shows the equipment used for determining G_{mb} and G_{mm}. The

Superpave mix design criteria for nominal maximum aggregate sizes used in this research is shown below in table 3.5.

Figure 3.6: Transferring Conditioned Mixture in Preheated Gyratory Mold

Figure 3.7: SUPERPAVE Gyratory Compactor

Figure 3.8: Gyratory Mold Placed in SGC

Figure 3.9: Extraction of Compacted Specimen

Figure 3.10: Theoratical Maximum Specific gravity and Bulk Specific gravity Apparatus

Table 3.5: SuperPave Mix Design Criteria

Design Esals (million)	Required Density (% of Theoratical Maximum Specific gravity)			Voids in the Mineral Aggregate (%) minimum					Voids filled with Asphalt (%)	Dust to binder ratio
				Nominal Maximum Aggregate Size (mm)						
	$N_{initial}$	N_{design}	N_{max}	37.5	25.0	**19.0**	**12.5**	9.5		
< 0.3	≤ 91.5								70 - 80	
0.3 to < 3	≤ 90.5								65 - 78	
3 to < 10										
10 to < 30	≤ 89.0	96.0	≤ 98.0	11.0	12.0	**13.0**	**14.0**	15.0	**65 - 75**	**0.6 - 1.2**
≥ 30										

3.4.6.1 Volumetric properties of NHA class – A specimens

The volumetric properties of specimens corresponding to nha class-A gradation without asphalt modifier are shown below in table 3.6 respectively. The asphalt contents corresponding to 4% air voids are known as the optimum asphalt contents. Therefore, for class A gradation mix without asphalt admixture the optimum asphalt content is 3.96%. The values of volumetric properties according to optimum asphalt contents were then found out from the graphs and by using formula. Table 3.7 shows the job mix formula of mixture prepared using class A gradation. The table clearly shows that all of the volumetric properties are meeting the criteria. The minimum value of VMA at 4% design air voids for 19.0 NMAS should be 13% and in this case, its value was 13.05%. VFA should be in between 65-75, its value calculated from the graph was 69.35, which was within the specified criteria. The dust to binder ratio value according to criteria should be within 0.8 – 1.6 and in this case it was 1.54. The measured value of required density (% Gmm) at $N_{initial}$ should be ≤ 89.0 and in this case, it was 83.74, which lies in the range of criteria.

Table 3.6: Volumetric Properties of Class A and Class B Specimens

%AC	G_{mb}	G_{mm}	G_{se}	% G_{mm}	VMA (%)	VFA (%)	Va (%)	Dust to binder ratio
NHA CLASS A SPECIMENS								
3.5	2.390	2.513	2.648	95.09	12.80	68.76	4.90	1.74
4.0	2.395	2.493	2.647	96.07	13.06	69.4	3.92	1.51
4.5	2.400	2.475	2.647	96.9	13.34	70.02	3.02	1.34
NHA CLASS B SPECIMENS								
3.5	2.385	2.512	2.648	94.94	13.97	69.16	5.05	1.59
4.0	2.389	2.493	2.648	95.80	14.29	69.92	4.19	1.39
4.5	2.392	2.475	2.647	96.65	14.62	70.63	3.35	1.23

Table 3.7: Job Mix Formula of Class A and Class B Specimens

Parameters	Measured Value		Criteria	Remarks
	Class A	Class B		
Optimum Asphalt Content (%)	3.96	4.12	NA	
VMA (%)	13.05	14.35	Min 13 Min 14	Pass
VFA (%)	69.35	70.05	65-75	Pass
Dust to binder ratio	1.54	1.36	0.8 – 1.6	Pass
%Gmm @ Ninitial	83.74	85.04	≤ 89.0	Pass

3.4.6.2 Volumetric properties of NHA class B specimens

The volumetric properties of specimens corresponding to nha class B gradation without asphalt modifier are shown above in table 3.6 respectively. The asphalt contents corresponding to 4% air voids are known as the optimum asphalt contents. Therefore, for class B gradation mix without asphalt admixture the optimum asphalt content is 4.12%. The values of volumetric properties according to optimum asphalt contents were then found out from the graphs and by using formula. Table 3.7 shows the job mix formula of mixture prepared using class B gradation. The table clearly shows that all of the volumetric properties are meeting the criteria. The minimum value of VMA at 4% design air voids for 12.5 NMAS should be 14% and in this case its value was 14.35%. VFA should be in between 65-75, its value calculated from the graph was 70.05 which was within the specified criteria. The dust to binder ratio value according to criteria should be within 0.8 – 1.6 and in this case it was 1.36. The measured value of required density (%Gmm) at $N_{initial}$ should be ≤ 89.0 and in this case it was 85.04 which lies in the range of criteria.

3.4.6.3 Volumetric properties of class - A bakelite modified specimens

The volumetric properties of specimens corresponding to nha class A gradation with Bakelite modified asphalt are shown below in table 3.8 respectively. These properties were determined by varying the bakelite percentage from 1.5% to 9% by weight of the asphalt and keeping constant the optimum asphalt content determined previously. It can be clearly seen from table 3.8 that the values of G_{mb}, G_{mm} and G_{se} show an increasing trend with increase in percentage modifier with a maximum value at 6% modifier and then it starts to decrease. This suggests that optimum content of bakelite to be added in the mix is 6%. Table 3.9 shows the job mix formula of mixture prepared using class A gradation. The table clearly shows that all of the volumetric properties are meeting the criteria. The minimum value of VMA for 19.0 NMAS should be 13% and in this case its value was 13.54%. VFA should be in between 65-75, its value calculated from the graph was 70.45, which was within the specified criteria. The dust to binder ratio value according to criteria should be within 0.8 – 1.6 and in this case it was 1.54. The measured value of required density (%G_{mm}) at $N_{initial}$ should be ≤ 89.0 and in this case it was 87.35 which lies in the range of criteria.

Table 3.8: Volumetric Properties of Class A and Class B Bakelite Modified Specimens

%Bakelite	G_{mb}	G_{mm}	G_{se}	% G_{mm}	VMA (%)	VFA (%)	Va (%)	Dust to binder ratio
NHA Class A (@ 3.96 OAC)								
3.0	2.388	2.493	2.646	95.74	13.77	70.95	4.26	1.54
4.5	2.390	2.495	2.647	95.80	13.69	70.73	4.20	
6.0	2.399	2.496	2.649	96.12	13.54	70.45	4.00	
7.5	2.397	2.494	2.648	96.09	13.48	70.33	3.91	
9.0	2.393	2.492	2.645	95.96	13.25	69.81	4.04	
NHA Class B (@ 4.12 OAC)								
3.0	2.376	2.488	2.647	95.45	14.90	73.16	4.55	1.36
4.5	2.379	2.490	2.648	95.56	14.75	72.89	4.44	
6.0	2.389	2.491	2.649	95.93	14.61	72.62	4.00	
7.5	2.387	2.489	2.646	95.89	14.56	72.53	4.11	
9.0	2.385	2.490	2.644	95.79	14.54	72.44	4.21	

3.4.6.4 Volumetric properties of class – B bakelite modified specimens

The volumetric properties of specimens corresponding to nha class B gradation with Bakelite modified asphalt are shown below in table 3.8 respectively. These properties were determined by varying the bakelite percentage from 3% to 9% by weight of the asphalt and keeping constant the optimum asphalt content determined previously. It can be clearly seen from table 3.8 that the values of G_{mb}, G_{mm} and G_{se} show an increasing trend with increase in percentage modifier with a maximum value at 6% modifier and then it starts to decrease. This suggests that optimum content of bakelite to be added in the mix is 6%. Table 3.9 shows the job mix formula of mixture to be prepared using class B gradation. The table clearly shows that all of the volumetric properties are meeting the criteria. The minimum value of VMA for 12.5 NMAS should be 14% and in this case its value was 14.61%. VFA should be in between 65-75, its value calculated from the graph was 72.62, which was within the specified criteria. The dust to binder ratio value according to criteria should be within 0.8 – 1.6 and in this case it was 1.36 The measured value of required density (%Gmm) at $N_{initial}$ should be ≤ 89.0 and in this case it was 85.6 which lies in the range of criteria.

Table 3.9: Job Mix Formula for Class A and Class B Bakelite Modified Specimens

Parameters	Measured Value		Criteria	Remarks
	Class A	Class B		
Optimum Modifier (%)	6.0	6.0	NA	
VMA (%)	13.54	14.61	Min 13 Min 14	Pass
VFA (%)	69.45	72.62	65-75	Pass
Dust to binder ratio	1.54	1.36	0.8 – 1.6	Pass
%Gmm @ Ninitial	87.35	85.6	≤ 89.0	Pass

3.5 SAMPLE PREPARATION FOR PERFORMANCE TESTS

The job mix formula obtained from Superpave mix design were used to prepare specimens for dynamic modulus and wheel tracker tests. After sieving the aggregates were dried to constant weight at 105ºC to 110ºC. The quantity of aggregates required for preparing each 6 inch diameter gyratory compacted specimen was 7500 gm. The specimens for dynamic modulus test were prepared using superpave gyratory compactor according to AASHTO TP 62-07. Compaction of specimens was controlled by providing 125 gyrations. Six specimens for each gradation were prepared using virgin 60/70 grade asphalt and six specimens for each gradation were prepared by modifying the asphalt with 6% bakelite by weight of optimum asphalt content was mixed with dry aggregates before adding the asphalt to prepare specimens for each gradation. A total of 24 cylindrical compacted specimens, having height 188 mm and 150 mm diameter were prepared for dynamic modulus and wheel tracker test. Figure 3.14 shows the compacted specimens extracted from mold.

Figure 3.11: Gyratory Compacted HMA Specimens

Out of 24 specimens, prepared 12 specimens were selected at random for dynamic modulus test and remaining 12 were selected for wheel tracker test. The specimens selected for dynamic modulus tests were cored at center to obtain 4-inch diameter specimens, which were, then saw cut from top and bottom to obtain a standard 6 inch height specimen for dynamic modulus test. Figure 3.11 shows the cored specimens for dynamic modulus test. The remaining 12 specimens were only saw cut from top and bottom of each specimen to obtain a standard specimen of 1.5 inch height and 6-inch diameter. Figure 3.12 shows the saw cut specimens for wheel tracker test.

Figure 3.12: Cored and Trimmed Specimens with Waste ring

Figure 3.13: Saw Cut Specimens for Wheel tracker

3.6 DYNAMIC MODULUS TEST

The dynamic modulus test was performed in accordance with AASHTO TP 62-07.The IPC Global Simple Performance Tester (SPT) was used for the determination of dynamic modulus. Its other name is Asphalt Mix Performance Tester (AMPT). The SPT consists of an environmental chamber, a tri-axial cell, a pump, a hydraulic actuator a refrigeration and heating unit with heat exchanger and a data acquisition system. Figure 3.13 shows the general schematic of dynamic modulus test equipment.

Figure 3.14: Simple Performance Tester (AMPT)

Before placing the specimens in SPT, gauge points were fixed on the specimens obtained after coring and saw cutting using R-Bellite epoxy glue as shown in figure 3.14. Once the gauge points were fixed, clamps were fixed to the each specimen. These clamps were designed to accommodate the Linear Variable Displacement Transducers (LVDTs) which to measure the axial deformation / strain during the test. Figure 3.15 shows the LVDTs attached to the specimens.

Figure 3.15: Studs fixing using gauge point fixing device

Figure 3. 16: Clamps and LVDT's mounted on the sample

The specimens were then placed in the environmental chamber and allowed to equilibrate to the target test temperature within ±0.5℃. Each specimen was tested at 25℃ 40℃ and 50℃ using frequencies of 25, 10, 5, 0.5 and 0.1 Hz, respectively. A continuous uniaxial sinusoidal compressive stress was applied to unconfined cylindrical test specimen. The deformation of the specimen was captured using linear variable displacement transducers mounted 120° apart. The results were automatically generated by the software at the completion of the test and the values of dynamic modulus were reported against the given temperature and corresponding test frequencies.

3.7 INVESTIGATION OF SAMPLE POTENTIAL FOR RUTTING

The specimens were tested to determine their resistance to permanent deformation using Precision Machine Welding (PMW) wheel tracker. Wheel tracker is an electrically powered device, which is capable of moving a 203.2mm diameter, 47-mm wide steel wheel over a test specimen. The load on the steel wheel is 158±1.0 lb. and the average contact stress produced by the contact of wheel is approximately 0.73 MPa with a contact area around 970 mm^2. The contact pressure induced by the steel wheel produces the same effect as produced by the rear tire of a double-axle truck. With increase in rut depth the contact area increase as result of which the contact stress becomes variable. The steel wheel moves over the specimen in forward and backward direction. The steel wheel should complete approximately 50 passes over the specimen per minute. Its maximum speed is approximately 1 ft. /sec, which is reached at the midpoint of the specimen. Using this device rutting test can be performed on Air, Wet and Dry modes. These modes can be used by adjusting the device at desired test conditions. Figure 3.16 shows the PMW wheel-tracking device used for conducting rutting tests.

Before conducting the test, the sample were saw cut from the top and bottom surface so that two 1.5-inch thick specimens could be obtained. These specimens were cut according to the silicon mold of the wheel tracker tray.

Figure 3.17: PMW Wheel Tracking Machine

After placing the specimen in the mold, extra spaces were filled with plaster of Paris so that the specimen does not move with the movement of wheel. The steel tray with the specimen mounted in it was placed under the wheel and fixed. The wheel tracker device was switched on. Then, the details of specimen were entered in the software. The speed of the wheel was adjusted to 50 ppm (passes per minute). The number of passes were fixed to 20,000. Dry mode of wheel tracker device was selected. Finally the test was run and wheel started moving to and fro on the mounted specimen. The number of passes were shown on the LCD of the system attached with machine. One complete to and fro movement of the wheel was taken as 2 passes. The LVDT measures the rut impression in millimeters of unit at the same time with the motion of wheel. The machine automatically stopped when required number of passes achieved. Results were saved for the further use.

3.7.1 OUTPUT OF TEST

The software gives two types of results as output.

- Graph: which shows number of passes verses rut depth in mm.
- Excel Sheet data: This displays numerical information of the rut depth at 11 points of the wheel path.

Wheel Tracker (WT) Graph is an application that will display graphs and header information for the Wheel Tracking Machine. It has the ability to select a database upon startup so that archived data can be viewed and graphed. The application has the ability to save the graphs and header information to a file.

Directions for Graph display

a) Double-click on the WT Graph icon on the Desktop
b) Select the database to be used.
    - To open a current database: double-click either "PMW5.MDB" or "PMW6.MDB" (depending on the Wheel Tracker version)
    - To open an archived database: double-click the "Archive" folder, and select the database from the dialog
c) Select the test number.
d) Select the report type.
e) Select the wheel (if applicable).
f) Select the test point (if applicable).
g) Select the graph scaling.
h) Click "Display Graph".
i) Repeat steps 3 through 8 to display a different graph.

The graph will be displayed in the form of image and the rut depth at every number of passes can be obtained by generating report and then importing the report in the MS excel file.

3.8 SUMMARY

The first part of this chapter explains the laboratory characterization of aggregates and bitumen for the preparation of bituminous paving mixes. Those materials that satisfied the standard specifications were used for bituminous mix preparation. The volumetric properties of bituminous mix have been calculated and optimum asphalt contents were determined. In second part, the testing procedure adopted for the dynamic modulus and permanent deformation testing of bituminous mix specimens has been explained

CHAPTER 4

ANALYSIS OF EXPERIMENTAL RESULTS

4.1 INTRODUCTION

This chapter explains in detail the analysis of data obtained from laboratory testing. The analysis on test results was performed using the statistical software MINITAB -15. The effectiveness of bakelite as anti-rutting agent to reduce permanent deformation was illustrated. Full factorial design of experiment method was used to obtain the interactions and significance among various factors for dynamic modulus data. The results from factorial analysis were presented as graphs such as normal plot, half normal probability plot, Pareto plot and factorial plots. Factors considered for the dynamic modulus data analysis are temperature, frequency, gradation and bakelite percentage whereas the response is dynamic modulus. Regression analysis was also performed for dynamic modulus data. In the end influential analysis and residual analysis were performed to check the validity of model.

4.2 RUTTING PROPENSITY

Permanent deformation is evaluated by comparing the specimen's resistance to rutting with and without bakelite modification. Gyratory compacted specimens were prepared with two proportions of bakelite (0% and 6%) for class A and class B aggregate gradations. Wheel tracking test was conducted on controlled specimens and then on bakelite modified specimens for each aggregate gradation separately. A total of 12 specimens were prepared for each gradation with and without bakelite modification. Each specimen's resistance to rutting was checked in wheel tracking machine. All the controlled specimens showed good resistance to rutting whereas the bakelite modified specimen's resistance to rutting was greater than the controlled specimens. All of the specimens passed the wheel tracker test.

4.2.1 WHEEL TRACKER OUTPUTS

The graphical output of specimen are shown in the following figures. On the right side y-axis shows the rut depth scale, while on the x-axis is the number of passes. The red line shows the rut in the wheel path whereas the green line shows the line of failure depth which was set 12.5 mm for all the tests. The reason for conducting the test at 20000 wheel passes is that the researchers found that after increasing the number of wheel passes to

19,200, some mixtures will deteriorate due to effect of moisture damage shortly after 10,000 passes. Therefore, greater than 10,000 wheel passes were generally needed to show the effect of moisture damage.

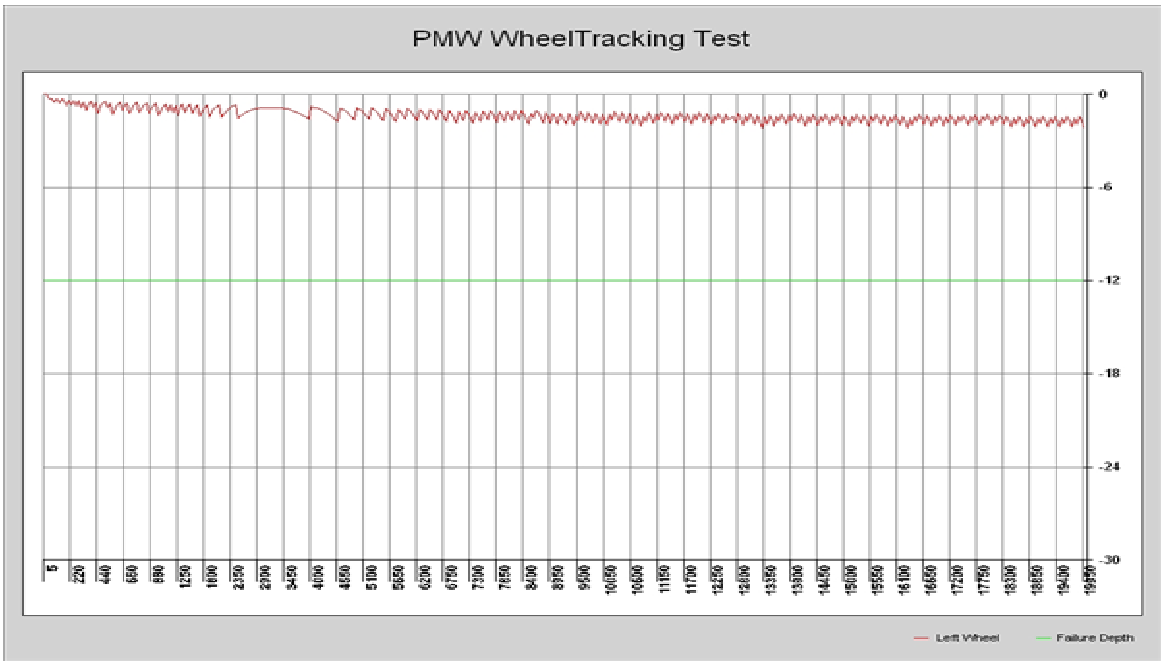


Figure 4.1: Graphical Output of Rutting Test for Class-A Controlled Mixture

4.2.2 WHEEL TRACKER RUTTING RESULTS

Controlled and modified mixtures of class A gradation (NMAS 19 mm) were tested against rutting at room temperature in dry mode of wheel tracker. Figure 4.2 shows the rut depth plotted against 20,000 number of passes (approx.). It is clear from figure that the rut depth obtained after 20,000 number of passes for controlled mixtures is greater than the rut depth obtained with bakelite-modified mixtures. The maximum rut depth obtained for class-A controlled specimens is 2.19 mm whereas the maximum rut depth obtained for bakelite-modified mixtures is 1.04 mm respectively. The rut depths obtained for controlled and modified mixtures was well in acceptable range as the failure depth was set at 12.5 mm.

Controlled and modified mixtures of class B gradation (NMAS 12.5 mm) were tested against rutting at room temperature and in dry mode of wheel tracker. Figure 4.3shows the rut depth is plotted against 20,000 number of passes (approx.) for controlled and bakelite modified mixtures. It is clear from figure that the rut depth obtained after 20,000 number of passes for controlled mixtures is greater than the rut depth obtained with bakelite modified mixtures. The maximum rut depth obtained for class-B controlled mixtures is 1.84 mm whereas the maximum rut depth obtained for bakelite modified mixtures is 1.27

mm respectively. The rut depths obtained for controlled and modified mixtures was well in acceptable range as the failure depth was set at 12.5 mm.

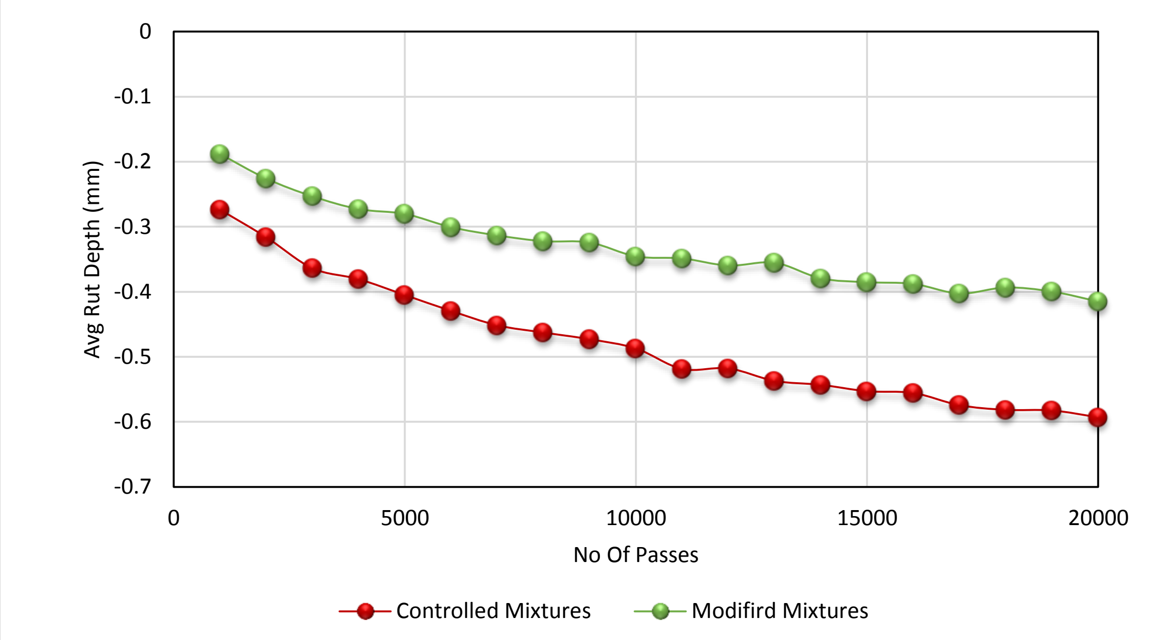


Figure 4.2: Rut Depth versus No. of Passes for Class-A Mixtures

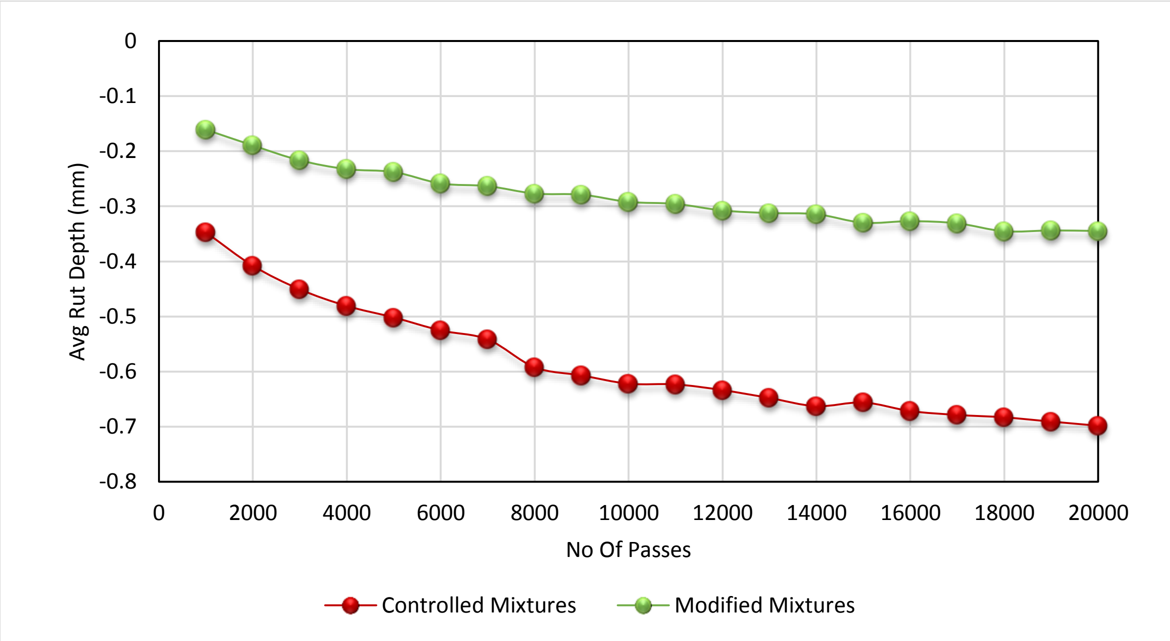


Figure 4.3: Rut Depth versus No. of Passes for Class-B Mixtures

4.2.3 RUTTING EVALUATION

From test results, rutting can be evaluated by comparing the rut depths obtained for controlled mixtures of both gradations with the bakelite-modified mixtures. Rut depth obtained after 20,000 passes was used to calculate the percentage improvement in specimen's resistance to rutting with the addition of bakelite. Table 4.1 and 4.2 shows the percentage improvement in rutting with the addition of bakelite for class A and class B mixtures.

Table 4.1: Rut Depth (mm) After 20,000 Passes for Class –A Mixtures

Rut Depth (mm)			
Mixture	Controlled Mixtures	Modified Mixtures	Improvement in Rut Depth (%)
1	1.13	0.92	**18.6**
2	1.24	0.93	**25.0**
3	1.27	0.90	**29.1**

Table 4.2: Rut Depth (mm) After 20,000 Passes for Class -B Mixtures

Rut Depth (mm)			
Specimen	Controlled Mixtures	Controlled Mixtures	Improvement in Rut Depth (%)
1	1.34	0.93	**30.6**
2	1.42	0.95	**33.1**
3	1.57	0.97	**38.2**

With the addition of bakelite (6%) in hot mix asphalt mixes of class - A along with the binder the resistance to rutting is improved largely. From table 4.1 it is clear that after 20,000 passes the bakelite modified mixture's resistance to rutting is increased up to 29% as compared to the controlled mixtures. Similarly, with addition of bakelite (6%) in hot mix asphalt mixes of class -B along with binder the resistance to rutting is greatly improved. From table 4.2 it is clear that after 20,000 passes the bakelite modified specimen's resistance to rutting is increased up to 38% as compared to the specimens without bakelite modification. Figure 4.4 and 4.5 shows the graphical illustration of response of specimens with and without bakelite modification after rutting test.

4.3 DYNAMIC MODULUS TEST RESULTS

The dynamic modulus values obtained for modified mixtures of both gradations were slightly higher as compared to dynamic modulus values of controlled mixtures. The results of both gradations i.e. NHA class A and B for controlled and modified mixtures were then compared separately to determine the percentage improvement in dynamic modulus with the addition of modifier. The comparison was carried out on dynamic modulus values obtained for all frequencies (25, 10, 5, 1, 0.5 and 0.1 Hz) and at temperatures 25, 40 and 50 ˚C. The results obtained are shown through figure 4.6 to 4.8 for class A and for class B are shown through figure 4.9 to 4.11 respectively. The tabulated values of these results shown in Appendix viii at the end. For modified mixtures of class A, with increase in temperature significant percentage increase in dynamic modulus values was observed as compared to controlled mixtures. Similar pattern was observed in modified mixtures of class B as compared to controlled mixtures as shown in figures below.

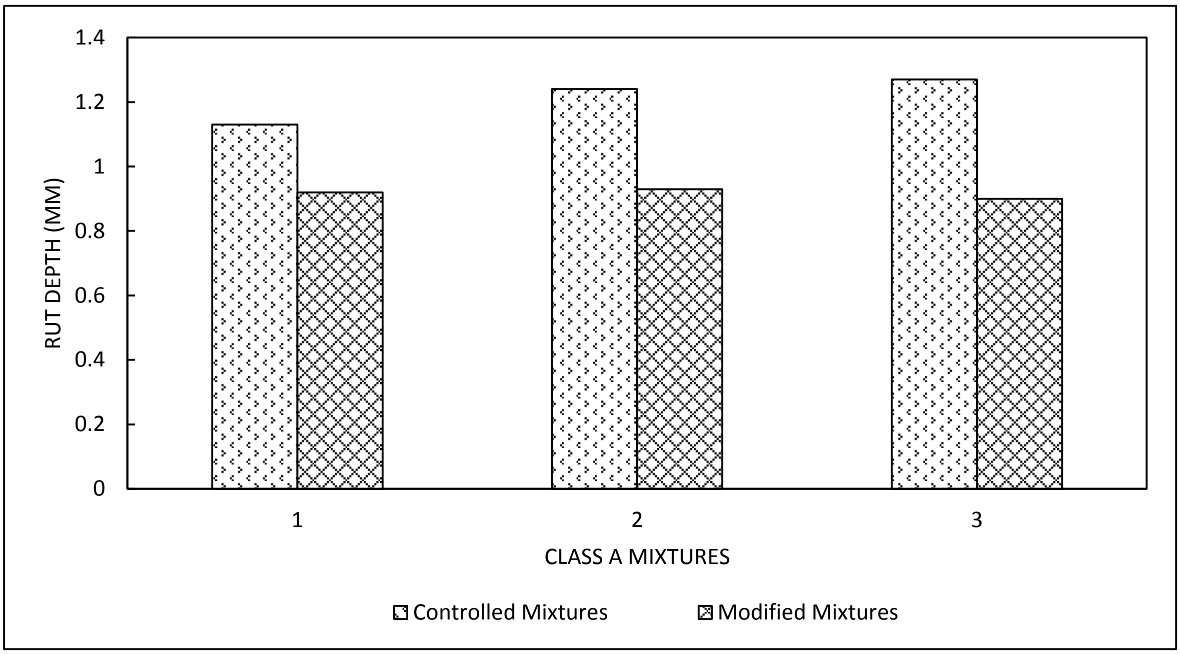


Figure 4.4: Measured Rut Depths after 20,000 passes for Class –A Mixtures

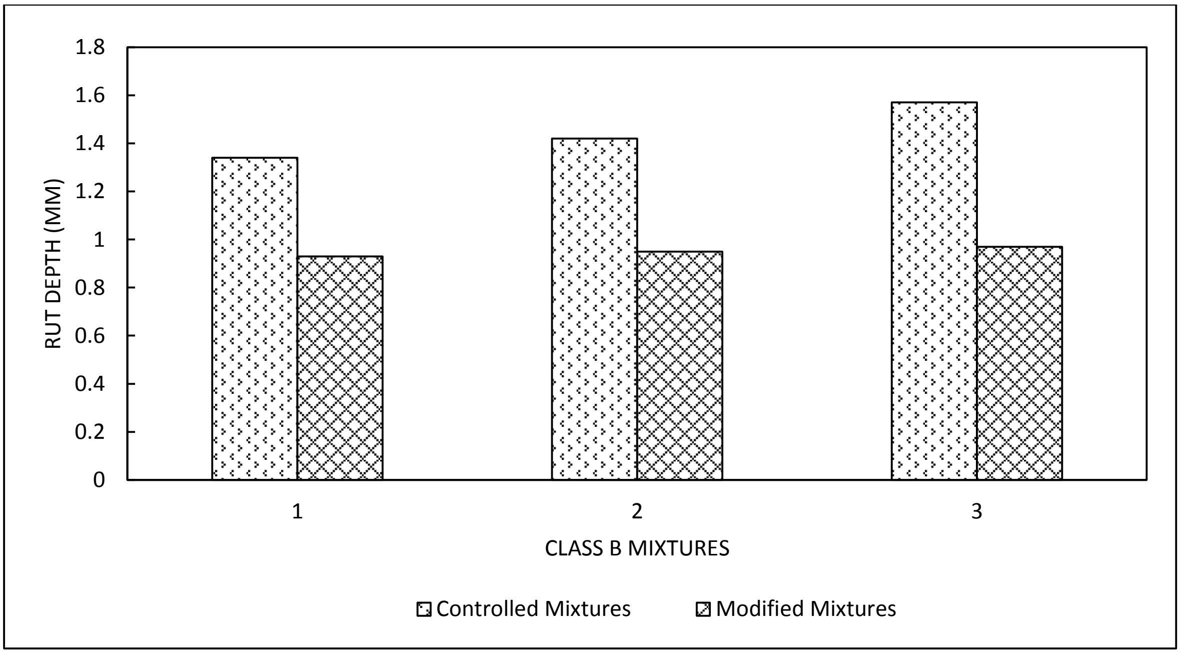


Figure 4.5: Measured Rut Depths after 20,000 passes for Class –B Mixtures

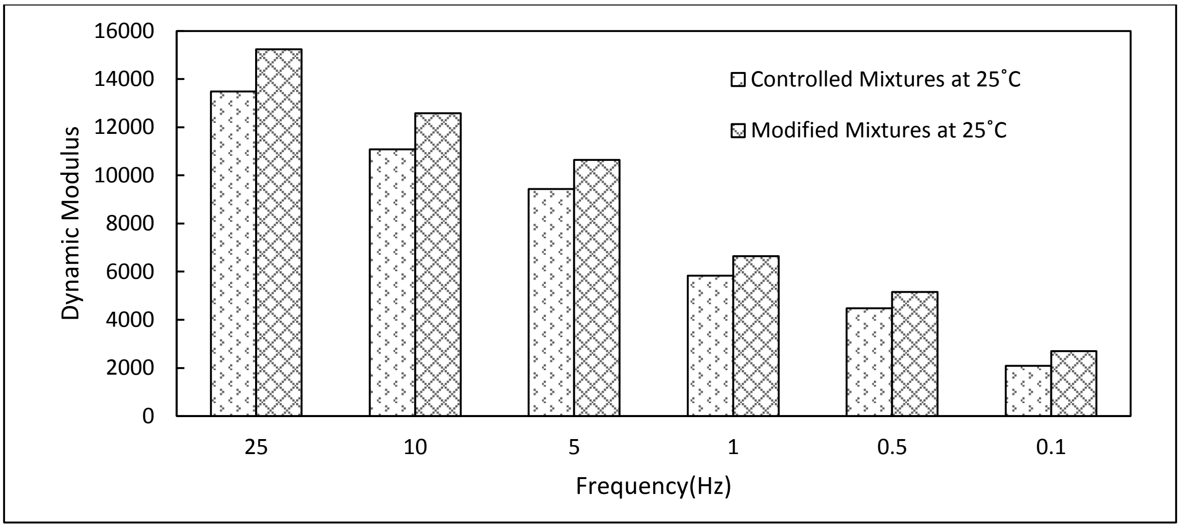


Figure 4.6: Modified and Controlled mixtures of class A at 25˚C

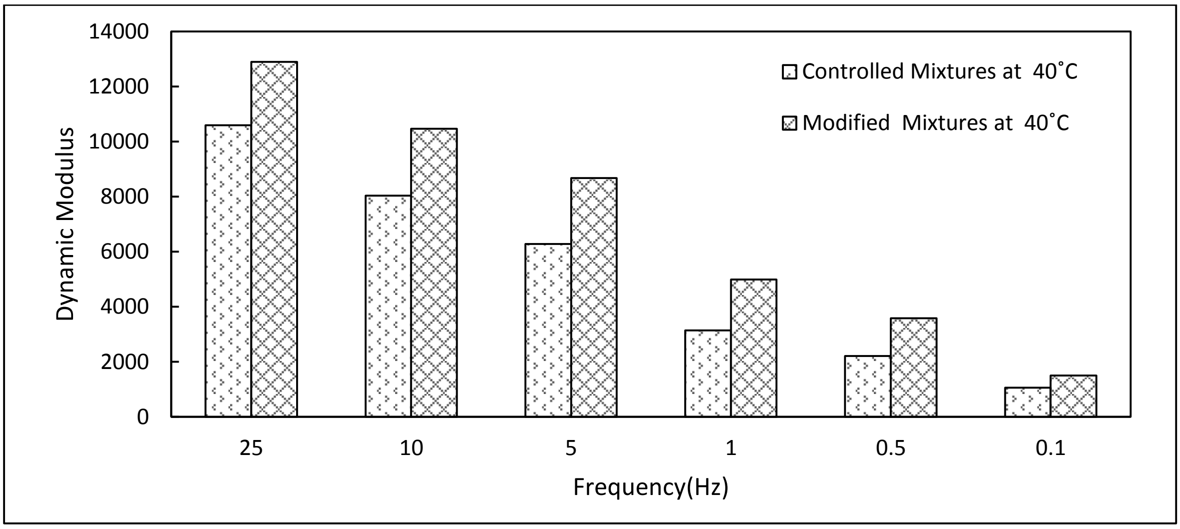


Figure 4.7: Modified and Controlled mixtures of class A at 40˚C

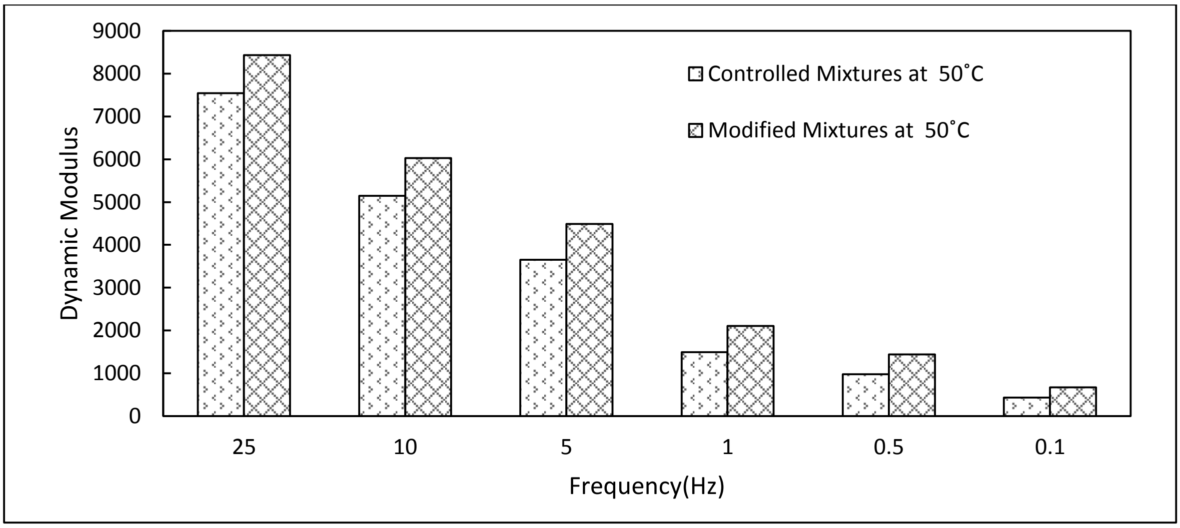


Figure 4.8: Modified and Controlled mixtures of class A at 50˚C

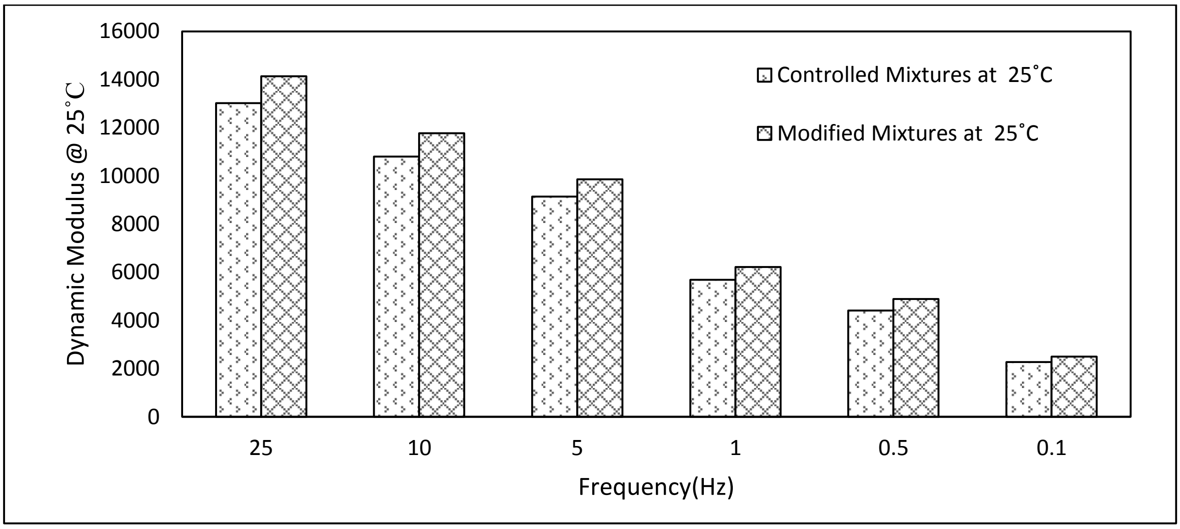


Figure 4. 9: Modified and Controlled mixtures of Class B at 25˚C

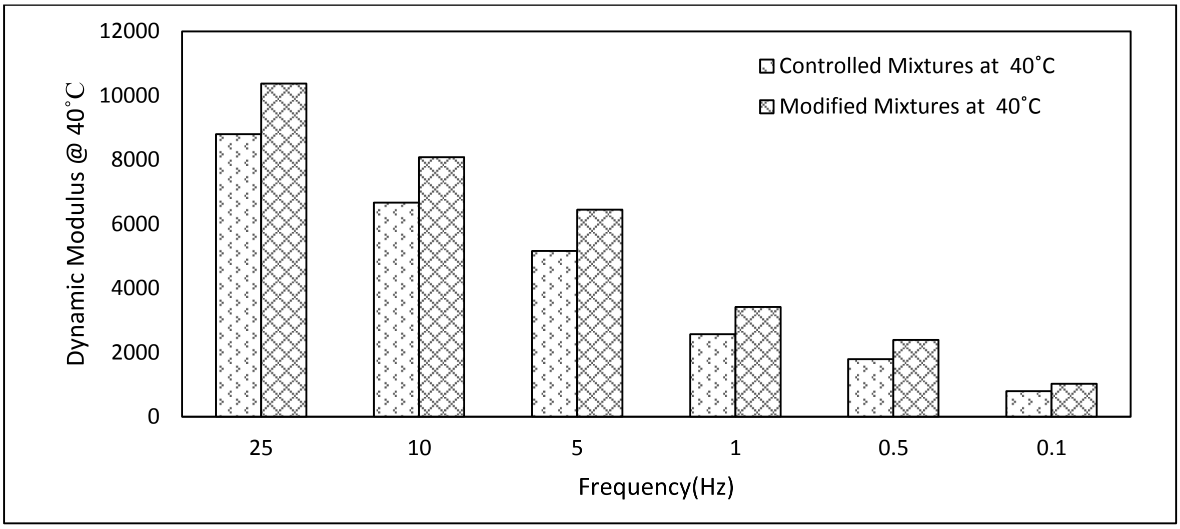


Figure 4.10: Modified and Controlled mixtures of Class B at 40˚C

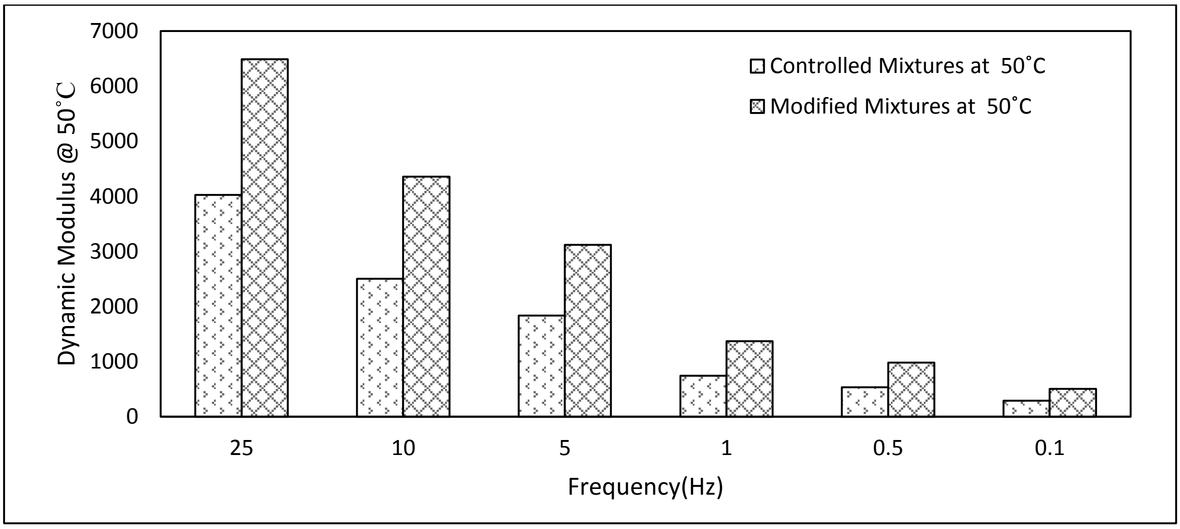


Figure 4.11: Modified and Controlled mixtures of Class B at 50˚C

4.4 FULL FACTORIAL DESIGN FOR DYNAMIC MODULUS

The analysis of dynamic modulus data for each gradation with and without bakelite modification was performed separately by considering three factors i.e. frequency, test temperature and bakelite percentage each with 2 levels. Therefore, 2^3 full factorial design of experiment was performed using MINITAB -15 software. Table 4.3 shows the factors that have been considered in the factorial design with their high and low levels and abbreviations for both the gradations. Inputting these factors into software resulted in sixteen combinations. Table 4.4 and 4.5 shows the combination of factors generated by software in the full factorial design.

Table 4.3: Factors and their Level for Factorial Design

Abbreviation	Factors	Levels		Units
A	Frequency	0.1	25	Hz
B	Temperature	25	50	˚C
C	Bakelite	0	6	%

Table 4.4: Design table with Actual values of Class A Specimens for Factorial Design

Frequency(Hz)	Temperature(C)	Bakelite (%)	Dynamic Modulus		
			1	2	3
25	50	0	9173	7619	5851
25	50	6	9685	8680	6932
25	25	6	15442	15381	14891
0.1	25	0	2388	1915	1962
0.1	50	0	548.7	388	351.3
0.1	25	6	2733	2339	3004
25	25	0	13857	14102	12488
0.1	50	6	792.1	596.6	613.3

Table 4.5: Design table with Actual values of Class B Specimens for Factorial Design

Frequency(Hz)	Temperature(C)	Bakelite (%)	Dynamic Modulus		
			1	2	3
25	25	6	13590	13907	14940
0.1	25	6	2330	2363	2826
25	50	0	4149	2111	5814
0.1	25	0	2256	1886	2679
0.1	50	6	507.5	517.9	492.7
0.1	50	0	304.5	225.9	332.8
25	50	6	6970	6859	5634
25	25	0	13222	12226	13623

4.4.1 EFFECTS AND COEFFICIENT TABLE

Table 4.6 and 4.7 shows the effects and coefficients values obtained by Minitab 16 software for the significant effects of each gradation. The factors and interaction of factors with high (negative or positive) values of effects and coefficients indicate that they have a greater impact on the dynamic modulus of flexible pavements. The effect of each term is equal to the twice of coefficient. The factors or interaction of factors with P- value greater than significance level indicates that these factors and interactions are significant at significance level of 5%. Also for each gradation the calculated value of t-statistic for the terms greater than the critical value of t-statistic ($t_{critical}$ = 1.98 for degree of freedom 23 and 5% significance level) shows that the interactions and main effects are significant.

Table 4.6: Effects and Coefficients Table for Dynamic Modulus of Class A Specimens

Term	Effects	Coefficient	SE Coeff	t- test	P - value
Constant		8171	208.1	39.27	0.000
Frequency (Hz)	9033	4517	248.5	18.18	0.000
Temperature (C)	-5359	-2680	252.4	-10.62	0.000
Bakelite (%age)	1402	701	208.1	3.37	0.001
Frequency(Hz)*Temperature(C)	-1563	-781	301.4	-2.59	0.011
Frequency (Hz)*Bakelite (%age)	470	235	248.5	0.95	0.347
Temperature(C)*Bakelite (%age)	-220	-110	252.4	-0.44	0.663
Frequency (Hz)*Temperature(C)*Bakelite (%age)	-147	-73	301.4	-0.24	0.808

Table 4.7: Effects and Coefficients Table for Dynamic Modulus of Class B Specimens

Term	Effects	Coefficient	SE Coeff	t- test	P - value
Constant		6871	178.0	38.61	0.000
Frequency (Hz)	7587	3793	212.5	17.85	0.000
Temperature (C)	-6723	-3362	215.8	-15.58	0.000
Bakelite (%age)	1211	605	178.0	3.40	0.001
Frequency(Hz)*Temperature(C)	-2426	-1213	257.7	-4.71	0.000
Frequency (Hz)*Bakelite (%age)	638	319	212.5	1.50	0.137
Temperature(C)*Bakelite (%age)	387	194	215.8	0.90	0.372
Frequency (Hz)*Temperature(C)*Bakelite (%age)	329	164	257.7	0.64	0.525

4.4.2 SIGNIFICANT EFFECTS AND INTERACTION PLOTS

The factors and interaction of factors, which are most significant and affect dynamic modulus of hot mix asphalt, are shown also in terms of Normal probability plot and Pareto plot generated as result of analysis using Minitab 15 software for each gradation separately. Figure 4.12 shows the Pareto plot with absolute values of effects for class A specimens with a reference line drawn, which shows the critical value of student-t (i.e. 1.98). The main factors i.e. Frequency, Temperature and Bakelite %age and the 2-way interactions i.e. frequency and temperature are beyond the reference line which indicates that these main effects and interactions (individual and 2-way) are critical and have influence on dynamic modulus of class A hot mix asphalt mixes at a significance level of 5%.The other plot for getting the significant main effects and interactions is the normal probability plot as shown in figure 4.13 respectively. The factors or interactions in the normal probability plot, which are far away from the reference line, are considered as significant at 5% significance level while the factors or interactions, which are near the reference line or on the reference line, are insignificant.

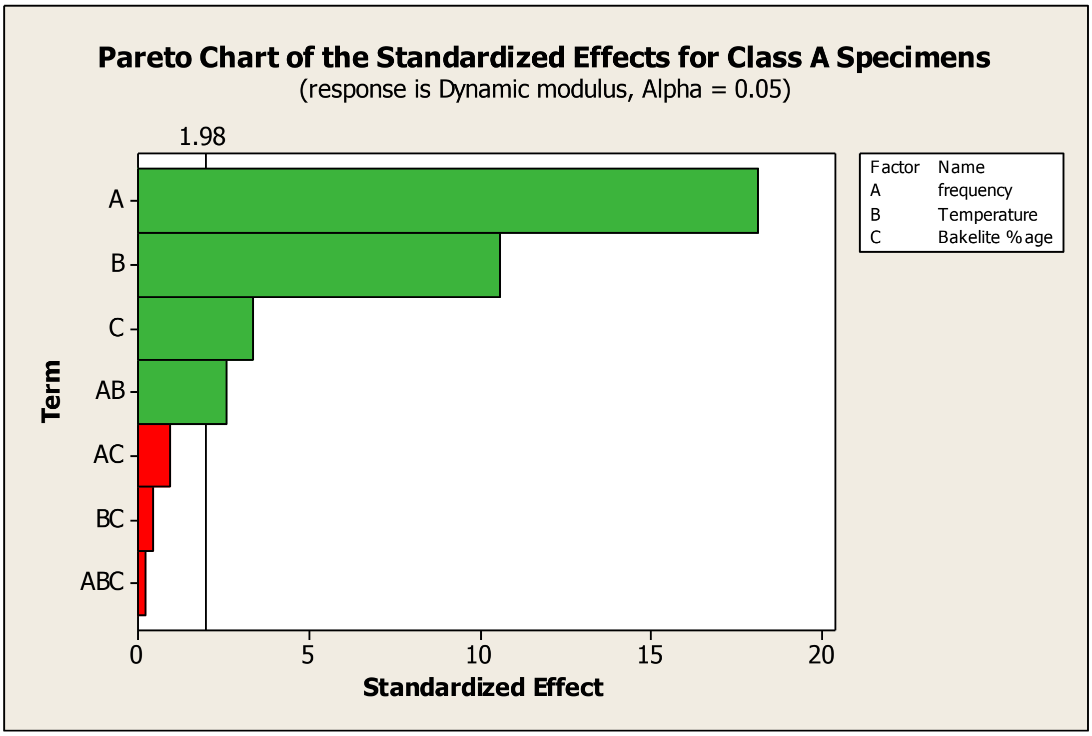


Figure 4.12: Pareto Plot for the Standardizesd Effects of Class A Specimens

Similarly, Figure 4.14 shows the Pareto plot with absolute values of effects for class B specimens with a reference line drawn, which shows the critical value of student-t (i.e. 1.98). The main factors i.e. Frequency, Temperature and Bakelite %age and the 2-way interactions i.e. frequency and temperature are beyond the reference line which indicates that these main effects and interactions (individual and 2-way) are critical and have influence on dynamic modulus of class A hot mix asphalt mixes at a significance level of 5%. The other plot for getting the significant main effects and interactions is the normal probability plot as shown in figure 4.15 respectively. The factors or interactions in the normal probability plot, which are far away from the reference line, are considered as significant at 5% significance level while the factors or interactions that are near the reference line or on the reference line are insignificant.

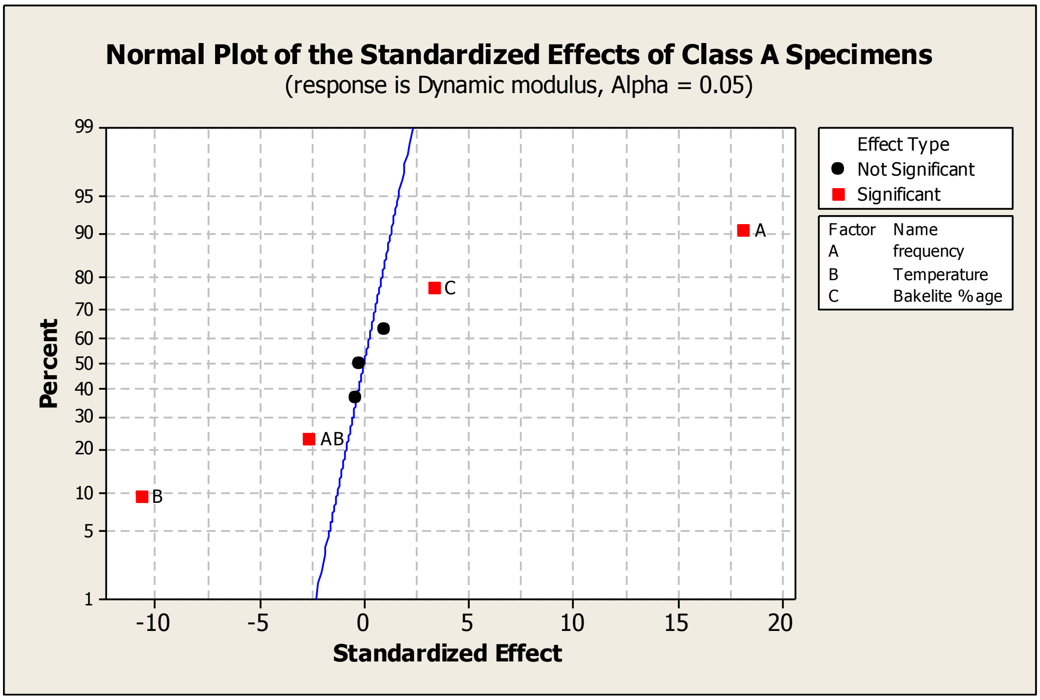


Figure 4.13: Normal Plot of the Absolute Standardized Effects of Class A Specimens

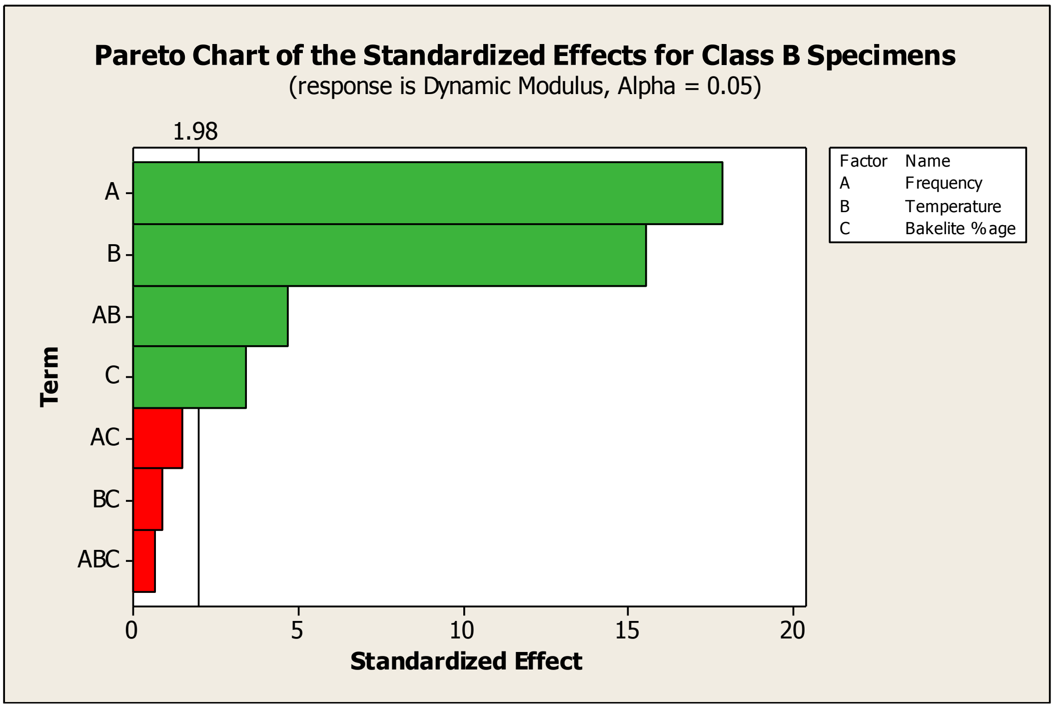


Figure 4.14: Pareto Plot for the Standardizes Effects of Class B Specimens

4.4.3 FACTORIAL PLOTS

The interaction and significant effects obtained from the normal probability plot and Pareto plots can be described in detail by factorial plots. The effects of main factors are shown by main effects plot, 2-way interactions by interaction plots and 3-way interaction by cubic plots respectively.

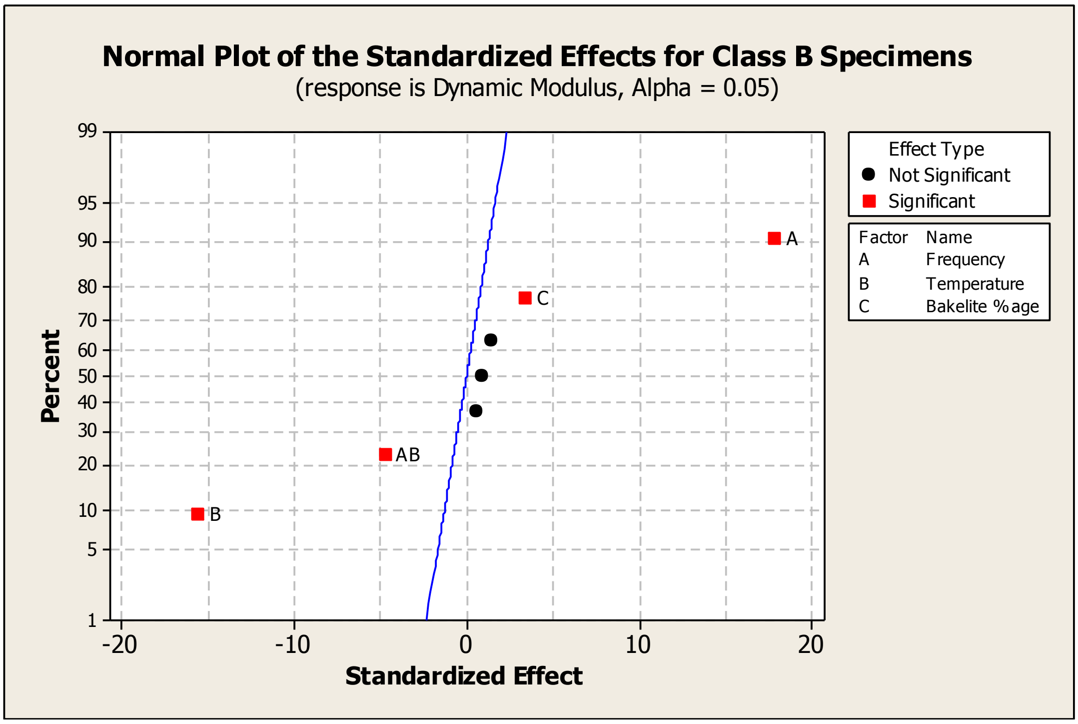


Figure 4.15: Normal Plot of the Absolute Standardized Effects of Class B **Specimens**

4.4.3.1 <u>Main effect plots</u>

The effects of frequency, temperature and bakelite %age of class A specimens are shown in figure 4.16 respectively. It can be clearly seen from the plot between frequency and dynamic modulus that the value of dynamic modulus is very high at 25 Hz frequency as compared to the value at 0.1 Hz frequency. The reason for this increase is that with increase in frequency more stresses are absorbed in specimen which results in an increased dynamic modulus value.

The plot between temperature and dynamic modulus shows that at lower temperature the value of dynamic modulus is high as compared to the dynamic modulus values at higher temperatures. The plot between dynamic modulus and bakelite %age shows a very mild slope. It may be due to the reason that at 0% bakelite the voids in mixes are more as compared to the voids at 6% bakelite as result of which fines are increased at 6% bakelite and voids are reduced so, the dynamic modulus values increase a little bit. Also the effect of this factor is not much significant.

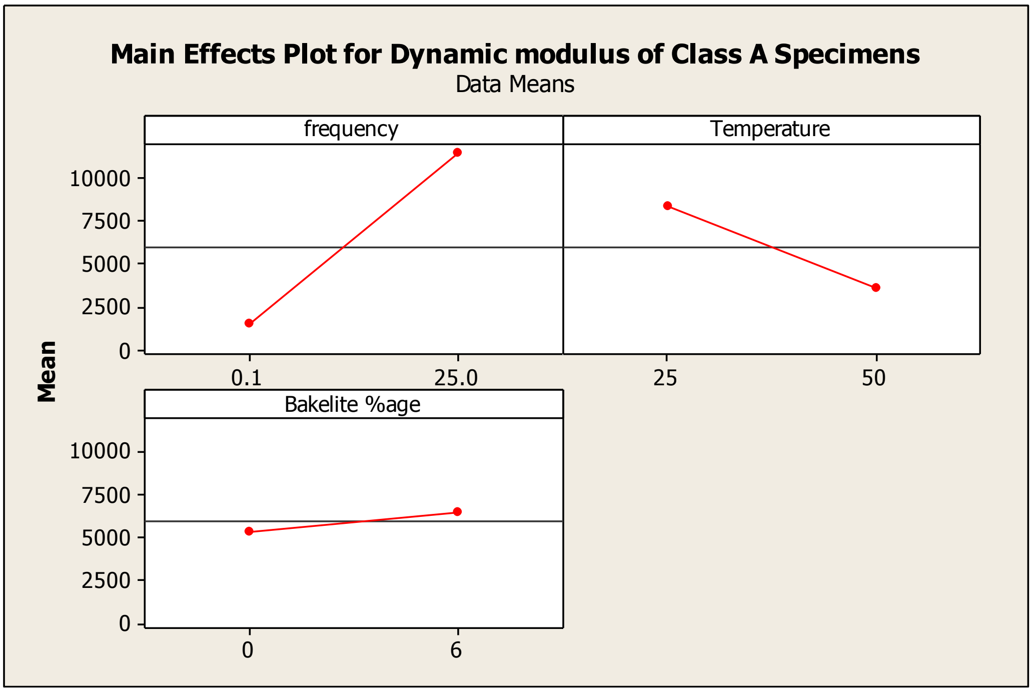


Figure 4.16: Main Effect Plot of Class A Specimens

The effects of frequency, temperature and bakelite %age of class B specimens are shown in figure 4.17 respectively. It can be clearly seen from the plot between frequency and dynamic modulus that the value of dynamic modulus is very high at 25 Hz frequency as compared to the value at 0.1 Hz frequency. The reason for this increase is that with increase in frequency more stresses are absorbed in specimen which results in an increased dynamic modulus value.

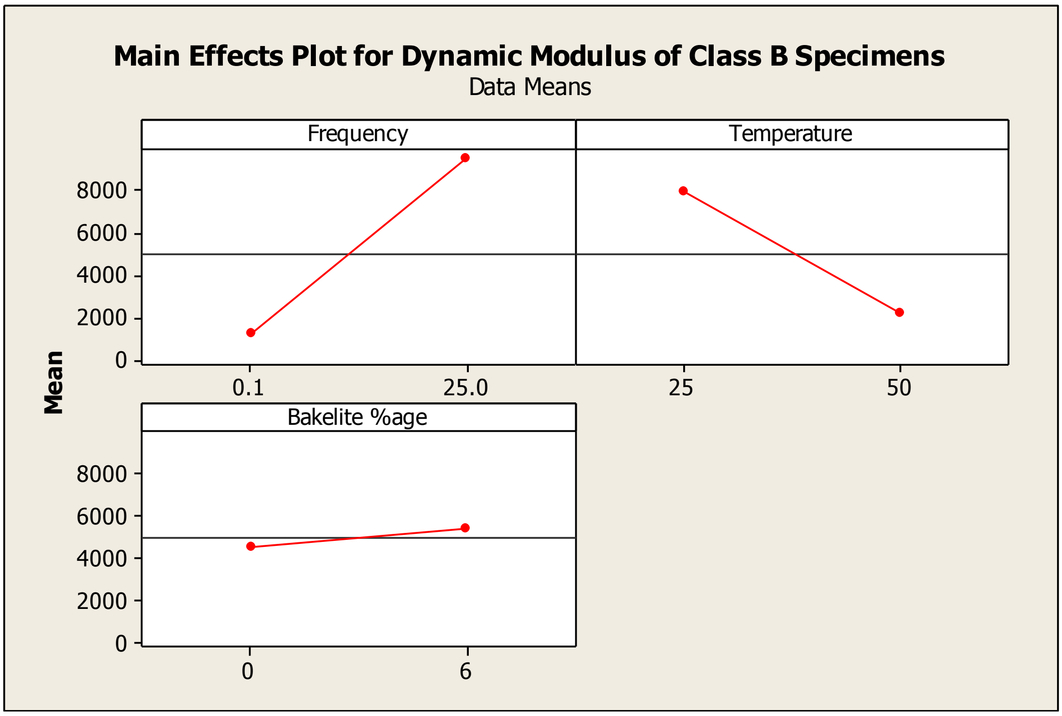


Figure 4.17: Main Effect Plot of Class B Specimens

The plot between temperature and dynamic modulus shows that at lower temperature the value of dynamic modulus is high as compared to the dynamic modulus values at higher temperatures. The plot between dynamic modulus and bakelite %age shows a very mild slope. It may be due to the reason that at 0% bakelite the voids in mixes are more as compared to the voids at 6% bakelite as result of which fines are increased at 6% bakelite and voids are reduced so, the dynamic modulus values increase a little bit. Also the effect of this factor is not much significant.

4.4.3.2 Interaction plots

Figure 4.18 shows the 2-way interaction plot of main factors for class A specimens. It is clear from the plot that the significant 2-way interactions are frequency and temperature, frequency and bakelite (%age) as represented by non-parallel lines. The most significant 2-way interaction is between frequency and temperature. It is clear from the plot that the effect of frequency is more prominent at a temperature of 25 ℃. It also shows that the combination of low temperature and higher frequency results in high dynamic modulus values. At higher temperature and lower frequency the values of dynamic modulus tend to decrease.

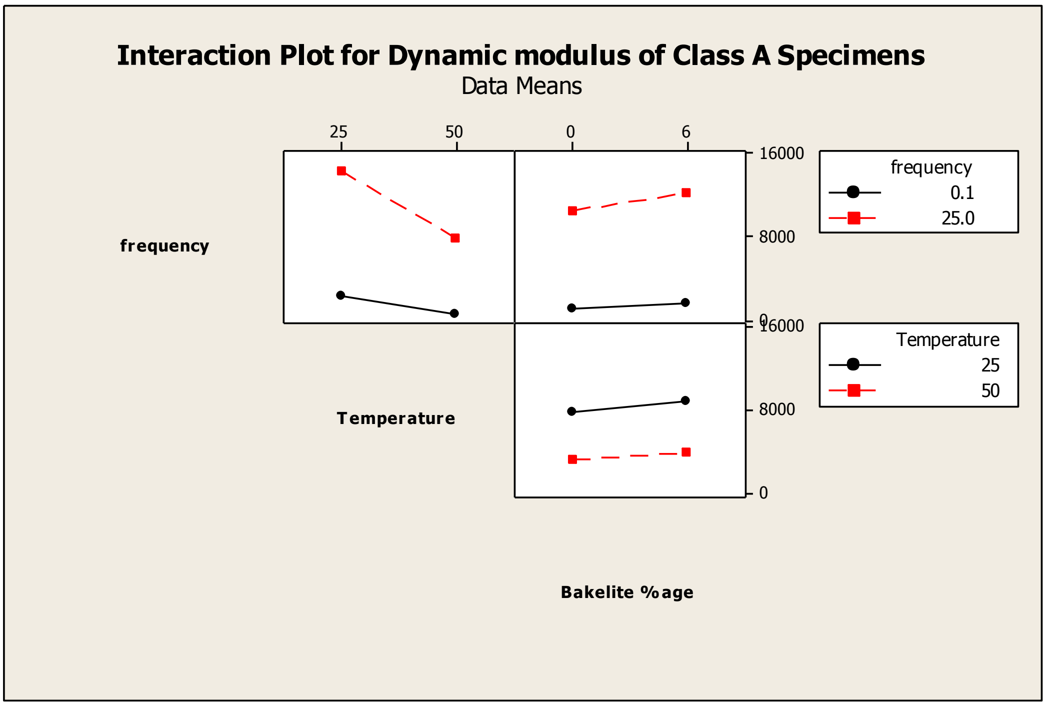


Figure 4.18: Interaction Plot of Dynamic Modulus for Class A Specimens

Figure 4.19 shows the 2-way interaction plot of main factors for class B specimens. It is clear from the plot that the significant 2-way interactions are frequency and temperature, frequency and bakelite (%age) as represented by non-parallel lines. The most significant 2-way interaction is between frequency and temperature. It is clear from the plot that the effect of frequency is more prominent at a temperature of 25 °C. It also shows that the combination of low temperature and higher frequency results in high dynamic modulus values. At higher temperature and lower frequency the values of dynamic modulus tend to decrease.

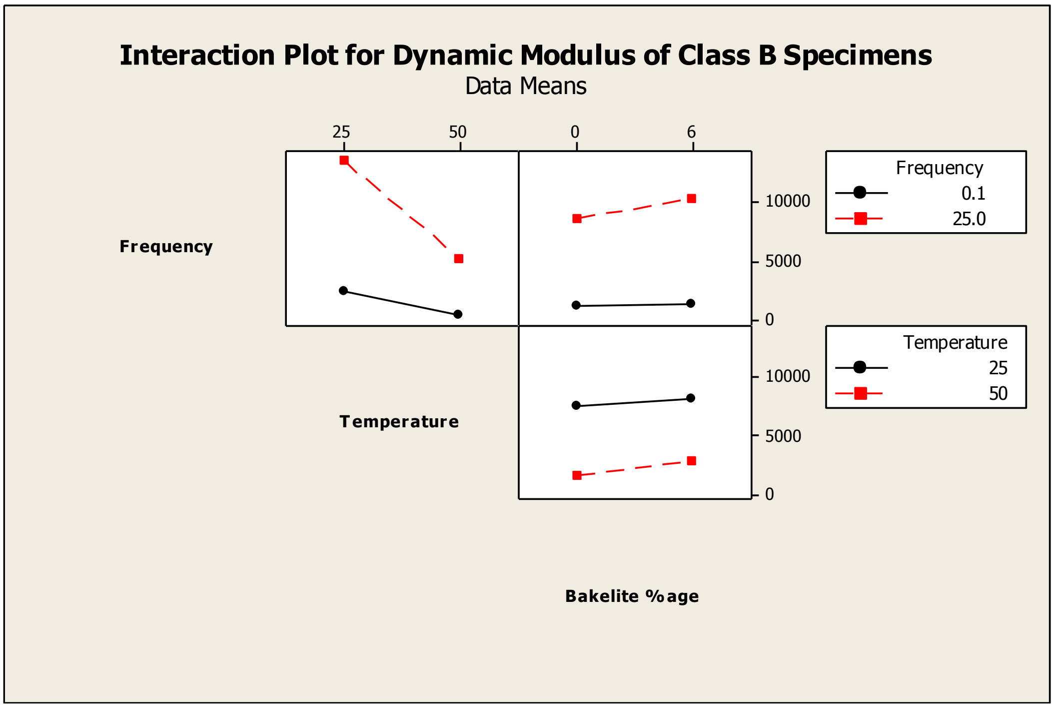


Figure 4.19: Interaction Plot of Dynamic Modulus for Class A Mixtures

4.4.4 ANALYSIS OF VARIANCE (ANNOVA)

In Analysis of Variance ANNOVA, three F-test are made. In order to evaluate these tests, probability values are given below in table 4.8 for class A Mixtures.

Table 4.8: Analysis of Variance for Dynamic Modulus of Class A Mixtures

Source	DF	Seq SS	Adj SS	Adj MS	F- test	P-value
Main Effects	3	1504061307	1445807008	481935669	146.15	0.000
2-Way Interactions	3	25443396	25629424	8543141	2.59	0.057
3-Way Interactions	1	195517	195517	195517	0.06	0.808
Residual Error	100	329755962	329755962	3297560		
Total	107	1859456182				

These three tests assess the significance of individual factors, 2-way interactions and 3-way interactions. The P-value < 0.05 indicates that these tests are satisfied.

Similarly, table 4.9 shows the analysis of variance obtained for dynamic modulus values of class B specimens

Table 4.9: Analysis of Variance for Dynamic Modulus of Class B Mixtures

Source	DF	Seq SS	Adj SS	Adj MS	F- test	P-value
Main Effects	3	1342509350	1325509749	441836583	183.21	0.000
2-Way Interactions	3	60317691	61096783	20365594	8.44	0.000
3-Way Interactions	1	980362	980362	980362	0.41	0.525
Residual Error	100	241163670	241163670	2411637		
Total	107	1644971073				

4.5 PHASE ANGLE RESULTS

Phase angle is the angle by which induced axial strain lags behind the applied compressive stress. It was observed that the phase angle initially increased with an increase in temperature and decrease in frequency. However, after reaching the temperature of 40˚C it tends to decrease with an increase in temperature with some exceptions. This trend can be observed as shown in Figure 4.20 and 4.21 for class A and class B phase angle values. It is evident from the figure that the phase angle initially increased with the increasing temperature, reached a peak value and then started decreasing. It can also be inferred from the figure that the phase angle increases with the increasing dynamic modulus at lower temperatures which implies that most of the energy is dissipated in viscoelasticity. The initial directly proportional relationship of the phase angle with the temperature can be explained by the fact that at lower temperatures and higher frequencies, the phase angle of asphalt mixtures is mainly affected by the binder. Therefore, it follows the trend of the phase angle of the binder. However, at low frequency and high temperatures, the phase angle is predominantly affected by the aggregate, and therefore the phase angle for asphalt mixtures decreases with decreasing frequency or increasing temperature, because of the aggregate influence and more energy is dissipated in viscoplasticity.

4.6 FULL FACTORIAL DESIGN FOR PHASE ANGLE

The process of factorial design of experiment was also used for phase angle as a response. The analysis of phase angle data for each gradation with and without bakelite modification was performed separately by considering three factors i.e. frequency, test temperature and bakelite percentage each with 2 levels. Therefore, 2^3 full factorial design of experiment was performed using MINITAB -16 software. Same factors as described in Table 4.3 were used for the said analysis.

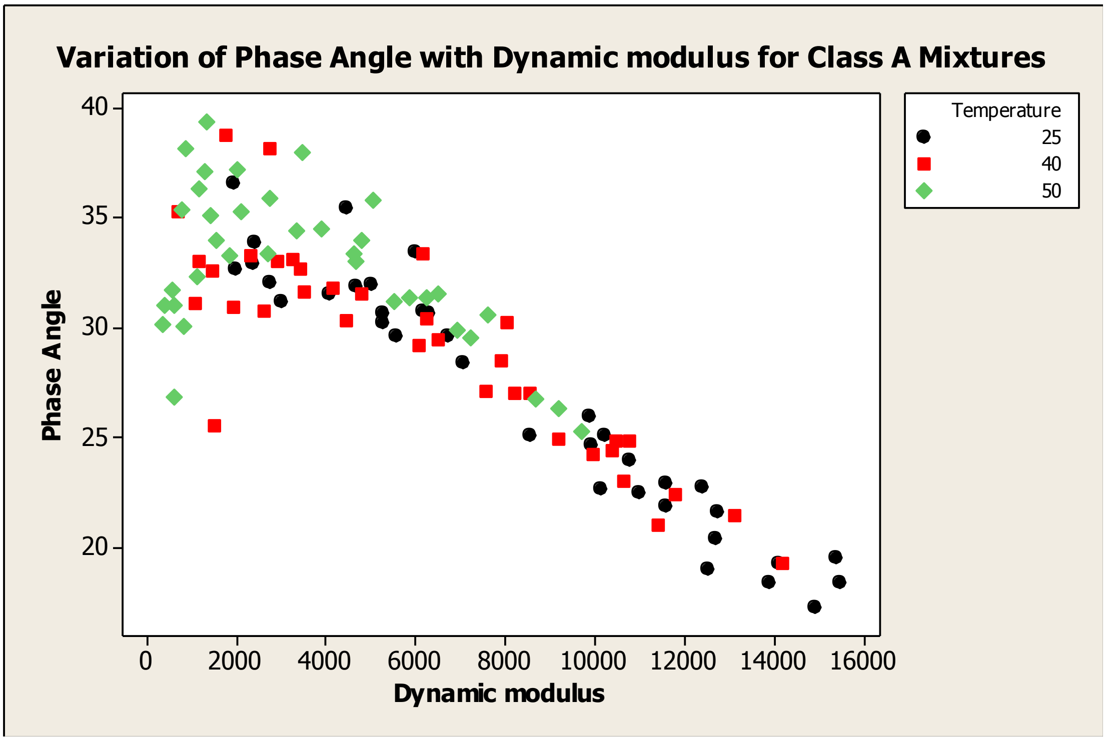


Figure 4.20: Variation of Phase angle for Class A Mixtures

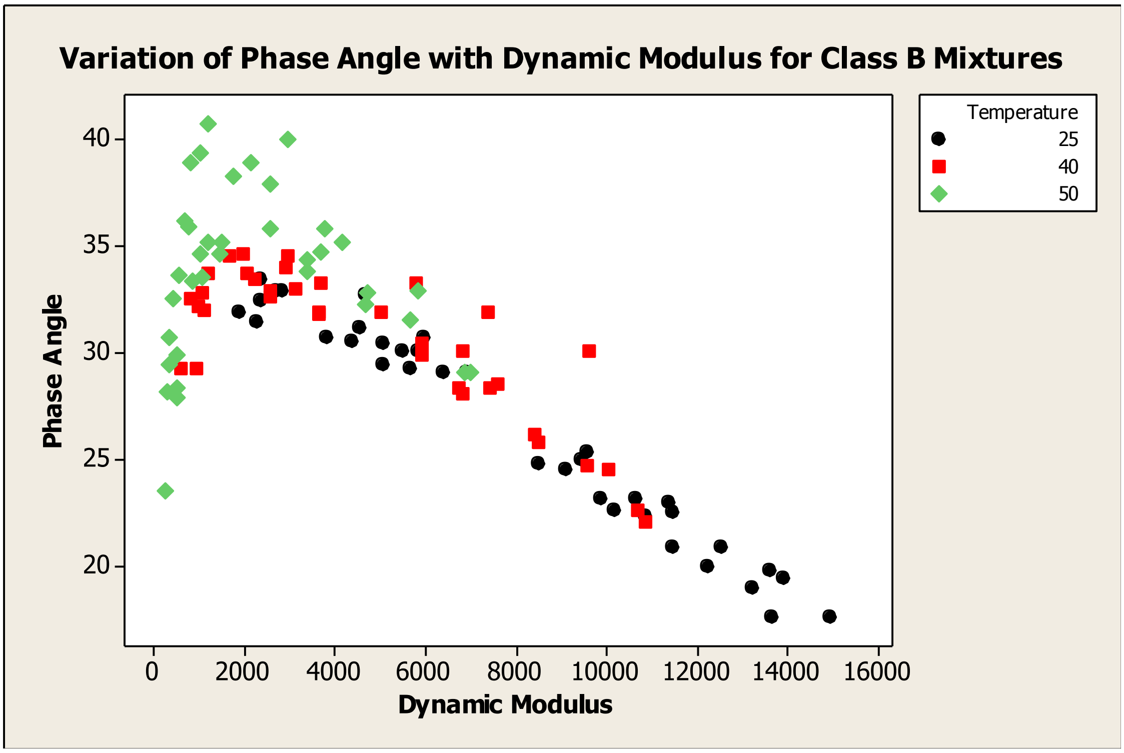


Figure 4.21: Variation of Phase Angle for Class B Mixtures

4.6.1 EFFECTS AND COEFFICIENTS

Table 4.10 and 4.11 shows the effects and coefficients values obtained by Minitab 16 software for the significant effects of each gradation. The factors and interaction of factors with high (negative or positive) values of effects and coefficients indicate that they have a greater impact on the Phase angle values. The effect of each term is equal to the twice of coefficient. A negative value of effect represents an inversely proportional relationship of the factor and the phase angle while, a positive value of effect represents a direct relationship of the factor and the phase angle.

Table 4.10: Effects and Coefficients Table for Phase angle of Class A Specimens

Term	Effects	Coefficient	SE Coeff	t- test	P - value
Constant		27.059	0.3222	83.98	0.000
Frequency (Hz)	-10.076	-5.038	0.3848	-13.09	0.000
Temperature (C)	7.623	3.811	0.3908	9.75	0.000
Bakelite (%age)	1.733	0.866	0.3222	2.69	0.008
Frequency(Hz)*Temperature(C)	4.073	2.036	0.4666	4.36	0.000
Frequency (Hz)*Bakelite (%age)	-0.459	-0.230	0.3848	-0.60	0.552
Temperature(C)*Bakelite (%age)	0.677	0.339	0.3908	0.87	0.388
Frequency (Hz)*Temperature(C)*Bakelite (%age)	0.300	0.150	0.4666	0.32	0.748

Table 4. 11: Effects and Coefficients Table for Phase Angle of Class B Specimens

Term	Effects	Coefficient	SE Coeff	t- test	P - value
Constant		23.81	0.2746	87.00	0.000
Frequency (Hz)	-7.195	-3.598	0.3279	-10.97	0.000
Temperature (C)	10.191	5.096	0.3330	15.30	0.000
Bakelite (%age)	7.571	3.785	0.2746	13.78	0.000
Frequency(Hz)*Temperature(C)	3.411	1.705	0.3977	4.29	0.000
Frequency (Hz)*Bakelite (%age)	-0.90	-0.405	0.3279	-1.37	0.173
Temperature(C)*Bakelite (%age)	-1.928	-0.964	0.3330	-2.89	0.005
Frequency (Hz)*Temperature(C)*Bakelite (%age)	1.789	0.895	0.3977	2.25	0.027

4.6.2 SIGNIFICANT EFFECTS AND INTERACTIONS

The factors and interaction of factors, which are most significant and affect phase angle of hot mix asphalt, are shown also in terms of Normal probability plot and Pareto plot generated as result of analysis using Minitab 16 software for each gradation separately. Figure 4.22 shows the Pareto plot with absolute values of effects for class A specimens with a reference line drawn, which shows the critical value of student-t (i.e. 1.98). The main factors i.e. Frequency, Temperature and Bakelite %age and the 2-way interactions i.e. frequency and temperature are beyond the reference line which indicates that these main effects and interactions (individual and 2-way) are critical and have influence on phase angle of class A hot mix asphalt mixes at a significance level of 5%.The other plot for getting the significant main effects and interactions is the normal probability plot as shown in figure 4.23 respectively. The factors or interactions in the normal probability plot, which are far away from the reference line, are considered as significant at 5% significance level while the factors or interactions, which are near the reference line or on the reference line, are insignificant.

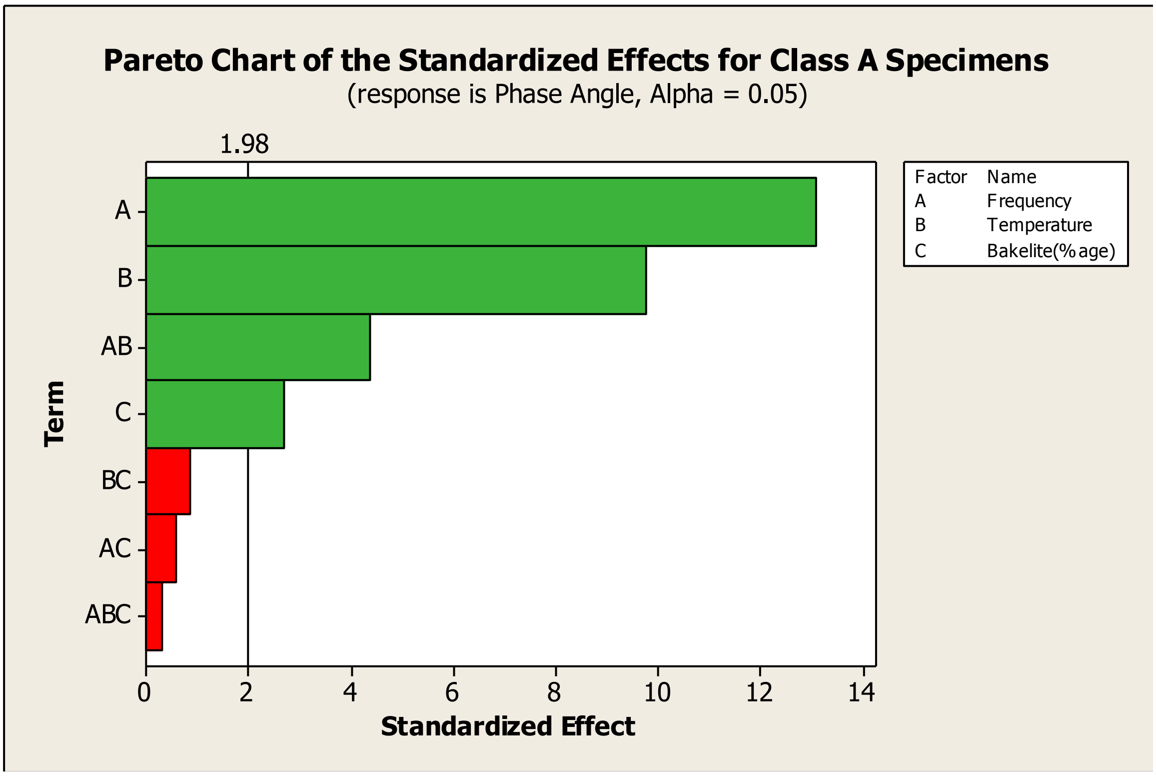


Figure 4.22: Pareto Plot for the Standardized Effects of Class A Specimens

Similarly, Figure 4.24 shows the Pareto plot with absolute values of effects for class B specimens with a reference line drawn, which shows the critical value of student-t (i.e. 1.98). The main factors i.e. Frequency, Temperature and Bakelite %age and the 2-way interactions i.e. frequency and temperature are beyond the reference line which indicates that these main effects and interactions (individual and 2-way) are critical and have influence on Phase angle of class B hot mix asphalt mixes at a significance level of 5%. The other plot for getting the significant main effects and interactions is the normal probability plot as shown in figure 4.25 respectively. The factors or interactions in the normal probability plot, which are far away from the reference line, are considered as significant at 5% significance level while the factors or interactions that are near the reference line or on the reference line are insignificant.

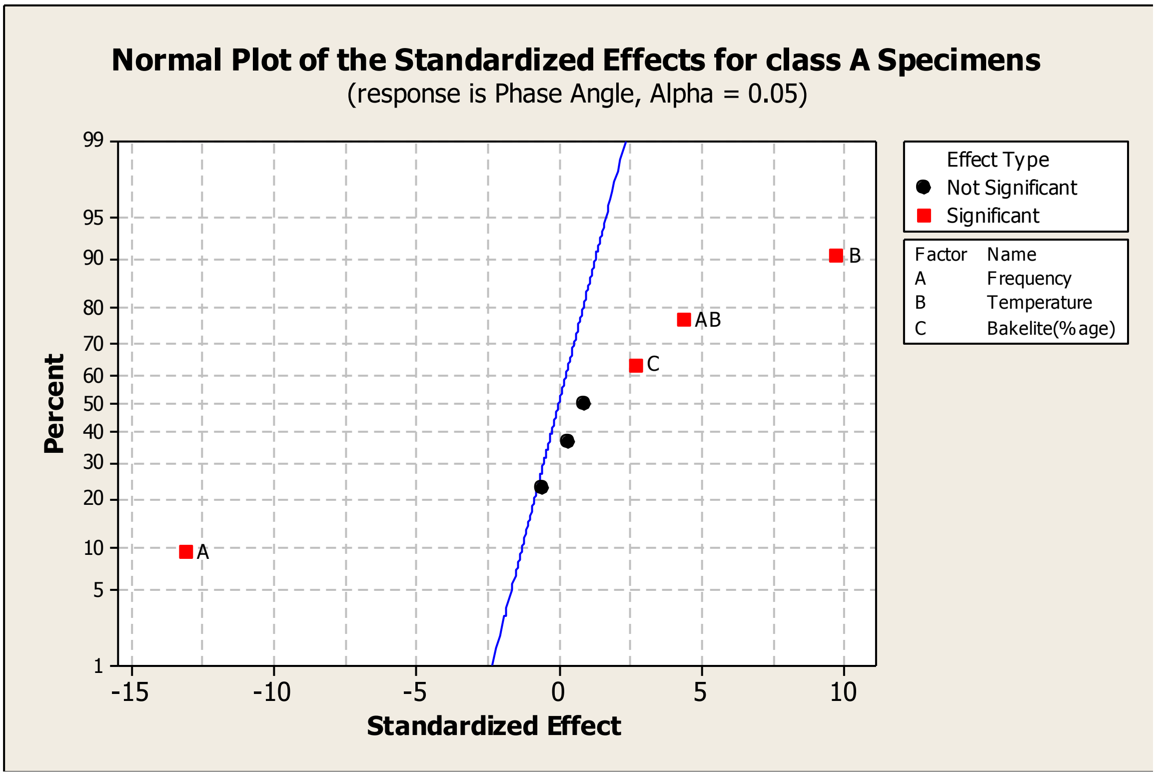


Figure 4. 23: Normal Plot of the Absolute Standardized Effects of Class A Specimens

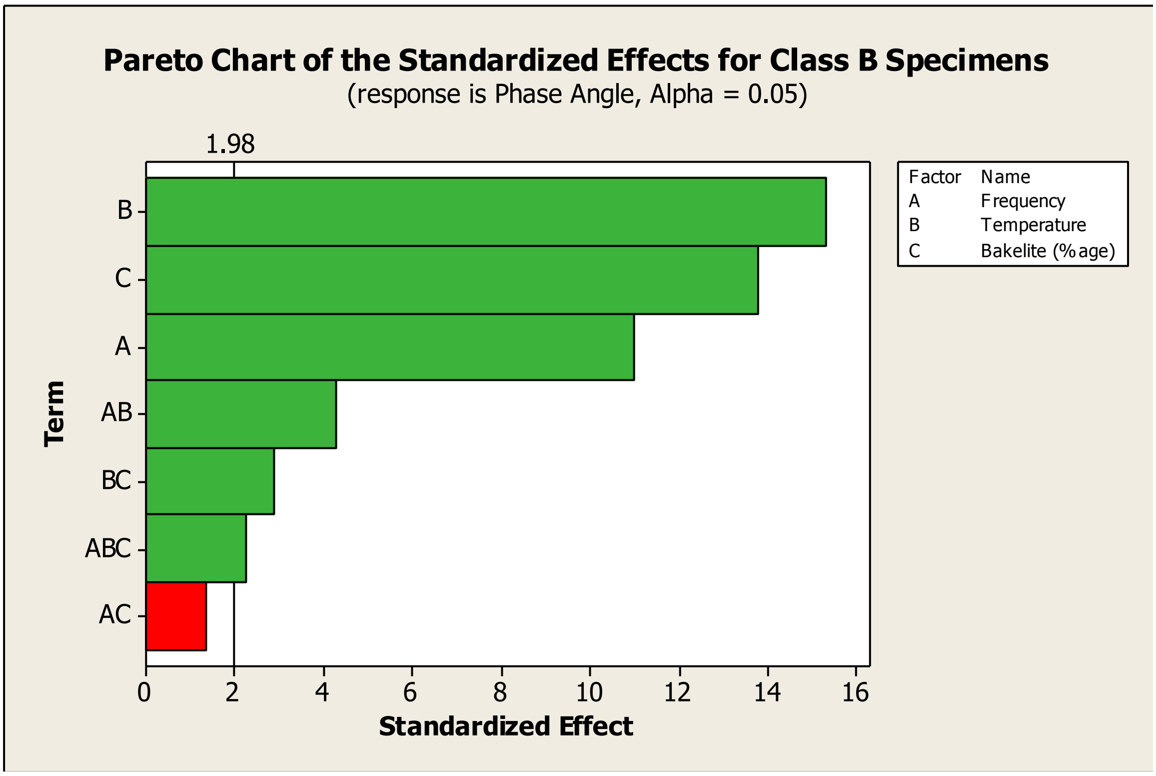


Figure 4.24: Pareto Plot for the Standardized Effects of Class B Specimens

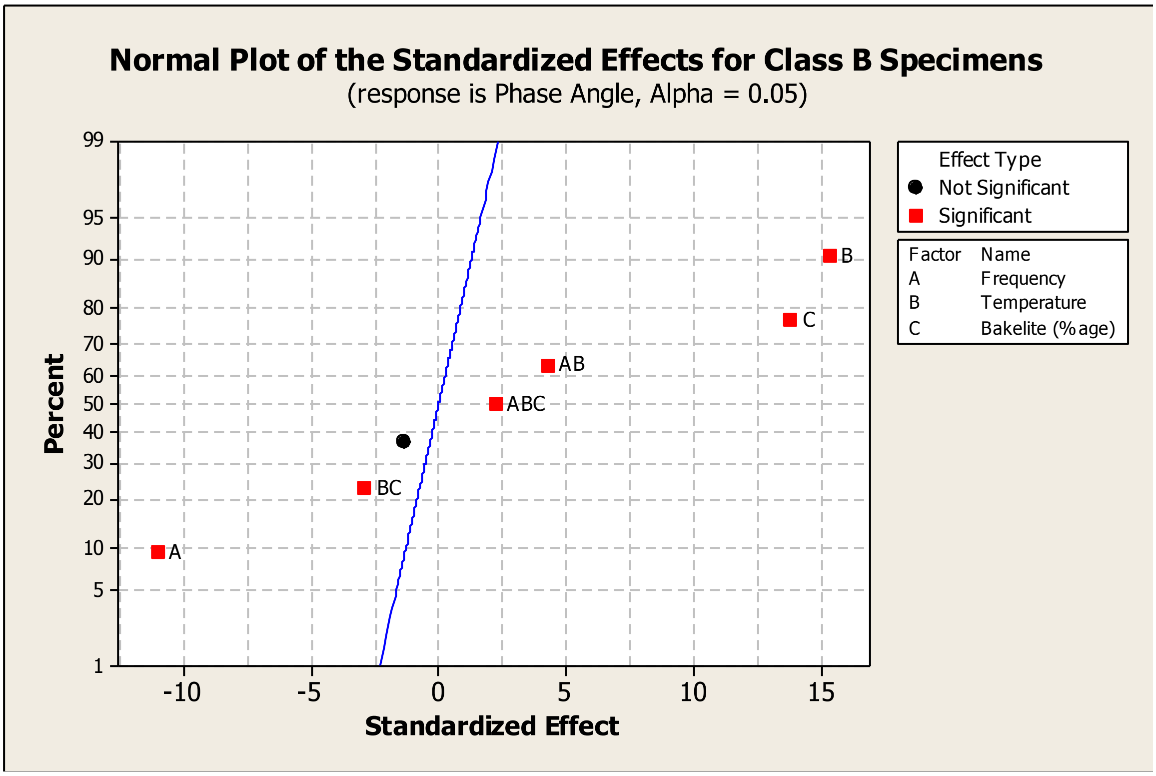


Figure 4.25: Normal Plot of the Absolute Standardized Effects of Class B Specimens

4.6.3 FACTORIAL PLOTS

The interaction and significant effects obtained from the normal probability plot and Pareto plots can be described in detail by factorial plots. The effects of main factors are shown by main effects plot, 2-way interactions by interaction plots and 3-way interaction by cubic plots respectively.

4.6.3.1 Main effects plot

The effects of frequency, temperature and bakelite %age of class A specimens are shown in figure 4.26 respectively. It can be clearly seen from the plot between frequency and phase angle that the value of phase angle is low at 25 Hz frequency as compared to the value at 0.1 Hz frequency.

The plot between temperature and phase angle shows that at lower temperature the value of phase angle is low as compared to the phase angle values at higher temperatures. The plot between phase angle and bakelite %age shows a very mild slope. Also the effect of this factor is significant.

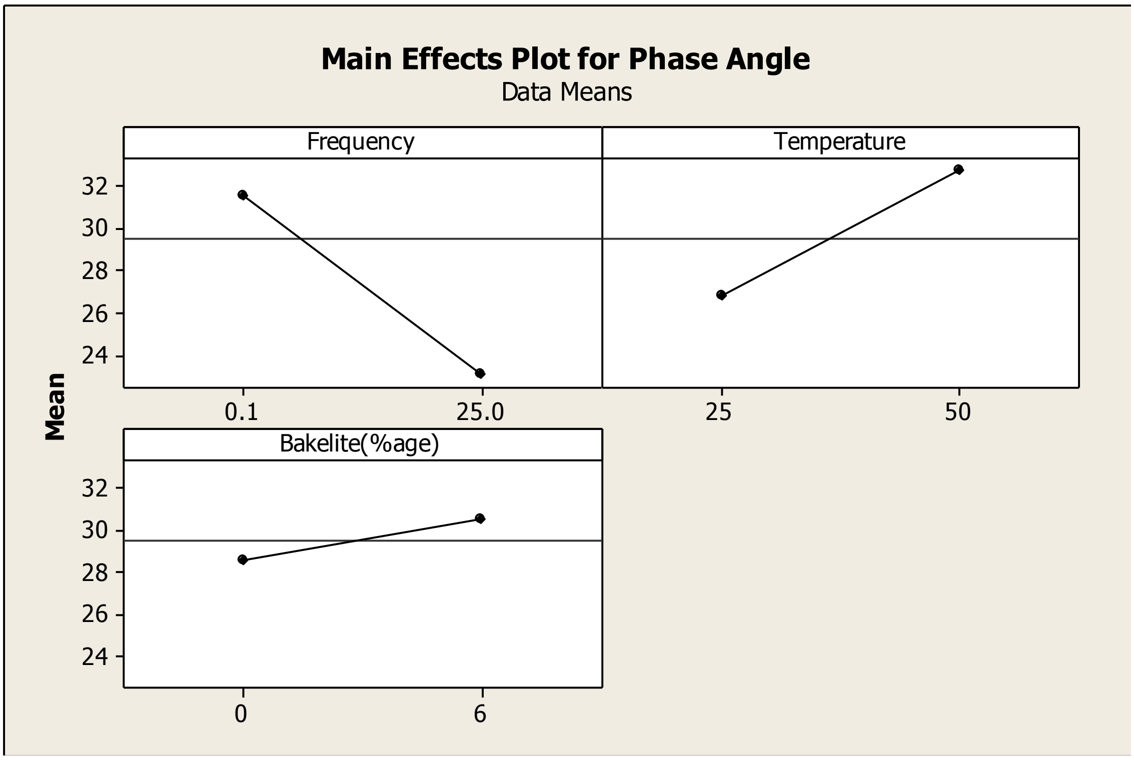


Figure 4. 26: Main Effect Plot of Class A Specimens

The effects of frequency, temperature and bakelite %age of class B specimens are shown in figure 4.27 respectively. It can be clearly seen from the plot between frequency and phase angle that the value of phase angle is low at 25 Hz frequency as compared to the value at 0.1 Hz frequency.

4.6.3.2 Interaction effect plots

Figure 4.28 shows the 2-way interaction plot of main factors for class A specimens. It is clear from the plot that the significant 2-way interactions are frequency and temperature, frequency and bakelite (%age) as represented by non-parallel lines. The most significant 2-way interaction is between frequency and temperature. It is clear from the plot that the effect of frequency is more prominent at a temperature of 25°C.

Figure 4.29 shows the 2-way interaction plot of main factors for class B specimens. It is clear from the plot that the significant 2-way interactions are frequency and temperature as represented by non-parallel lines. The most significant 2-way interaction is between frequency and temperature. It is clear from the plot that the effect of frequency is more prominent at a temperature of 50°C. It also shows that the combination of high temperature and higher frequency results in high phase angle values. At higher temperature and lower frequency the values of phase angle tend to decrease.

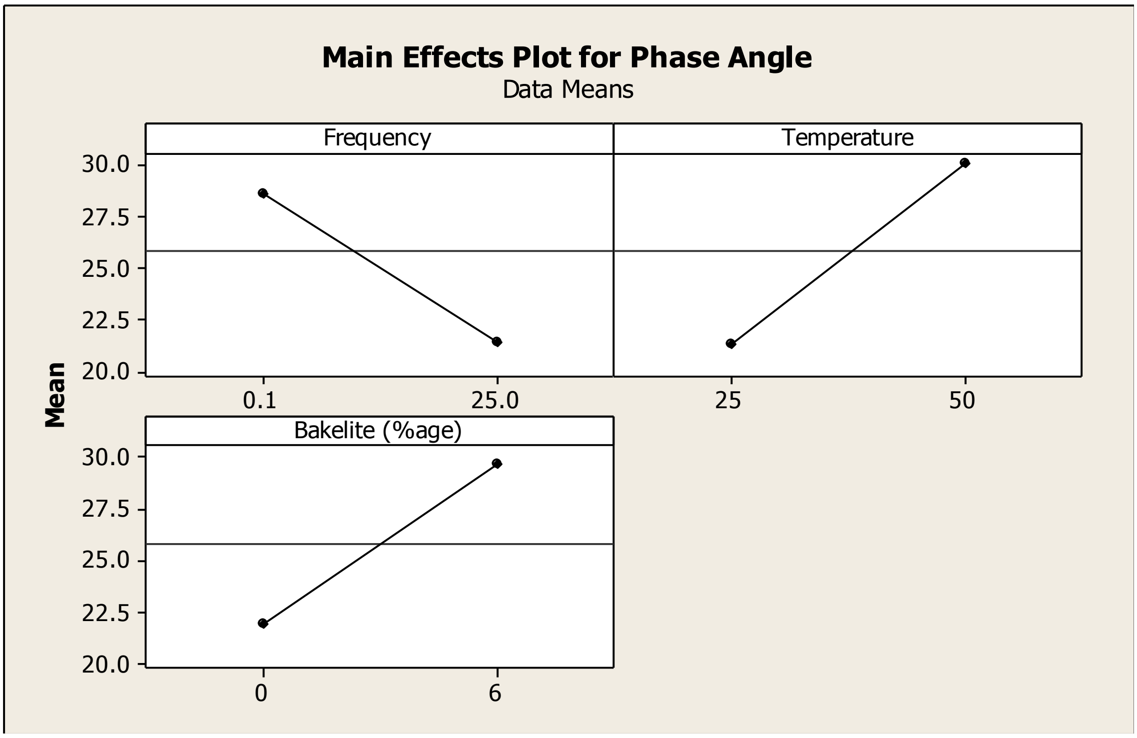


Figure 4. 27: Main Effect Plot of Class B Specimens

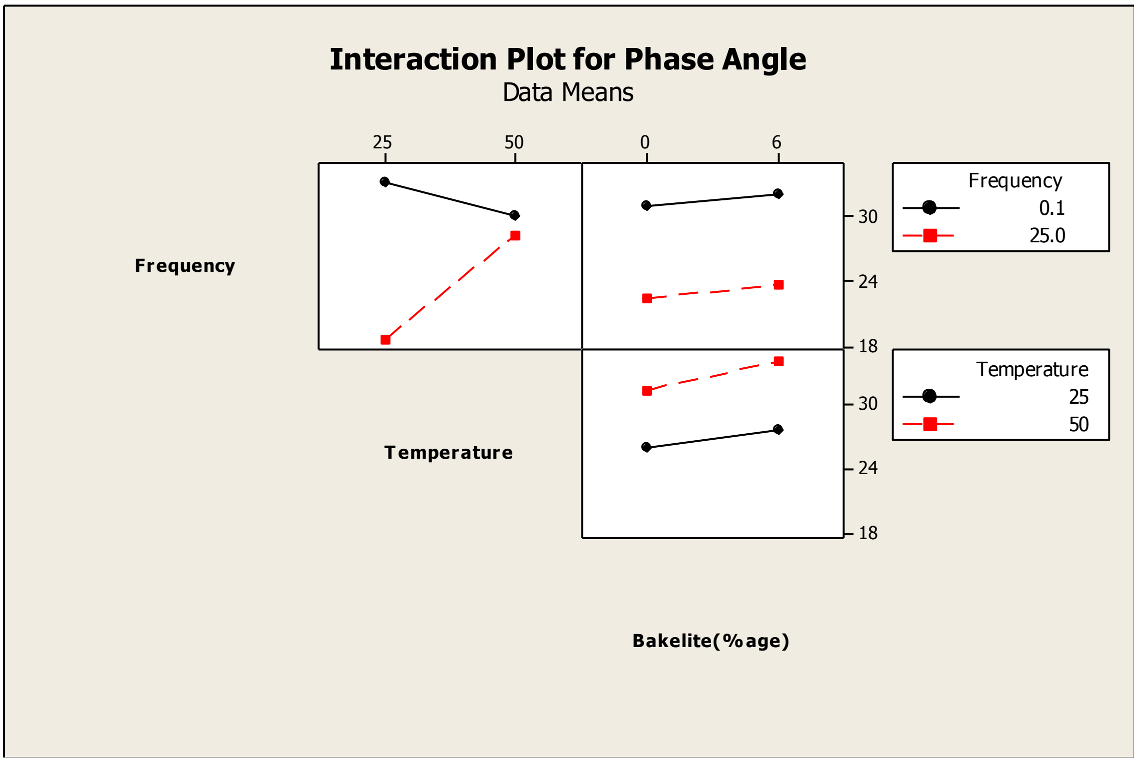


Figure 4. 28: Interaction Plot of Phase Angle for Class A Specimens

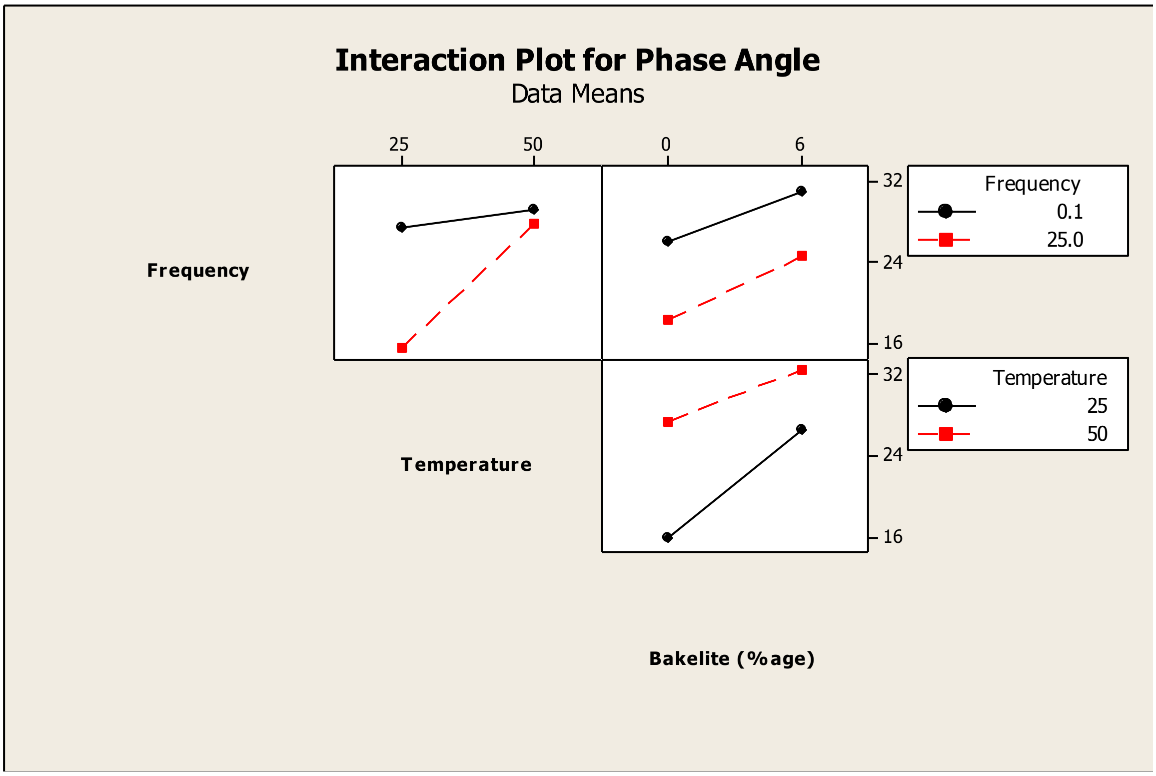


Figure 4.29: Interaction Plot of Phase Angle for Class B Specimens

4.7 SUMMARY

In this chapter the detailed statistical analysis of the results obtained after laboratory testing has been discussed. First of all, the pre-defined data analysis strategy was discussed and secondly, the data analysis carried out was presented in the form of tables and graphs. The results of wheel tracker tests for bakelite modified and controlled specimens of both gradations were presented in the form of bar charts which showed that bakelite modified specimens have greater resistance to rutting as compared to the controlled specimens. While full factorial design of experiment was performed for dynamic modulus data and phase angle data of each gradation separately.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

The purpose of this research work was to determine the effectiveness of bakelite on the performance of different HMA mixtures. Rutting is a very serious problem observed in flexible pavements. Wheel tracker and dynamic modulus tests are used for performance evaluation of hot mix asphalt. Two gradations (NHA class A and NHA class B for wearing course), bitumen penetration grade of ARL 60/70 and Margalla aggregates were used for tests. Bakelite was use as modifier to the asphalt mixtures for comparison of performance characterization. The optimum asphalt contents for NHA A and B gradation were determined using Superpave Mix design procedure with and without bakelite modification. The specimens with respect to their optimum asphalt contents were prepared for Asphalt Mixture Performance Tester (AMPT) and Wheel Tracker Test (WT) with and without bakelite modification. The amount of bakelite used in bakelite modified specimens was 6% by weight of the binder. The factors selected for the study of AMPT dynamic modulus tests, are wearing course gradations, temperature, asphalt modifier, loading frequencies and asphalt contents. While the factors selected for the study of Resilient Modulus tests, are wearing and base course gradations, asphalt contents and asphalt modifier. For each experimental combination, two replicate specimens were fabricated in randomized sequence. The major findings for Superpave Mix design, dynamic modulus testing, wheel tracker testing and analysis of experimental results are concluded as follows:

5.2 CONCLUSIONS

The conclusions drawn from the analysis of tests, as conducted in chapter 4, are categorized as conclusions for Wheel Tracker test and conclusions for Dynamic Modulus test, and presented as following;

5.2.1 WHEEL TRACKER TEST RESULTS

Based upon the performance parameters and analysis of wheel tracker tests, following conclusions are drawn:-

1 Modified mixtures of NHA class A and class B wearing course have least rutting susceptibility as compared to controlled mixtures of both gradations.

2 Modified mixtures of NHA class B has the least rutting susceptibility as compared to the other three mixtures.

3 20 to 38% increase in rutting resistance is observed when 6% bakelite is added.

5.2.2 DYNAMIC MODULUS TEST RESULTS

Based upon the performance parameters and analysis of AMPT Dynamic modulus tests, following conclusions are drawn:-

1. Stiffness of mixtures increased significantly with addition of modifier.
2. Factorial design reveals that loading frequency is the most significant factor followed by test temperature and bakelite content.
3. The most significant two-way interaction is observed between loading frequency and test temperature.

5.3 FUTURE WORK AND RECOMMENDATIONS

1 The purpose of this research was to investigate that how the addition of modifiers (bakelite) in bitumen influence the properties of hot mix asphalt mixtures specifically dynamic modulus and rutting using superpave mix design procedure.

2 Bakelite modified bitumen should be compared with PMB manufactured by ARL (in terms of performance and cost parameters).

3 Further studies should be carried out to investigate the effect of bakelite modification on the rheological properties of binders.

REFERENCES

AASHTO R 30-02. (2010). *Standard Procedure for Mixture Conditioning of Hot-Mix Asphalt (HMA).* American Association of State and Highway Transportation Officials.

AASHTO T 166. (2007). *Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface dry Specimens.* American Association of State and Highway Transportation Officials.

AASHTO T 312. (2004). *Standard Method of Test for Preparing and Determining the Density of Hot-Mix Asphalt (HMA).* American Association of State Highway and Transportation Officials.

AASHTO T 324-04. (2007). *Standard Test Method for Hamburg Wheel Track testing of Compacted Hot-Mix Asphalt (HMA).* American Association of State Highway and Transportation Officials.

AASHTO TP 62-07. (2007). *Standard Test Method for Determining Dynamic Modulus of Hot-Mix Asphalt (HMA).* American Association of State Highway and Transportation Officials.

Agardh, S. (2005). *Rut Depth Prediction on Flexible Pavements (Caliberation and Validation of incremental-recursive models), Doctoral Thesis.* Department of Technology and Society Lund Institute of Technology, Lund, Sweden.

Ahmed, J., Abdul Rehman, M.Y. and Hainin M.R.,. (2011). *Rutting Evaluation of Dense Graded Hot-MIx Asphalt Mixture.* Institute of Infrastructure Engineering and Susutainable Management (IIESM), Faculty of Civil Engineering, University of Technology MARA, Malaysia.

Al-Khateeb, G., Khedaywi, S.T., Al-Suleiman, T. I., and Najib, A.M.,. (2013). *Laboratory Study for Comparing Rutting Performance of Limestone and Basalt superpave Asphalt Mixtures.* ASCE Journal of Materials in Civil Engineering.

Asphalt Institute SP-2. (2001). *Superpave Mix Design.* Asphalt Institute Superpave Series No. 2 (SP-2), Third Edition, 2001.

ASTM C127. (2007). *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate.* ASTM International, West Conshohocken, PA.

ASTM C128. (2007). *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate.* ASTM International, West Conshohocken, PA.

ASTM C131. (2009). *Standard Test Method for Resistance to Degradation of Small-size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.* ASTM International, West Conshohocken, PA.

ASTM C535. (2007). *Standard Test Method for REsistance to Degradation of Large-size Coarse Aggregate by Abrasion and Impact in Los Angeles Machine.* ASTM International, West Conshohocken, PA.

ASTM D113. (2007). *Standard Test Method for Ductility of Bituminous Materials.* ASTM International, West Conshohocken, PA.

ASTM D2041. (2000). *Standard Test Method for Theoratical Maximum Specific Gravity and Density of Bituminous Paving Mixtures.* ASTM International, West Conshohocken, PA.

ASTM D2726. (2008). *Standard Test Method for Bulk Specific Gravity and density of Non-Absorptive Compacted Bituminous Mixtures.* ASTM International, West Conshohocken, PA.

ASTM D5. (2006). *Standard Test Method for Penetration of Bituminous Materials.* ASTM International, WEst Conshohocken, PA.

Bahia, H. U., Hanson, D. I., Zeng, M. and Anderson, R. M. (2001). *Characterization of Modified Asphalt Binders in Superpave Mix Design.* NCHRP REPORT 459,TRANSPORTATION RESEARCH BOARD, NATIONAL RESEARCH COUNCIL,NATIONAL ACADEMY PRESS WASHINGTON, D.C. — 2001.

Bonaquist, R.F., Christensen, D.W. and Stfump, W. (2003). *NCHRP Report 513: Simple Performance Test for Superpave Mix Design: First Article Development and Evaluation.* TRB, National Research Council, Washington, D.C.

Contreras, J., Fresno, D.C., Zamanillo, A.V., Celaya, M., and Vozmendiano, I. (2010). *Dynamic Modulus of Asphalt Mixtures using Ultrasonic Test.* Elsevier Journal of Non-Destructive Testing and Evaluation (NDT & E International).

Drakes, C. (2003). *Identification of a Physical Model to Evaluate Rutting Performance ofAsphalt Mixtures. Doctoral Dissertation.* University of Florida.

Elkins, G. E., Schmalzer, P., Thompson, T., and Simpson, A. (2003). *Long Term Pavement Performance - Information Management System - Pavement Performance Database User Reference Guide.* Report No: FHWA-RD-03-088, Federal Highway Adminstration.

Epps, J. (1990). *Cold Recycled Bituminous Concrete Using Bituminous Materials.* NCHRP Synthesis of Highway Practice. 160, Transportation Research Board, National reseach Council, Washington D.C .

FHWA. (2003). *The Distress Identification Manual for Long term Pavement Performance Program.* Federal Highway Authority, US Department of Transportation, Publication No:FHWA-RD-03-031, 2003.

Gardete, D., Santos, L.P. and Pais, J. (2005). *Permanent Deformation Characterization of Bituminous Mixtures: Laboratory Tests.* Department of Civil Engineering, University of Coimbra, Portugal.

Hafeez, I., Kamal, M.A. and Ahadi, M.R. (2012). *Rutting Prediction of Asphalt Mixtures from Asphalt Cements.* Transportation Research Journal (2012) Page 25-36.

Hafeez, I., Kamal, M.A. and Maher, M. (2012). *Characterization of Hot-Mix Asphalt Mixtures using Dynamic Modulus and Wheel Trackeing Testing.* Preceedings of Pakistan Academy of Sciences 49(2): 71-77 (2012).

Hafeez, I., Kamal, M.A. and Mirza, M.W. (2010). *Evaluation of Rutting in HMA Mixtures using Uniaxial Repeated Creep Load Test and Wheel Tracker Test.* Pak. J. Engg & Appl. Sci. Vol. 7, Pakistan.

Hafeez, I., Kamal, M.A., Mirza, M.W. and Aziz, A. (2012). *Investigating the Effect of Maximum Size of Aggregate on Rutting Potential of Stone Mastic Asphalt.* Pak. J. Engg & Applied Sciences, Vol, 10.

Hall, K.D. and Williams, S.G. (2000). *Aquisition and Evaluation of Hamburg Wheel Tracking Device.* Department of Civil Engineering, University of Arkansas.

Hassan, F.F. and Al-Jabri, F. (2011). *Laboratory Evaluation of Hot-Mix Asphalt Concrete containg Copper Slag Aggregate.* ASCE Journal of Materials in Civil Engineering.

Hussain, S. (2012). *Determining the Contribution of Different Structural Layers of Asphalt Pavement to Rutting using Transverse Profile Analysis* . MS Thesis, National University of Sciences and Technology, Pakistan.

Khan, K. (2008). *Impact of Superpave Mix Design Method on Rutting Behavior of Flexible Pavements.* Department of Civil Engineering, University of Engineering & Technology Taxila.

Khan, K.M. and Kamal, M.A. (2012). *Rutting Based Evaluation of Asphalt Mixes.* Pak. J. Engg. & Appl. Sci. Vol. 11, Pakistan.

kim, S., Sholar, G.A., Kim, J., and Byron, T. (2009). *Performance of Polymer Modified Asphalt Mixture with Reclaimed Asphalt Pavement.* Transportation Research Board Annual Meeting, January 2009 Washington, D.C.

Kim, Y., Lee, J., Baek, C., Yang, S., Kwon, S. and Suh, Y. (2012). *Performance Evaluation of Warm-and Hot-Mix Asphalt Mixtures based on Laboratory and Accelerated Pavement Tests.* Journal of Advances in Materials Science and Engineering, Volume 2012.

Miljkovic, M. and Radenberg, M. (2011). *Rutting Mechanisms and Advanced Laboratory Testing of Asphlat Mixtures Resistance Against Permanent Deformation* . (Vol. 9). Facta Universitatis, Series: Architecture and Civil Engineering.

Parker, F. and Brown, E.R. (1990). *A study of Rutting of Albama Asphalt Pavements.* Final Report Project Number ST 2019-9 Auburn University Highway Research Center, Auburn University, Albama. Sponsored by The State of Albama Highway Department Montgomery, Albama.

Rafique, H. (2012). *The Combined Effect of Varying Proportion of Fines an Anti-Strippimg Agent on Asphalt Concrete Mixtures.* MS Thesis, National University of Sciences and Technology, Pakistan.

Reddy, K. (2013). *Use of Waste Tire Rubber in Flexible Pavement Surfacing.* VSRD International Journal of Mechanical, Civil, Automobile and Production Engineering, Vol. 3 No. 5 May 2013.

Sund, E. (2002). *Optimal Road Maintenance and Operations-REsults of New Research and Analysis in Norway.* Nordic Road and Transportaion Research NPRA, Norway. http://www.nordicroads.com (12th July, 2012).

Warriach, A. (2012). *Mechanistic Characterization of Hot-Mix Asphalt for Pavemnts in Pakistan Using Simple Performance Test Protocols.* MS Thesis, National University of Sciences and Technology, Pakistan.

Weidong, L., Zheng, C., Shaopeng, W.U., Liantong, M.O. and Gang, L.I.U. (2006). *Rutting Resistance of Asphalt Overlay with Multilayer Wheel Trackering Test.* Jouranl of Wuhan Univeresity of Technology-Material Science Edition.

Witzack, M. (2005). *Simple Performance Tests: Summary of Recommended Methods and Database.* NCHRP Report 547, Arizona State University, Tempe, AZ.

Witzack, M.W. and Kaloush, k. (2002). *Simple Performance Test for Superpave Mix Design.* NCHRP Report 465, Arizona State University, Tempe, AZ.

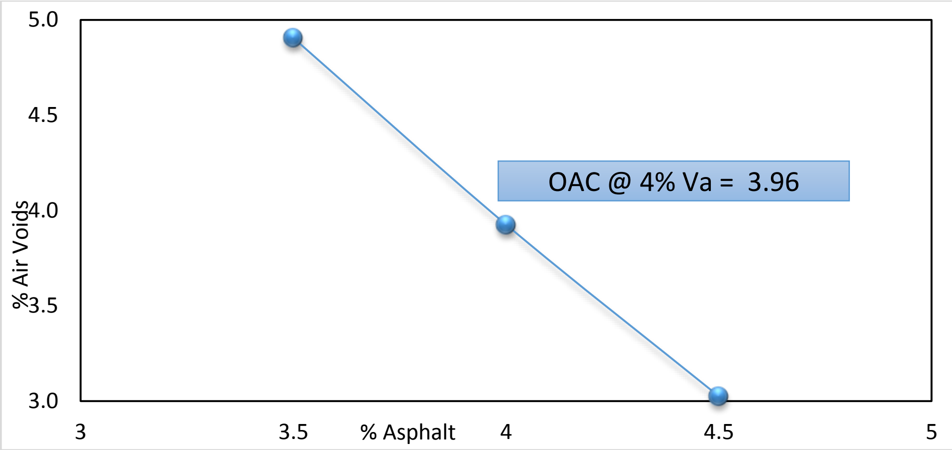
www. wikipedia.org. (2014, 5 10). Retrieved from www. wikipedia.org: http://en.wikipedia.org/wiki/Bakelite

www.pavementinteractive.org. (2014, 5 12). Retrieved from www.pavementinteractive.org: http://www.pavementinteractive.org/article/superpave-mix-design/

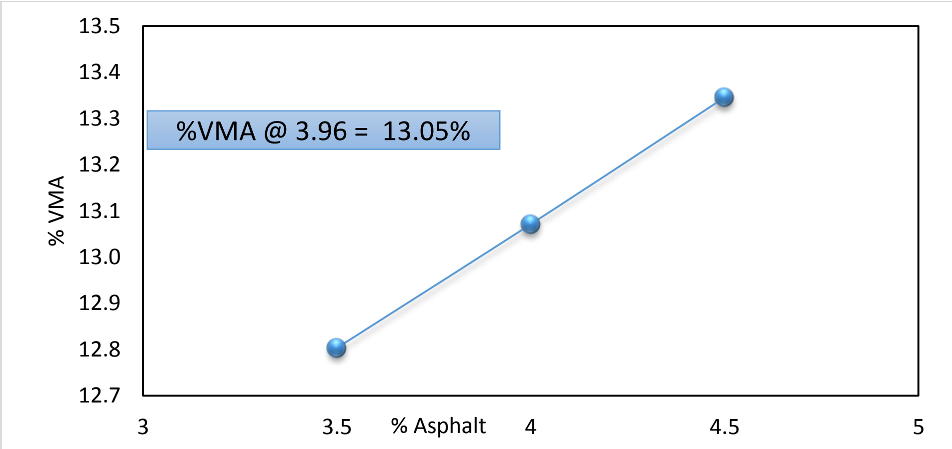
www.utexas.edu. (2014, 5 12). Retrieved from www.utexas.edu: http://www.utexas.edu/research/superpave/mix/

APPENDICES

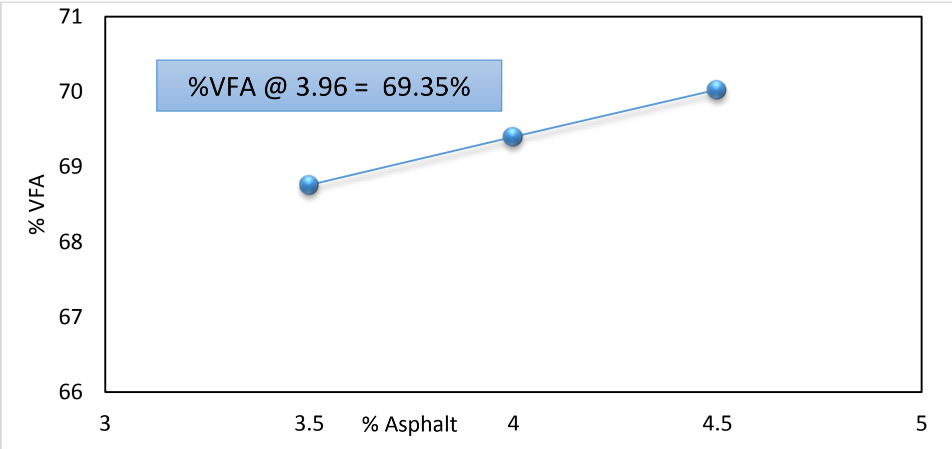
APPENDIX A - Volumetrics of Class A Unmodified Specimens



(a) Plot between Air voids and Asphalt Binder

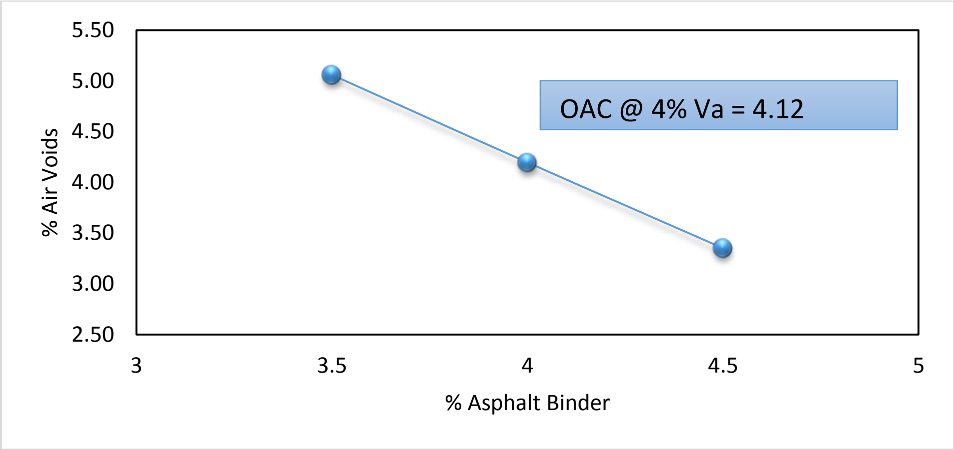


(b) Plot between VMA and Asphalt Binder

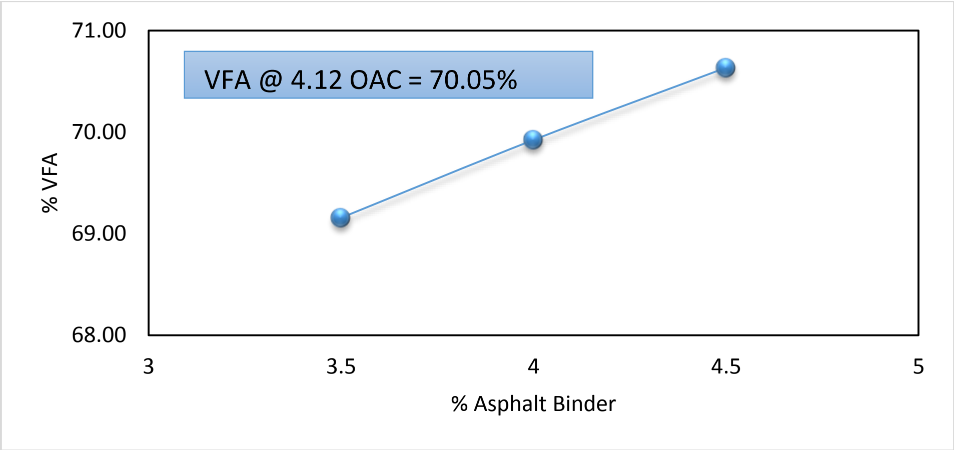


(c) Plot between VFA and Asphalt Binder

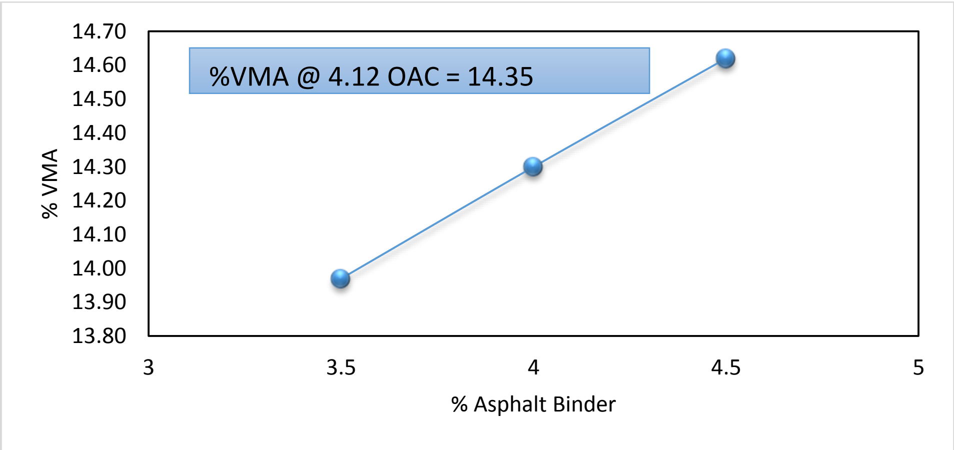
APPENDIX B - Volumetrics of Class B Unmodified Specimens



(a) Plot between Air voids and Asphalt Binder

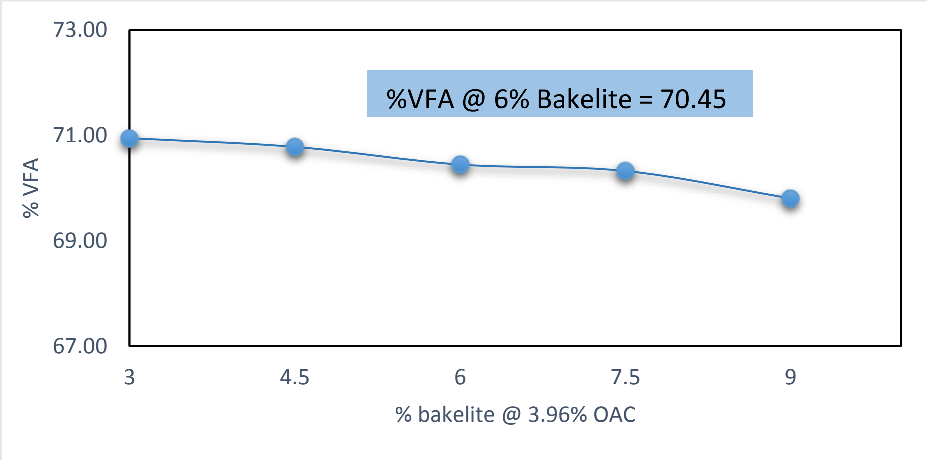


(b) Plot between VMA and Asphalt Binder

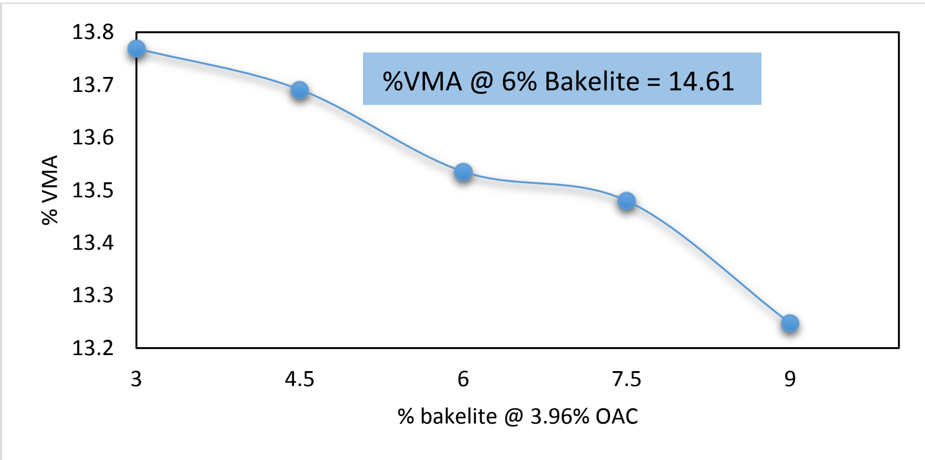


(c) Plot between VFA and Asphalt Binder

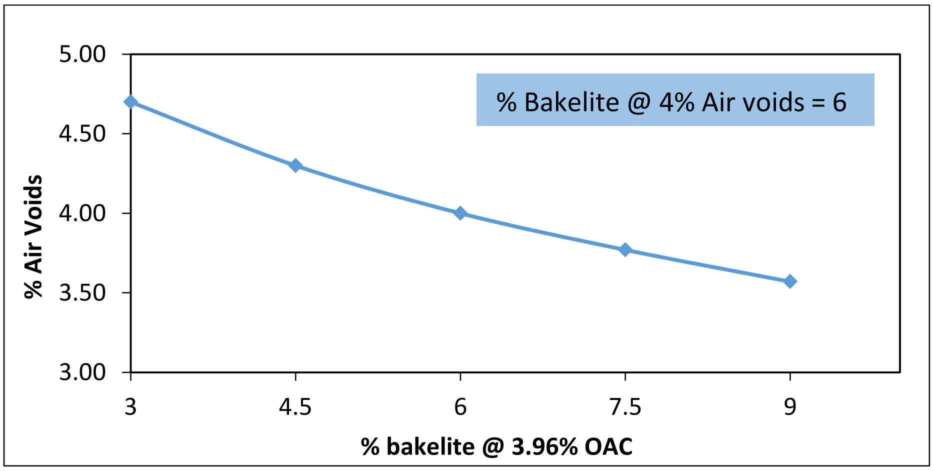
APPENDIX C - Volumetrics of Class A Modified Specimens



(a) Plot between VFA and %Bakelite

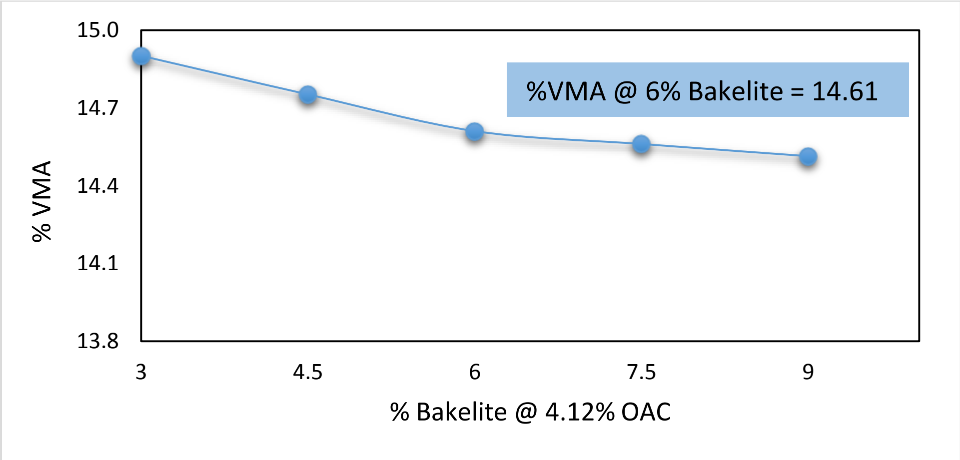


(b) Plot between VMA and %Bakelite

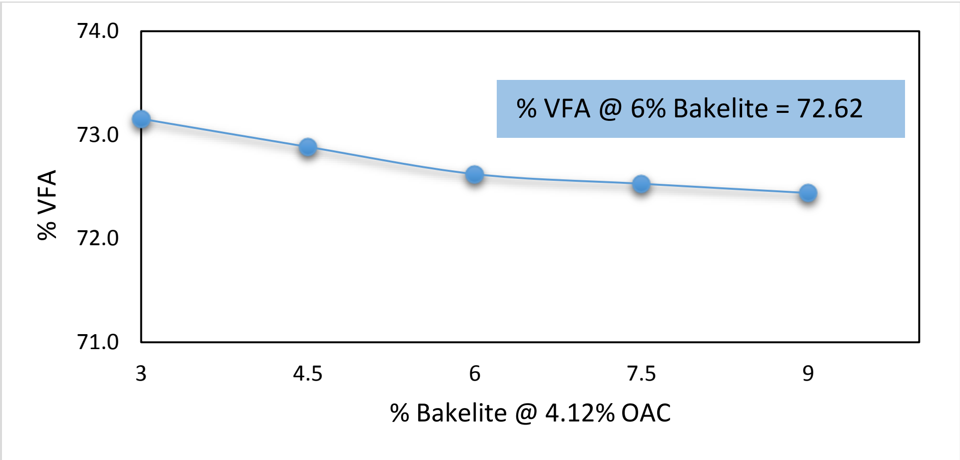


(c) Plot between Air voids and %Bakelite

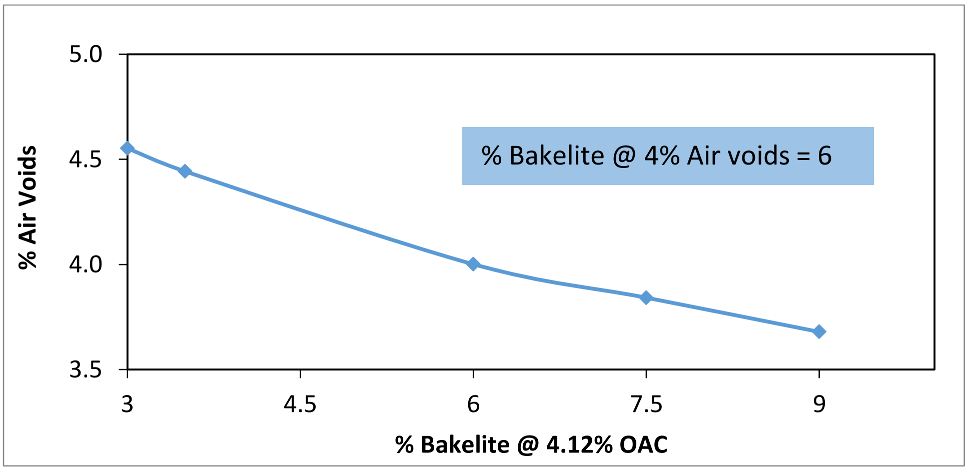
APPENDIX D – Volumetrics of Class B Modified Specimens



(a) Plot between VFA and %Bakelite



(b) Plot between VMA and %Bakelite



(c) Plot between Air voids and %Bakelite

APPENDIX E – AMPT Dynamic Modulus Software Results

Data file name: D:\RESULTS\adnan yousaf21spt\CLass A 4.5%\Sample 2A-50.D006
Project name: MS THESIS ADNAN
Operators name: Adnan Yousaf
Loading Rates: 25 Hz,10 Hz,5 Hz,1 Hz,0.5 Hz,0.1 Hz
Comments: DYNAMIC MODULUS

Target test temperature (°C): 50
Target confining stress (kPa): 0

Specimen Information

Identification: Sample 2NHA CLASS A
Conditioning time: 2 HRS
Properties/Comments: DYNAMIC MODULUS

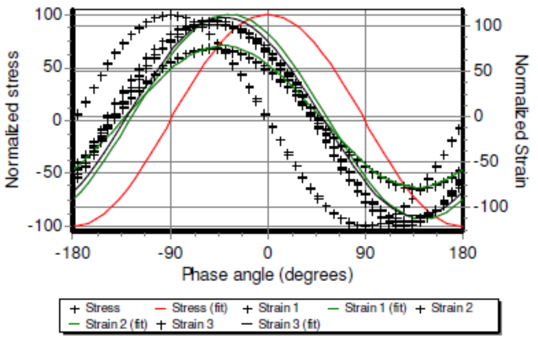
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	99.0	99.0	99.0				99.0	
Height (mm)	150.0	151.0	150.0				150.3	0.577

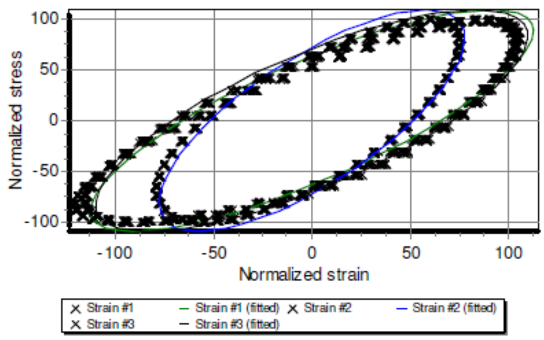
Cross-sectional area (mm²): 7697.7

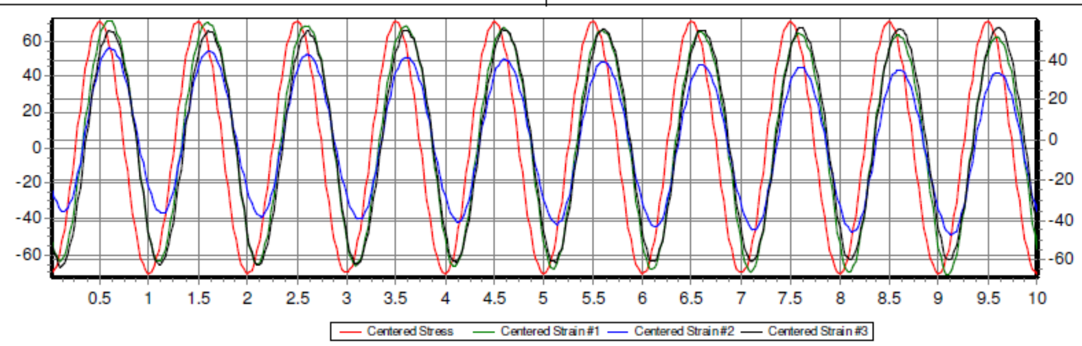
Test Data [1 Hz Plots]

Test date and time: Mon, Nov 25, 2013, 12:59 PM
Dynamic modulus (MPa): 1339
Phase angle (degrees): 39.32
Average temperature (°C): 50.0
Average confining pressure (kPa): 0.0
Warnings:

Drift for the applied load (%): 0.1
Standard error for the applied load (%): 0.4
Average drift for the deformations (%): 12.9
Average standard error for the deformations (%): 4.1
Uniformity coefficient for the deformations (%): 15.9
Uniformity coefficient for the deformation phase angles (degrees): 2.6







UTS006 2.21 SPT Dynamic Modulus Test

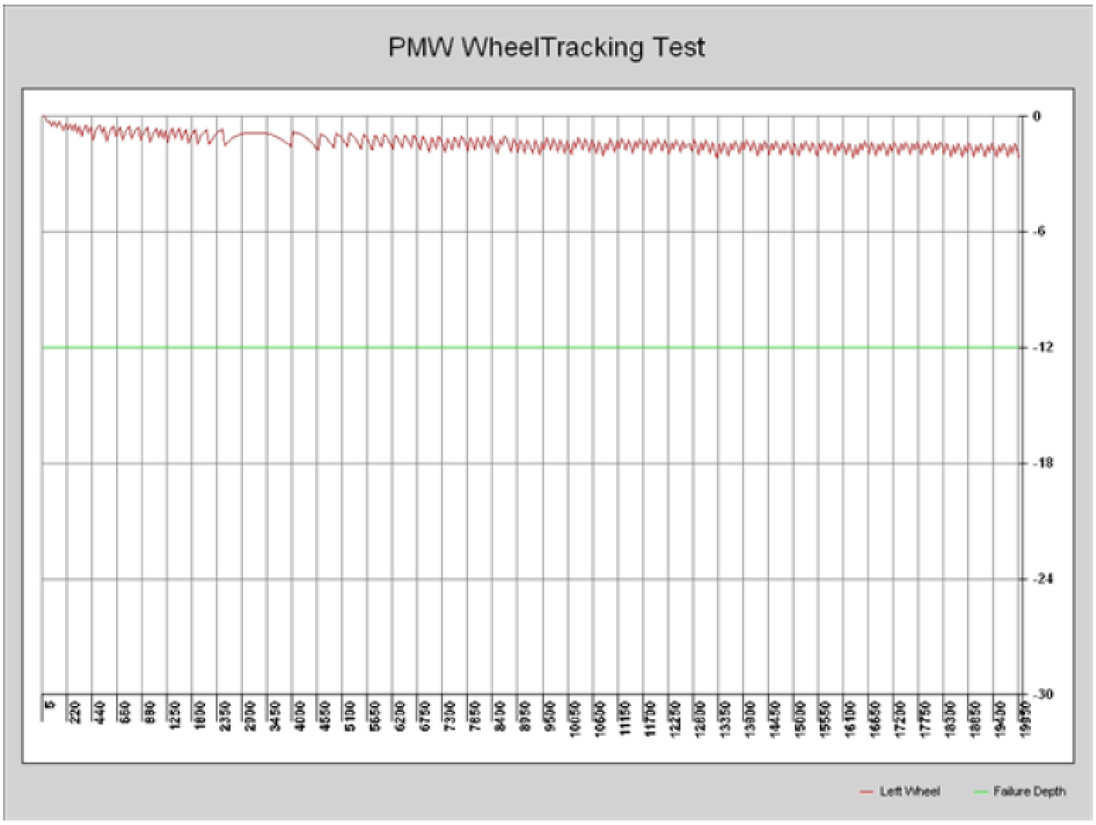
Print date: 11/26/2013 4:08:14 PM

APPENDIX F – Wheel Tracker Software Result

WheelTracker Report

Project Name:	MS THESIS	**Date:**	10/24/2013
Project Number:	01	**Date Sampled:**	10/22/2013
Job Number:	NHA CLASS A SAMPLE 1	**Lab Number:**	001
Project Engineer:	ADNAN	**Mix Type:**	NHA CLASS A
Submitted By:	ADNAN	**Asphalt Grade:**	3.96% 60/70
Temperature:	0	**Pit Source:**	Margalla
Comments:	Date 22-10-2013 NHA Class A No 1		

	Left
Max Impression:	-2.19 mm Pass #: 16300 / Pt: 9
Fail Depth: 12.5mm	PASSED



APPENDIX G – Factorial Analysis of Dynamic Modulus values Using Minitab – 16 Software

NHA Class A Dynamic Modulus Analysis

Estimated Effects and Coefficients for Dynamic modulus (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		8171	208.1	39.27	0.000
frequency	9033	4517	248.5	18.18	0.000
Temperature	-5359	-2680	252.4	-10.62	0.000
Bakelite %age	1402	701	208.1	3.37	0.001
frequency*Temperature	-1563	-781	301.4	-2.59	0.011
frequency*Bakelite %age	470	235	248.5	0.95	0.347
Temperature*Bakelite %age	-220	-110	252.4	-0.44	0.663
frequency*Temperature*Bakelite %age	-147	-73	301.4	-0.24	0.808

S = 1815.92   PRESS = 390332920

R-Sq = 82.27%   R-Sq(pred) = 79.01%   R-Sq(adj) = 81.02%

Analysis of Variance for Dynamic modulus (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	1504061307	1445807008	481935669	146.15	0.000
2-Way Interactions	3	25443396	25629424	8543141	2.59	0.057
3-Way Interactions	1	195517	195517	195517	0.06	0.808
Residual Error	100	329755962	329755962	3297560		
Lack of Fit	28	285974498	285974498	10213375	16.80	0.000
Pure Error	72	43781464	43781464	608076		
Total	107	1859456182				

NHA Class B Dynamic Modulus Analysis

Estimated Effects and Coefficients for Dynamic Modulus (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		6871	178.0	38.61	0.000
Frequency	7587	3793	212.5	17.85	0.000
Temperature	-6723	-3362	215.8	-15.58	0.000
Bakelite %age	1211	605	178.0	3.40	0.001
Frequency*Temperature	-2426	-1213	257.7	-4.71	0.000
Frequency*Bakelite %age	638	319	212.5	1.50	0.137
Temperature*Bakelite %age	387	194	215.8	0.90	0.372
Frequency*Temperature*Bakelite %age	329	164	257.7	0.64	0.525

S = 1552.94   PRESS = 288272203

R-Sq = 85.34%   R-Sq(pred) = 82.48%   R-Sq(adj) = 84.31%

Analysis of Variance for Dynamic Modulus (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	1342509350	1325509749	441836583	183.21	0.000
2-Way Interactions	3	60317691	61096783	20365594	8.44	0.000
3-Way Interactions	1	980362	980362	980362	0.41	0.525
Residual Error	100	241163670	241163670	2411637		
Lack of Fit	28	198899173	198899173	7103542	12.10	0.000
Pure Error	72	42264497	42264497	587007		
Total	107	1644971073				

APPENDIX H - Factorial Analysis of Phase Angle values using Minitab 16 Software

NHA Class A Phase angle Analysis

Estimated Effects and Coefficients for Phase Angle (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		27.059	0.3222	83.98	0.000
Frequency	-10.076	-5.038	0.3848	-13.09	0.000
Temperature	7.623	3.811	0.3908	9.75	0.000
Bakelite(%age)	1.733	0.866	0.3222	2.69	0.008
Frequency*Temperature	4.073	2.036	0.4666	4.36	0.000
Frequency*Bakelite(%age)	-0.459	-0.230	0.3848	-0.60	0.552
Temperature*Bakelite(%age)	0.677	0.339	0.3908	0.87	0.388
Frequency*Temperature*Bakelite(%age)	0.300	0.150	0.4666	0.32	0.748

S = 2.81185   PRESS = 920.906
R-Sq = 73.27%   R-Sq(pred) = 68.86%   R-Sq(adj) = 71.40%

Analysis of Variance for Phase Angle (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F
Main Effects	3	2007.67	2080.59	693.53	87.72
Frequency	1	1291.65	1355.27	1355.27	171.41
Temperature	1	610.56	752.27	752.27	95.15
Bakelite(%age)	1	105.46	57.17	57.17	7.23
2-Way Interactions	3	158.50	158.97	52.99	6.70
Frequency*Temperature	1	150.56	150.56	150.56	19.04
Frequency*Bakelite(%age)	1	2.59	2.82	2.82	0.36
Temperature*Bakelite(%age)	1	5.35	5.93	5.93	0.75
3-Way Interactions	1	0.82	0.82	0.82	0.10
Frequency*Temperature*Bakelite(%age)	1	0.82	0.82	0.82	0.10
Residual Error	100	790.65	790.65	7.91	
Lack of Fit	28	449.64	449.64	16.06	3.39
Pure Error	72	341.01	341.01	4.74	
Total	107	2957.64			

Source	P
Main Effects	0.000
Frequency	0.000
Temperature	0.000
Bakelite(%age)	0.008
2-Way Interactions	0.000
Frequency*Temperature	0.000
Frequency*Bakelite(%age)	0.552
Temperature*Bakelite(%age)	0.388
3-Way Interactions	0.748
Frequency*Temperature*Bakelite(%age)	0.748
Residual Error	
Lack of Fit	0.000
Pure Error	

NHA Class B Phase angle Analysis

Estimated Effects and Coefficients for Phase Angle (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		23.891	0.2746	87.00	0.000
Frequency	-7.195	-3.598	0.3279	-10.97	0.000

Temperature	10.191	5.096	0.3330	15.30	0.000
Bakelite (%age)	7.571	3.785	0.2746	13.78	0.000
Frequency*Temperature	3.411	1.705	0.3977	4.29	0.000
Frequency*Bakelite (%age)	-0.900	-0.450	0.3279	-1.37	0.173
Temperature*Bakelite (%age)	-1.928	-0.964	0.3330	-2.89	0.005
Frequency*Temperature* Bakelite (%age)	1.789	0.895	0.3977	2.25	0.027

S = 2.39633   PRESS = 681.011
R-Sq = 87.27%   R-Sq(pred) = 84.91%   R-Sq(adj) = 86.38%

Analysis of Variance for Phase Angle (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F
Main Effects	3	3658.22	3046.54	1015.51	176.85
Frequency	1	652.40	691.12	691.12	120.35
Temperature	1	1365.55	1344.55	1344.55	234.14
Bakelite (%age)	1	1640.27	1091.14	1091.14	190.02
2-Way Interactions	3	250.23	166.63	55.54	9.67
Frequency*Temperature	1	105.60	105.60	105.60	18.39
Frequency*Bakelite (%age)	1	8.19	10.81	10.81	1.88
Temperature*Bakelite (%age)	1	136.45	48.12	48.12	8.38
3-Way Interactions	1	29.06	29.06	29.06	5.06
Frequency*Temperature*Bakelite (%age)	1	29.06	29.06	29.06	5.06
Residual Error	100	574.24	574.24	5.74	
Lack of Fit	28	355.77	355.77	12.71	4.19
Pure Error	72	218.46	218.46	3.03	
Total	107	4511.75			

Source	P
Main Effects	0.000
Frequency	0.000
Temperature	0.000
Bakelite (%age)	0.000
2-Way Interactions	0.000
Frequency*Temperature	0.000
Frequency*Bakelite (%age)	0.173
Temperature*Bakelite (%age)	0.005
3-Way Interactions	0.027
Frequency*Temperature*Bakelite (%age)	0.027
Residual Error	
Lack of Fit	0.000
Pure Error	
Total	

APPENDIX I – Dynamic Modulus values of Class A & B Mixtures

NHA CLASS A Dynamic Modulus values

Dynamic Modulus Test Results For 19mm NMAS with 0% Bakelite

Temperature(Celcius)	Frequency(Hz)	Dynamic Modulus(MPa)			Mean	Std Dev	CV(%)
		Specimen 1	Specimen 2	Specimen 3			
25	25	13857	14102	12488	13482.33	710.18	5.27
	10	11557	11567	10122	11082.00	678.83	6.13
	5	9886	9864	8553	9434.33	623.26	6.61
	1	6275	5976	5258	5836.33	426.77	7.31
	0.5	4974	4438	4035	4482.33	384.62	8.58
	0.1	2388	1915	1962	2088.33	212.76	10.19
40	25	10383	10760	10633	10592.00	156.62	1.48
	10	7885	8045	8196	8042.00	126.98	1.58
	5	6226	6129	6503	6286.00	158.47	2.52
	1	3231	2711	3502	3148.00	328.21	10.43
	0.5	2293	1758	2595	2215.33	346.09	15.62
	0.1	1053	665.3	1475	1064.43	330.66	31.06
50	25	9173	7619	5851	7547.67	1357.14	17.98
	10	6506	5028	3897	5143.67	1068.26	20.77
	5	4760	3473	2723	3652.00	841.18	23.03
	1	2008	1339	1136	1494.33	372.55	24.93
	0.5	1292	871.7	759.8	974.50	229.11	23.51
	0.1	548.7	388	351.3	429.33	85.72	19.97

Dynamic Modulus Test Results For 19mm NMAS with 6 % Bakelite

Temperature(Celcius)	Frequency(Hz)	Dynamic Modulus(Mpa)			Mean	Std Dev	CV(%)
		Specimen 1	Specimen 2	Specimen 3			
25	25	15442	15381	14891	15238.00	246.63	1.62
	10	12701	12362	12686	12583.00	156.39	1.24
	5	10738	10218	10953	10636.33	308.55	2.90
	1	6717	6150	7046	6637.67	370.07	5.58
	0.5	5240	4669	5555	5154.67	366.71	7.11
	0.1	2733	2339	3004	2692.00	273.03	10.14
40	25	14163	13118	11411	12897.33	1134.28	8.79
	10	11768	10441	9194	10467.67	1051.00	10.04
	5	9957	8527	7560	8681.33	984.64	11.34
	1	6040	4784	4145	4989.67	787.18	15.78
	0.5	4457	3415	2893	3588.33	650.16	18.12
	0.1	1933	1433	1138	1501.33	328.13	21.86
50	25	9685	8680	6932	8432.33	1137.47	13.49
	10	7200	6249	4631	6026.67	1060.51	17.60
	5	5501	4642	3322	4488.33	896.18	19.97
	1	2677	2113	1527	2105.67	469.51	22.30
	0.5	1818	1404	1103	1441.67	293.11	20.33
	0.1	792.1	596.6	613.3	667.33	88.49	13.26

NHA CLASS B Dynamic Modulus values

Dynamic Modulus Test Results For 12.5mm NMAS with 0% Bakelite							
Temperature(Celcius)	Frequency(Hz)	Dynamic Modulus(MPa)			Mean	Std Dev	CV(%)
		Specimen 1	Specimen 2	Specimen 3			
25	25	13222	12226	13623	13023.67	587.31	4.51
	10	10825	10145	11461	10810.33	537.35	4.97
	5	9082	8474	9859	9138.33	566.83	6.20
	1	5652	5049	6369	5690.00	539.56	9.48
	0.5	4373	3807	5055	4411.67	510.23	11.57
	0.1	2256	1886	2679	2273.67	323.98	14.25
40	25	10026	6795	9567	8796.00	1427.28	16.23
	10	7570	4994	7421	6661.67	1180.79	17.73
	5	5907	3673	5905	5161.67	1052.65	20.39
	1	2915	1676	3133	2574.67	641.66	24.92
	0.5	1980	1178	2221	1793.00	445.86	24.87
	0.1	814.9	606.2	969.4	796.83	148.83	18.68
50	25	4149	2111	5814	4024.67	1514.30	37.63
	10	2543	1182	3777	2500.67	1059.83	42.38
	5	1737	820.8	2941	1832.93	868.22	47.37
	1	775.2	422	1022	739.73	246.23	33.29
	0.5	564.9	339.3	694.1	532.77	146.62	27.52
	0.1	304.5	225.9	332.8	287.73	45.22	15.72

Dynamic Modulus Test Results For 12.5mm NMAS with 6% Bakelite							
Temperature(Celcius)	Frequency(Hz)	Dynamic Modulus(MPa)			Mean	Std Dev	CV(%)
		Specimen 1	Specimen 2	Specimen 3			
25	25	13590	13907	14940	14145.67	576.39	4.07
	10	11344	11425	12537	11768.67	544.30	4.62
	5	9558	9417	10612	9862.33	533.21	5.41
	1	5973	5815	6897	6228.33	477.20	7.66
	0.5	4677	4522	5469	4889.33	414.74	8.48
	0.1	2330	2363	2826	2506.33	226.44	9.03
40	25	10832	9609	10681	10374.00	544.44	5.25
	10	8482	7381	8386	8083.00	497.93	6.16
	5	6811	5799	6733	6447.67	459.78	7.13
	1	3651	2965	3626	3414.00	317.65	9.30
	0.5	2543	2060	2557	2386.67	231.06	9.68
	0.1	1052	914	1119	1028.33	85.35	8.30
50	25	6970	6859	5634	6487.67	605.33	9.33
	10	4717	4677	3672	4355.33	483.47	11.10
	5	3388	3384	2583	3118.33	378.54	12.14
	1	1472	1453	1174	1366.33	136.22	9.97
	0.5	1036	1042	860.3	979.43	84.28	8.60
	0.1	507.5	517.9	492.7	506.03	10.34	2.04

APPENDIX J - Phase Angle Values of Class A & Class B Mixtures

NHA CLASS A Phase Angle values

Phase Angle Results For 19mm NMAS with 0% Bakelite

Temperature(Celcius)	Frequency(Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Mean	Std Dev	CV(%)
25	25	18.43	19.31	19.03	18.92	0.37	1.94
	10	21.88	22.92	22.64	22.48	0.44	1.95
	5	24.67	25.96	25.05	25.23	0.54	2.15
	1	30.63	33.41	30.21	31.42	1.42	4.52
	0.5	31.95	35.39	31.51	32.95	1.73	5.26
	0.1	33.89	36.58	32.63	34.37	1.65	4.79
40	25	24.36	24.82	22.97	24.05	0.79	3.27
	10	28.46	30.23	26.99	28.56	1.32	4.64
	5	30.37	33.36	29.43	31.05	1.68	5.40
	1	33.04	38.09	31.61	34.25	2.78	8.12
	0.5	33.22	38.71	30.77	34.23	3.32	9.70
	0.1	31.05	35.23	25.51	30.60	3.98	13.01
50	25	26.28	30.57	31.35	29.40	2.23	7.58
	10	31.55	35.79	34.44	33.93	1.77	5.21
	5	33.91	37.94	35.86	35.90	1.65	4.58
	1	37.17	39.32	36.28	37.59	1.28	3.39
	0.5	37.05	38.1	35.31	36.82	1.15	3.12
	0.1	31.68	31.02	30.16	30.95	0.62	2.01

Phase Angle Results For 19mm NMAS with 6 % Bakelite

Temperature(Celcius)	Frequency(Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Mean	Std Dev	CV(%)
25	25	18.41	19.54	17.29	18.41	0.92	4.99
	10	21.65	22.78	20.36	21.60	0.99	4.58
	5	23.96	25.1	22.47	23.84	1.08	4.52
	1	29.59	30.72	28.39	29.57	0.95	3.22
	0.5	30.67	31.87	29.61	30.72	0.92	3.01
	0.1	32.04	32.9	31.15	32.03	0.71	2.23
40	25	19.3	21.41	21.03	20.58	0.92	4.46
	10	22.4	24.82	24.89	24.04	1.16	4.82
	5	24.23	26.96	27.12	26.10	1.33	5.08
	1	29.2	31.48	31.8	30.83	1.16	3.76
	0.5	30.34	32.66	33.02	32.01	1.19	3.71
	0.1	30.91	32.56	32.97	32.15	0.89	2.77
50	25	25.23	26.74	29.87	27.28	1.93	7.08
	10	29.49	31.35	33.31	31.38	1.56	4.97
	5	31.16	32.98	34.38	32.84	1.32	4.01
	1	33.34	35.25	33.94	34.18	0.80	2.33
	0.5	33.25	35.1	32.27	33.54	1.17	3.50
	0.1	30.07	31.01	26.87	29.32	1.77	6.04

NHA CLASS B Phase Angle values

Phase Angle Results For 12.5mm NMAS with 0% Bakelite

Temperature(Celcius)	Frequency(Hz)	Phase Angle (Degrees)			Mean	Std Dev	CV(%)
		Specimen 1	Specimen 2	Specimen 3			
25	25	18.9	19.92	18.01	18.94	0.78	4.12
	10	22.33	22.54	20.95	21.94	0.71	3.21
	5	24.48	24.78	23.11	24.12	0.73	3.01
	1	29.23	29.45	28.23	28.97	0.53	1.83
	0.5	30.46	30.69	29.46	30.20	0.53	1.77
	0.1	31.44	31.84	31.08	31.45	0.31	0.99
40	25	24.49	30.07	24.68	26.41	2.59	9.79
	10	28.54	31.83	28.34	29.57	1.60	5.41
	5	30.41	33.21	29.88	31.17	1.46	4.69
	1	34	34.5	32.94	33.81	0.65	1.92
	0.5	34.61	33.73	33.42	33.92	0.50	1.49
	0.1	32.53	29.26	32.12	31.30	1.45	4.65
50	25	35.15	38.93	32.87	35.65	2.50	7.01
	10	37.88	40.7	35.83	38.14	2.00	5.23
	5	38.28	38.93	40.01	39.07	0.71	1.83
	1	35.84	32.52	39.34	35.90	2.78	7.76
	0.5	33.64	29.45	36.2	33.10	2.78	8.41
	0.1	28.13	23.52	30.7	27.45	2.97	10.82

Phase Angle Results For 12.5mm NMAS with 6 % Bakelite

Temperature(Celcius)	Frequency(Hz)	Phase Angle (Degrees)			Mean	Std Dev	CV(%)
		Specimen 1	Specimen 2	Specimen 3			
25	25	19.7	19.37	17.57	18.88	0.94	4.96
	10	22.92	22.5	20.8	22.07	0.92	4.15
	5	25.34	24.97	23.13	24.48	0.97	3.95
	1	30.68	30.09	29.02	29.93	0.69	2.30
	0.5	32.71	31.15	30.4	31.42	0.96	3.06
	0.1	33.42	32.41	32.88	32.90	0.41	1.25
40	25	22.05	30.07	22.6	24.91	3.66	14.69
	10	25.77	31.83	26.15	27.92	2.77	9.93
	5	28.03	33.21	28.33	29.86	2.37	7.95
	1	31.87	34.5	31.76	32.71	1.27	3.87
	0.5	32.84	33.73	32.62	33.06	0.48	1.45
	0.1	32.18	29.26	31.99	31.14	1.33	4.28
50	25	29.04	29.04	31.49	29.86	1.15	3.87
	10	32.77	32.24	34.73	33.25	1.07	3.22
	5	34.38	33.8	35.81	34.66	0.84	2.44
	1	35.11	34.57	35.16	34.95	0.27	0.76
	0.5	34.59	33.53	33.37	33.83	0.54	1.60
	0.1	29.85	27.85	26.87	28.19	1.24	4.40

APPENDIX K– Sequence of Sample Preparation

(a) Heating Aggregates Prior to Mixing

(b) Heating Asphalt prior to Mixing

(c) Mixing Machine

(d) Mixing of Mixture

(e) Mixed Sample

(f) Loose Mixture after Mixing, to be Conditioned

(g) Transferring Conditioned Mixture in Preheated Gyratory Mold

(h) SUPERPAVE Gyratory Compactor

(i) Placing Gyratory Mold in SGC

(j) Extraction of Compacted Specimen

(k) Coring of Specimen

(l) Cored Specimen

(m) Saw Cutting of Specimen

(n) Cored and Sawed Specimen

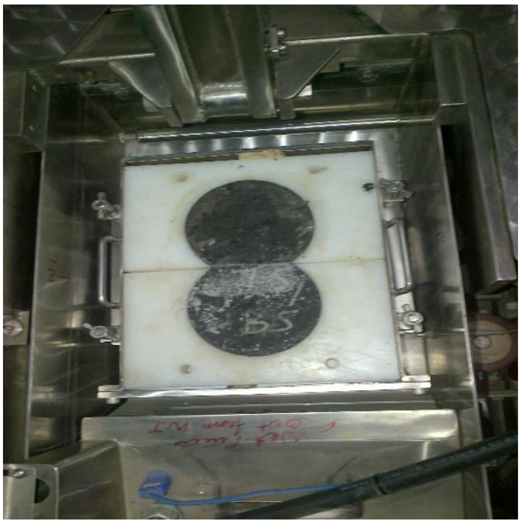
(o) Stacked Specimens for AMPT Dynamic modulus Tests

(p) Sawed Specimens for Wheel Tracker Test

APPENDIX L – Wheel Tracker Test

(a) Hamburg wheel tracker Device

(b) Fixing Specimen in Silicon Mould



(c) Placing Mould in Wheel tracker

(d) Setting the Test Parameters in Software

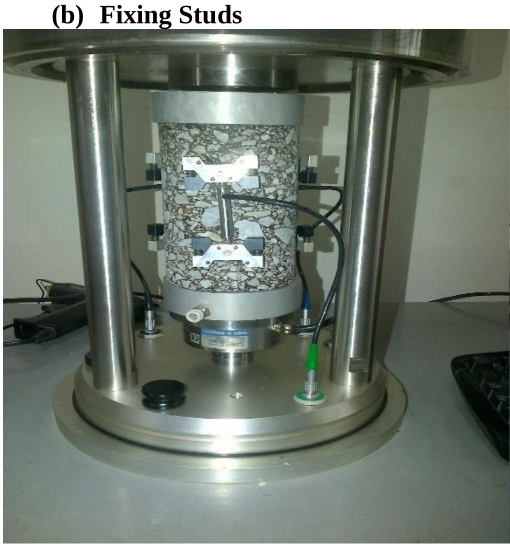
(e) Running the Test

APPENDIX M – Dynamic Modulus Test

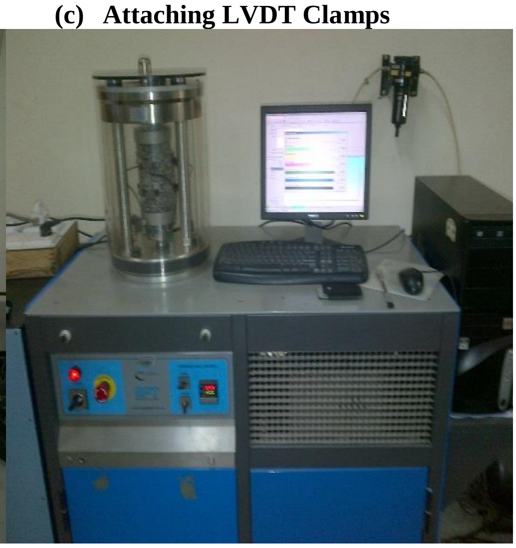
(a) Asphalt Mixture Performance Tester

(b) Fixing Studs

(c) Attaching LVDT Clamps



(d) Placing Specimen in Environmental Chamber and Mounting LVDT's



(e) Equilibrating Specimen to Test temperature and Running the Test