PERFORMANCE EVALUATION OF BAKELITE AS AN ADDITIVE IN HOT MIX ASPHALT MIXES

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Certified that the contents and form of thesis titled **“Performance Evaluation of Bakelite as an Additive in Hot Mix AsphaltMixes”** submitted by Yousaf Ali have been found satisfactory for the requirement of the degree.

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DEDICATED

TO

MY FAMILY AND TEACHERS

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(Yousaf Ali)

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LIST OF ACRONYMS

AASHTO	- American Association of State Highway and Transportation Officials
ASTM	- American Society for Testing and Materials
BS	- British Standard
ESALs	- Equivalent Single Axle Loads
HMA	- Hot Mix Asphalt
ITS	- Indirect Tensile Strength
LVDTs	- Linear Variable Differential Transformer
OBC	- Optimum Bitumen Content
TSR	- Tensile Strength Ratio
UTM	- Universal Testing Machine
VMA	- Voids in Mineral Aggregates
VFB	- Voids Filled with Bitumen

ABSTRACT

Pakistan is heading towards a major infrastructure growth especially the highway and motorway network system. Most of the roads are flexible pavements which have higher susceptibility to rutting, moisture damage and stripping. To overcome this we have to find ways to solve these problems. Keeping in view the current economic conditions, one must find solution which is cost effective and locally available. One such solution is the addition of cheap additives in the available asphalt being produced by our refineries. Therefore research should be carried out on additives which are cheap and locally available. This study investigates the effects of Bakelite as an additive, on various mechanical properties such as Marshall Stability, flow, quotient, retained stability and resilient modulus of asphalt concrete mixes. Bakelite is a high density plastic, industrially manufactured for making buttons, electrical switch boards, car bumpers and telephone sets etc. It is cheap and locally available material. The modified asphalt concrete mix was prepared by wet process which involves the direct mixing of bitumen (60/70 penetration grade) and Bakelite at high temperature (160˚C-165˚C) followed by aggregate during mixing process. The modified asphalt concrete specimens were prepared with following Bakelite percentages (2%,4%,6%,8%,10%,12%). Both modified and un modified samples were prepared by Marshall mix design (ASTM D6926), using NHA Class B gradation. Prior to sample preparation, the bitumen (60/70 penetration grade) and aggregates (Margalla aggregate) were tested to check their compatibility according to the standards of NHA. The optimum bitumen content (OBC) was found using Marshall Mix design (ASTM D6926), which was then used in the preparation of both conventional and modified samples. Performance tests including resilient modulus (ASTM D4123), Marshall Stability, flow (ASTM D6926) and retained stability (AASHTO T283) were performed to check performance of modified mixes. The test results revealed that modified mix containing 6% Bakelite by weight of optimum bitumen content provides best resistance against moisture damage, rutting and enhances the stability of asphalt concrete, than the other modifier percentages. In the end resilient modulus (ASTM D4123) test was performed under variable Bakelite (0% & 6%), temperature (25˚C &40˚C) and load duration (100 ms& 300 ms) conditions. The experimental investigation of these conditions and their interaction was analyzed by full factorial design experiment. The factorial analysis showed that Bakelite content was the most significant factor influencing the resilient modulus and ultimately the strength of the asphalt concrete mix. Therefore it is concluded that addition of Bakelite as an additive in hot mix asphalt mixes gives better results regarding pavement performance.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In Pakistan, roads are experiencing extreme rutting, moisture damage and stripping, Due to the prevailing traffic conditions where axle loads and traffic intensities are on the rise along with the harsh climatic conditions which include very high temperatures in summer season. To overcome this high quality asphalt is required. Unfortunately in Pakistan, the highways are made using 60/70 or 80/100 penetration grade asphalts which are not suitable for highway pavements and do not perform under extreme loading and temperature conditions. These penetration graded asphalts fail prematurely mainly due to brittle cracking when the temperatures are low and plastic deformation at extreme temperatures. This is because these asphalts contain high amount of wax, which imparts softening when the temperature is high and reduces stability, adhesion and consequently the strength (Al-Hadidy and Tan 2009). Therefore, it is essential to shift either to the super-pave design or we can modify the asphalt which is being produced by our refineries. Shifting to super-pave is costly; on the other hand using locally available modifiers like polyethene bags, Bakelite, fibers, rubber and other cheap additives is cost effective. Research carried out on additives indicated that among their different types, polymers proved to be the most significant (Lu et al. 1999). In addition, polymer modification of asphalt possesses a great potential for applications in the field of pavement design. The benefits include reduced rutting potential, increased useful life and reduction in thickness of the pavement (Al-Hadidy and Tan 2009). The polymer addition usually results in higher degree of stiffness in asphalt accompanied with enhancement in temperature and moisture susceptibility which results in increased rut resistance. Polymers are also used as a coating material for aggregates where they increase surface roughness and also make aggregates moisture resistant.

The polymer family is sub divided into many types but only two basic types are used to modify asphalt for road applications. These include plastomers and elastomers. Bakelite is classified as plastomer. Plastomers decrease the elasticity of bitumen and low temperature flexibility is decreased but strength is increased at higher temperatures due to increase in stiffness and decrease in penetration (Cagri and Burak 2009).

There are two processes to produce the modified asphalt. In the wet method, the modifier and asphalt are mixed and heated to melting points thus producing modified asphalt. This modified asphalt is then added to the heated aggregates to produce asphalt concrete. While in the dry process, the modifier is added to the heated aggregates and thoroughly mixed, followed by the addition of binder in heated liquid state during mixing process (Sivapatham et al. 2009).

This study investigates the effects of Bakelite as a modifier, based on performance parameters including Marshall Properties (stability, flow, quotient), resilient modulus and moisture susceptibility of asphalt concrete mixes. The modified asphalt concrete specimens were prepared with following Bakelite percentages (2%,4%,6%,8%,10%,12%). Both modified and unmodified samples were prepared by Marshall Mix design (ASTM D6926), using NHA- B gradation and 60/70 penetration grade asphalt. The optimum bitumen content (OBC) was found using Marshall mix design (ASTM D6926), which was then used in the preparation of both conventional and modified samples. Performance tests including resilient modulus, Marshall stability, flow and retained stability were performed to check comparative performance of properties of conventional and modified mixes.

1.2 RESEARCH OBJECTIVES

This research is based on achieving the following objectives:

- Perform laboratory tests to evaluate the compatibility of Bakelite as an additive.
- To identify the optimum Bakelite content for modified asphalt concrete.
- To investigate the performance comparison of control and modified HMA mixes for Marshall Stability, Flow, and Quotient Resilient Modulus and Retained Stability tests.
- Investigate the individual and joint effects of different factors including Bakelite content on the Resilient Modulus by factorial analysis.

1.3 SCOPE OF THE THESIS

In order to accomplish the objectives of this research, the following research methodology was adopted:

- Literature review of the previous research performed on plastics, their findings, testing procedures, material characterization and interpretation of results.
- Selection of gradation curve and materials including aggregates, bitumen and type of modifier.
- Laboratory characterization of materials including tests on bitumen and the aggregates.
- Finding optimum bitumen content by Marshall mix design (ASTM D6926) corresponding to NHA specifications.
- Using OBC preparing modified asphalt concrete samples containing 2%, 4%, 6%, 8%, 10% and 12% Bakelite by weight of OBC and testing for Marshall stability, flow quotient and retained stability.
- Selection of the optimum Bakelite content considering the performance in the above tests.
- Comparison of conventional (60/70 penetration grade with OBC) and modified (best performance among different Bakelite contents) mixes by Marshall stability, flow, quotient, retained stability test (AASHTO T283) and resilient modulus test(ASTM D4123).
- Statistical analysis of resilient modulus test results by MINITAB.

1.4 ORGANIZATION OF THESIS

The organization of this thesis is booked into five chapters.

Chapter 1 is about scope and objectives of polymer modification, its significance in the hot mix asphalt pavements, the testing procedure and the methodology adopted, for this research.

Chapter 2 is about the literature review of previous research carried out on the polymer modified asphalts, discussion of the input parameters for hot mix asphalt pavement design, material characterization, the performance tests and the effects of enhancing the properties on the mix design and its significance.

Chapter 3 explains the selection of materials, tests procedures including, the bituminous mix preparation procedures, Marshall stability, flow, quotient tests, tensile ratio test and the resilient modulus tests using indirect tension test and the test results giving optimum bitumen and Bakelite contents.

Chapter 4 presents statistical analysis of test results including factorial design, ANOVA and residual analysis using MINITAB-16 software.

Chapter 5 draws the conclusions from the analysis of test results and recommends future research prospects based on this research.

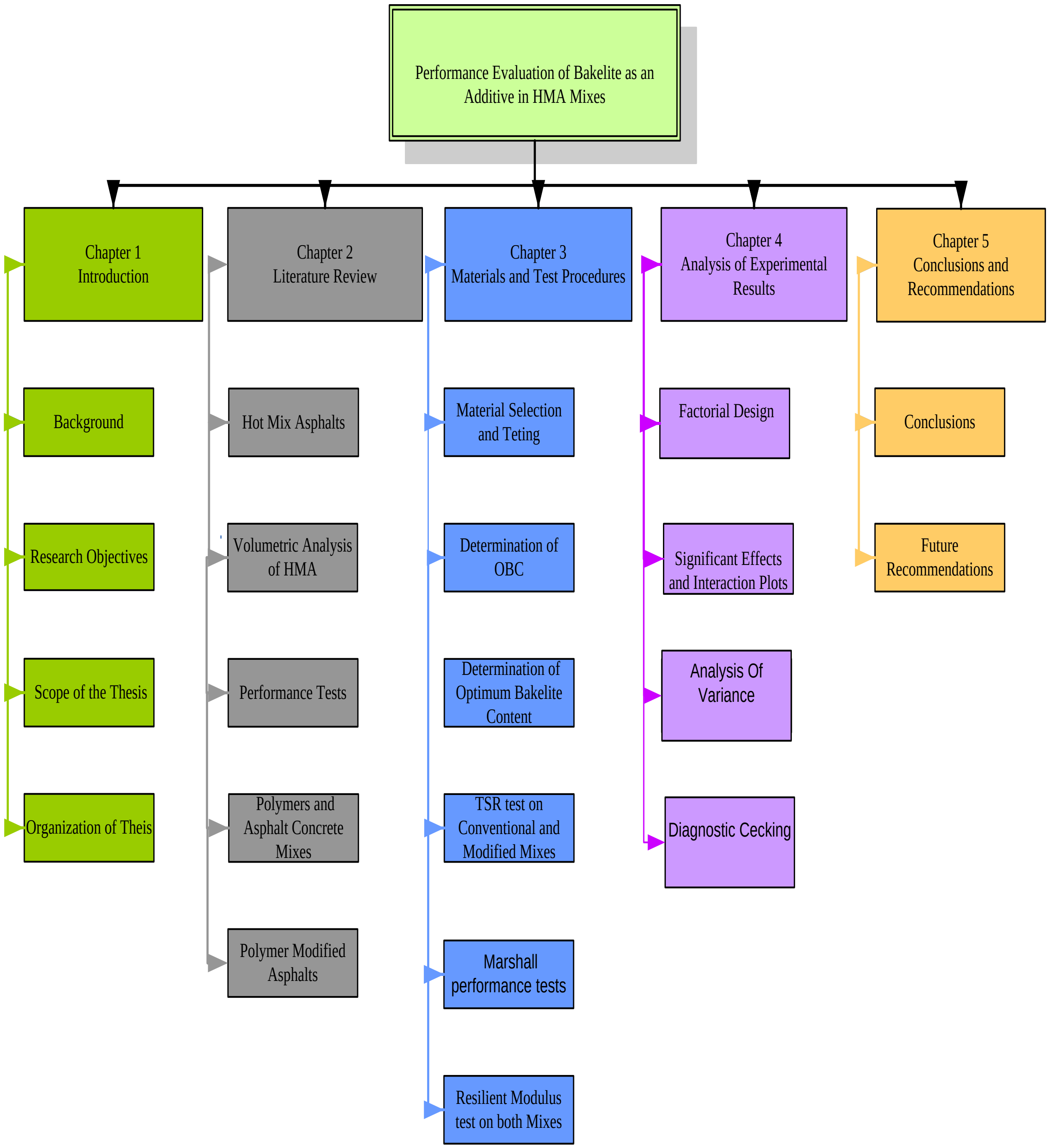

Figure 1.1: Organization of Thesis

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is a review of the literature and theory about hot mix asphalts (HMA), their types and material properties of HMA pavements. Marshall mix design and its volumetric properties are also discussed in detail. A brief introduction about polymerization, its types and different types of polymers are discussed. The effects of polymers as additives on the properties of asphalt concrete mixes are discussed. The main focus will be on the properties of Bakelite as a thermosetting resin which influenced its use as an additive in this study.

2.2 HOT MIX ASPHALTS

The bituminous paving mixes or hot mix asphalt (HMA) is a combination of properly graded aggregates which are uniformly mixed and coated with the bitumen (MS-4 Asphalt Institute). Both the aggregates and asphalt must be heated prior to the mixing to obtain fluidity of bitumen for proper mixing.

For the hot mix asphalt (HMA) pavement structures, the design should be economical and durable like other engineering structures. An under-designed pavement fails prematurely ahead of its design life, costing more money for repair. To lessen the chances of future repair and maintenance problems, the most effective way is to properly select the materials for construction and use adequate values of design parameters for the flexible pavements design (MS-4 Asphalt Handbook).

The most expensive material in HMA pavements is the bitumen. In order to make durable and economical pavements, the bitumen should be made more durable and resistant to the pavement distresses including stripping, raveling, rutting and the like. The bitumen can be made more durable by adding certain modifiers which enhance its properties and make it more resistant to moisture induced damages, rutting and other pavement distresses.

2.2.1 Types of Hot Mix Asphalts

The hot mix asphalts are divided into three different types of mixes, depending upon aggregate gradation used. These three types of mixes are; dense, open and gap graded (MS-2 Asphalt Institute).

- **Dense Graded Mixes**

Dense graded bituminous mixes are the one that consist mainly of well graded aggregates i.e. all sizes of coarse and fine aggregates, and filler mixed with asphalt cement binder. The dense graded mixes are usually referred by their nominal maximum aggregate size. These mixes work well for the structural, patching and friction.

- **Open Graded Mixes**

The open graded bituminous mixes usually consist of large quantity of coarse aggregates and small amount of fine aggregates mixed with bitumen. The use of these mixes is to provide an open surface texture that will allow the water to drain into the mix. The mix design procedure of the open graded mixes is different from dense graded bituminous mixes due of the lack of fines in the mix. Also the quantity of bitumen is less in open graded mixes as compared to dense graded mixes.

- **Gap Graded Mixes**

A gap graded asphalt mixes are usually same as open graded mixes but the amount of fine aggregates into the mix are usually greater than the amount of fine aggregates in the open graded mixes. The materials for gap graded mixes are crushed stone and gravels with bitumen and the manufactured sand. The middle size aggregates that are between # 4and # 30 sieves are missing or present only in very small quantity.

2.3 MATERIAL PROPERTIES FOR BITUMINOUS MIX

In overall design of pavements, the hot mix asphalt (HMA) layer has a significant importance. As it is the upper most layers, it takes the high magnitude stresses. Therefore, it is necessary to perform the tests on materials used for preparation of bituminous mixes.

- **Aggregates Evaluation**

In order to prepare a mix by using Marshall Apparatus, it is necessary to determine the aggregate acceptability. The tests often performed include Los Angeles abrasion, impact test, crushing value test and shape tests. In case if material satisfy the specification of these test results, then other tests including gradation, specific gravity and absorption must be performed. Table 2.1 shows the required tests for aggregates.

Table 2.1: Tests and Specifications for Aggregates

Test Type	Designation		NHA Standards
Shape test (%)	Flakiness Index Elongation Index	ASTM D4791	≤ 15
Impact test (%)	ASTM D5874		≤ 30
Abrasion test (%)	ASTM C131		≤ 30
Specific gravity	Coarse	ASTM C127	
	Fine	ASTM C128	

2.3.1 Bitumen Evaluation

Like aggregates, for preparation of bituminous paving mixes, it is necessary to determine the bitumen acceptability. Different tests must be conducted on the bitumen before bituminous mixture preparation. Table 2.2 shows the required tests and specifications which the bitumen should pass for its eligibility as a binder.

Table 2.2: Tests and Specifications for Bitumen

Test type	Designation	Specifications
Penetration @ 25 °C, mm	ASTM D 5	60-70
Flash and fire point, °C	ASTM D 92	232
Specific gravity	ASTM D 70	1.01 – 1.06
Ductility Test, cm	ASTM D113	>100

2.3.2 Asphalt Concrete Mix Evaluation

Asphalt Concrete mix is designed by Marshall mix design criteria and it should meet the design specifications of National Highway Authority, failing to do so, the HMA mix prepared should be discarded and a new trial blend should be prepared and tested until and unless it meets the design specifications of NHA. Table 2.3 shows the NHA specifications for wearing course mix designed by Marshall procedure (ASTM D6926) for heavy traffic conditions.

Table 2.3: NHA Specifications for Asphalt Concrete Mix

Design Criteria	Specifications
Compaction, blows at each end	75
Stability (Kg)	1000 (Min)
Flow, 0.25 mm (0.01 inch)	8-14
VA (%)	3-5
VMA (%)	16 (Max)
Loss of Stability (%)	20 (Max.)

2.4 PREPARATION OF BITUMINOUS PAVING MIXES

The standard method for preparation of bituminous paving mixes is by using Marshall Apparatus (ASTM, D6926). The laboratory preparation of bituminous paving mixes require batching out of the aggregates, mixing in the proper amount of bitumen, heating the mixture to proper temperature and then compaction of specimens. Approximately 1200 gm of aggregates and filler is heated upto 105 °C to 110 °C. Bitumen is also heated until it is in a range of 100 °C to 125 °C. Bitumen and aggregates after heating separately are mixed at about 154 °C to 160 °C. This temperature must be the similar to temperature of asphalt mixing plant. Mechanical mixer is recommended for laboratory bituminous mixture preparation because mixing large quantity of material by hand is too difficult. Mixing must be thorough such that the bitumen is coated uniformly over the aggregate. Prior to compaction, the mould must be heated. The mix is placed in and compacted with blows on either side with a rammer at 138 °C to 149 °C depending upon the traffic condition. In order to obtain the compacted thickness of 2.5-inch it is allowed to change the mix proportion of aggregates (MS-2 Asphalt Institute).

2.5 COMPACTION OF BITUMINOUS PAVING MIX

The standard method for bituminous mix design by Marshall Procedure (ASTM D6926), recommends three kinds of Marshall Compaction apparatus i.e. Compaction hammers with a manually held handle, Compaction hammers with a fixed hammer handle, and compaction pedestal

- **Compaction Hammers with a Manually Held Handle**

The manually held hammers usually have a flat, circular compaction foot with spring loaded swivel and 4.54 kg sliding mass with a height of fall 457 mm. The manual compaction hammers should be equipped with a finger safety guard.

- **Compaction Hammers with a Fixed Hammer Handle**

It is mechanically operated with a base which is rotating constantly due to a surcharge on top of the handle. The tamping face shall have a 4.54kg moving weight with height of fall 457.2-mm. A rotating mechanism is incorporated in the base. The base rotation rate and hammer blow rate shall be 18 to 30 rpm and 64 blows per minute, respectively.

2.5.1 Compaction Pedestal

The compaction Pedestal consist of a nominal 8 by 8-inch wooden post approximately 18-inch long capped with a steel plate approximately 12 by 12-inch and 1-inch thick. The wood should have an average dry density of 42 to 48 lb/ft^3.

2.6 VOLUMETRIC ANALYSIS OF COMPACTED PAVING MIXTURES

The pavement service performance is indicated by volumetric analysis of the properties of compacted bituminous paving mixtures (MS-2 Asphalt Institute). Various test procedures, including specific gravity tests for aggregates, bitumen and bituminous mixes are used to obtain the input parameters for calculating these volumetric properties. After determination of aggregates and bitumen properties and after mixing and compaction, the next step is measurement of volumetric properties of compacted paving mixes. Generally it includes following important properties:

- Range of acceptable Air Void Contents (Va)
- Minimum amount of Voids in the Mineral Aggregate (VMA)
- Percent of Voids Filled with Asphalt (VFA)

2.6.1 Voids in the Mineral Aggregate (VMA)

The voids in mineral aggregate, VMA, are defined as the spaces between compacted bituminous paving mixtures. These voids are the sum of air voids and the bitumen content that is effective (exclusive of the absorbed bitumen), and are expressed as a percentage of total volume of the mix. The calculation of VMA is based on the bulk specific gravity of the aggregate. The specific gravity in turn is expressed as percentage of the bulk volume of compacted paving mixture. Therefore, by subtracting total volume from bulk volume, the VMA can be calculated. The equation for calculation VMA is as follows:

$$VMA = 100 - \left[\frac{G_{mb} P_s}{G_{sb}}\right] \quad (2.1)$$

Where,

VMA = Voids in mineral aggregate (percent of bulk volume).

Ps = Percent of total aggregates in the mix.

G_{mb} = Bulk specific gravity of the compacted mix (ASTM D2726)

G_{sb} = Combined specific gravity of aggregates.

VM A is a prime determinant of the durability of the mixes, if its value is small, the mix will not be durable, on the other hand large value is indicative of low stability and high flow problems and will be too costly to make. The bitumen film around the particles is a function of volume of bitumen and the aggregate size. Economizing asphalt with minimum VMA leads to durability problems because in the absence of sufficient film thickness, the bitumen oxidizes faster, the films are more easily penetrated by water, and strength of the mix is reduced. So the VMA should be high enough to make room for both bitumen and air voids.

2.6.2 Percent Air Voids

The coated aggregates in a compacted bituminous paving mixture consist of small air spaces between them which are called air voids. Durability is a function of air void content. The determination of air voids in a compacted mixture can be calculated using following equation:

$$V_a = 100\left[\frac{G_{mm} - G_{mb}}{G_{mm}}\right] \quad (2.2)$$

Where,

G_{mb} = Bulk specific gravity of the compacted mix.

G_{mm}= Maximum theoretical specific gravity of the mix.

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

2.6.3 Voids Filled with Asphalt

The voids filled with asphalt, VFA, is the percentage of the spaces between the aggregates (VMA) that is filled with asphalt. VFA, does not include the absorbed asphalt and is determined by following

$$VFA = 100\left[\frac{VMA - V_a}{VMA}\right] \tag{2.3}$$

Where,

VFA =Voids filled with asphalt.

VMA= Void is mineral aggregates.

V_a = Air voids in the compacted mix.

2.7 STABILITY, FLOW & QUOTIENT TEST

The Marshall stability and flow along with density, VMA, VA and VFA are used for the evaluation of bituminous mixture and mix design (ASTM D6927). In addition, Marshall Stability is a measure of the ability of asphalt concrete mix to resist the compression load applied while flow is the deformation recorded at maximum force (ASTM D6926). Stability can also be defined as the measure of the ability of asphalt concrete to rut resistance under heavy loads (Kuloglu et al. 1999). The flow on the other hand is the ability to adjust to gradual deformations without any cracking. Thus it is the opposite of stability (Kuloglu et al. 1999). Marshall Quotient is stability to flow ratio and therefore is an indicative of material's resilience to deformation (Shell 2003).

After determining the bulk specific gravity of the specimens, the stability and flow values are determined using compression testing machine. The stability of the mix determines the utmost load that the test specimen supports at the steady loading rate of about 2-inch/minute until the maximum load is reached at failure. The loading is stopped when the load starts to decrease. The flow and stability value are directly recorded by a digital meter in the required units. Usually stability is recorded in kilograms and flow in millimeters. The Marshall quotient is then calculated based on their ratio.

2.8 TENSILE STRENGTH RATIO

The ratio of indirect tensile strength (ITS) of conditioned specimens to the unconditioned specimens is known as tensile strength ratio (TSR).

$$TSR = \frac{ITS\ (Conditioned)}{ITS(Dry)} \quad (2.4)$$

Where,

$ITS_{(conditioned)}$= Indirect tensile strength of conditioned specimen

$ITS_{(Dry)}$ = Indirect tensile strength of dry specimen

The tensile strength ratio (TSR) test was conducted according to AASHTO T283 to test the susceptibility of compacted bituminous mix specimens to moisture induced damage. Currently AASHTO T283 is the most widely used test procedure to determine the potential of moisture induced damage to the HMA pavements (Do et al.2010). The HMA produced may be sensitive to the presence of moisture in the finished pavement; therefore it is essential to check the adequacy of the modified HMA as a product capable of withstanding moisture induced damages. The testing procedure involves finding the indirect tensile strength of both conditioned and unconditioned specimens and then taking their ratio to find the TSR for test specimens.

2.8.1 Indirect Tensile Strength Test

This test is a measure of the tensile strength of HMA mixes, which influences its cracking behavior (Tayfur et al. 2005). ITS for both conditioned and dry samples can be determined by finding the splitting tensile strength in a compression testing machine at 25˚C with a deformation rate of 2 inch/min. ITS can be calculated using equation

$$\text{ITS} = \frac{2Pmax}{\pi td} \quad (2.5)$$

Where,

P_{max} = Maximum load (kg),

T = Thickness of the specimen (cm),

D = Diameter of the specimen (cm).

2.8.2 Tensile Strength Ratio Test

Tensile ratio test (TSR) is calculated after the conditioned and unconditioned specimens have been tested for indirect tensile strength. It is a ratio of conditioned to unconditioned indirect tensile strength of a set of specimens that are the same in all material and size characteristics. TSR test result is a measure of retained stability of the mixes against moisture damage (Do et al. 2010). ASTM D4867 and AASHTO T283 standards set the lowest value for any TSR test to be within the constraints of 70% to 80%, failing which the mix is to be discarded and a new mix must be prepared. TSR values above 90% indicate that the mix has adequate resistance against moisture damage. Higher values of TSR indicate less moisture susceptibility and vice versa.

2.9 RESILIENT MODULUS OF BITUMINOUS PAVING MIXES

The elastic modulus obtained from the ratio of repeated stress (loads) to the recoverable strain is called the resilient modulus M_R, defined as

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{2.6}$$

Where, σ_d is the stress applied axially repeatedly. The binder used in the surface course materials i.e. bitumen is assumed to be completely elastic in theory but in practice it was found that it is not the case and small deformations are observed every time a load is applied. But if the bitumen used has higher strength and the applied load is small then and repeated many times then ultimately the deformations after every load application becomes almost recoverable and the binder can be regarded as elastic. Figure 2.1 depicts the stress-strain behavior under a repeated stress test. Figure illustrates that at first the material is experiencing permanent deformation due to plastic strain but as the process continues and more stress repetitions are applied, the deformations start to decrease until the number of cycles reach 100 to 200, after which the material behaves elastic and deformation is totally recoverable (Huang 2003).

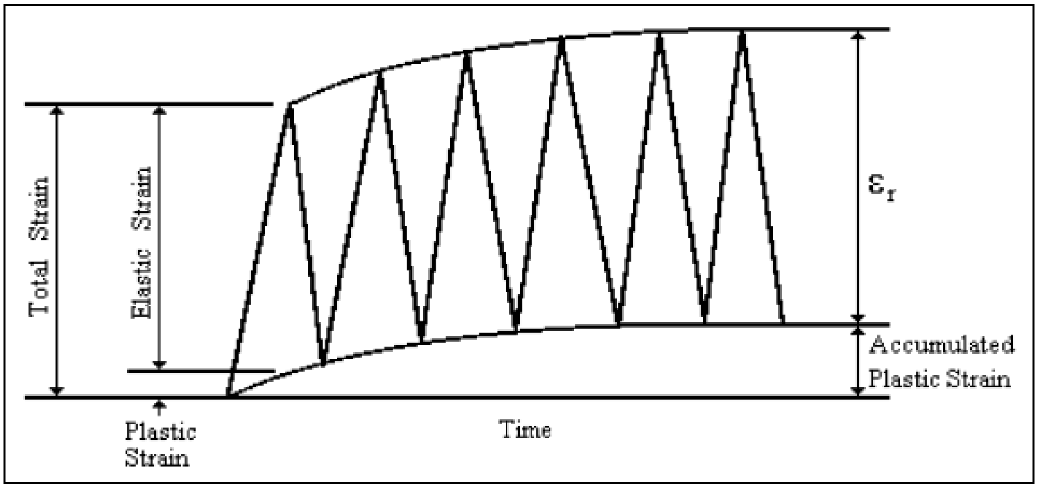

Figure 2.1: Recoverable Strain under Cyclic Load (Huang 2003)

2.9.1 Indirect Tension Test

The indirect tensile strength test standardized as ASTM D6931 is used to evaluate the comparative quality of paving binding materials and mixes and determining its potential for cracking and rutting. This test is performed by applying a pointed compressive load parallel to the vertical diametral plane of 4-inch diameter of a cylindrical specimen at a constant deformation rate of 50 mm/min at a temperature of 25 °C. This loading arrangement is selected because it helps in reasonable homogeneous tensile stresses distribution along the vertical diametral plane and perpendicular to the applied load (Yoder 1975). The ultimate result is the splitting of specimen. The stress distribution is shown in Figure 2.2.

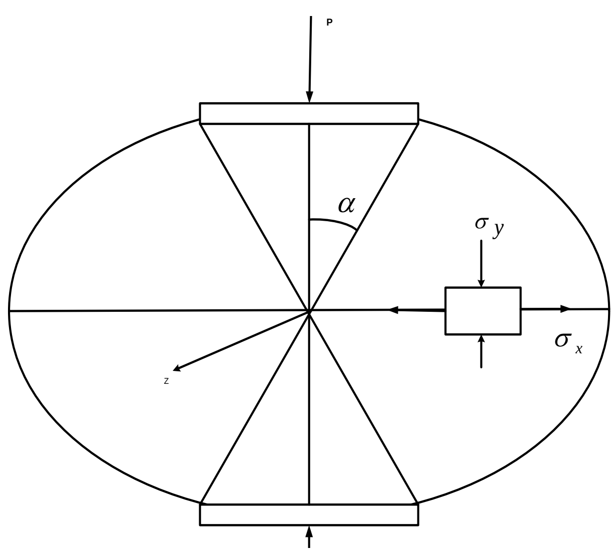

Figure 2.2: Schematic for Indirect Tension Test (Yoder 1975)

2.9.2 Resilient Modulus Test

Resilient modulus test can be performed on cores, obtained from the field or on the laboratory compacted specimens. The resilient modulus of bituminous paving mixes prepared in laboratory depends on the following factors:

- The test setup used. (indirect tension vs. triaxial)
- Level of compaction (number of gyration or number of blows).
- Temperature. (high or low)
- Loading factor (Loading duration and rest period, waveform, strain level).
- Geometry (diameter and thickness)
- Binder

The test method for measurement of resilient modulus using indirect tension test (ASTM D4123), and it recommends that the load should be applied in the form of alternate loading and unloading form also known as haversine load form. This test procedure is divided into three stages which are, ITS determination on one specimen, conditioning for 100 load pulses and finally determining the actual resilient modulus.

- **Pretest Tensile Strength Determination**

It is recommended by the ASTM D6931 that before the commencement of actual resilient modulus test, the ITS on one of the specimens should be performed that is representative of other specimens in size and material properties. The purpose of performing indirect tensile strength test is to select the base line for the preconditioning peak loading force.

- **Preconditioning**

The preconditioning of specimens shall be conducted while the specimen is located in a temperature controlled cabinet. The selection of applied loads for preconditioning is based on the indirect tensile strength of bituminous paving mix in accordance with test method ASTM D6931. The peak loading force during preconditioning shall be 10 to 20% of the peak load found by the indirect tension test at 25 °C. The specimen contact loads or seating loads i.e. the vertical load on the specimen to maintain the positive contact between the loading strip and specimen shall be 4% of the maximum load. The number of load applications to be applied for preconditioning cycles shall be 100 to 200. However; the minimum number of load applications for a given situation depends on the stable deformation.

- **Resilient Modulus Determination**

Following the ITS and conditioning procedures, the RM is determined by applying five load pulses with nearly constant deformation. The following equation is used to determine the resilient modulus of bituminous paving mixes:

$$E = \frac{P(\upsilon + 0.27)}{Ht} \quad (2.7)$$

Where,

E = Resilient Modulus (MPa)

P = Peak loading force (N)

υ = Poisson ratio (assumed as 0.4)

H = Recovered horizontal deformation of specimen (mm)

t = Thickness of specimen (mm)

2.10 INVESTIGATING FACTORS

The main factors affecting resilient modulus are temperature, bitumen content, and load duration, diameter of specimen and gradation of aggregate. Many studies already have been carried on these factors, which influence the resilient modulus of bituminous paving mixes. Only the investigating factors which are related to this research are discussed here:

2.10.1 Load Duration Effect

The influence of the load duration on the performance of the asphalt layer is similar to the influence of temperature i.e. elastic, plastic, and fatigue behavior are affected. Under a rolling wheel load the loading time increases with depth. Because only the influence on the asphalt is considered the loading time corresponding to the middle of the asphalt layer is considered.

Almudaiheem et al. (1991) in their study concluded that in order to achieve a conservative design the magnitude of loading should be large because it gives lesser value of resilient modulus. They conducted a test with load magnitude ranging from 10 to 30% of ITS of the specimen. The test results revealed that the resilient modulus values for a load of 1000N were 4% lower than that of 2700N load for the bitumen content of 4% specimens.

The results also revealed that the variation in values decreased with increase in bitumen content.

Loulizi et al. (2002) recommended that in order to simulate the loading time of trucks traveling at average speeds the duration must be reduced to 100 ms for HMA dynamic test. It is also recommended that haversine duration times must be 200ms for a automobile speed of 70 km/h to 1sec for a vehicle speed of 10 km/h.

Saleh et al. (2006) concluded in their study that the loading factors including durations, strain level and the waveforms also affect the resilient modulus of bituminous mix. Resilient modulus testing was performed on the 4-inch and 6-inch specimens with 2 levels of loading i.e. 100ms and 200ms, keeping the test pulse period of 3000ms. The waveform of harvesine and triangular was considered in the study. It was observed that the loading duration had significant affect on resilient modulus. The resilient modulus decreased with the increase in the load duration due to high strain for longer duration of loading whereas the load waveform and strain level had insignificant effect on the resilient modulus of bituminous mixture.

2.10.2 Temperature Effect

The temperature greatly influences the resilient modulus of asphalt concrete and the performance of pavement is directly related to temperature variations. Above 20°C, the RM decreases quickly and reaches to impractically low values at 40°C. therefore; this temperature range is critical for asphalt layer (Per Ullidtz 1987).

Stroup et al. (1997) carried out extensive research on effect of load duration and temperature on the resilient modulus. The loading ranges of 0.1 and 1.0 second at the temperatures of -18, 1, 25, and 40°C were investigated. It was observed that increasing the load duration decreased the resilient modulus for all temperatures except for -18°C. At -18°C, it was found that the resilient modulus had slightly increased but at higher temperature the resilient modulus decreased.

Ziari et al. (2005) concluded in their research that increasing temperature decreases the resilient modulus. This is due to the decrease in stiffness of the bitumen at higher temperatures.

2.10.3 Bakelite Content Effect

The main purpose of conducting this research is to find the effect of Bakelite on the properties of asphalt concrete mixes, of which one important parameter is the resilient modulus. It characterizes the elastic behaviour of asphalt concretre under dynamic loading conditions and also represents structural strength and material quality. If the resilient modulus test results show any improvement than the control mix then it will signify that Bakelite can be used as an additive in asphalt concrete mixes.

2.11 POLYMERS AND ASPHALT CONCRETE MIXES

In this section, polymers are discussed in detail including basic definitions, polymerization, basic types of polymers, the polymers used to modify asphalts and the results of such modifications on asphalt concrete mixes.

2.11.1 Polymers and Plastics:

The term polymer is used interchangeably with the term plastic and neither is accurate. Plastic means pliable, but most engineering polymers are not plastic at room temperature. On the other hand, polymers can include every sort of material made by polymerization with repeated molecule. The ASTM definition (D883) of plastic is a " material that contains a an essential ingredient, an organic substance of a large molecular weight, is solid in its finished state, and at some stage in its manufacture or in its processing into finished article, can be shaped by flow." Basically, a plastic is an organic material with repeating molecular units that can be formed into usable solid shapes by sintering, casting or melt processing.

2.11.2 Polymerization Reactions:

Polymerization is the process by which individual molecules (monomers) attach to each other to form a polymer. There are two ways in which the monomers can attach to each other.

In the first way, the molecules can physically link to each other, like beads on a string and the second way is that a new molecule is attached to another molecule by a chemical reaction when the other molecule is formed. The first one is called addition polymerization and the second condensation polymerization.

In addition polymerization, the starting molecule is a monomer and the resulting polymer has the same repeating unit as starting monomer. In condensation polymerization, the repeating molecules in the polymer chain are different from the starting molecule, since water is a common by-product, thus the term condensation is used.

2.11.3 Basic Types of Polymers:

There are many types of polymers including those that are part of human body, but this discussion will be limited to those polymers that common users call plastics.

Plastics can be divided into two categories depending upon their temperature characteristics. They can be either thermoplastics or thermosetting.

The thermoplastics are those which flow at elevated temperatures above crystalline melting point, and after solidification, can be reheated as many times as desired. Examples are PVC, PS, and SBS.

On the other hand, thermosetting polymers, are those which once take their shape during casting at high temperature, cannot be remelted upon reheating. This is because the polymerization has occurred due to strong network bond. Cross linking between the chains are too strong keeping the material from remelting. If reheating is attempted, they char, burn or sublime but cannot be recycled. They can only be used as a filler material after disposal. Examples are Bakelite, epoxies, poly amides etc.

2.11.4 Phenol- Formaldehyde (Bakelite):

Phenols are the oldest family of thermosetting polymers. This polymer family has ring structure alcohol named phenol. The main process to obtain phenols is from the petroleum distillates like propylene and benzene. Phenol resins are formed by the reaction of phenol with formaldehyde (CH_2O) making following monomer.

Three monomers form a rigid network structure, which in turns form a hard, rigid plastic. Polymerization is obtained by cross-linking of these monomers into a 3-D network. The cross-linking reaction requires heat, but they can exist in various stages. The two basic stages are A & B. In stage A, the cross-linking is not yet started so the individual components sit around before any significant cross-linking occurs. This interval is called pot life. In B stage, called the transition period, the cross-linking gradually occurs. Most thermosetting polymers are rubbery and tacky at this stage and they can exist at this stage for as long as 24 hours (Budinski 2012).

The first commercial PF polymer were produced in the early part of the 20th century under the trade name Bakelite. Bakelite was used mainly for compression molded electrical parts such as switches, distribution caps and the like. Phenols are still being used largely for this purpose because they are characterized by their good properties like low moisture absorption, high resistance to temperature, high compressive strength, creep resistance, less brittle nature and cost effective as compared to most of thermosets and few thermosetting polymers (Budinski 2012).

2.12 POLYMER MODIFIED ASPHALTS (PMA):

Polymer modification is a process in which a certain modifier is added to the asphalt in order to enhance its properties. Modifier can be added either by dry process or by wet process. In the dry process, the aggregate is mixed with the modifier prior to the addition of binder to the mixture while in the wet process, the modifier is added to the binder and heated together and then this modified binder is added to the aggregate. (Abtahi et al. 2010). The wet process was adopted for the present study to ensure proper blending and mixing of Bakelite with bitumen and ultimately achieving uniform mixing and coatation of aggregate by the modified asphalt.

Polymer modified asphalts (PMA) used today are composed of variety of polymers which are commonly classified into two groups, namely: elastomers and plastomers. The elastomers improve the elasticity of the bitumen thus making the resultant asphalt concrete more elastic. The elastomers commonly used are SBS copolymers. SBS copolymers are generally classified as highly appropriate for alteration of asphalt. SBS is composed of two blocks with very different properties. The polystyrene block gives strength and stiffness at elevated temperatures, while polybutadiene rubbery midblock give viscosity, elasticity and flexibility at low temperature.

While plastomers increase strength and rigidity under heavy traffic loads (Al-Hadidy and Yi-qiu 2009). Plastomers generally increase the viscosity and stiffness under normal temperatures but in fluctuating temperatures they donot provide appropriate results when it comes to increasing bitumen elasticity (Awwad and Shbeeb 2007). Some of the plastomers commonly used for asphalt modification include, high density polyethylene (HDPE), low density polyethylene (LDPE) and polyethylene tereрphthalate (PET).

Cagri and Burak 2009 concluded that the use of polymers imparts low temperature flexibility but at the cost of decrease in strength and penetration resistance at low temperatures.

Al-Hadidy and Tan 2009 in their research on polymer modified stone mastic asphalt (PMSMA) came to a conclusion that polymer modified mixes improve the service life of the pavement and also reduces the number of construction materials. Results also showed that the modified mixes reduce the temperature susceptibility of the pavement. They compared the unmodified 70/100 penetration grade asphalt with modified asphalt containing 5% SBS copolymer.

Awanti et al. (2008) concluded that addition of polymers in the bitumen as a modifier not only decreased the penetration value by 36% but also showed considerable increase in stability and flow values for modified asphalts. Moisture susceptibility also decreased for modified mixes. Static indirect tensile strength values for modified asphalt were also higher than the conventional 80/100 penetration grade asphalt.

Feipeng et al. (2007) investigated the effects of modification on resilience against cracking of Superpave mixes. The results indicated improved cracking resistance, but did not affect aging and healing characteristics of asphalt concrete mixture.

The purpose of this research is to determine the effects of incorporating Bakelite as an additive on the performance of HMA pavements. The mechanical properties of asphalt concrete mixes with and without Bakelite will be calculated by laboratory tests and the results will be analyzed.

It is noteworthy to mention that there is no research to date about the use of Bakelite as a modifier in HMA pavements.

2.13 DESIGN OF EXPERIMENTS

The Design of Experiment is a technique to study many variables at a time rather than conducting separate study for every variable present, thus increasing efficiency and reducing testing time (Barrentine 1999). The normal practice of *one-factor-at-a-time* fails to deem the relationship between the factors. Therefore; in order to consider various factors, the best method is to conduct Design of Experiment (Montgomery 2001). The

Design of Experiment is the sole way of knowing, whether the relationships are present among the factors or not (Montgomery 2003).

There are different types of Design of Experiments. The most basic type of Design of experiment is the 2^K full factorial design of experiment which is also known as two level full factorial design of experiment. The 2 denotes two levels of experiment i.e. high and low level and K represent the number of factors involved in factorial design of experiment. The MINITAB-16 is a software package designed for statistical analysis, including Regression Analysis and Design of Experiment.

2.13.1 Factorial Design

Factorial design is widely used in the experiments involving several factors where it is necessary to study the joint effect of these factors on a response (Montgomery 2010). The full factorial design of experiment consists of all the possible combinations of levels for all the factors(Antony 2003). In case of two level full factorial design of experiment, each factor is to be considered at two levels. There are some analytical tools used for the analysis of full factorial design.

2.13.2 Analytical Tools of Full Factorial Design

For analysis of factors and their interaction by full factorial design of experiment, various tools are used for significance check, variation of response with levels (low and high), effects and interaction analysis, residual analysis and influential analysis. These different tools are described below:

- **Pareto Chart of Effect**

The Pareto chart allows one to detect the factor effect as well as interaction effect that are very important to the process (Antony 2003). It indicates the comparative importance of the effect. The effect is standardized for each term i.e. factor or combination of factors for the mean response and draws a reference line on the chart which represents the critical-t value. The bars for the terms that extend past the reference line indicate that they are significant. It also gives information about significance of main factors or interactions.

- **Main Effect**

The Main Effect is the variation in the mean response between low and high level of a factor (Tamhane 2009). The plot of main effect shows the average response at every level of a factor. The sign indicates the direction of a main effect, i.e. whether the mean value decreases or increases with increase in level of a factor. The magnitude is an indicator of the strength of the effect. Greater the magnitude, greater will be the strength and therefore the significance of that effect. If the effect of a factor is positive, it implies that the average response is higher at high level than at low level of the factor setting as shown in Figure 2.5 and Figure 2.6 shows direct and indirect relationship between an effect and level of factor respectively.

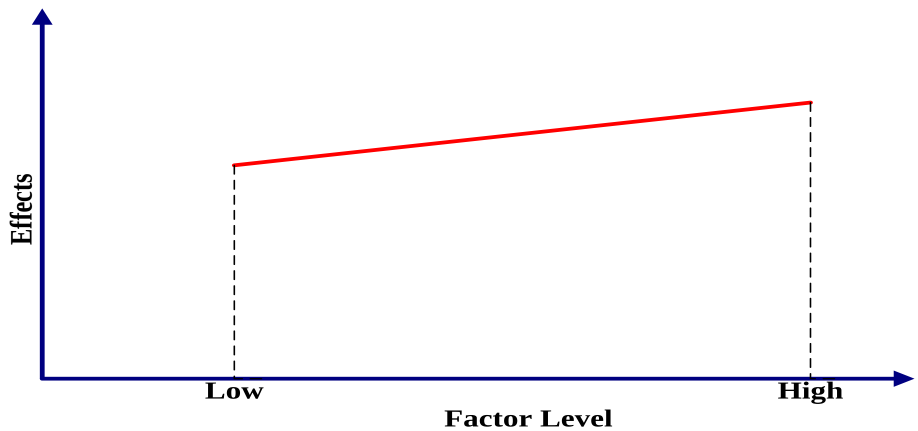

Figure 2.4: Positive Main Effect Plot (Adapted from Montgomery 2001)

Figure 2.5: Negative Main Effect Plot (Adapted from Montgomery 2001)

- **Interaction Effect**

The interactions occur when a particular combination of the two factors do something unexpected from simply observing their main effect (Barrentine 1999). It is the effect of each factor at each level of every other factor for the mean response. In the interaction plot, the parallel lines, indicate lack of interaction while non-parallel lines are indicative interaction between the factors (Antony 2003) as shown in Figure 2.7 and Figure 2.8 respectively.

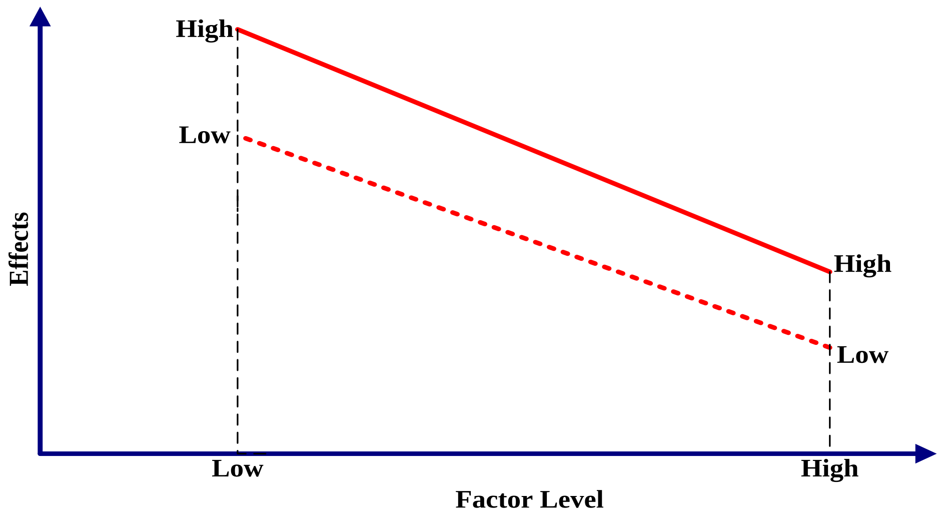

Figure 2.6: Parallel Interaction Plot (Adapted from Montgomery 2001)

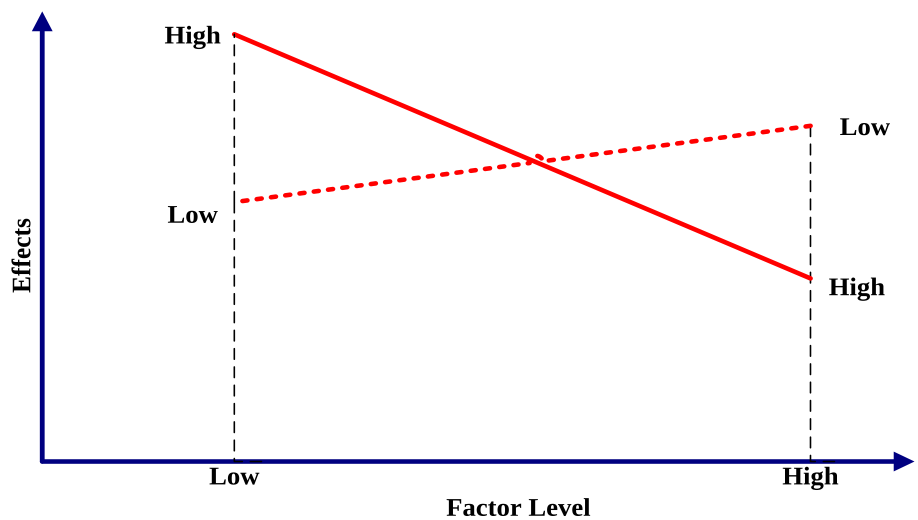

Figure 2.7: Non-Parallel Interaction Plot (Adapted from Montgomery 2001

- **Residuals Plots**

Residuals are the differences between the observed and predicted response values at each combination of factorial values. The residuals should be approximately normally distributed. Residuals plots are presented only when there is error in the design. It helps to determine the adequacy of the model for the selected response. All residuals plots allow the user to select the type of residual to be used:

- Regular Residual is the difference between the observed Y and the predicted Y.
- Standardized Residual is the regular residual divided by the constant standard deviation.
- Studentized Residual is the regular residual divided by an estimate of its standard deviation.

➢ **Residual Probability Plot**

It is the normal probability plot of the residuals (Antony 2003). On this plot, the residuals are arranged in the increasing order. The line is plotted which represents the normal distribution. If all the points fall on the line, it means the model is good and it satisfies the first condition of diagnostic checking i.e. the residuals follow a pattern of normal distribution, which means there is normality in the distribution of errors, so model is a good fit and conclusions can be drawn based on this model. If there is a noticeable pattern, then it indicates that a transformation is necessary for further analysis. Figure 2.9 shows the residual probability plot, for a normal distribution of residuals.

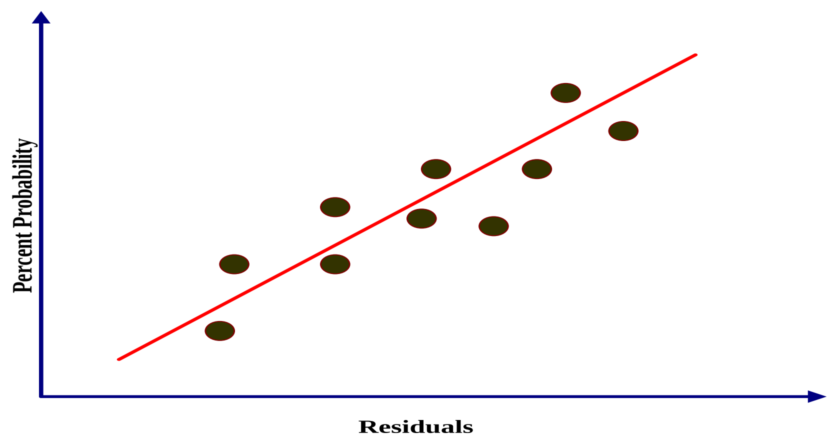

Figure 2.8: Residual Probability Plot (Adapted from Montgomery 2001)

➢ **Residual vs. Fitted Plot**

The Residual vs. Fitted plot shows the residuals plotted against the predicted or fitted values of the response. If the points are randomly distributed around the zero reference line in the plot, then it means the model is good. If there is a pattern then it either means that the model is not good or that fitted values are not normally distributed and transformation is necessary for the further analysis. Figure 2.10 shows the general plot for the residuals vs. fitted values.

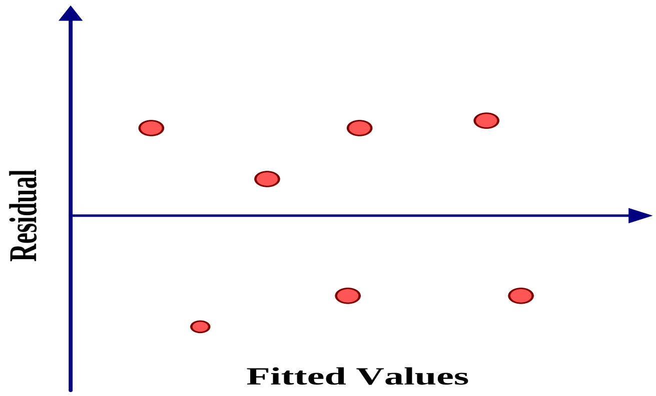

Figure 2.9: Residual vs. Fitted values Plot (Adapted from Montgomery 2001)

- **Residual vs. Observation Order Plot**

The Residual vs. Order plot can show the residuals plotted against either run order or standard order. If the points are randomly distributed in the plot, it means that the test sequence of the experiment has no effect. If a pattern or trend is apparent, this indicates that a time-related variable may be affecting the experiment and blocking is required. Figure 2.11 shows a general plot of Residual vs. observation order.

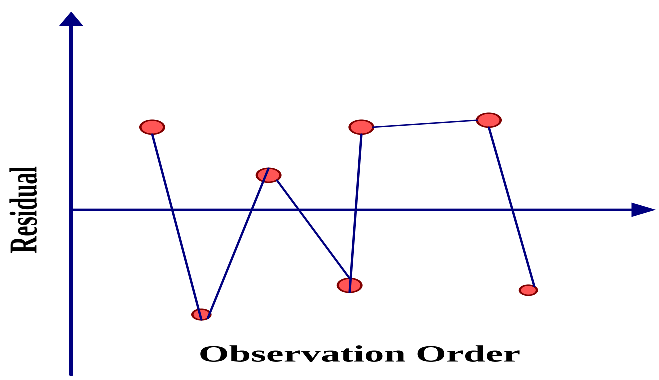

Figure 2.10: Residual vs. Observation order (Adapted from Montgomery 2001)

- **Residual Histogram**

The Residual Histogram is used to demonstrate whether the residual is normally distributed by dividing the residuals into equally spaced groups and plotting the frequency of the groups. When data is symmetrically distributed around the zero, t means that the residuals are normally distributed and the normality assumption for the residuals is satisfied.

2.14 SUMMARY

This chapter briefly discusses the HMA mixes, the laboratory characterization of materials, bituminous paving mixes, desirable properties and types of bituminous paving mixes. In the second part, the bituminous mix preparation procedure, the literature about the tests performed in this research including Marshall Stability, flow, quotient, retained stability and resilient modulus were discussed in detail along with their significance and the factors affecting these tests. In the third section, the literature about the polymer modification, and the research carried out on polymers has been discussed along with the results obtained from each research. In the last section the full factorial design of experiment and the associated analytical terms have been explained.

Chapter 3

MATERIALS AND TEST PROCEDURES

3.1 INTRODUCTION

The purpose of this chapter is to discuss the research methodology and the materials and test procedures used for this research, in order to achieve the research objectives. The laboratory characterization of aggregates, bitumen and Bakelite used in the mix design are presented in detail. The method for specimen preparation and compaction is described. All the performance test including Marshall Stability, flow, quotient, retained stability and resilient modulus test using indirect tension test setup are discussed.

3.1 FRAMEWORK OF RESEARCH METHODOLOGY

The methodology adopted for this research can be seen in figure 1. Class B mix under the envelope of NHA gradation for wearing courses was selected. This specification is most frequently used by highway agencies for wearing courses in Pakistan. The first step was finding the optimum bitumen content (OBC) by Marshall mix design (ASTM D6926), which was then used in the preparation of both control and modified specimens. The modified asphalt concrete specimens were prepared by wet process using 60/70 penetration grade bitumen, Bakelite (2%,4%,6%,8%,10% and 12% by weight of OBC). The second step was the performance tests including Marshall Stability, flow, quotient (ASTM D6926) and retained stability (AASHTO T283) on control and modified specimens to compare their performance and find the optimum Bakelite percentage which showed better strength, flow and resistance to moisture induced damages. In the end resilient modulus (ASTM D4123) test was performed under variable Bakelite (0% & 6%), temperature (25˚C & 40˚C) and load duration (100 ms& 300 ms) conditions and the experimental investigation of these conditions and their interaction was analyzed by full factorial design experiment by MINITAB-16 software.

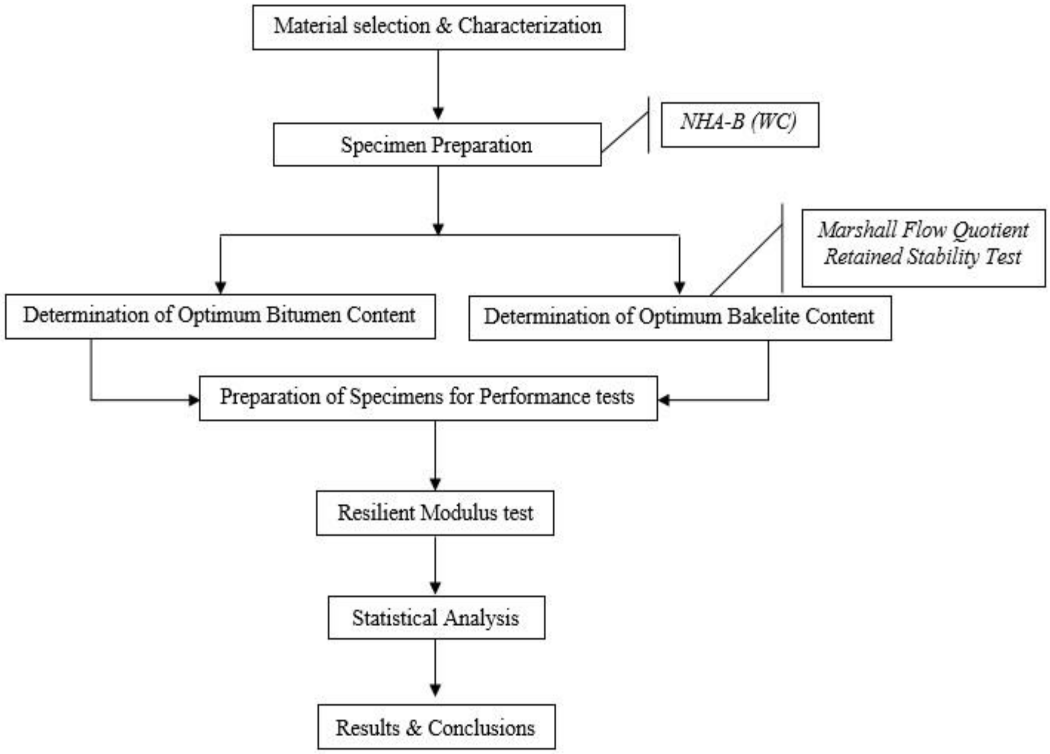

Figure 3.1: Flow Chart of Research Methodology

3.3 MATERIAL SELECTION

The laboratory characterization of materials selected for this research includes coarse aggregate, fine aggregate and bitumen. All these materials were selected according to the standard specifications for hot mixed asphalt pavements (ASTM D3515). The dense gradation was used in this research because Hot Mix Asphalt (HMA) pavements are designed using this type of gradation.

3.3.1 Aggregates (Coarse and Fine)

Coarse and fine aggregates used in this study were obtained from a rock crushing plant in Margalla quarries located near Taxila. This source was selected because it is recommended by National Highway Authority (NHA) for road construction projects. Aggregates were obtained in various sizes and then sieve analysis was performed to separate them into the desired sizes. The coarse and fine aggregates were then mixed according to NHA Class B wearing coarse trial gradation which is based on ASTM D3515 standard specifications. Stone dust from the same rock was used as mineral filler. Aggregate gradation used in this research is shown in table 3.1 and 3.2.

Tests were performed on aggregates to check their acceptability as a wearing coarse material in light of the specifications and standards of NHA. The test results are tabulated in table 3.3 and show that the aggregates lie within the specified parameters of NHA specifications.

Table 3.1: Gradation Specification for Dense Asphalt Mixes

Dense Mixture								
Mix Designation and Nominal Maximum Size of Aggregate								
Sieve Size	2 in.	1.5 in.	1 in.	0.75 in.	0.5 in.	0.375 in.	# 4	#8
Grading of Total Aggregate (Coarse plus fine) Amount finer than Each Laboratory Sieve, weight %								
2.5 in.	100	…	…	…	…			…
2 in.	90 to 100	100	…	….	…			…
1.5 in.	…	90 to 100	100	…	…			…
1 in.	60 to 80	…	90 to 100	100	…			…
0.75 in.	…	56 to 80	…	90 to 100	100			…
0.5 in.	35 to 60	…	56 to 80	…	75 to 90	100		…
0.375 in.	…	…	…	56 to 80	60 to 80	90 to 100	100	…
# 4	17 to 47	23 to 53	29 to 59	35 to 65	40 to 60	55 to 85	80 to 100	…
# 8	10 to 36	15 to 41	19 to 45	23 to 49	20 to 40	32 to 67	65 to 100	…
# 16	…	…	…	…	5 to 15	…	40 to 80	…
# 30	…	…	…	…	…	…	25 to 65	…
# 50	3 to 15	4 to 16	5 to 17	5 to 19	…	7 to 23	7 to 40	…
# 100	…	…	…	…	…	…	3 to 20	…
# 200	0 to 5	0 to 6	1 to 7	2 to 8	3 to 8	2 to 10	2 to 10	...
Bitumen, Weight % of Total Mixture								
	2 to 7	3 to 8	3 to 9	4 to 10	4 to 11	5 to 12	6 to 12	7to12

Source. After ASTM D3515

Table 3.2: Gradation of Aggregate for Bituminous Mix

Sieve Size (mm)	NHA Class B Master band(% Passing)	Trial Blend	% Retained	Sample Weight (gm)
19	100	100	0	0
12.5	75-90	82.5	17.5	210
9.5	60-80	70	12.5	150
4.75	40-60	50	20	240
2.38	20-40	30	20	240
1.18	5-15	10	20	240
0.075	3-8	5.5	4.5	54
Pan	-	-		66

Table 3.3: Laboratory Tests Performed on the Aggregates

Test Type	Designation		Test Results	Standard Limits
Shape test (%)	Flakiness Index	ASTM D4791	13.16	≤ 15 %
	Elongation Index		13.72	
Impact test (%)	ASTM D5874		15	30 % max
Abrasion test (%)	ASTM C131		23	≤ 40 %
Specific gravity	Coarse	ASTM C127	2.63	
	Fine	ASTM C128	2.54	

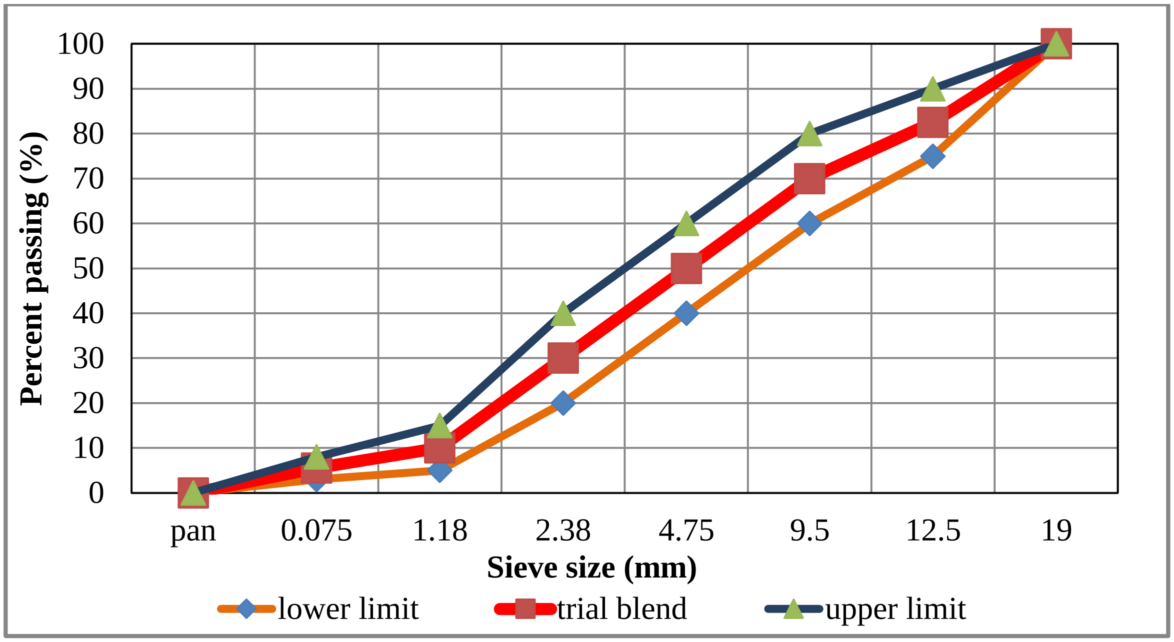

Figure 3.2: Gradation of Aggregate for Bituminous Mix

3.3.2 Bitumen

Bitumen used in this study was 60/70 penetration grade which is the most commonly used bitumen in Pakistan. It was obtained from Attock Oil Refineries Rawalpindi. Prior to sampling, the bitumen was tested for laboratory characterization as a binder by specifications and standards of ASTM and AASHTO. The results are tabulated in table 3.3 and show that the bitumen used in this research is 60/70 penetration grade by all standards of NHA.

Table 3.4: Laboratory Tests Performed on the Bitumen

Test Type	Designation	Results	Standard Limits
Penetration (25°C,100g,5s) mm	ASTM D5	63	60-70
Softening point (°C)	ASTM D91	50	46-54
Flash point (°C)	ASTM D92	265	> 232
Fire point (°C)	ASTM D92	301	> 232
Ductility (25°C) cm	ASTM D113	130+	> 100
Specific gravity	ASTM D70	1.03	> 1.00

3.3.3 Bakelite

The Bakelite used in the study was obtained from Ismail Industries Gujranwala in grinded form. The Bakelite was sieved and the portion of Bakelite passing #100 sieve was then used. The results are presented in table 3.5 below.

Table 3.5: Properties of Bakelite

Properties	Results
Specific gravity	1.36
Melting point range	150-165°C
Decomposition temp. range	270-350°C
Sieve analysis	Passing sieve#100

3.4 DETERMINATION OF OPTIMUM BITUMEN CONTENT

After gradation, material selection and testing, the next step was the selection of testing procedure for specimen preparation. In this research all the specimens were prepared by Marshall Mix design (ASTM D6926) procedure using NHA-B gradation for wearing course and 4 inch diameter. Following is the test procedure.

3.4.1 Marshall Specimen Preparation Matrix

The specimens were divided into four categories; Marshall specimens for optimum bitumen content (OBC) determination, conventional specimens having OBC, specimens with varying percentages of Bakelite and the specimens with optimum Bakelite content. Three specimens were prepared for each individual increasing percentage of bitumen and Bakelite. The detail of the specimens and their mixes are given in table 3.6 below.

Table 3.6: Detail of Specimens Prepared

Type of Mix	Percent Bitumen	Percent Bakelite	Specimens Prepared	Diameter (inch)
Marshall specimens	3.5, 4, 4.5, 5	0	4×3= 12	4
Modified with bakelite	4.3	2, 4, 6, 8, 10, 12	6×9= 54	4
Control	4.3	0	25	4
Modified with Optimum Bakelite	4.3	6	16	4

- **Amount of Aggregates, Bitumen and Bakelite for Sampling**

For the preparation of test specimens, first of all the aggregates were sieved into various desired sizes according to NHA Class B gradation. Sieve analysis was performed manually and all the aggregates were separated into required gradations. These aggregates along with mineral filler were then mixed according to the desired gradation and dried to constant weight at 100 - 110˚C in an oven for about an hour

Table 3.7: Amount of Aggregate & Filler required for each Specimen

Sieve Size (mm)	Sample Weight (gm)
19	0
12.5	210
9.5	150
4.75	240
2.38	240
1.18	240
0.075	54
Filler	66
Total weight	1200

.

The amount of aggregates and filler required for each specimen according to Marshall Mix design criteria (ASTM D6926) is provided in table 3.7 above**.**

The amount of bitumen required for each specimen was taken as the percentage of weight of total mix obtained from equation 3.1 and 3.2.

$$M_A + M_B = M_T \quad (3.1)$$

$$M_B = \frac{X}{100}(M_T) \quad (3.2)$$

Where,

X= Percentage of Bitumen

M_A= Mass of the Aggregate

M_B= Mass of the Bitumen

M_T= Mass of the Total Mix

Table 3.8 shows the amount of bitumen required for each specimen by Marshall Mix design, calculated by Equation 3.2.

Table 3.8: Amount of Bitumen required for each Percentage

Bitumen (%)	Weight (gm)
3.5	43.4
4	49.9
4.3	54
4.5	56.4
5	63

The amount of Bakelite added was taken as the percentage of the weight of optimum bitumen content (OBC), is given by equation 3.3.

$$M_b = \frac{X}{100} \times 54 \quad (3.3)$$

Where,

X= Percentage of Bakelite

M_b= Mass of the Bakelite

Table 3.9 shows the amount of Bakelite required for each specimen by Marshall Mix design, calculated by Equation 3.3.

Table 3.9: Amount of Bakelite required for each Percentage

Percent Bakelite	Weight of bakelite(grams)
2	1.1
4	2.16
6	3.25
8	4.32
10	5.4
12	6.5

- **Mixing of Aggregate, Bitumen and Bakelite**

The mixing of aggregates, filler and bitumen was done by a mechanical mixer as recommended by ASTM D6926 to ensure proper mixing. Heated aggregate (165˚C) and bitumen were transferred to the mechanical mixer which was pre-heated to 165˚C. This mixing temperature was selected as specified by NHA. The mix was given 1000 cycles for thorough mixing. In case of modified asphalt, Bakelite and bitumen were mixed (thorough hand mixing for 15 minutes) and heated (150-165˚C) first before mixing with aggregates. Figure 3.3 shows the mixing of aggregates, bitumen and Bakelite in a temperature controlled mechanical mixer.

Figure 3.3: Mixing of Aggregates and Bitumen in Mechanical Mixing Machine

- **Compaction and Extraction of Specimens**

After mixing, the prepared mix was compacted at 135˚C in case of conventional mix while in the modified mix was compacted at 160˚C by Marshall Method using mechanical hammer. The Marshall moulds consisted of a base plate, mould cylinder and collar extension. The moulds were heated, oiled and filter paper was placed inside. The mix was transferred to the mould and by vigorously spading with spatula around the perimeter. A filter paper was placed on the top and mould assembly was placed in mould holder on compaction pedestal and the hammer was set properly. For compaction, 75 blows of hammer were given on both the faces of the specimen. This was done because the design criteria adopted for this research was heavy traffic which requires 75 blows on each face of the specimen if it is 4 inches in diameter, which was the case in this study. After compaction the mould assembly was allowed to cool and then disassembled and specimen removed by an extraction jack. Figure 3.4 shows compaction of a specimen while figure 3.5 shows an extraction jack.

Figure 3.4: Compaction of Specimens by Compaction Pedestal

Figure 3.5: Extracting Jack for Extraction of Specimens

3.4.2 Determination of Optimum Bitumen Content (OBC)

The specimens were prepared at four asphalt contents. Three specimens were prepared for each asphalt content thus making a total of 12 specimens. After samples were prepared they were kept at room temperature for 24 hours and then before testing for stability and flow, they were kept in water bath at 60ºC for 30 minutes. Stability and flow values were noted while loading specimen at constant rate of deformation of 2 inch/min until failure occurred. Volumetric properties were determined. Graphs were plotted against the asphalt contents versus, stability bulk density, flow, VA, VMA and VFB. Optimum bitumen content (OBC) was calculated on the basis of bitumen content at 4% air voids.

The other volumetric properties were then determined at OBC with reference to the graphs. The values were later checked against the design requirements for selection as design values.

The volumetric properties determined for different bitumen contents are tabulated in Table 3.11.

Table 3.11: Volumetric Properties of Bituminous Concrete Mixes

Asphalt %	**G_{mb}**	**G_{sb}**	**G_{mm}**	**VMA (%)**	**VA (%)**	**VFB (%)**	**Stability(KN)**	**Flow (mm)**
3.5	2.33	2.59	2.49	15.80	6.61	58.16	9.313	1.88
4.0	2.34	2.59	2.46	15.49	5.00	67.72	10.5461	2.74
4.5	2.36	2.59	2.45	15.56	3.37	78.34	11.118	3.07
5.0	2.35	2.59	2.44	16.74	2.99	82.13	10.631	3.30

Figure 3.6 shows the interaction of different volumetric properties versus bitumen content. The optimum bitumen content is the value corresponding to 4% air voids, which came out to be 4.3% by weight of the mix. All other volumetric properties were determined in reference to the 4.3% binder content using the plotted graphs. The results were checked against the NHA design specifications (Table 2.3). All the results were within the design limits. The results are tabulated in Table 3.12.

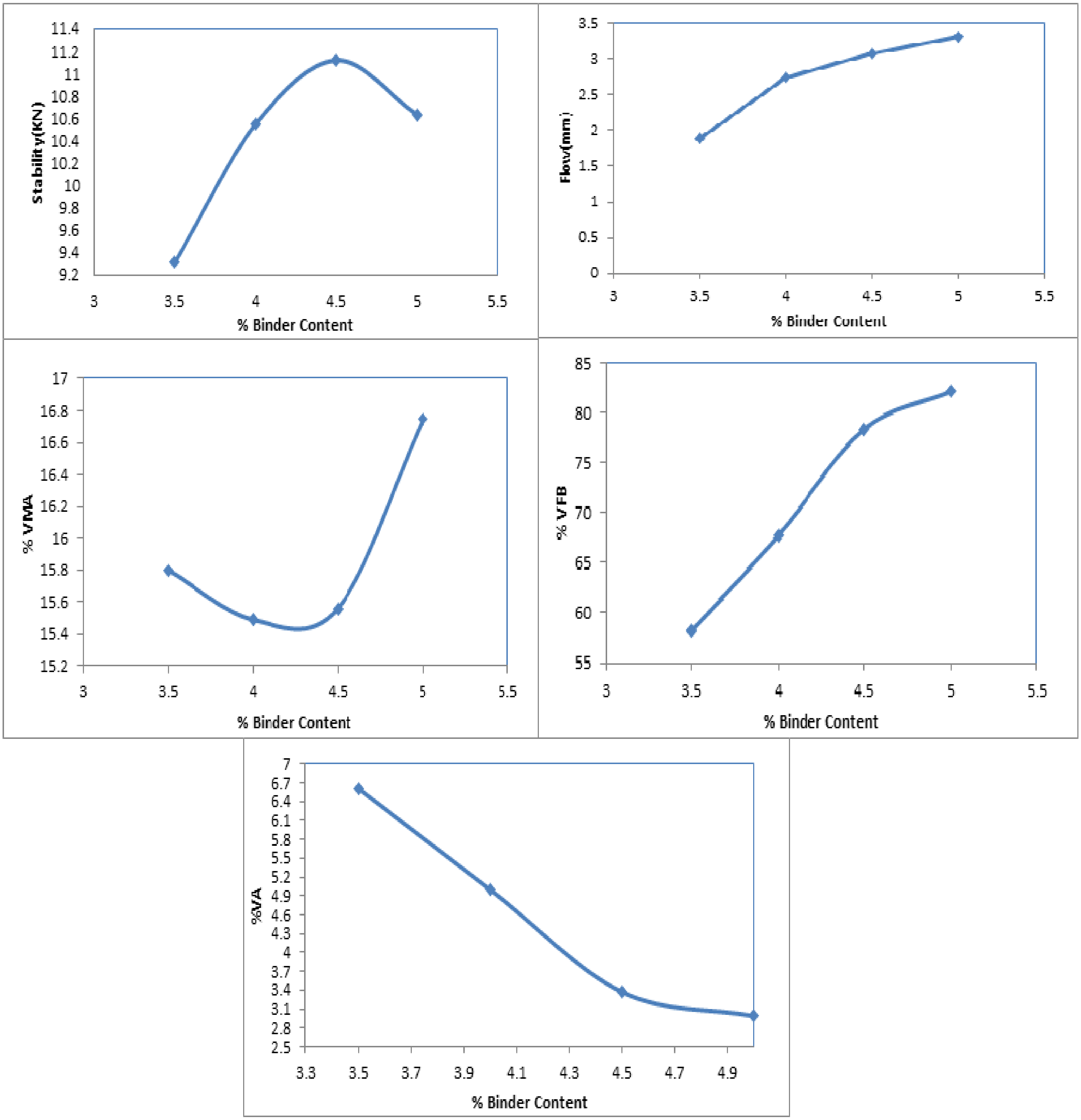

Figure 3.6: Volumetric Properties versus Binder Content

Table 3.12: Volumetric properties at OBC and NHA Specifications

Properties Investigated	Test Results	NHA Specifications
Binder Content (%)	4.3	3.5 (Minimum)
Stability (kg)	1111 kg	1000
Flow (mm)	2.94	2 - 3.5
VA (%)	4	3 - 5
VMA (%)	15.53	15 - 16
VFB (%)	68	65 - 75

3.5 PERFORMANCE TESTS

The performance tests were performed to analyze the comparative analysis of both control(60/70 penetration grade at OBC) and modified asphalt specimens with Bakelite content of 2%,4%,6%,8%,10% and 12% by weight of optimum bitumen (OBC). The tests conducted were Marshall Stability, Flow, Quotient, Resilient Modulus and Tensile Strength Ratio (TSR) tests.

3.5.1 Marshall Stability, Flow and Quotient Tests

These tests were performed on both control and modified specimens at optimum bitumen content. A total of 21 specimens were prepared 3 for control and 3 for each modified asphalt mix. The specimens were kept overnight and then prior to testing were kept in water bath for 30 minutes at 60˚C. After that, the samples were dried with a towel and placed in the compression testing machine. The compression testing machine measures the maximum load a specimen can withstand by applying load at the rate of 2 inch/min until failure. The stability and flow values were directly given on the screen. The Marshall quotient was calculated by taking the ratio of stability to the flow for each specimen. Figure 3.7 shows the compression testing machine prepared for Marshall Stability and flow testing of specimens.

Figure 3.7: Marshall Compression Machine

3.5.2 Tensile Strength Ratio (TSR) test

The tensile strength ratio (TSR) test was conducted according to AASHTO T283 to test the resistance of compacted asphalt concrete specimens to moisture induced damage. Currently AASHTO T283 is the most widely used test procedure to evaluate the potential of moisture induced damage to the HMA pavements. The HMA produced may be sensitive to the presence of moisture in the finished pavement; therefore it is necessary to check the adequacy of the modified asphalt concrete as a product capable of withstanding moisture induced damages. The test was performed in the following sequence. This test procedure is established for 4 inch specimens prepared by Marshall Mix design procedure.

Table 3.14: AASHTO T283 test parameters

Test Parameters	Specifications
Specimen size	2.5”× 4”
Compacted HMA curing	24 hours @ room temperature
Compaction temperature	150˚C- 160˚C
Saturation	70-80%
Swell determination	NO
Freezing	-18˚C for 18 hours
Water soaking	60˚C for 24 hours
Compaction method	Marshall
Strength property	Indirect tensile @ room temperature

- **Specimen size and Grouping**

This test procedure is established for 4 inch specimens prepared by Marshall Impact compaction method. Marshall Test specimens were divided into two groups: the conditioned and unconditioned groups. Both groups consisted of 21 specimens (total of 42), 3 specimens each of conventional and every increasing percentage of modified mixes.

- **Compacted mix aging**

After the specimens were prepared they were kept at room temperature for 24 hours for compacted mix aging. The specimen were divided into two groups, the conditioned and unconditioned. For the specimens in the conditioned group, prior to saturation, air voids in cubic centimeters (cm^3) was calculated using equation.

$$V = \frac{P \times E}{100} \tag{3.4}$$

Where,

V = Volume of air voids, cm^3

P = Air voids, percent

E = Volume of specimen, cm^3

- **Saturation of Specimens**

The group named conditioned specimens was weighed and the values were recorded as air dry weight. The next step was vacuum saturation using a saturation chamber. Figures 3.8 and 3.9 are showing conditioning chamber and samples conditioning.

Figure 3.8: Saturation Chamber

Figure 3.9: Specimens in Saturation Chamber

In this chamber, the specimens were dipped in water such that 1 inch of water is above their surface. A vacuum of 10 mm of Hg was applied for 10 minutes according to the requirements of the standard test procedure. The specimens were kept submerged for 10 minutes after the removal of vacuum. After removal from the conditioning chamber, the specimens were dried, weighted and the values recorded as saturated surface dry weight (SSD).

The volume of absorbed water (J) in cubic centimeters was calculated by the equation 3.5.

$$J = \mathrm{B} - \mathrm{A} \tag{3.5}$$

Where,

J = Volume of adsorbed water, cm^3

B = Weight of saturated surface dry (SSD) specimens, g

A = Weight of air dry specimens, g

The degree of saturation (S) was calculated by the following equation.

$$\mathrm{S} = \frac{100 \text{ x J}}{\mathrm{V}} \tag{3.6}$$

Where,

S = Degree of saturation, percent (%)

J = Volume of absorbed water, cm^3

V = Volume of air voids, cm^3

According to the design guidelines, the degree of saturation should be within 70 to 80 percent. If it is less than 70 percent then the vacuum saturation is repeated and if it is more than 80 then the specimens are discarded. All the specimens were within saturation range of 70 to 80 percent.

- **Freeze/thaw conditioning**

The saturated specimens were then subjected to freeze/thaw cycle. Firstly they were placed in a freezer at -18˚C (0˚F) for 18 hours and then placed in a water bath at 60˚C (140˚F) for 24 hours. Figure 3.6 shows a water bath used for the saturation of specimens at elevated temperatures.

Figure 3.9: Specimen being put in Water bath for Conditioning

- **Indirect tensile strength (ITS) determination**

After the freeze/thaw conditioning, the conditioned specimens were dried using a towel and then kept at room temperature for 2 hours before testing. After 2 hours both conditioned and unconditioned specimens were tested for splitting tensile strength by placing them on their side between the bearing plates of testing machine at room temperature and load applied at constant rate of 2 inch per minute until the specimen splits. ITS was calculated using equation 3.7.

$$ITS = \frac{2Pmax}{\pi td} \qquad (3.7)$$

Where,

P_{max}= Maximum load (kg)

t= thickness of the specimen (cm)

d = diameter of the specimen (cm)

Figure 3.10 shows the compression testing machine while figure 3.11 shows the specimen starting to split under the load.

Figure 3.10 Splitting Tensile Test Set up

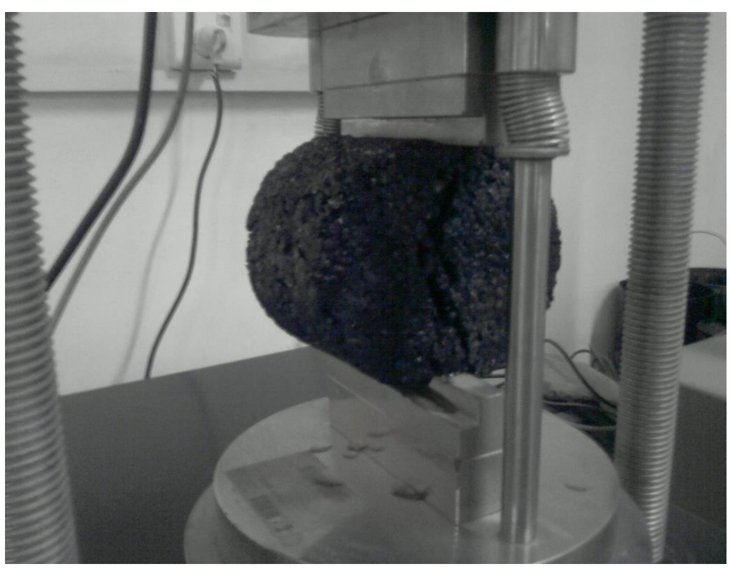

Figure 3.11 Specimen Starting to Split under the Load

- **Tensile strength ratio (TSR)**

The ratio of ITS of conditioned (60˚C, 24 h) to unconditioned specimens is known as tensile strength ratio (TSR). The test was conducted at room temperature. The conditioned group specimens were brought to room temperature prior to indirect tensile strength determination. After test was performed on all the specimens, TSR was calculated by equation 3.8.

$$TSR = \frac{ITS\ (Conditioned)}{ITS(Dry)} \tag{3.8}$$

Where,

$ITS_{\,(conditioned)}$ = Indirect tensile strength of conditioned specimen

$ITS_{\,(Dry)}$ = Indirect tensile strength of dry specimen

3.5.3 Resilient Modulus test

The resilient modulus is an important mechanical property in the design of flexible pavements. The resilient modulus was determined from tests on Marshall Specimens of both modified and un modified mixes using Indirect tension test. Universal testing machine (UTM-25) was used to conduct these tests according to ASTM D4123. The first step of determining the resilient modulus was the indirect tensile strength test performed in the following sequence.

- **Indirect tensile strength determination**

The ASTM D6931 specifies that prior to resilient modulus determination; indirect tension test should be performed on one specimen. The specimen was placed in the test jig and was braced from top and bottom to hold it in place. A compressive load across the vertical diametral plane was applied at a controlled deformation rate of 50 mm/min at 25˚C.The failure stress was taken as the indirect tensile strength of the specimen. For the resilient modulus test, 20 % of that indirect tensile test peak force value was taken. Figure 3.12 shows the failure of specimens during indirect tension test.

Figure 3.12: Failure of Specimens during Indirect Tension Test

Table 3.16 shows the indirect tension peak force values. These values were obtained from the Stress-strain test software developed by IPC global.

Table 3.16: Peak Force Values in Indirect Tensile Strength Test

Compactive Effort	Bakelite (%)	Diameter (inch)	Peak force (KN)
Marshall	0	4	10.76
Marshall	6	4	13.19

- **Jig Set-up for Resilient Modulus test**

After the indirect tension test, the actual resilient modulus test was performed on the remaining specimens. Figure 3.13 shows the component of jig for resilient modulus testing. The metallic fixtures for LVDTs (linear variable differential transformer) were installed in the jig. The LVDTs are used for measuring the linear displacement. The specimen was then loosely fitted into the jig on the bottom loading platen. The yoke support cross-arm was raised by lifting then turning the support spacers. The height of the support cross-arm was adjusted in such a way that the displacement transducers remain exactly in line with the horizontal center of the specimen. The displacement transducer yoke was then placed and adjusted with the help of screws then the clamps were tightened. Top loading platen was then placed and lowered it onto the specimen as shown in Figure 3.13.

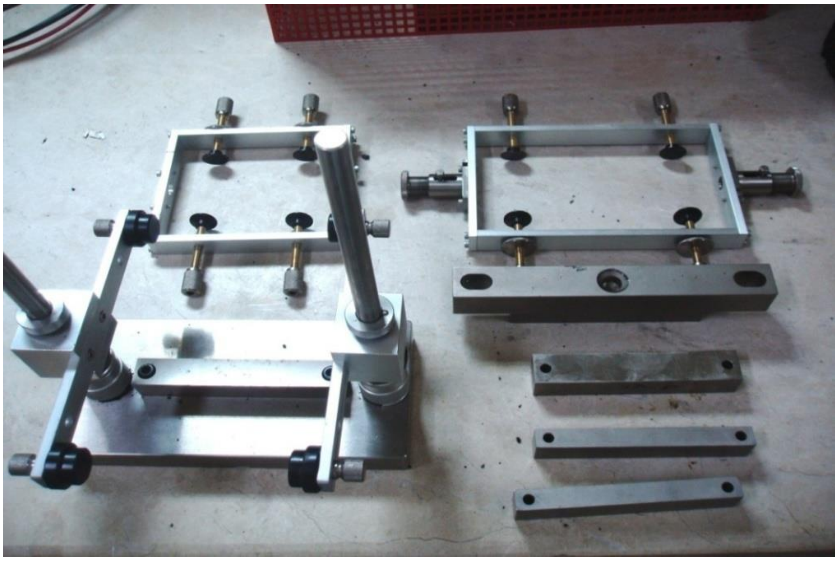

Figure 3.13: Specimen Jig Accessories for Resilient Modulus Test

Figure 3.14: Jig Setup for Resilient Modulus Test

- **Loading and testing of specimens**

After the jig setup, the jig was transferred for resilient modulus testing into universal testing machine. The LVDTs were installed through the fixtures and adjusted to operate within their range as shown in Figure 3.15. The levels display view helped to adjust the LVDTs. The virtual pendant window containing the functionality controlled the hydraulic power pack and service manifold of the machine. Therefore; by using axis jog control, the loading ram was lowered to such a level that it just a made contact with the jig but without applying any loading force. As specified by ASTM D4123, the peak loading force was taken as 20% of the failure load and seating force was kept 10% of the peaking loading force. Poisson's ratio was assumed as 0.4.

After inputting the target temperature, load pulse width, pulse repetition period, and conditioning pulse count, the test sequence started and specimen was subjected to have sine loading. The indirect tension modulus software charted and tabulated the force and displacement as the conditioning stage proceeded. At the conclusion of the conditioning stage, i.e. after 100 conditioning pulses, the Levels display automatically invoked. The out of range LVDTs were adjusted and by closing the Level display window, automatically 5 pulses of nearly constant deformation were applied to conclude the test.

Figure 3.15: LVDTs Setup in UTM for Resilient Modulus Test

- **Results**

Deflection and load readings were recorded by the software for the last 5 pulses after conditioning pulses of the test. The readings were averaged to determine the resilient modulus. Four resilient modulus values were determined for each specimen. The test matrix consisted of 32 specimens, out of which 16 were control specimens containing 0% Bakelite and 16 were modified containing 6% Bakelite. Both control and modified specimens were tested in a group of four for two temperatures (25˚C & 40˚C) and two loading (100 ms& 300 ms) conditions.

3.6 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 stability and flow tests were conducted and optimum bitumen content was determined. In second part, the performance testing procedures adopted for finding the optimum Bakelite content and comparison of conventional and modified mixes were explained.

CHAPTER 4

ANALYSIS OF EXPERIMENTAL RESULTS

4.1 INTRODUCTION

This chapter tabulates the detail of the results obtained from the various performance tests including Marshall and retained stability tests followed by a detailed analysis of data obtained from the Resilient Modulus test. The results of resilient modulus were analyzed by a statistical software known as MINITAB-16. The significance of each factor and also their interactions were found and presented with the help of graphs such as Pareto plot, normal probability plot, and factorial plots. Lastly, the model adequacy and accuracy was checked by residual analysis, so that inferences can be drawn based on the results of this model.

4.2 MARSHALL STABILITY, FLOW & QUOTIENT RESULTS

The results of Marshall Stability, flow and quotient tests, performed on conventional and modified mixes are tabulated in tabulated in Table 4.1.

Table 4.1: Marshall Test Results for Conventional and Modified Mixes

Properties Tested	**Bakelite percentage by weight of Optimum binder content**						
	0%	**2%**	**4%**	**6%**	**8%**	**10%**	**12%**
Marshall Stability (KN)	10.89	11.95	12.60	13.26	12.80	12.486	12.09
Flow, (mm)	2.94	2.81	2.64	2.49	2.79	3.04	3.29
Marshall Quotient	378	434	486	543	468	419	375

Figure 4.1 shows the Marshall stability of the conventional and modified mixes versus the percent Bakelite content. It can be seen that Marshall Stability of modified mixes is higher compared to conventional mix. The stability increases with increasing Bakelite content until 6%, which gives highest stability value. However, further increase in Bakelite content (8-12%) results in the decrease of stability. The stability is increasing with the addition of polymer is due to increase in adhesion between the mix (Awwad et al 2007, Chen et al 2009, Sabina et al 2009). However further increase causes decrease in stability

due to decrease in adhesion. Therefore the optimum Bakelite content came out to be 6% by weight of bitumen.

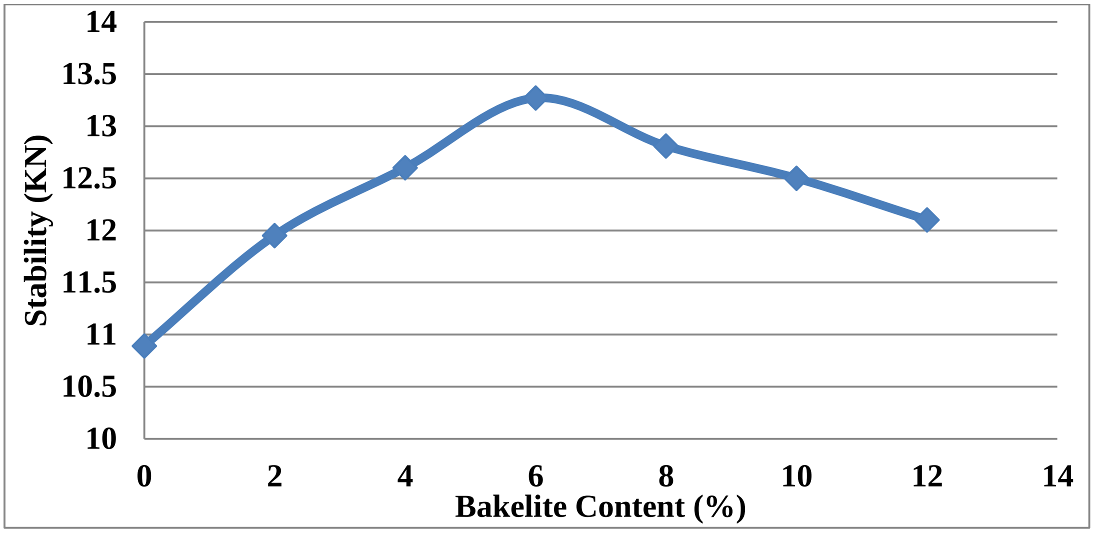

Figure 4.1: Marshall Stability versus Bakelite Content

The flow values for the conventional and modified mixes at various Bakelite percentages are shown in Figure 4.2. The flow decreases initially with Bakelite addition until 6% but increases after further addition from 8% to 12%.As displayed in the figure addition of polymer initially decreases the flow which is due to increase in stiffness of the mix however further increase causes fatigue cracking due to which the flow increases (Ahmadinia et al 2011).

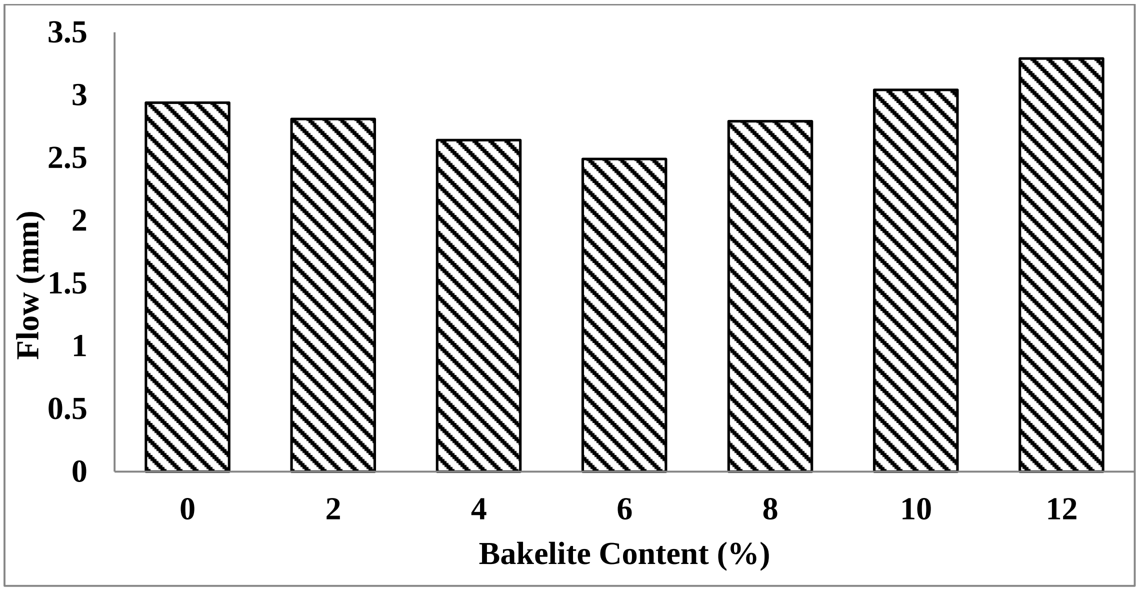

Figure 4.2: Marshall Flow versus Bakelite Content

The Marshall quotient is a measure of resistance to permanent deformation, shear stress and rutting (Ahmedzed et al 2008). Figure 4.3 shows that 6% Bakelite is the optimum value and its value is 44% higher as compared to the control mix. This increase is due to the increase in stiffness of the mix by the addition of Bakelite. Therefore the modified mix is more resistant to deformation than the control mix.

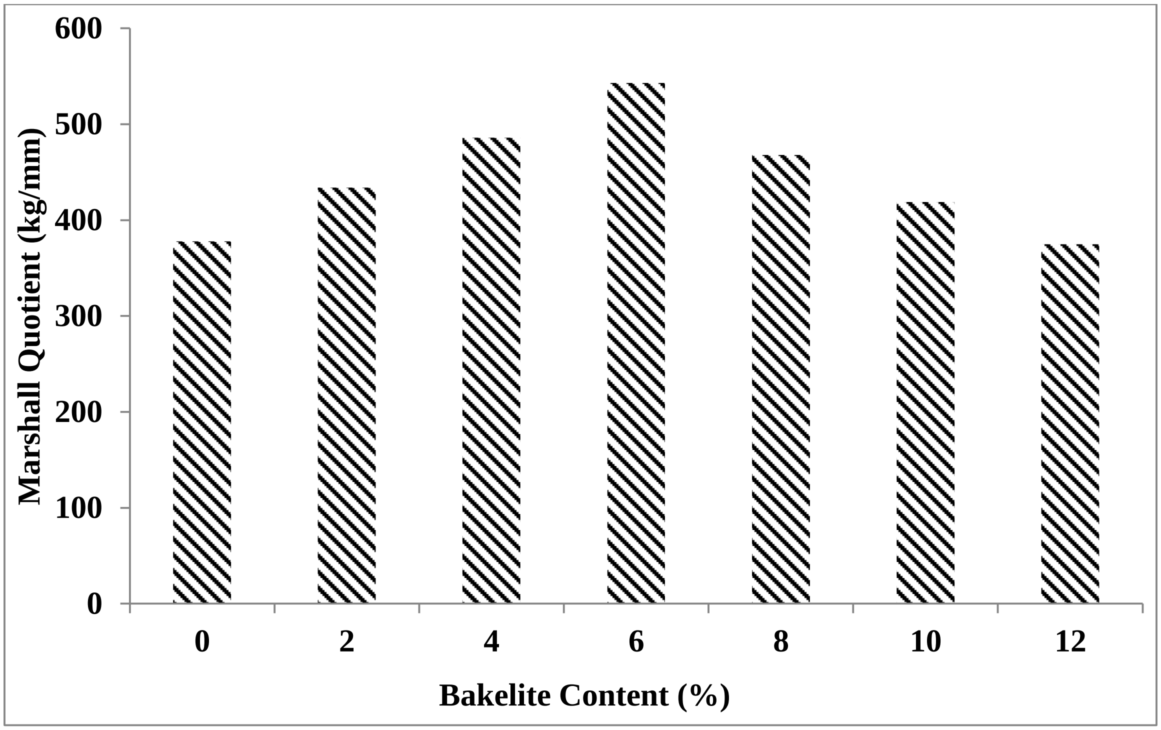

Figure 4.3: Marshall Quotient versus Bakelite Content

4.3 TENSILE STRENGTH RATIO RESULTS

TSR is a measure of retained stability of the mixes against moisture damage. Higher the TSR value the better the asphalt mixture resistance against moisture damage.

The results of the ITS test and TSR are given in Table 4.2.

Table 4.2: ITS and TSR Results for Dry and Wet Specimens

Properties Tested	Bakelite percentage by weight of Optimum binder content						
	0%	**2%**	**4%**	**6%**	**8%**	**10%**	**12%**
ITS(DRY), (kg/cm^2)	9.98	10.95	11.60	12.15	11.73	11.44	11.08
ITS(WET), (kg/cm^2)	9.13	10.11	10.69	11.55	11.12	10.75	10.33
TSR (%)	91.5	92.3	92.6	95	94.8	94	93.6

The indirect tensile strength results of control and Bakelite mixes are shown in Figure 4.4. As the results illustrate, the mixes with Bakelite as an additive show better results as compared to the control mix. ITS (dry) value obtained at 25˚C for conventional mix is 9.98 kg/cm^2 while it is 12.15 kg/cm^2 for 6% Bakelite modified mix. This implies that the Bakelite modified mix can withstand much larger tensile strain prior to cracking and thus they are less susceptible to moisture induced damages as compared to control mixes.

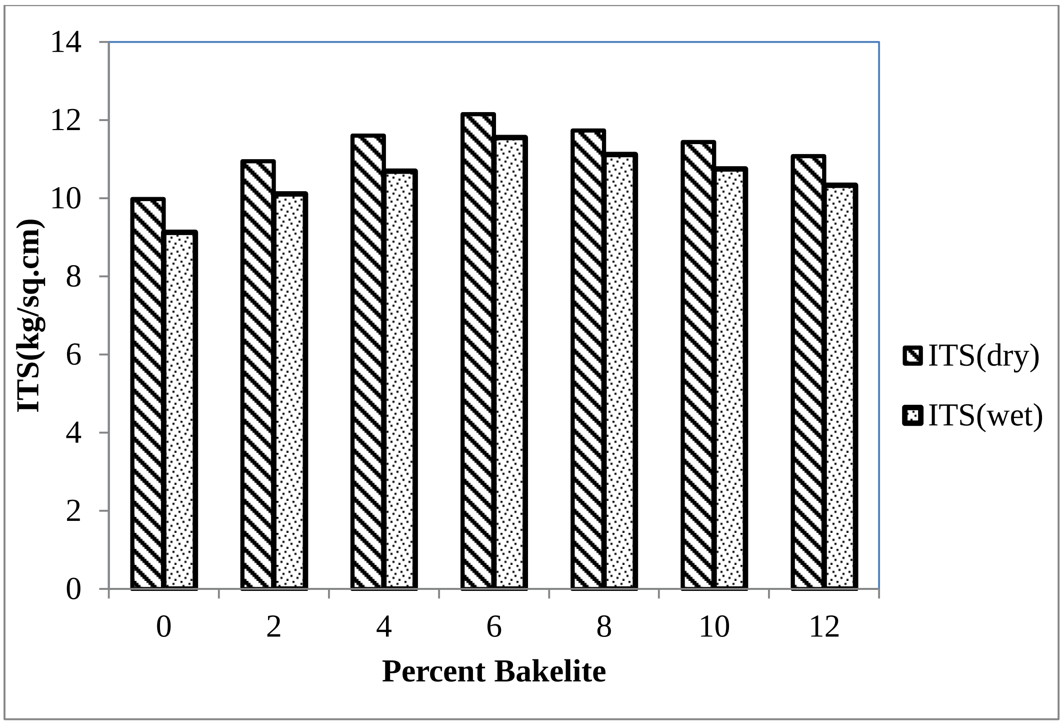

Figure 4.4: Indirect Tensile Strength versus Bakelite Content

Figure 4.5 shows TSR results of control and modified mixes. results indicate that 6% modified asphalt concrete retained 95% of its strength as compared to control which retained 91.5% thus indicating an increase of about 3.5 % in the capability of the HMA to resist moisture induced damages and retain its strength as compared to control mix. This indicates that modified mixes have high moisture resistant capabilities as compared to the control mixes.

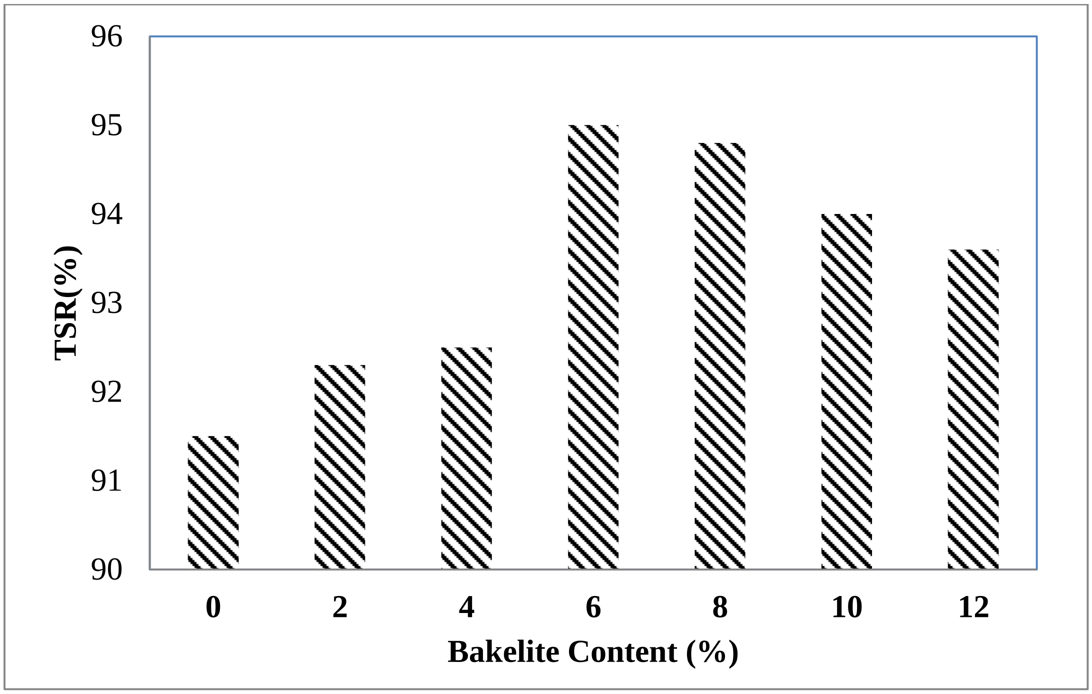

Figure 4.5: Tensile Strength Ratio versus Bakelite Content

4.4 FACTORIAL DESIGNFOR RESILIENT MODULUS TEST

In this research, three factors were considered i.e. Bakelite content, test temperature and loading duration, each with two levels. Therefore 2^3full factorial design of experiment was carried out using MINITAB-16 software. Table 4.3 illustrates the factors that have been taken in the 2^3full factorial design with their individual abbreviations and higher and lower levels. Inputting these three factors in software resulted in eight combinations. In order to achieve realistic estimation of errors, each combination was simulated four times thus a total of 32 tests were performed. Table 4.2 shows the combination of factors generated by software in the full factorial design of experiment.

Table 4.3: Factors and their Levels for Experiments

Abbreviation	**Factors**	**Levels**		**Units**
A	Bakelite content	0	6	%
B	Load duration	100	300	ms
C	Temperature	25	40	°C

Table 4.4: Design Table with Actual Values for Full Factorial Design

Bakelite (%)	Load duration (ms)	Temperature (°C)	Resilient modulus (Mpa)			
			1	2	3	4
0	100	40	5619	6012	5274	6190
0	300	40	4170	4567	4480	4355
0	100	25	7331	7562	7291	7583
0	300	25	6308	6311	6519	6405
6	100	40	8718	8507	8998	8683
6	300	40	7746	7604	7856	7623
6	100	25	9633	9782	9678	9814
6	300	25	8236	8468	8172	8327

4.5 EFFECTS AND COEFFICIENT TABLE

The Effects and coefficients values calculated by usingMINITAB-16 for the significant effects are shown in Table 4.5. The factors and interaction of factors with high (positive or negative) values of Effect and Coefficient indicate that they have large impact on the resilient modulus of bituminous paving mixes. The Effects for each term is equal to half of the coefficient. The individual factors or interaction of factors with P-value > significant level indicate that these factors and interactions are statistically significant at 5% significance level. Similarly the calculated value of t-statistics for the terms greater than the critical value of t-statistics ($t_{critical} =$ 2.06) for degree of freedom 31 and significance level of 5 %) indicates that the main effects and interactions are significant.

Table 4.5: Effects and Coefficients for Resilient Modulus

Term	Effects	Coefficient	SE coefficient	t-test	p - value
Constant		7306.9	34.77	210.16	0.00
Bakelite Content	2616.7	1308.4	34.77	37.63	0.000
Load Duration	-1220.5	-610.3	34.77	-17.55	0.000
Temperature	-1313.6	-656.8	34.77	-18.89	0.000
Bakelite - Load Duration	-2.1	-1.1	34.77	-0.03	0.976
Bakelite Content-Temperature	516.8	258.4	34.77	7.43	0.000
Load Duration-Temperature	20.5	10.3	34.77	0.29	0.771

Bakelite-Load Temperature	Duration-	182.9	91.4	34.77	2.63	0.015

4.6 SIGNIFICANT EFFECTS AND INTERACTIONS PLOTS

The significant effects and interaction plots show all those factors which effect the resilient modulus of bituminous paving mixtures. These are shown with the help of Pareto plot and Normal probability plot obtained from the analysis of the test results with MINITAB-16 software.

Figure 4.6 shows the Pareto plot of the standardized effects. The reference line indicates the critical value of student-t, which means that any factor which is beyond this point is influential and effects the resilient modulus of the bituminous mix. The Pareto plot shows that all the main factors i.e. temperature, load duration, Bakelite content are influential and effect the resilient modulus at 5 percent significance level. The 2-way interaction of Bakelite content and temperature, is well beyond the critical point shown by the reference line which shows that both these factors individually and their 2-way interaction are critical at 5 percent significance level and have influence on the resilient modulus of bituminous paving mixtures.

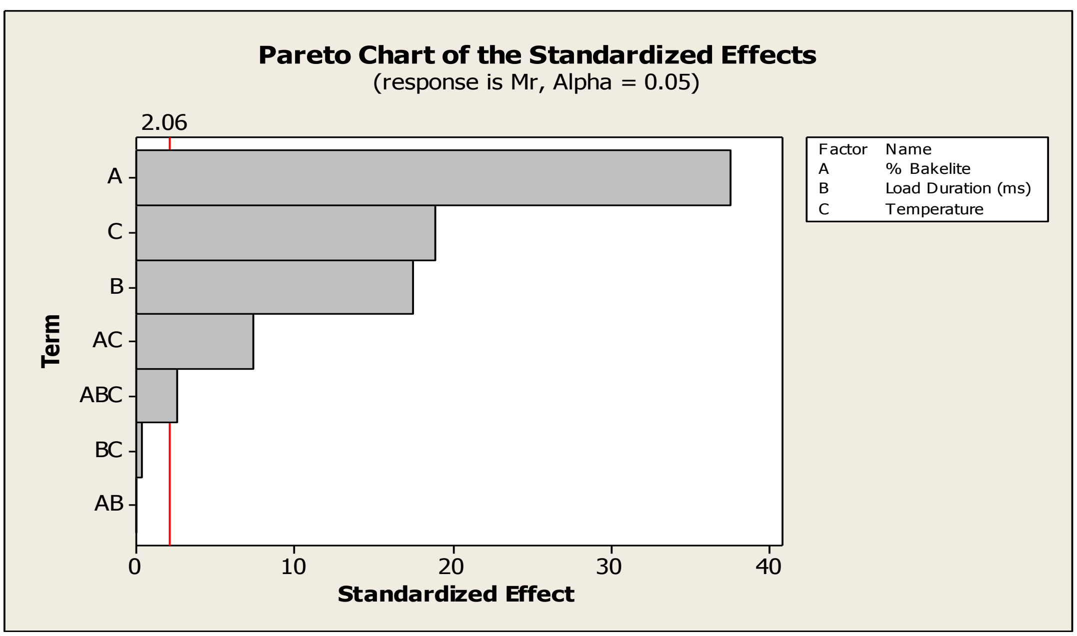

Figure 4.6: Pareto Chart of the Standardized Effect

The Bakelite content alone has most significant impact on the resilient modulus of bituminous mix when its level changes from 0% to 6% but its 2-way interaction with load duration, has no significant impact on the resilient modulus which may be due to the fact that addition of Bakelite makes the HMA more stiffer thus reducing the elasticity and increasing its potential for cracking under increasing load durations. It is interesting to note that 3-way interaction of Bakelite content, load duration and temperature is significant as compared to 2-way interactions of load duration with temperature. Thus the addition of Bakelite enhances the interaction of load duration and temperature and makes it significant for resilient modulus.

The standardized effects and their interactions can also be obtained from Normal probability plots. The significance of all the factors and their interactions are measured based on their distance from the reference line. Greater the distance, greater will be the significance (at 5% significance level) whereas those factors or interactions that are close to or on the reference line are less significant and insignificant respectively. The factors and interactions are shown in the Figure 4.7.

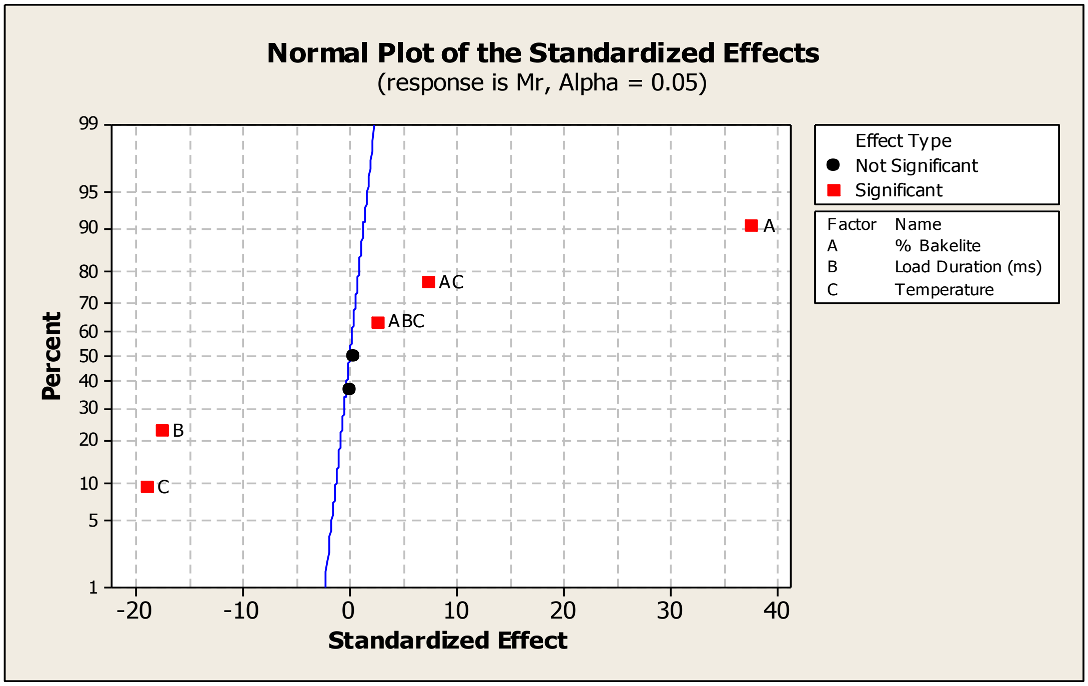

Figure 4.7: Normal Plot of the Standardized Effect

4.7 FACTORIAL PLOTS

The significant Effect and interaction obtained from the Pareto plot and normal probability plot can be discussed in detail in factorial plots. The effects of individual factors are shown with the main effect plots, 2-way interaction with interaction matrix and 3-way interaction with cubic plot. The Response surface plots are the graphical representation of model and can be used for interpolation.

4.7.1 Main Effect Plots

The main effects are Bakelite content, test temperature and load duration which are shown in Figure 4.8. It is clear from the temperature plot that resilient modulus is much lower for 40°C as compared to 25°C temperatures. The reason behind this observation is that the temperature increase makes the bitumen soft which consequently results in the decrease in the stiffness of the mix and ultimately decrease in elastic modulus of the mix.

The plot for the load duration shows that longer the duration of loading, lesser the resilient modulus. This is expected because greater the time of loading greater will be the amount of strain produced, reducing the resilient modulus. The reason for this observation is that by nature the bitumen is viscoelastic and such materials are nature of bitumen that causes the mixes to be dependent on condition and time of loading. Thus the slow moving vehicle has the more adverse consequences for the bituminous pavements, result in excessive rutting, and destruction of the pavement structure.

The Bakelite content plot shows a very steep slope as compared to load duration and temperature plots which shows that it is the most significant effect. The plot shows that addition of Bakelite increases the resilient modulus. Therefore; the effect of Bakelite content is significant as compared to other factors.

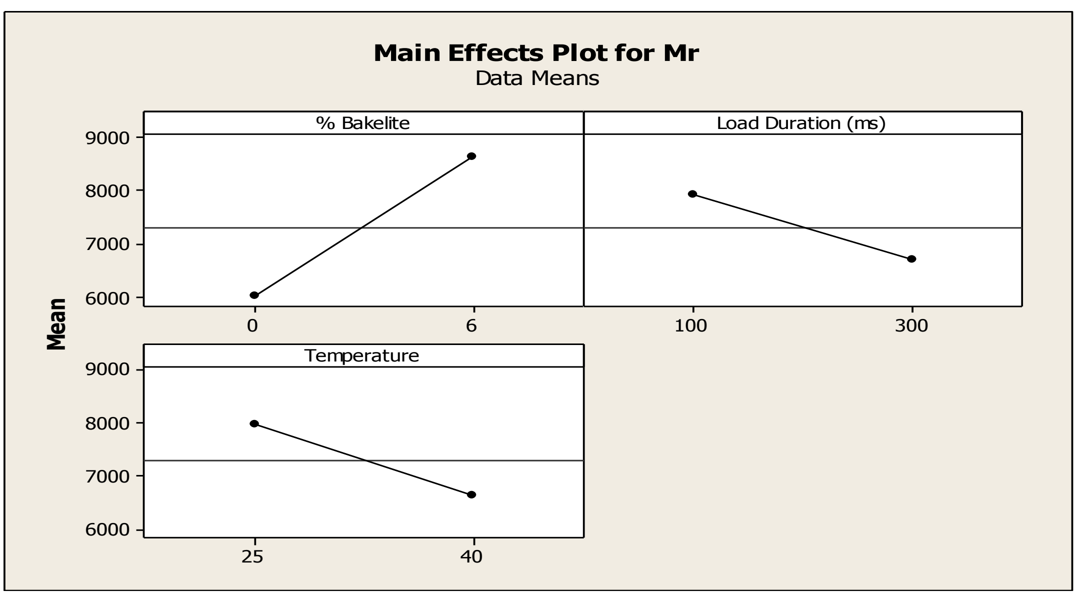

Figure 4.8: Main Effect Plots for Resilient Modulus of Bituminous Mixes

4.7.2 Interaction Plots/ Matrix

Figure 4.9 shows the interaction plot of different factors. It is clear from the plot that the only2-way significant interaction is Bakelite content and temperature which is represented by non-parallel lines, while Bakelite content-load duration and load duration-temperature are insignificant.

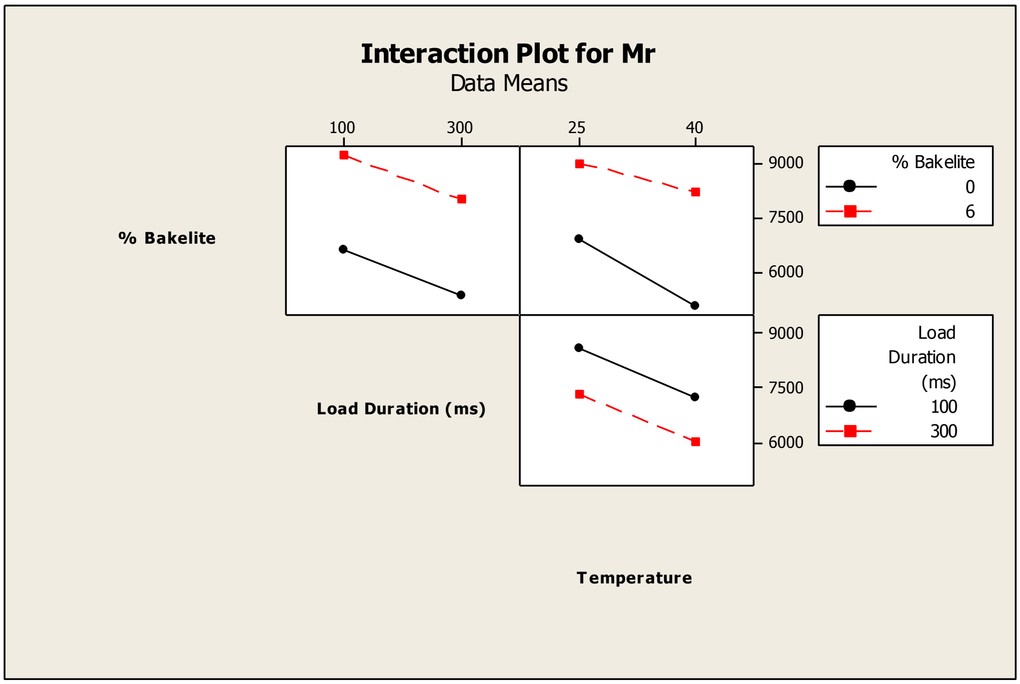

Figure 4.9: Interaction Plots for Resilient Modulus of Bituminous Mixes

Figure 4.9 also shows that variation in the resilient modulus for 6%Bakelite specimens is high as compared to 0% specimen when the temperature changes from 25 $^\circ C$ to 40 $^\circ C$. Similarly, large variation in resilient modulus occurs from 100 ms to 300ms at temperature of 25 $^\circ C$ as compared to the test temperature of 40 $^\circ C$ thus indicating that Bakelite content and temperature are the most significant factors influencing the resilient modulus of HMA mixes.

4.7.3 Cubic Plot

Figure 4.10 shows the 3-way interaction between the Bakelite, load duration and temperature. It is interesting to note that 2-way interaction of load duration and temperature were insignificant but their 3-way interaction with Bakelite is significant, which indicates that amount of Bakelite incorporated in the HMA mix has significant effect on the performance of the mix regarding resilient modulus. It is clear that highest resilient modulus value is observed at $25^{\circ}C$; 100 ms load duration and 6% Bakelite content. This could be the result of very small deformations that occur during this condition. The strain production during these conditions is very low and hence it results in highest resilient modulus. The lowest resilient modulus occur when the Bakelite content, temperature and load duration were at 0%, 40°C and 300 ms respectively. This again could be due to the high value of strains that result in the high level conditions lead to the reduction of resilient modulus.

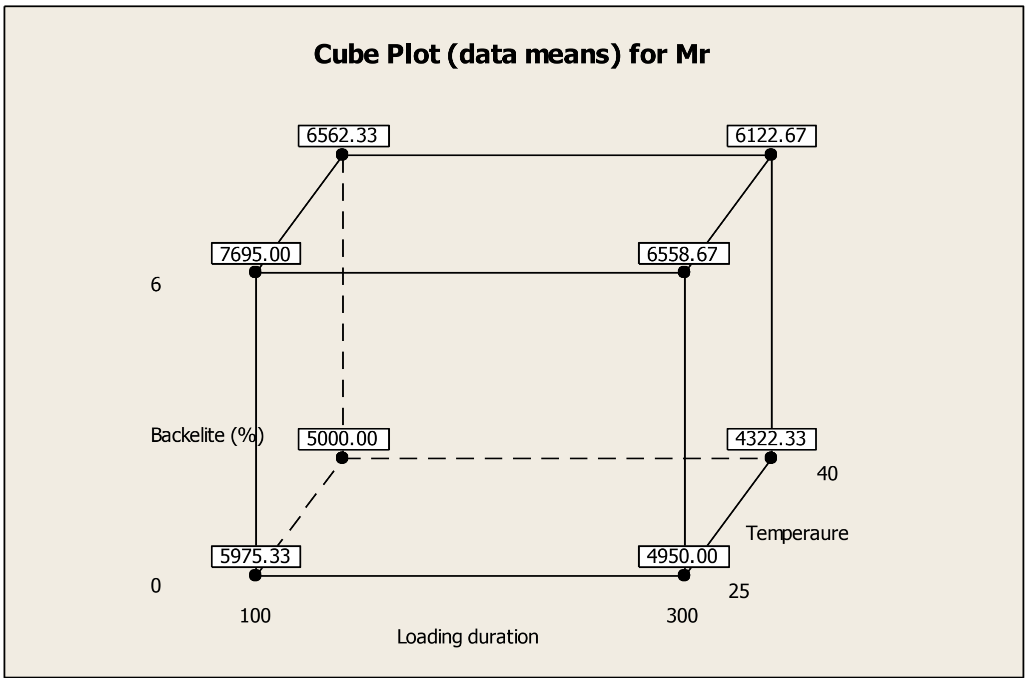

Figure 4.10: Cube Plot of 3-Way Interaction of Factors

4.8 ANALYSIS OF VARIANCE (ANOVA)

The Analysis of Variance ANOVA was conducted by forming four F-tests. These tests were then evaluated and probability values are given as shown in Table 4.6

Table 4.6: Analysis of Variance for Resilient Modulus

Source	DF	SS	MSS	F-Test	P-value
Main Effects	3	49185593	32790395	693.67	0.000
2-Way Interaction	3	415477	138492	18.44	0.000
3-Way Interaction	1	45675	45675	6.92	0.015
Residual Errors	24	12804304	261312		

Lack of Fit	1	385331	385331	1.49	0.976
Total	31	187124621			

The main effects test is used to assess the significance of individual factors, 2-way interactions test is for the combination of two factors while the 3-way interactions check the interaction among all the three factors at the same time. The P-value < 0.05 indicates that these tests are satisfied and they are significant in accessing the resilient modulus of the HMA mixes. The lack of fit test is used to access the model for errors. When the error is low, the model shows good fit and there is no *lack of fit*.

4.8 DIAGNOSTIC CHECKING

The diagnostic checking is applied to the residuals to check the accuracy of the model based on 2^3 factorial design matrix. The Experimental Design should be checked for assumptions like normality of error and constant variance. If these assumptions are violated, it will invalidate the Experimental Design and any conclusion based on such model. The major tool for the diagnostic checking is the residual analysis.

4.8.1 Residual Analysis

The residual (e) is the difference between the dependent variable (y) and the predicted value ($\hat{y}$). If the model fulfills the assumptions then it is a valid model and any conclusions based on such model will be considered valid. Following assumptions must be satisfied:

- **Normality Assumption**

The first assumption to be checked is the normality assumption. In order to do that the residuals should be plotted in the form of a histogram similar to the one presented in Figure 4.11. It reveals that the assumption is more or less satisfied since the plot looks like a normal distribution which is centered at zero. There is slight skewness from the normality which is not significant, so the assumption is not violated.

Normal probability plot of residuals is another way of checking the normality assumption. If the plot follows a straight line then it shows that it is normally distributed and the assumption of normality is fulfilled. The Figure 4.12, shows the plot which is following a straight line meaning that the errors are distributed normally and the assumption is satisfied.

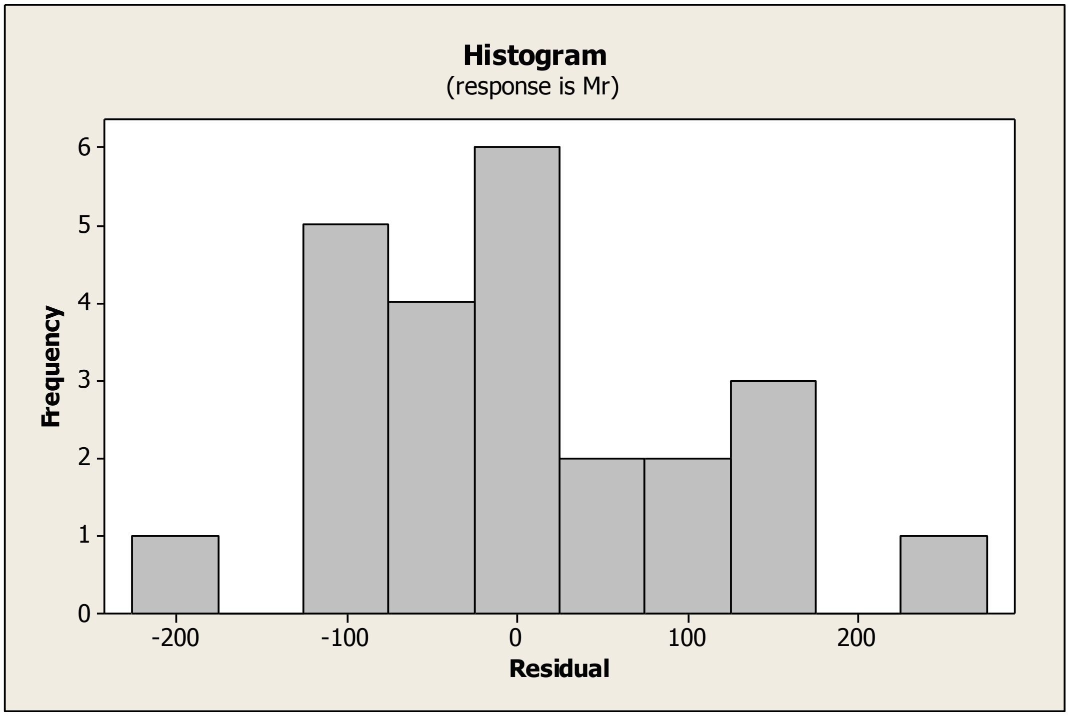

Figure 4.11: Histogram Plot of the Residuals

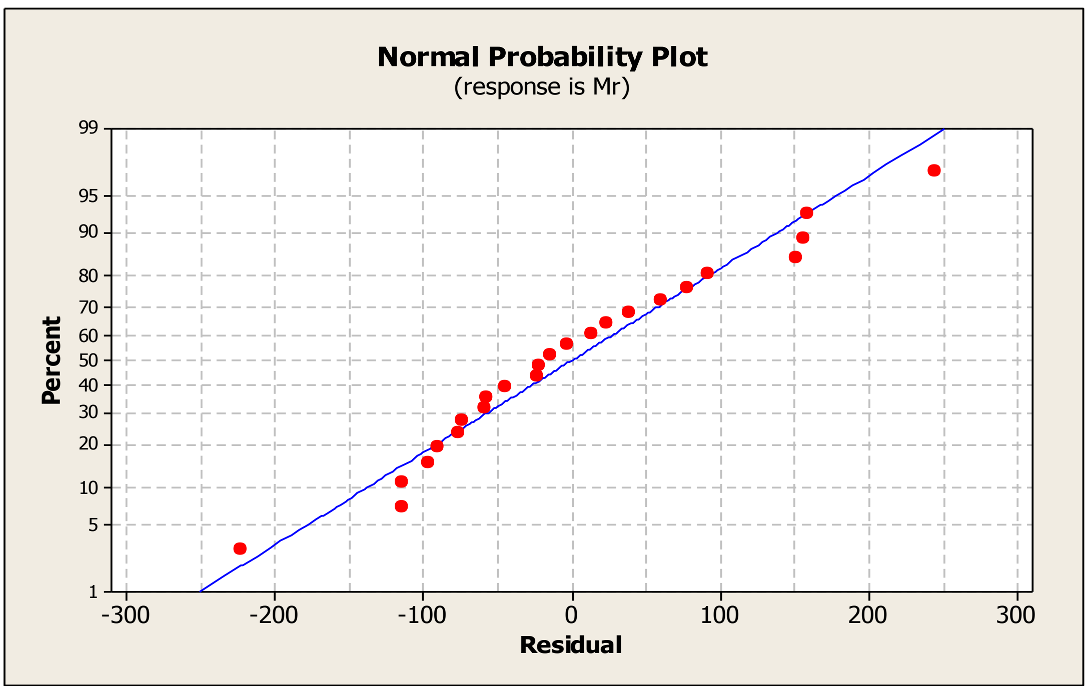

Figure 4.12: Normal Probability Plot of Residuals

- **Constant Variance Assumption**

The second assumption is the constant variance assumption which the model should fulfill. For checking the variance Residual vs. Fitted values scatter plot is made such that on *y*-axis we have residuals and on the *x*-axis we have the fitted values. The plotting should be done such that the residuals are distributed randomly across zero. If the residuals follow an increasing or decreasing pattern with the fitted values then the variance is not constant and the model is invalid for any predictions. From the Figure 4.13, it is clear that the residuals are structure less and randomly distributed around zero with neither megaphone or funnel shaped patterns. This shows that the constant variance assumption is also fulfilled, and the model is valid.

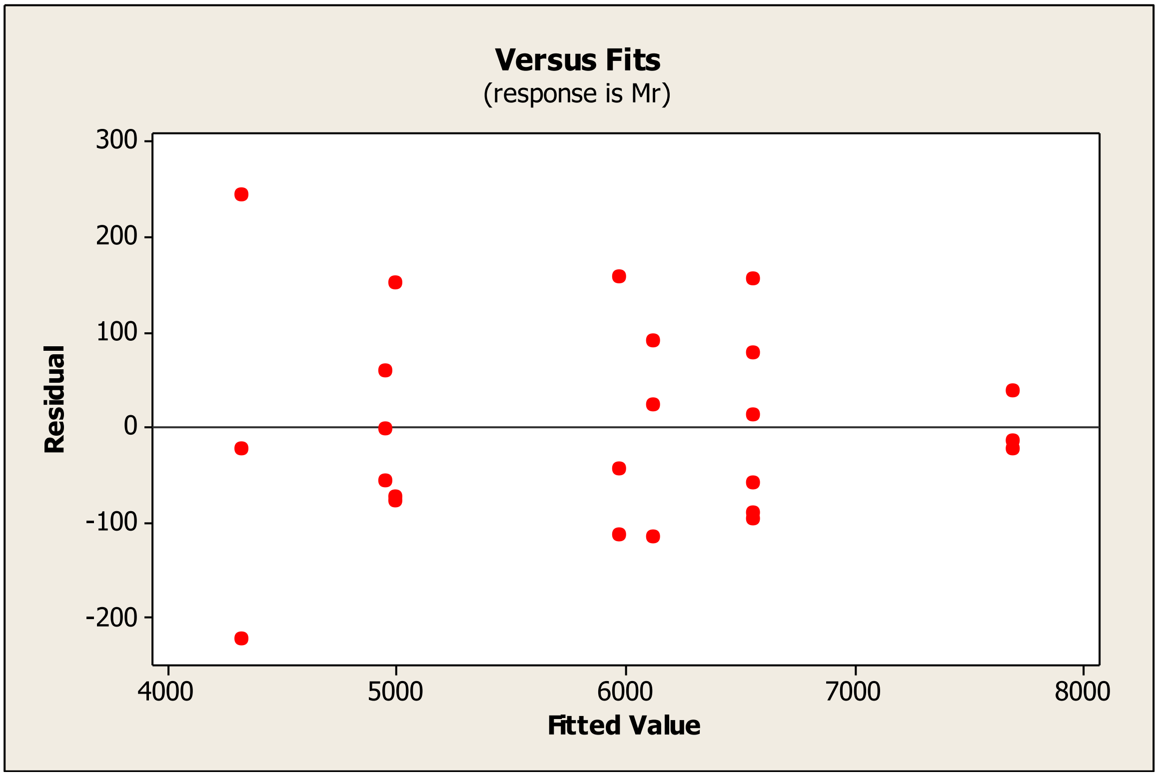

Figure 4.13: Plot for Residual versus Fitted Values of Resilient Modulus

- **Independence of Residual Assumption**

This assumption is checked by plotting the residuals in order of data collection sequence i.e. observation order. This assumption is used to detect correlation between the residuals. If the residuals are independent of each other then it means that there is no correlation among the residuals. A cyclic trend of residuals with alternating positive and negative values indicates the correlation exists between them and the implication is that the assumption of independence of residuals is violated. The proper randomization of experiment and remembering the order of data collection is important to obtain independence. Figure 4.14 shows that the residuals are not correlated and they are independent. The plot does not show any definite patterns.

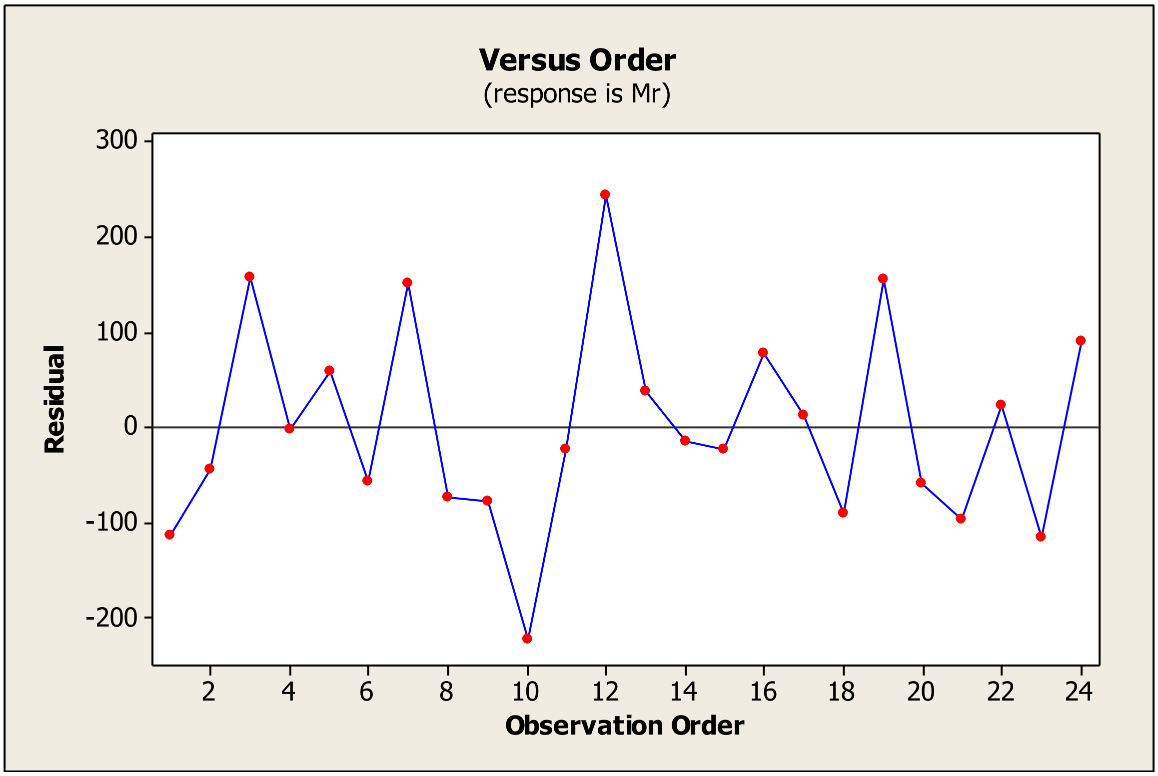

Figure 4.14: Plot for Residual versus Observation Order

4.9 SUMMARY

In this chapter, detailed results and discussions were presented along with the statistical analysis. The results of statistical analysis were presented with the help of graphs and detailed deliberations were made regarding the trends they were showing. In the end model was checked for adequacy by carrying out residual analysis. In the next chapter, the conclusions and recommendations are made based on results of performance tests and data analysis.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

The principle aim of this research was to study the effectiveness of Bakelite as an additive for asphalt concrete mixes. This was done by comparing various mechanical properties such as Marshall Stability, flow, Marshall Quotient, moisture susceptibility and resilient modulus of modified asphalt concrete mixes versus the control mixes. The control asphalt concrete mix was prepared by using 60/70 penetration grade bitumen while in modified mixes same bitumen was added with 2%, 4%, 6%, 8%, 10% and 12% of Bakelite by weight of optimum bitumen content(OBC). OBC was found by Marshall Mix design criteria (ASTM D6926) which came out to be 4.3% by weight of aggregates. The Bakelite was added by wet process, in which firstly Bakelite is added to the bitumen at selected mixing temperature, and then this mixture is added to heated aggregates. In order to achieve accuracy of the experimental results three specimens were prepared for each combination. The aggregate gradation selected was NHA-B with nominal maximum size of ½ inch. Binder content of 4.3% obtained from OBC was used in the making of all bituminous paving mixes. Mixing and compaction temperatures of 165°C were selected for preparation of mixes. To replicate the extreme loading environment of Pakistan, the specimens were densified with 75 blows at each end. The resilient modulus tests were performed in Universal Testing Machine (UTM-25), while the stability, flow, quotient and retained stability tests were performed using Marshall Compression testing machine.

5.2 CONCLUSIONS

Based on the results obtained from the Marshall Stability, flow, quotient, retained stability and resilient modulus testing of both conventional and modified asphalt concrete samples and analysis of experimental results, the following conclusions have been drawn

1. The Bakelite enhanced various mechanical properties of asphalt concrete mixes like Marshall Stability, flow, quotient, retained stability and resilient modulus thus it can be used as an additive.

2. Optimum bitumen content (OBC) found by Marshall Mix design criteria (ASTM D6926) came out to be 4.3% by weight of aggregates.
3. Marshall Stability, flow, Marshall Quotient and retained stability test results showed that optimum Bakelite content for asphalt concrete mixes is 6% by weight of OBC.
4. Marshall Stability, flow, Marshall Quotient test results showed that up to 6% Bakelite content, strength and flow of the mixes increased.
5. Retained stability test showed that with the addition of Bakelite, the moisture susceptibility of asphalt concrete decreased thus making it more resistant to moisture damage as compared to conventional mix. The test showed 6% Bakelite content to be the optimum modifier content.
6. The indirect tension test was performed on 4-inch diameter specimens of both conventional and modified (6% Bakelite) mixes at constant deformation rate of 50mm/min at 25°C. The strength values obtained with modified specimens were higher than that obtained with conventional specimens.
7. The Resilient modulus test results showed a 20% increase for the modified mix containing 6% Bakelite as compared to conventional mix.
8. Thus it is concluded that modified mixes containing 6% Bakelite by weight of optimum bitumen content gives the best results as compared to conventional mix with 60/70 penetration grade asphalt. So Bakelite can be used as a modifier for conventional penetration grade bitumen.

5.3 FUTURE WORK AND RECOMMENDATIONS

1. The scope of this thesis was to analyze the effects of Bakelite as a modifier for conventional 60/70 penetration grade bitumen. The specimens were tested for Marshall Stability, flow, quotient, retained stability (moisture susceptibility) and resilient modulus.in all these tests the specimens were prepared by Marshall Mix design using NHA Class B gradation, Margalla aggregate and 4-in specimen diameter. For future study one can prepare Gyratory specimens using different gradation, aggregate and specimen diameter.

2. This study provides a basis to experimentally investigate the effect of Bakelite on various properties of asphalt concrete specimens like resilient modulus, retained stability, Marshall Stability, flow and Marshall Quotient. For future study other properties, such as rutting potential, dynamic creep and flexural stiffness can be tested.
3. In this research, the Bakelite alone was used as a modifier. For future study it can be mixed with other modifiers such as crumb rubber, fibers and other types of plastics.
4. This study compared the properties of modified and conventional 60/70 penetration grade bitumen. For future study one must compare the results obtained by testing both 60/70 & 80/100 specimens against performance grade specimens.
5. Field performance of Bakelite modified mixes should be evaluated.

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APPENDICES

APPENDIX: I UTM-25 TEST RESULTS

Indirect Tension Test

Stress Strain Test

Data file name: C:\Users\Yusaf\Desktop\final thesis report of MS\6% Bakelite stress strain.D002
Template file name:
Test date & time: 12/12/2012 1:04:48 PM
Project: Yousaf Bakelite
Operator: yousaf
Comments:

Specimen Information
Identification: 6% Bakelite
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.0						64.0	
Diameter (mm)	100.0						100.0	

Cross-sectional area (mm²): 7854.0

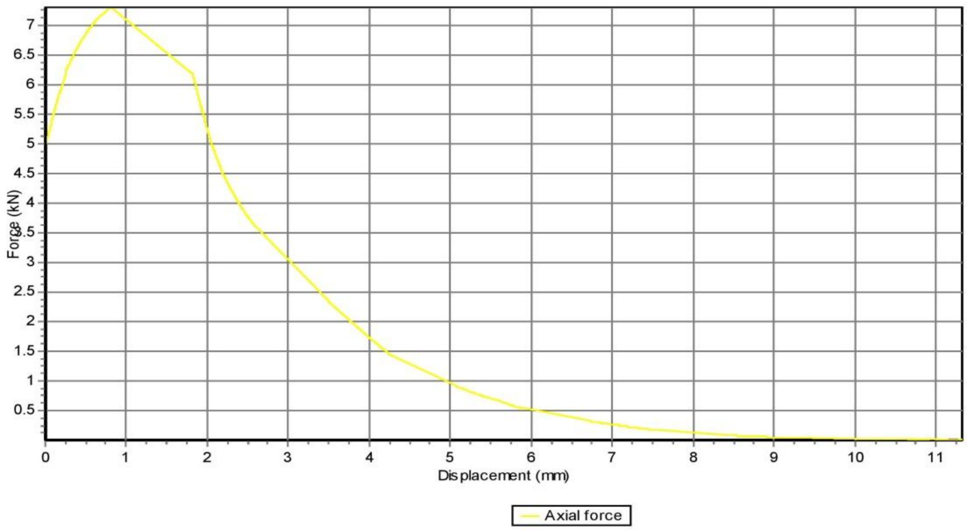
Setup Parameters
Axial loading control: Actuator displ.
Rate (mm/min): 50
Force (kN): 0.05
Pre-load time (s): 5

Strain conversion parameters
Actuator gauge length (mm): 64

Stress conversion parameters
Actuator area (mm²): 7854.0

Test Results
Total time (hhmmss): 00:00:08
Displayed time (hhmmss): 00:00:08
Displayed seconds: 8
Actuator displ. (mm): 11.285
Actuator microstrain: 1.7632E005
Actuator position (mm): -9.671

Axial force (kN): 0.017
Axial stress (kPa): 2.228
Maximum axial force (kN): 7.296
Minimum axial force (kN): 0.005



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Resilient Modulus Test

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: C:\Users\Yusaf\Desktop\specimen 2.D003
Template file name: 122
Test date & time: 12/12/2012 12:02:01 PM
Project: 4.3% 4inch
Operator: yousaf
Comments: 1st axis

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 100
Pulse repetition period (ms): 1000
Conditioning pulse count: 100
Peak loading force (N): 1895
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: specimen 2
Remarks...

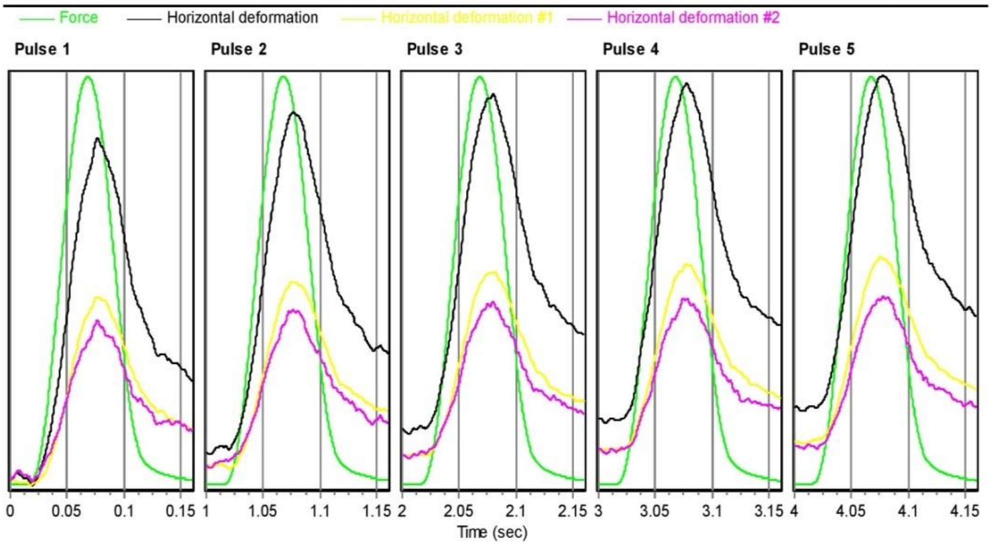
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.0						64.0	
Diameter (mm)	100.0						100.0	

Cross-sectional area (mm²): 7854.0

Test Results

Conditioning pulses: 100
Core temperature (°C): 0.0
Skin temperature (°C): 0.0
Perm't horiz'l def'n/pulse (μm): 0.320300

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6619	6569	6416	6427	6484	6503	79.45	1.22
Total recoverable horiz. deform. (μm)	3.01	3.02	3.09	3.09	3.06	3.05	0.03	1.13
Peak loading force (N)	1900	1896	1895	1895	1895	1896	2.06	0.11
Recoverable horiz. deform. #1 (μm)	1.61	1.64	1.68	1.69	1.68	1.66	0.03	1.72
Recoverable horiz. deform. #2 (μm)	1.39	1.38	1.42	1.40	1.38	1.40	0.01	0.85
Seating force (N)	189	190	190	190	189	190	0.40	0.21



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: C:\Users\Yusaf\Desktop\final thesis report of MS\specimen 3.D003
Template file name: 122
Test date & time: 12/12/2012 12:34:56 PM
Project: 4.3% 4inch
Operator: yousaf
Comments: 1st axis

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 100
Pulse repetition period (ms): 1000
Conditioning pulse count: 100
Peak loading force (N): 1895
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: specimen 3
Remarks...

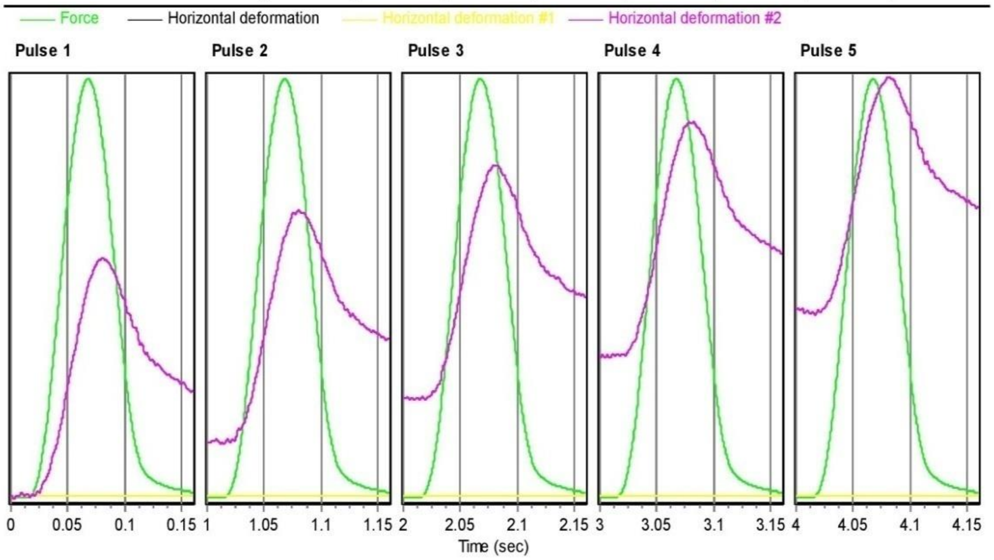
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.0						64.0	
Diameter (mm)	100.0						100.0	

Cross-sectional area (mm²): 7854.0

Test Results

Conditioning pulses: 100
Core temperature (°C): 0.0
Skin temperature (°C): 0.0
Perm't horiz'l def'n/pulse (µm): 1.284000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7677	7473	7320	7515	7344	7466	129.05	1.73
Total recoverable horiz. deform. (µm)	2.59	2.66	2.71	2.64	2.70	2.66	0.04	1.63
Peak loading force (N)	1902	1899	1896	1895	1897	1898	2.23	0.12
Recoverable horiz. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable horiz. deform. #2 (µm)	2.59	2.66	2.71	2.64	2.70	2.66	0.04	1.63
Seating force (N)	189	189	189	190	190	189	0.22	0.11



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Indirect Tensile Modulus Test

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Template file name: 122
Test date & time: 12/12/2012 12:47:27 PM
Project: 4.3% 4inch
Operator: yousaf
Comments: 1st axis

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 100
Pulse repetition period (ms): 1000
Conditioning pulse count: 100

Peak loading force (N): 1895
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: specimen 4
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.0						64.0	
Diameter (mm)	100.0						100.0	

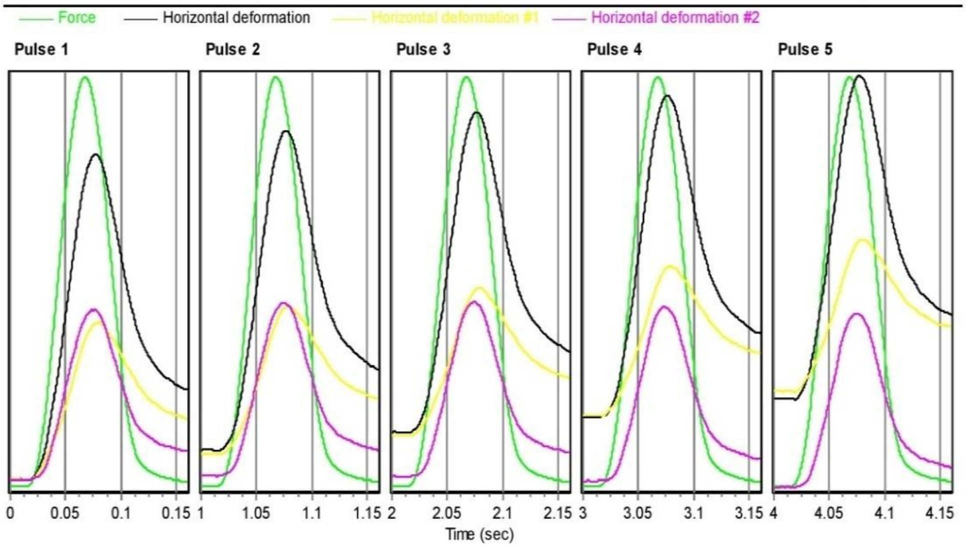
Cross-sectional area (mm²): 7854.0

Test Results

Conditioning pulses: 100
Core temperature (°C): 0.0
Skin temperature (°C): 0.0

Perm't horiz'l def'n/pulse (µm): 1.006000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2560	2518	2485	2500	2461	2505	33.42	1.33
Total recoverable horiz. deform. (µm)	7.75	7.88	7.98	7.93	8.06	7.92	0.10	1.29
Peak loading force (N)	1895	1896	1893	1895	1894	1895	0.97	0.05
Recoverable horiz. deform. #1 (µm)	3.43	3.35	3.32	3.23	3.29	3.32	0.07	1.96
Recoverable horiz. deform. #2 (µm)	4.32	4.53	4.65	4.70	4.77	4.60	0.16	3.41
Seating force (N)	190	189	190	190	189	190	0.37	0.20



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Indirect Tensile Modulus Test

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Template file name: 122
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Project: 4.3% 4inch
Operator: yousaf
Comments: 1st axis

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 100
Pulse repetition period (ms): 1000
Conditioning pulse count: 100

Peak loading force (N): 1895
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: specimen 5
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.0						64.0	
Diameter (mm)	100.0						100.0	

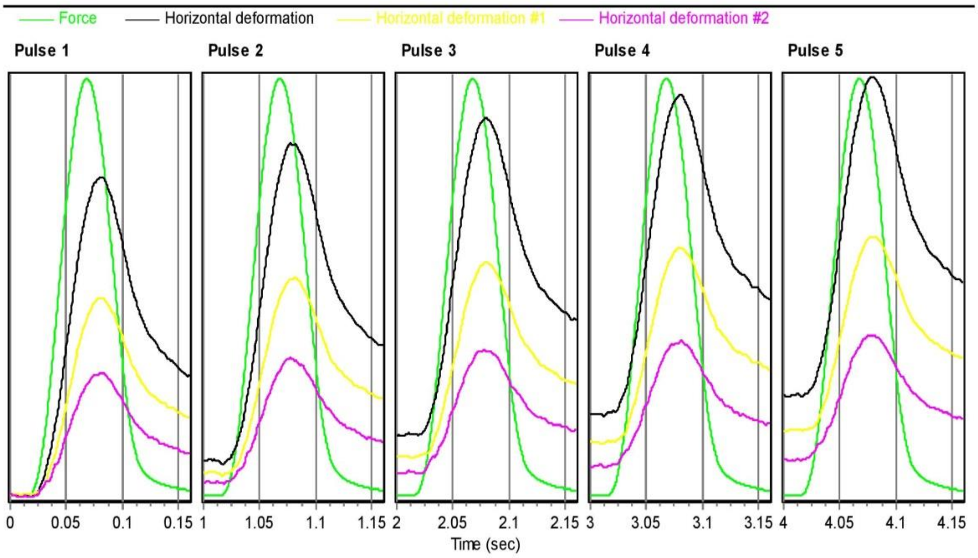
Cross-sectional area (mm²): 7854.0

Test Results

Conditioning pulses: 100
Core temperature (°C): 0.0
Skin temperature (°C): 0.0

Perm't horiz'l def'n/pulse (µm): 0.661300

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5012	4862	4808	4711	4755	4830	104.62	2.17
Total recoverable horiz. deform. (µm)	3.96	4.08	4.13	4.21	4.17	4.11	0.09	2.11
Peak loading force (N)	1897	1895	1895	1895	1895	1896	0.55	0.03
Recoverable horiz. deform. #1 (µm)	2.44	2.47	2.51	2.56	2.54	2.50	0.04	1.72
Recoverable horiz. deform. #2 (µm)	1.52	1.61	1.61	1.65	1.64	1.61	0.05	2.83
Seating force (N)	189	190	190	189	190	190	0.34	0.18



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APPENDIX: II VOLUMETRIC PROPERTIES

1. Bulk Specific Gravity of Coarse Aggregates

Mass of oven-dry test sample in air = A = 1000gm

Mass of saturated-surface-dry test sample in air = B = 1039 gm

Mass of saturated test sample in water = C= 656 gm

Bulk specific gravity of coarse aggregates = $\frac{A}{B-C} = \frac{1000}{(1039-656)} = 2.61$

2. Bulk Specific Gravity of Fine Aggregates

Mass of dry aggregates = A = 1000 gm

Mass of pycnometer filled with water = B = 667 gm

Mass of aggregates + water + pycnometer = C =795.25 gm

Bulk specific gravity of fine aggregates =

$$\left[\frac{A}{B+500-C}\right] = \left[\frac{1000}{667+500-795.25}\right] = 2.69$$

3. Bulk Specific Gravity of Aggregates

Percentage of coarse aggregate = P_1= 40 %

Percentage of fine aggregate = P_2= 60%

Specific gravity of coarse aggregate = G_{CA}=2.61

Specific gravity of coarse aggregate = G_{FA}=2.69

$$G_{sb} = \frac{100}{\frac{P_1}{G_{CA}} + \frac{P_2}{G_{FA}}} = \frac{100}{\frac{40}{2.61} + \frac{60}{2.69}} = 2.63$$

4. Aggregate Gradation

Sieve Size	Percent Passing	Percent Retained
3/4 -inch	100	0
1/2 -inch	95	5
#4	60	35
#8	43	17
#16	13	30
#200	5	8

5. Los Angeles Abrasion Test

Initial mass of aggregate = 5000 gm

Final mass of aggregate (retained 1.75 mm sieve) = 3367 gm, 3518gm

- % loss = $\frac{A-B}{A} = \left(\frac{5000-3367}{5000}\right)\times 100 = 32.66\%$
- % loss = $\frac{A-B}{A} = \left(\frac{5000-3518}{5000}\right)\times 100 = 29.64\%$

Average % loss = $\frac{32.66+29.64}{2} = 31.15\%$

6. Impact Value Test

Weight of container = 712gm

Weight of aggregate= A = 315gm

Weight of aggregate after impact test = B = 51gm, 56gm

- Impact value = $\frac{B}{A} = \left(\frac{51}{315}\right)\times 100 = 16.19\%$
- Impact value = $\frac{B}{A} = \left(\frac{56}{315}\right)\times 100 = 17.17\%$

Average Impact value = $\frac{16.19+17.17}{2} = 16.68$

7. Bulk Specific Gravity of Compacted bituminous Mix

Specimen 1

Weight in Air = A = 1236 gm

Weight in Water = B = 698 gm

Weight in SSD = C = 1238 gm

$$G_{MB} = \left(\frac{A}{C-B}\right) = \left(\frac{1236}{1238-698}\right) = 2.29$$

Specimen 2

Weight in Air = A = 1244 gm

Weight in Water = B = 707 gm

Weight in SSD = C = 1246 gm

$$G_{MB} = \left(\frac{A}{C-B}\right) = \left(\frac{1244}{1246-707}\right) = 2.31$$

Specimen 3

Weight in Air = A = 1243 gm

Weight in Water = B = 701 gm

Weight in SSD = C = 1245 gm

$$G_{MB}=\left(\frac{A}{C-B}\right)=\left(\frac{1243}{1245-701}\right)=2.28$$

8. Maximum theoretical specific gravity of bituminous Mix

Weight of loose mix = A = 1200 gm

Weight of pycnometer + water= B = 6350 gm

Weight of pycnometer +water + mix = C = 7055 gm

$$G_{MM}=\left(\frac{A}{A+C-B}\right)=\left(\frac{1200}{1200+6350-7055}\right)=2.42$$

9. Voids in Mineral Aggregates (VMA)

Specimen 1

Percentage of aggregates in the mix = P_s= 96%

Bulk Specific Gravity of Compacted bituminous Mix = G_{MB} = 2.29

Bulk Specific Gravity of Aggregates = G_{sb} = 2.63

$$VMA=\left[100-\frac{G_{mb}P_s}{G_{sb}}\right]\times 100=\left[100-\frac{2.29\times 96}{2.63}\right]\times 100=17.35\%$$

Specimen 2

Percentage of aggregates in the mix = P_s= 96%

Bulk Specific Gravity of Compacted bituminous Mix = G_{MB} = 2.31

Bulk Specific Gravity of Aggregates = G_{sb} = 2.63

$$VMA=\left[100-\frac{G_{mb}P_s}{G_{sb}}\right]\times 100=\left[100-\frac{2.31\times 96}{2.63}\right]\times 100=16.63\%$$

Specimen 3

Percentage of aggregates in the mix = P_s= 96%

Bulk Specific Gravity of Compacted bituminous Mix = G_{MB} = 2.28

Bulk Specific Gravity of Aggregates = G_{sb} = 2.63

$$VMA=\left[100-\frac{G_{mb}P_s}{G_{sb}}\right]\times 100=\left[100-\frac{2.28\times 96}{2.63}\right]\times 100=17.71\%$$

10.Air Voids (VA)

Specimen 1

Bulk Specific Gravity of Compacted bituminous Mix = G_{MB} = 2.29

Maximum theoretical specific gravity of bituminous Mix = G_{MM}= 2.42

$$V_a = 100\left[\frac{G_{mm} - G_{mb}}{G_{mm}}\right] = 100\left[\frac{2.42 - 2.29}{2.42}\right] = 4.88\%$$

Specimen 2

Bulk Specific Gravity of Compacted bituminous Mix = G_{MB} = 2.31

Maximum theoretical specific gravity of bituminous Mix = G_{MM}= 2.42

$$V_a = 100\left[\frac{G_{mm} - G_{mb}}{G_{mm}}\right] = 100\left[\frac{2.42 - 2.30}{2.42}\right] = 4.80\%$$

Specimen 3

Bulk Specific Gravity of Compacted bituminous Mix = G_{MB} = 2.28

Maximum theoretical specific gravity of bituminous Mix = G_{MM}= 2.42

$$V_a = 100\left[\frac{G_{mm} - G_{mb}}{G_{mm}}\right] = 100\left[\frac{2.42 - 2.28}{2.42}\right] = 5.58\%$$

11.Voids Filled Asphalt (VFA)

Specimen 1

Air Voids (V_a) = 4.88 %

Voids in Mineral Aggregates (VMA) = 17.35%

$$VFA = 100\left[\frac{VMA - V_a}{VMA}\right] = 100\left[\frac{17.35 - 4.88}{17.35}\right] = 71.87\%$$

Specimen 2

Air Voids (V_a) = 4.80 %

Voids in Mineral Aggregates (VMA) = 16.63%

$$VFA = 100\left[\frac{VMA - V_a}{VMA}\right] = 100\left[\frac{16.63 - 4.80}{16.63}\right] = 71.13\%$$

Specimen 3

Air Voids (V_a) = 5.58 %

Voids in Mineral Aggregates (VMA) = 17.71%

$$VFA = 100\left[\frac{VMA - V_a}{VMA}\right] = 100\left[\frac{17.71 - 5.58}{17.71}\right] = 68.48\%$$

APPENDIX: III FULL FACTORIAL ANALYSIS USING MINITAB-16

Factorial Fit: Mr versus % Bakelite, Load Duration (ms), Temperature

Estimated Effects and Coefficients for Mr (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		7306.9	34.77	210.16	0.000
% Bakelite	2616.7	1308.4	34.77	37.63	0.000
Load Duration (ms)	-1220.5	-610.3	34.77	-17.55	0.000
Temperature	-1313.6	-656.8	34.77	-18.89	0.000
% Bakelite*Load Duration (ms)	-2.1	-1.1	34.77	-0.03	0.976
% Bakelite*Temperature	516.8	258.4	34.77	7.43	0.000
Load Duration (ms)*Temperature	20.5	10.3	34.77	0.29	0.771
% Bakelite*Load Duration (ms)* Temperature	182.9	91.4	34.77	2.63	0.015

S = 196.682 PRESS = 1650506

R-Sq = 98.89%, R-Sq(pred) = 98.03%, R-Sq(adj) = 98.57%

Analysis of Variance for Mr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS
Main Effects	3	80500892	80500892	26833631
% Bakelite	1	54779044	54779044	54779044
Load Duration (ms)	1	11916962	11916962	11916962
Temperature	1	13804885	13804885	13804885
2-Way Interactions	3	2139643	2139643	713214
% Bakelite*Load Duration (ms)	1	36	36	36
% Bakelite*Temperature	1	2136244	2136244	2136244
Load Duration (ms)*Temperature	1	3362	3362	3362
3-Way Interactions	1	267546	267546	267546
% Bakelite*Load Duration (ms) *Temperature	1	267546	267546	267546
Residual Error	24	928409	928409	38684
Pure Error	24	928410	928410	38684
Total	31	83836490		

Source	F	P
Main Effects	693.67	0.000
% Bakelite	1416.07	0.000
Load Duration (ms)	308.06	0.000
Temperature	356.87	0.000
2-Way Interactions	18.44	0.000
% Bakelite*Load Duration (ms)	0.00	0.976
% Bakelite*Temperature	55.22	0.000
Load Duration (ms)*Temperature	0.09	0.771
3-Way Interactions	6.92	0.015
% Bakelite*Load Duration (ms)*Temperature	6.92	0.015

Unusual Observations for Mr

Obs Std	Order	Mr Fit	SE	Fit	Residual	St Resid
17	17	5274.00	5773.75	98.34	-499.75	-2.93R
25	25	6190.00	5773.75	98.34	416.25	2.44R

R denotes an observation with a large standardized residual.

Estimated Coefficients for Mr using data in uncoded units

Term	Coefficient
Constant	10479.1
% Bakelite	327.778
Load Duration (ms)	-2.57375
Temperature	-100.375
% Bakelite*Load Duration (ms)	-1.32431
% Bakelite*Temperature	3.35556
Load Duration (ms)*Temperature	-0.108250
% Bakelite*Load Duration (ms)*Temperature	0.0406389