PERFORMANCE EVALUATION OF AGGREGATE GRADATIONS ADJUSTED THROUGH THE BAILEY METHOD

Thesis submitted in partial fulfillment of

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In

Transportation Engineering

Submitted By

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(NUST-2012-60940-MSCEE-15112F)

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A Thesis

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Master of Science

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Dedication

Special dedication to my parents
My supervisor, my beloved friends,
and all faculty members

For all support, encouragement and believe in me. Thank you so much.

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Last but not least, my deepest gratitude goes to my beloved parents particularly my father Dr. Aurangzeb Khan who is always a symbol of encouragement and inspiration to me throughout my life. Special thanks to my Mother and my sisters for their never-ending love and prayers. To those who in some way contributed in this research, your kindness means a lot to me. Thank you very much.

Jamal Ahmed Khan

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LIST OF ABBREVIATIONS/SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Cement
ASTM	American Society for Testing and Materials
CA	Coarse Aggregate
CA Ratio	Coarse Aggregate Ratio
DG	Dense Graded
FA_c Ratio	Fine Aggregate Coarse Ratio
FA_f Ratio	Fine Aggregate Fine Ratio
Gsb	Combined bulk specific gravity of total aggregate
Gmb	Bulk specific gravity of compacted mix
Gmm	Theoretical maximum density
HMA	Hot Mix Asphalt
LUW	Loose Unit Weight
NAPA	National Asphalt Pavement Association
NHA	National Highway Authority
NMAS	Nominal Maximum Aggregate Size
OBC	Optimum Bitumen Content
PCS	Primary Control Sieve
PG	Performance Grade
RUW	Rooded Unit Weight
SCS	Secondary Control Sieve
SP	Superpave
TCS	Tertiary Control Sieve
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
VTM	Voids in Total Mix

ABSTRACT

In asphalt mix design, the aggregate structure of the compacted mix is an important factor to evaluate, that contributes to the performance of Hot-Mix Asphalt (HMA). Bailey method provides a systematic way of blending coarse and fine mineral aggregates based on the concepts of aggregate interlock. This research is carried out with primary objective to determine if the Bailey Method can be a useful tool to design mixtures with improved performance for mixes commonly used in Pakistan. Four (04) asphalt concrete wearing course mixtures were chosen for redesign with the Bailey Method, including National highway authority gradations NHA-A and NHA-B, Superpave SP-1 and asphalt institute manual series MS-2 gradations. The Bailey parameters for the original mixtures were calculated and the gradations were redesigned to fall within the recommended ranges. The aggregates structures designed using Bailey method and the original mixes were applied in Marshall Mix design method to obtain the Marshall properties. The Hamburg wheel tracker test is employed on Superpave gyratory compactor (SGC) specimens for checking their rutting susceptibility. For this purpose, specimens were tested at a test temperature of 40 ^{o}C. All the redesigned mixtures did show an increase in rutting resistance, however significant improvement is observed in rutting for NHA-A and MS-2 gradations i.e. 9% and 10 % respectively. Two Non-linear regression models were also developed to explain the, VMA as a function of Bailey parameters (CA, FA_c and FA_f) and Rutting as a function of FA_c and NMPS. Overall, this research project concluded that Bailey method can be a useful tool in the evaluation and design of HMA mixtures.

Chapter 1

INTRODUCTION

1.1 Background

In road construction around the world hot mix asphalt (HMA) is most commonly used material. It is composed of two main ingredients asphalt binder and mineral aggregate. It is defined as a blend of different aggregate sizes mixed with a bitumen binder to form a composite structure. HMA provides toughness and strength to the structure via combination of aggregate coated with binder. The performance of HMA largely depends upon the physical and mechanical properties of its components and their behaviour with each other in the mixture. Alshamsi (2006) has defined HMA as a composite material comprising of different size of mineral aggregate particles, air voids and bitumen binder that is totally different in their composition from the aggregate.

There are two main parts of HMA design process, volumetric design and empirical mechanical testing to validate the designed mix. Since the development of asphalt mixture design, it was desired to understand the relation of aggregate particles, asphalt binder, and the voids created during their compaction. There is still a lack of guidance in the choice of the design aggregate gradation in asphalt mix design process. It has been under discussion for over a century that how to control volumetric in HMA mixture design. In 1903, a volumetric based HMA mix design was presented by Frederick J. Warren, creator of Warren Brothers Company in Boston, Massachusetts. Later on, the optimum size and gradation of aggregate particles necessary to fill a container of known volume was designed through an experiment by Mr. Warren (Roberts *et al.*, 1996).

This approach is relatively new at Pakistan level, because no such attempt is made to adjust the gradations in practice currently. So before execution laboratory assessment of different HMA mixes it of utmost importance. In this regards, laboratory testing was carried out to investigate the effectiveness of application of Bailey method on four selected gradations i.e. NHA-A, NHA-B, SP-1, and MS-2.Rutting behavior of the original mix design and adjusted gradation is being used as a criteria for assessment of proposed adjustments. Laboratory samples are tested on 40°c for 20000 passes. The testing is performed in two different stages. Marshall Properties of compacted specimens were determined in first stage and in second stage rutting susceptibility was investigated.

1.2 Problem Statement

Usually, in the conventional method the mix is consider good or bad based on certain criteria without authentication of their expected performance in field. The Super pave asphalt mixture design procedure provides the tools necessary to design and constructs excellent mixtures. This improvement is realized through the exercise of the Superpave Gyratory Compactor (SGC), aggregate quality specifications, and performance tests. However, in the existing Marshall Mix method, proper guidelines are still missing in the selection of optimum design gradation. (Asphalt Institute, 2001). It is also needed to build up a technique for designing asphalt mixtures that utilizes aggregate packing concept to build up a mixture that fulfil all volumetric's criteria's , is easy to construct, and gives excellent Performance. Generally the only guideline available to the designers for the assessment of mix design is the 0.45-power grading chart. It only explains some very common rules, like VMA can be increased by staying away from the maximum density line. Mostly the designer's just find out by experience that how gradation affects mixture properties.

For a mix design to balance and successful there should be stability between the physical properties of material and volumetric composition in the mixture. One of the major measures to achieve that is to understand how different mixture components and gradation affect the mechanical performances of asphalt mixtures (Kandhal et al. 1998).

From the above discussion, there is clearly a need to build up a method for designing asphalt mixtures that utilizes aggregate interlock to develop a mixture that full fills all volumetric criteria's and gives good Performance. In this background, the Bailey Method provides a set of tools that can be used to analyze aggregate size division, while using the degree of particles interlock as a design input. It focuses on the properties of aggregate when they are mixture together in the final blend and compacted to form a structure. This method describes four key principles that split the overall mixture into four separate portions. Each portion is then evaluated for its role to the overall mix volumetric (Vavrik *et al.*, 2001).

It is likely that, the results of this research will validate the presented concepts and present a enhanced understanding of the correlation between aggregate gradations, the mix performance and volumetric properties.

1.3 Objective of the Study

The key objective of this study was to find out if the Bailey Method can be a useful tool to design mixtures with improved performance. The mode of improvement given attention in this project is resistance to rutting under wheel tracker loading.

The objectives of study were:

- To evaluate the selected asphalt concrete wearing course mixtures, according to Bailey Method and recommend adjustment in their gradations.
- To compare rutting resistance of the adjusted gradations with their corresponding original mixtures using the Hamburg wheel tracker.
- To statistically analyze the obtained data and develop regression models.

1.4 Scope of the Study

In order to archive the above mention objectives, a study plan was organized and the subsequent tasks were outlined.

- A review of the past studies on the effectiveness of Bailey method application on properties of HMA.
- Design of aggregate structure by means of new aggregate gradation evaluation method i.e. The Bailey method.
- Preparation of 4- inch Marshall Test samples of four different designs blends in order to check the volumetric properties like stability, flow, air voids, VFA and VMA.
- Fabrication of Superpave gyratory compactor (SGC) samples to evaluate rutting resistance for aggregate skeleton for each gradation.
- Analysis of the test results to determine the efficacy of Bailey method.

Table 1.1 Test Matrix for Rutting Evaluation of Asphalt Mixtures Gradations

Gradation	Mix Type	Binder	Test Temperature (°C)	Test Samples
NHA-A Control	Wearing Course	60/70	40	3 Replicate Specimens
NHA-B Control	Wearing Course	60/70	40	3 Replicate Specimens
Superpave A-1 Control	Wearing Course	60/70	40	3 Replicate Specimens
Asphalt Institute MS-2 Control	Wearing Course	60/70	40	3 Replicate Specimens
NHA-A Bailey	Wearing Course	60/70	40	3 Replicate Specimens
NHA-B Bailey	Wearing Course	60/70	40	3 Replicate Specimens
Superpave A-1 Bailey	Wearing Course	60/70	40	3 Replicate Specimens
Asphlat Institute MS-2 Bailey	Wearing Course	60/70	40	3 Replicate specimens

Test matrix for this study is shown in Table 1.1. The Table presents the scope of research which includes the control and Bailey gradations, binder type and testing temperature.

1.5 Organization of the Thesis

The thesis is ordered in five chapters; brief description of each is as follows:

- Chapter 1 elaborate a short overview to the HMA mix design, the role of the aggregate packing in mix design, scope and objective of the study.
- Chapter 2 comprises of review of the past researches carried out regarding packing characteristics of aggregates and rutting related properties of HMA. Bailey method is also discussed in detail in this chapter. Focus was to study the effectiveness of Bailey method.
- Chapter 3 includes the methodology adopted in this thesis to achieve the objectives, the source of materials used in this research, and laboratory characterization of materials. It also includes the details of testing for optimum calculation, Superpave gyratory sample preparation and performance testing.

- Chapter 4 includes analyses of the wheel tracker rutting test results and gradation adjustments. Assessment of gradations based on bailey parameters is also included in this chapter. Statistical analysis is also presented which includes the regression model development and validation.
- Chapter 5 summarizes the findings and conclusions of testing results. The recommended work for future and suggestions are also discussed.

Chapter 2

LITRATURE REVIEW

2.1 Introduction

This chapter includes a summary of the studies and researches that are already carried out at the packing characteristics of aggregates and rutting related properties of HMA. The literature review is carried with the aim to become familiar with pervious researches on the area under discussion of aggregate gradation adjustment and the consequent results that it may cause to a pavement performance. In the first stage, studies related to gradation selection and aggregate packing characteristics were incorporated and in the second phase of research, studies related to Marshall testing and rutting susceptibility were included. The history of Bailey method, different steps involved in this method and Bailey method principles are also part of this chapter. The background of HMA, the role of aggregate, binder and gradation selection is also explained. Moreover, the concepts of aggregate packing and the work performed regarding to gradation associated issues of hot mix asphalt in different periods are also mentioned. In the last part of the chapter, studies related to rutting susceptibility of HMA mixes are also given.

2.2 Background of HMA

In road construction around the world hot mix asphalt is most commonly used material. It is also recognized as blacktop or bitumen, and sometimes with the terminology of hot mix asphalt. It has been used as a construction material from the earliest days of civilization. Despite these early uses of asphalt, several hundred years passed prior to European or American builders tried it as a paving material. The basic necessity of mix design is to decide on optimum asphalt content (OBC) for a required aggregate gradation to meet approved criteria. The behaviour of HMA is mainly dependent on the characteristics of individual materials and their response when together in a mixture (Baladi *et al.*, 1998).

It mainly consists of two components asphalt cement binder and mineral aggregates. Asphalt and aggregate are blended together in precise proportion. Physical properties and behaviour of mix depends upon the mix proportion. Different construction project will have different kind of mixture to suit to the site conditions. There are many methods of designing a HMA mix, which among them are the conventional method of Hveem and Marshall, and the newest method called Superpave (Garber and Hoel, 2002).

2.2.1 Aggregate Role

One of the main materials in the composition of HMA is the mineral aggregate. Performance of asphalt mixes largely depends on aggregate. For hot mix asphalt, they build up to about 90 % to 95 % by weight and by volume of the mix is about 75 % to 85 % (Roberts *et al*., 1996). Therefore in order to design high performance mixes there should be enough knowledge about the aggregates in use.

In an HMA pavement the behaviour and physical characteristics of aggregates depends upon its mineral composition. Therefore understanding of the aggregate mineral composition can be very helpful regarding the appropriateness of the ensuing mineral aggregate for hot mix asphalt Roads structures (Cooper and Brown, 1991).

Regardless of the source, aggregates are likely to provide a strong stone framework to stand firm to the repeated traffic load applications. With the application of excessively high loads on mass of aggregate that develops a shear consequential in the aggregate particles movement with respect to one another. This results in permanent deformation in asphalt pavement like rutting (Lavin, 2003).

The composition of aggregate i.e. its shape and texture plays a vital job in providing a good solid aggregate structure. Usually aggregate having Cubical, rough texture mostly give better resistance to deformation than rounded, smooth textures aggregate as shown in Figure 2.1 and Figure2.2 respectively. In order to resist the applied traffic load the internal friction between aggregates provides the ability to become interlocked and form a strong structure.

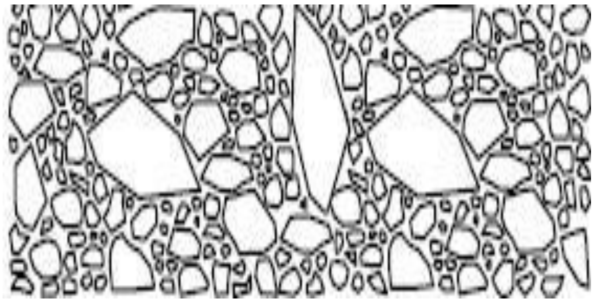

Figure 2.1 Cubical Aggregate (Alshamsi, 2006)

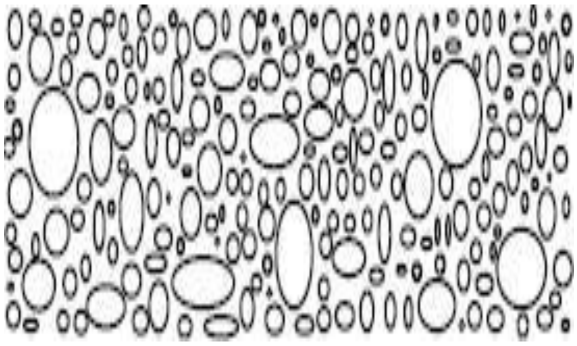

Figure 2.2 Smooth-Rounded Aggregate (Alshamsi, 2006)

2.2.2 Binder Role

Asphalt cement binder is one of the two principal constituents of HMA pavement. It is a black cementations material that is either naturally occurring or produced by distillation of crude oil. The aggregate particles are bonded together into a cohesive material with the help of asphalt binder. Three of the asphalt binder characteristics were considered to be very important from the perspective of flexible pavements i.e. temperature, viscoelasticity and ageing (Roberts *et al.*, 1996). Characteristic of the bitumen binder depends very much upon its resistance against temperature. When subjected to higher loads and temperature, bitumen binder becomes viscous and displays plastic response. This behaviour is a causative reason to one of the most commonly occurring asphalt pavement distresses known as rutting as shown in Figure 2.3.

Figure 2.3 Rutting in Flexible Pavements

2.2.3 Role of Gradation Selection

Performance of a mix design is dependent on one of the key property of aggregate i.e. the aggregate gradation. Beside the physical properties of aggregate, stability of the asphalt pavement largely depends upon gradation of the mix. Many aspects of mix performance like strength, compactibility and resistance to permanent deformations can be related to gradation of the mix design. Aggregate gradation is the division of the different size of particles in a group of aggregates and is usually articulated as percent of the total weight (Roberts et al., 2002). Aggregate skeleton provides the largest bit of the mixture opposition to applied traffic load. Aggregate gradation is determined in the laboratory by process called Sieve analysis. In this process aggregates are passed all the way through a sequence of stacked sieves with progressively smaller openings from top to bottom, and at the end taking weight of the material reserved on each sieve. Traditionally the results of sieve analyses were represented in form of graph known as the gradation curve. In this plot the total percent passing by weight is presented on ordinate on arithmetic scale, whereas the x-axis represents the particle size plotted on a logarithmic scale shown in Figure 2.4 (Roberts *et al*., 1996).

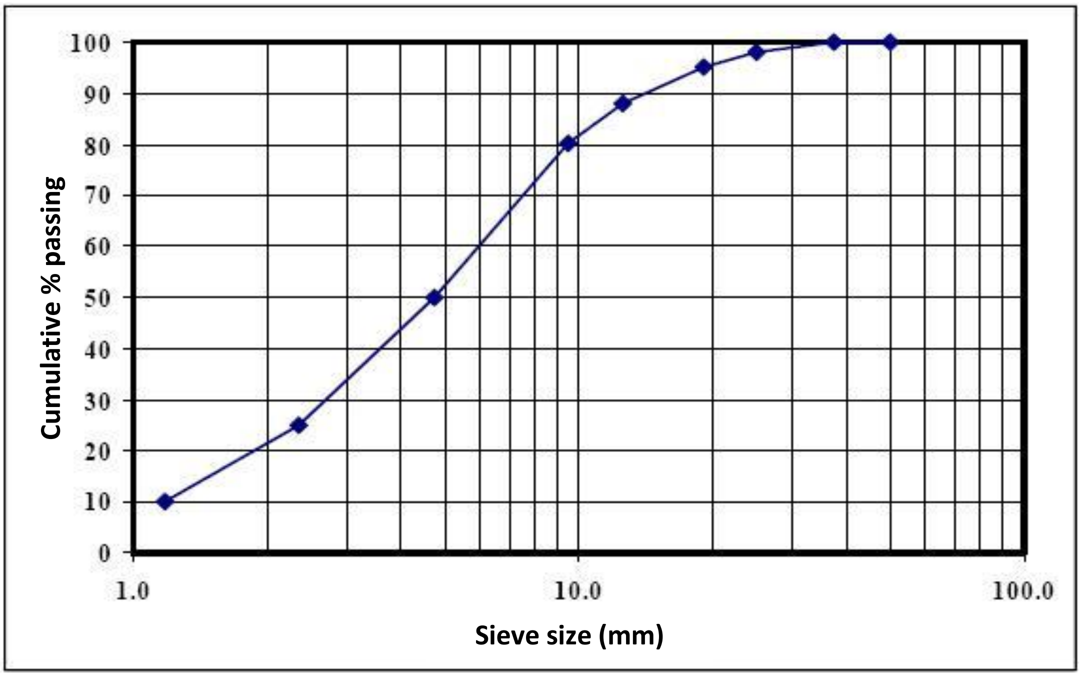

Figure 2.4 Typical Conventional Aggregate Gradation Curve (Adopted from Robert et al., 1996)

The choice and consequence of mix design gradation on the performance of HMA has long been a controversial matter. Different agencies in the world have there on different gradation for asphalt mixes according to their requirements. Both the gradation of the mix and nominal maximum aggregate size (NMPS) affects the rutting susceptibility for pavement section. To develop a better performing HMA mix it is essential to find out the correct percentage of individual size of aggregate in the blends.

Generally for asphalt mixture it is considered that a well balanced and continuous gradation will provide the maximum resistance to permanent deformation and it also depends upon the type and quality of aggregates. Gradation of the mix design is among the one the important factors in the resistance of mixture against permanent deformation specially in case of rutting (Roberts *et al.*, 1996; NAPA, 2002).

Aurilio et al., (2009) have concluded that by knowing the effects that a gradation have on the properties of the asphalt mixture, proper alterations to the construction process can be made. They described a methodology of gradation selection in detail considering some real life examples of five projects to help mix designers and contractor to better understand mixes that are currently being used across Canada.

2.3 History of Bailey Method

The Bailey method was at first developed by Mr. Robert Bailey of the Illinois Department of Transportation (IDOT). Idea of aggregate packing was proposed by Mr. Robert Bailey based on the years of experience in designing mixtures. These ideas were used by Mr. Bailey in the design of asphalt mixtures in District 5 of IDOT.

The Bailey Method is based on the packing features of mineral aggregates. In this method four parameters are defined that are directly related to voids in mineral aggregate (VMA), air voids (VA) and compaction properties. Using this method the aggregate properties and mix design can evaluated both by weight as well as by volume (Aurilio et al., 2005). Mr. Bailey developed this methodology of aggregate packing as a way to control the rutting of asphalt mixes while maintaining the proper strength characteristics (Vavrik *et al.*, 2002). Moreover it maintains volumetric properties that provided resistance to environmental stress (Thompson, 2006). Dr. Bill Vavrik, and Mr. Bill Pine later on refined the process by presenting a organized approach to aggregate blending in order to apply the method to all dense-graded asphalt mixtures. Moreover, Vavrik also mentioned the relationship among the gradation of the blend and the consequential mixture volumetric properties in his study. He refined the procedure using this new tool to predict volumetric of the mix. (Vavrik *et al*., 2002).

Aurilio et al. (2005) concluded that to better understand the aggregate packing; we need to find out which particles create voids when mixed together and which ones fills the voids formed within coarse aggregate structure. The principles in Bailey system can be used for controlling the quality during asphalt mix design, but are not a mix design method (Vavrik *et al*., 2002).

2.4 Basic Principles of Bailey Method

There are two key principles to consider with the Bailey Method:

1) Coarse and fine aggregate definition and which one is in control of the aggregate structure.

2) Packing of the coarse fraction and the packing of the fine fraction.

2.4.1 Coarse and Fine Aggregate

According to conventional definition, coarse aggregates are the particle that is retained on 4.75mm sieve whereas the particles passing 4.75mm sieve are known as fine aggregate (Figure 2.5).

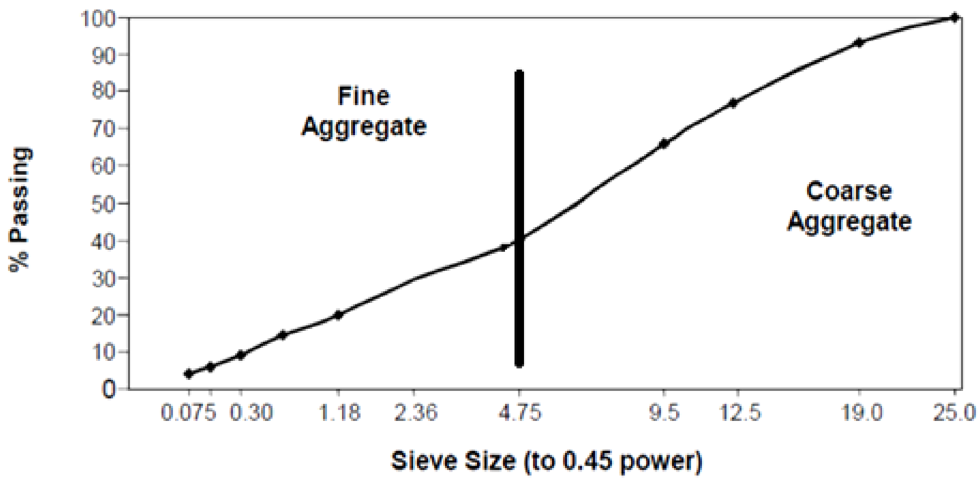

Figure 2.5 Boundary between Course and Fine Aggregate

However in case of Bailey system the definition of coarse and fine aggregate depends upon the NMPS of the mixture. According to Superpave terminology, one sieve larger than first sieve to retain more than 10 % is called NMPS for the overall blend. According to Bailey method:

- **Course Aggregate** are the large aggregate particles that create voids when placed in a unit volume.
- **Fine Aggregates** are aggregate particles that fill the voids created by course aggregate.

In Bailey Method, the sieve that splits the coarse and fine aggregate is known as the primary control sieve (PCS) (Vavrik *et al.*, 2001). The PCS is defined as the nearest sieve size calculated from the following formula.

$$PCS = NMPS * 0.22 \qquad (2\text{-}1)$$

Whereas:

PCS = Primary control sieve.

NMPS = Nominal maximum particle size for the whole mixture

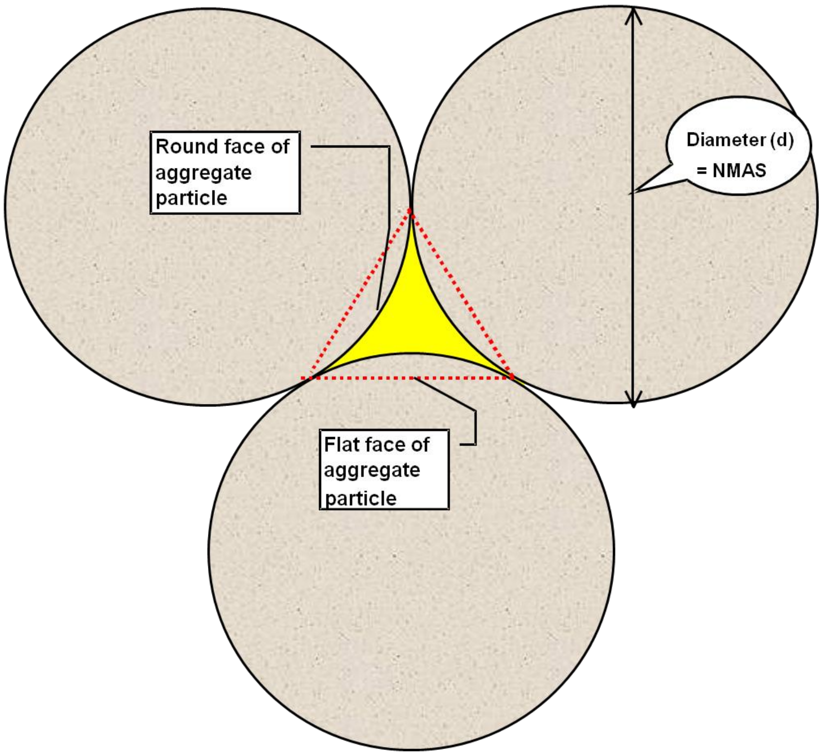

Figure 2.6 Two Dimensional Aggregate Packing Model

The value of 0.22 used in above equation was derived from 2-D and 3-D analysis of the packing of different shape of particles. Table 2.1 shows the PCS for different NMPS of mixture.

Table 2.1 Primary Control Sieve for Different NMPS (Adopted Vavrik *et al.*, 2001: TRB Circular, 2002)

Mixture NMPS (mm)	NMPS *0.22 (mm)	Primary Control Sieve(mm)
37.5	8.250	9.5
25.0	5.500	4.75
19.0	4.180	4.75
12.5	2.750	2.36
9.5	2.090	2.36
4.75	1.045	1.18

2.4.2 Aggregate Packing

The study of particle packing is essential to understand the basis of the combination of mineral aggregates in an HMA mixture. Significant work has been recorded regarding the combination of particles and the resulting voids.

One of the initial attempts regarding the packing of aggregate was performed by Tons et al. (1968). They found that the packing volume concepts and rugosity are the theoretical basis for understanding the bulk behaviour and interlocking mechanisms of aggregates. Rugosity is higher with more angular rocks in mixture which is due to irregular shape of aggregate particles. Therefore, the packing also includes the volume of the surface voids along with the solid mass.

For each coarse aggregate type, there is a particular size of fine aggregate that develops the aggregate interlock between the surfaces of the coarse aggregate and fine aggregate, when they combine in a mix. The strength of rounded gravel mixes can be made equal or closer to the strength of mixes using crushed limestone aggregate simply by matching the rugosity and the size of the fines suitably in the mix (Khedaywi et al. 1998).

A volume cannot be completely filled with aggregate particles. Gap will be always there between the aggregate particles. There are several factors that affect the degree of packing. Those factors are (Vavrik *et al.*, 2001: TRB Circular, 2002).

- Compactive effort
- Shape of the particles:
- Surface texture of the particles.
- Aggregate size distribution (gradation)
- Particles strength.

Both coarse and fine aggregate can be characterized using the properties listed above. The amount used of a given aggregate, along with the individual characteristics directly affects the resulting behaviour of mixture. Final aggregate mixture and their consequent individual aggregate properties, decides the packing features of the overall mixture and is also dependent on the type and amount of compaction effort applied. Therefore in asphalt mix design process aggregate source selection and source in formation in an important aspect.

2.5 Primary Steps in Bailey Method

The main steps in the Bailey Method are:

- Combine aggregates by volume
- Analyze the combined blend

2.5.1 Combine Aggregates by Volume

A fair amount of voids are present in all aggregate blends that depend upon packing features of the mixture. So, we must initial find out the amount and size of the voids produced by the coarse aggregates and fills those with the suitable size of fine aggregate. Existing practice involves combining aggregates by weight; however, to attain maximum density aggregates must be combined by volume. Furthermore, combining aggregates by weight does not offer designer the information essential to build up a parameter to find out the degree of aggregate interlock (vivrik., 2000). Inconsistent specific gravities will produce different quantities of each particle size for the same weight, so in order to accomplish this volumetric amalgamation of aggregates other details have to be collected. For each of the coarse aggregates the loose and rodded unit weights must be known, and for the fine aggregate the rodded unit weight is required.

2.5.1.1 Aggregate Loose Unit Weight (LUW)

The LUW of an aggregate is the quantity of aggregate that fills a unit volume without any compactive effort applied (Vavrik *et al.*, 2001. This state represents the beginning of coarse aggregate interlock with no compactive effort applied. The LUW is shown in Figure 2.7

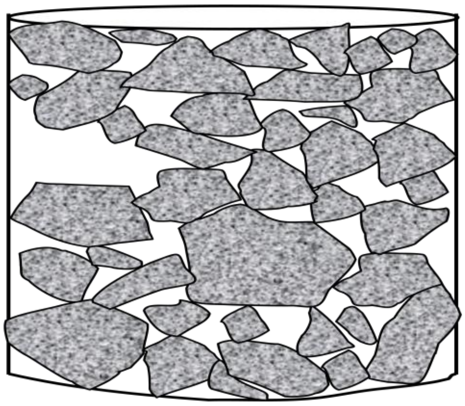

Figure 2.7 Loose Unit Weight of Coarse Aggregate (Vavrik et al., 2001: TRB Circular, 2002)

Loose unit weight is determined on each coarse aggregate and fine aggregate stock pile. The loose unit weight (LUW) can be obtained by dividing the weight of aggregate by the volume of the metal bucket (density in kg/m3).Figure 2.8 shows the unit weight test apparatus.

Figure 2.8 Unit Weight Test Apparatus

2.5.1.2 Aggregate Rodded Unit Weight

RUW of aggregate is the quantity of aggregate that fills a unit volume with compactive effort applied on it. By increasing the compactive effort, particle to particle contact increases whereas voids in aggregate structure decreases. Rodded unit weight is explained in Figure 2.9.

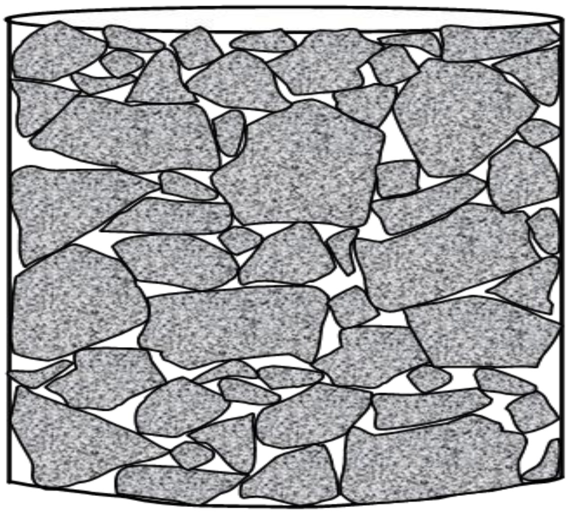

Figure 2.9 Rodded Unit Weight of Coarse Aggregate (Vavrik et al., 2001: TRB Circular, 2002)

By following the rodding procedure mentioned in AASHTO T-19, RUW is determined on each coarse aggregate. Calculations performed to obtain the RUW by dividing the weight of aggregate by the volume of the metal bucket. Voids can also be determined for this condition by means of the bulk specific gravity and rodded unit weight. This state represents the volume of voids there when the particles are more in contact with each other due to the compactive effort applied.

2.5.1.3 Chosen Unit Weight of Aggregate

With the aim of decide on the coarse aggregate interlock required in the mix, the designer need to select a % CUW. It develops the volume of coarse aggregate in the aggregate mixture along with the degree of aggregate intertwine. According to the Bailey system, the mixture with coarse aggregate skeleton is known as coarse graded mixtures. While with fine aggregate skeleton is known as fine graded. So in order to select a %CUW it is necessary for the designer to choose if the blend will be coarse or fine graded. Figure 2.10 shows the different considerations for selecting a chosen unit weight.

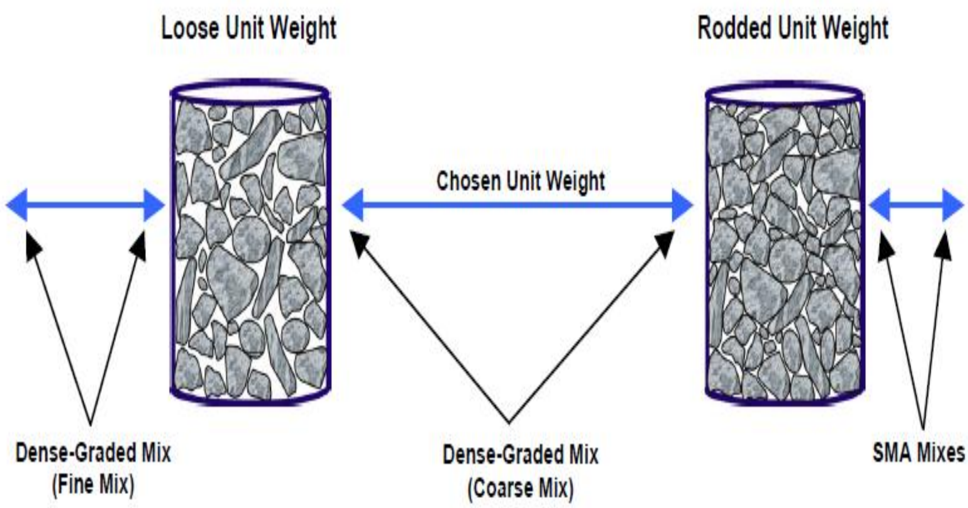

Figure 2.10 Selection of Chosen Unit Weight of Coarse Aggregate (Vavrik et al., 2001: TRB Circular, 2002)

Usually the percentage for chosen unit weight ranges from 95% to 105% of the LUW for coarse mixes. Values greater than 105% should be avoided because of the increased likelihood of aggregate degradation and increased difficulty during field compaction. The % CUW should be less than 90% in case of fine graded mixtures

(Vavrik *et al.*, 2001: TRB Circular, 2002). For fine-graded mixes chosen unit weight of 90 percent or less give better results. Similarly for coarse-graded mixes we suggest a CUW in the range of 95-105 is favourable (Aurilio et al., 2005)

2.5.2 Analyze the Combined Blend

After gathering the typical information for the individual aggregates and performing the unit weight tests, a combined blend can be developed and evaluated prior to actually blending the mix in the laboratory. For this purpose the combined mixture is broken into three distinctive portions i.e. primary control sieve, secondary control sieve and tertiary control sieve. Each portion is evaluated individually.

To determine the secondary control sieve (SCS) the same factor i.e. 0.22 is multiplied with primary control sieve PCS that decides where to split the fine aggregates. The Secondary control sieve then becomes the split among coarse particles and fine particles. Tertiary control sieve is then determined to further evaluate the fines. It is calculated by multiplying the Secondary control sieve by the 0.22 factor. Figure 2.11 shows the division of gradation into three portions.

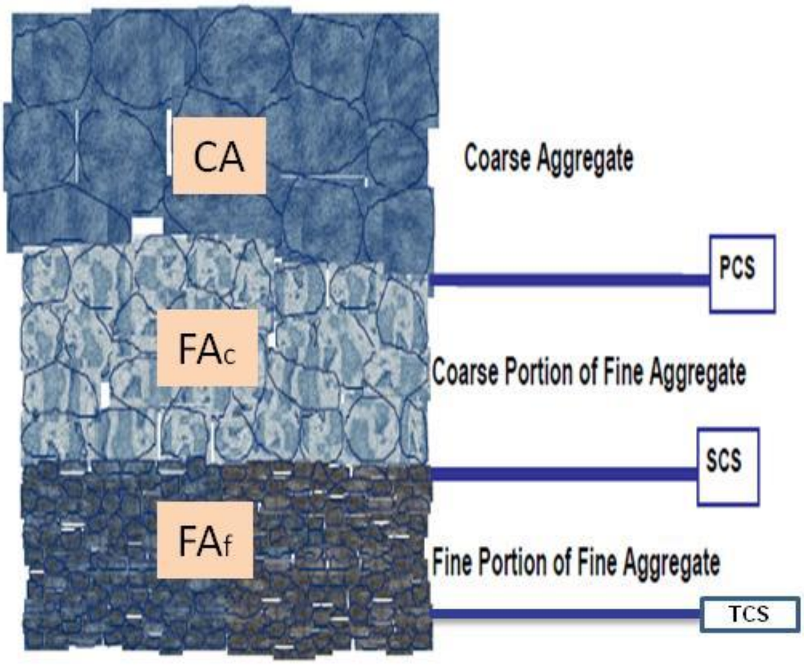

Figure 2.11 Division of Gradation into PCS, SCS, TCS

Now three aggregate ratios that are: coarse aggregate ratio (CA ratio), fine aggregate coarse ratio (FA_c ratio) and fine aggregate fine ratio (FA_f) are used to assess the packing within each of three portions.

2.5.2.1 Bailey Principles

There are four principles to the Bailey Method that are explained in Figure 2.12.

- Determines the break between coarse and fine.
- Evaluates the coarse fraction, which relates to the packing of the coarse fraction and in turn how this influences the packing of the fine fraction.
- Evaluates the packing of the overall fine fraction in the combined blend.
- Evaluates the packing of the fine part of the fine fraction.

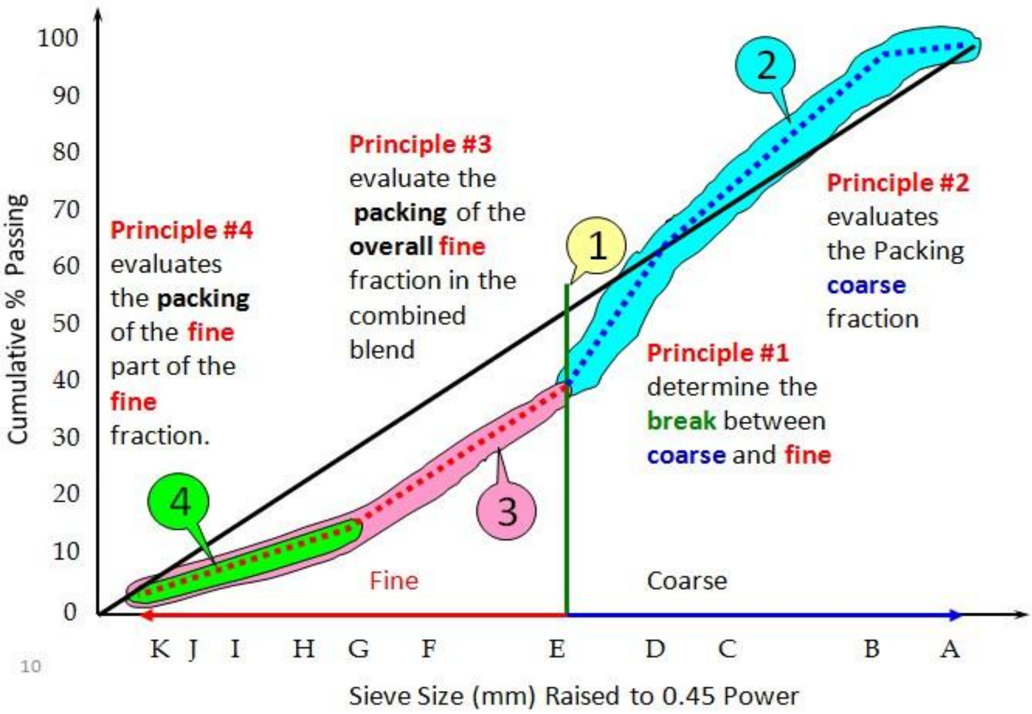

Figure 2.12 Four Bailey Principles

The Bailey method uses three ratios of the various sieves above to evaluate the final gradation. The ratios are as follows: (Vavrik *et al*., 2001)

The CA Ratio defines the packing of the aggregate gradation's coarse portion and analyzes the resulting structure. Compaction of coarse fraction increases as the CA ration decreases below 1.0. Moreover, a CA Ratio lowers than suggested range mentioned in Table 2.2 could specify a mix that may be susceptible to segregation. The formula for the CA Ratio is:

$$\text{CA Ratio} = \frac{(\text{Passing \% Half Sieve} - \text{Passing \% PCS})}{(100 - \text{Passing \% Half Sieve})} \qquad (2\text{-}2)$$

The FA_c Ratio fine portion of the fine aggregate fill the voids created by coarse portion of the fine aggregate. The fine aggregate packs together tighter as this ratio increases. The reason behind increase in packing is the increase in volume of the fine portion of fine aggregate. However FA_c ratio higher than 0.50 should be avoided.

$$\text{FAc Ratio} = \frac{\%\ \text{Passing SCS}}{\%\ \text{Passing PCS}} \qquad (2\text{-}3)$$

The FA_f Ratio coarse portion of the fine aggregate create voids that were filled by fine portion of the fine aggregate. FA_f ratio depicts how the fine portion of the fine aggregate fit mutually in mix. Now another seive is essential to compute the FA_f that is known as the TCS. It is defined as the nearest sieve to 0.22 times the Secondary control seive.

$$FA_f\ \text{Ratio} = \frac{\%\ \text{Passing TCS}}{\%\ \text{Passing SCS}} \qquad (2\text{-}4)$$

Where:

CA = Coarse Aggregate Ratio

FA_c = Fine Aggregate Coarse Ratio

FA_f = Fine Aggregate Fine Ratio

PCS = Primary Control Sieve

SCS = Secondary Control Sieve

TCS = Tertiary Control sieve

Table 2.2: Recommended Ranges of Aggregate Ratios (Adopted from Vavrik *et al.*, 2001: TRB Circular, 2002)

NMPS (mm)	37.5	25	19	12.5	9.5	4.75
CA	0.8 - 0.95	0.7 - 0.85	0.6 - 0.75	0.5 - 0.65	0.4 - 0.55	0.3 - 0.45
FA_c	0.35 - 0.5					
FA_f	0.35 - 0.5					

2.5.3 Effects on VMA

The Changes in VMA is related to the four basic parameters of Bailey Method. These parameters include the percent chosen unit weight (%CUW), CA, FA_c, and FA_f. Each parameters effect on the resulting VMA is reliant on whether the aggregate mix is taken as a coarse or a fine as defined Bailey method. General effect of varian in four parameters on resulting VMA is shown in Table 2.3 (Vavrik, et. al., 2002).

Table 2.3 Effects of Increasing Bailey Parameters on VMA

Parameter	Coarse Blend	Fine Blend
% CUW	Increases	Decreases
CA	Increases	Increases
FA_c	Decreases	Decreases
FA_f	Decreases	Decreases

As we can see in Table shown above, VMA increases as there is an increase in percentage chosen unit weight in case of coarse blends, whereas opposite in case of fine mixes. So, the voids in mineral aggregate predicted by using this technique have to be positioned at the division among course and fine Bailey mixtures. That point of division is a chosen unit weight of 90%. The correlation among the change in chosen unit weight (% CUW) and its consequence on the VMA is shown in Figure .13.

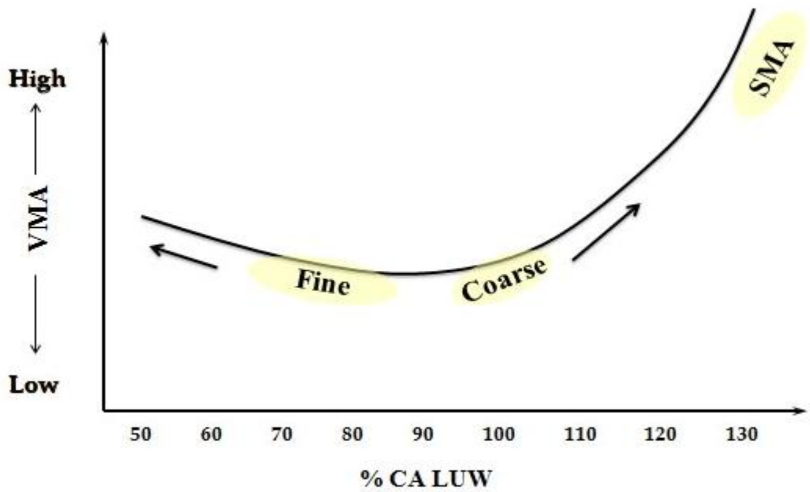

Figure 2.13 Chosen Unit Weight vs. Change in VMA

The Figure 2.13 depicts the change in minimum predicted VMA value as the mix changes from course to fine. The %CUW values less than or equal to 90% signify the fine blends whereas the values between 95% and 105% represent the coarse blends. It is recommended that to avoid high likelihood of the mixture transferring in and out of coarse aggregate interlock region from 90 to 95 should be avoided .The values greater than or equal to 110 % signify the SMA blends.

According to Bailey, the extent of change in VMA is also reliant on whether the aggregate mixture is a coarse or a fine. The change in value of the Bailey parameters that result in a 1% change in VMA is shown in Table 2.4.

Table 2.4 Change in Value of Bailey Parameter to Produce Change in VMA

	Coarse Blend	**Fine Blend**
%CUW	**4% change in PCS**	**6% change in PCS**
CA	0.20	0.35
FA_c	0.05	0.05
FA_f	0.05	0.05

2.6 Past Researches on Bailey Method

Vavrik (2000) carried out a research that investigated the comprehensive mix analysis concepts for developing and analyzing HMA gradations. The results of study have improved the state-of-the-art in asphalt mix design by providing a method to characterize HMA mixture and compaction characteristics through the fundamental principles of particle packing. Author provided the foundation for a comprehensive asphalt mixture design method i.e. The Bailey Method of Gradation Analysis.

Aurilio et al., (2005) have described methodology of gradation selection using some real life examples of five projects in order to provide help to mix designer and contractors to understand the behaviour of the mixes that are commonly used in Canada. They concluded that, understanding the principles involves in bailey method provides a valueable aid and a good starting point of mix design when making adjustments at the plant or in the field to improve mix volumetric properties.

Khosla and Sadasivam (2005) modified different coarser gradations using the Bailey system to obtain the required void structure. Their aim was to evaluate the gradations developed in terms of permeability. Authors concluded that performance of mixtures against permanent deformation is directly associated to permeability of the mixtures. To help the designers to select appropriate gradations they also presented procedure for developing aggregate blends for a desired level of permeability. Data from study showed a correlation between permeability and the CA ratio. This can be related to the VMA and gives some indication about the durability against weathering of the asphalt mix.

Thompson (2006) carried out a study to assess the Bailey method of gradation design. The researcher evaluated Oregon specific aggregate blends using the Bailey method. The Oregon study looked at the correlation of changes in the weight ratios to rutting performance under testing by their APT device. This study found that the same weight ratios from the unused sieve sizes that most strongly influenced the voids were also the main influence on rut resistance. The author recommended modified Bailey method analysis as an additional tool to develop and select trial blends for the design of dense-graded mixes.

Alshamsi (2006) considered three aggregate types and uses bailey method of aggregate gradation evaluation for each aggregate type. Author suggested that using Bailey method, appropriate mixes can be developed having dense aggregate structure that provides good resistance to permanent deformation and at the same time still maintaining satisfactory levels of durability.

Another study by Zaniewski and Mason (2006) evaluated the Bailey Method ability to predict voids in the mineral aggregate (VMA). They found that as the mixture gradation changes, Bailey method does help to provide a forecast value for the VMA. They also suggested that the Bailey Method can provide useful approach to the mix designers by providing a satisfactory prediction to the VMA parameter at design stage.

Denneman et al. (2007) explored in their research the gradation features of good and poor performing mixes in South Africa along with the permeability characteristics of the mix, using the principles described by the Bailey method. This study found that Bailey method concepts allow the designer better approach in the significance of the packing of different fractions for the overall performance of the mix.

Mamat (2008) investigated the properties of HMA mixes with aggregate gradations designed using Bailey system and compared with the jabatan kerja raya (JKR) specification. She concluded that Bailey method gives a logical approach of aggregate mixing and evaluation. Moreover strongest correlation exists between mixture volemetrics and CA ratio a gradation parameter as defined by the Bailey method.

Daniel and Felix (2009) carried out a research to evaluate the applicability of the Bailey Method to New Hampshire materials. Overall, this research concluded that the Bailey method of gradation evaluation can be a useful tool in the assessment and design of New Hampshire mixtures. The Bailey Method should not be used solely, but can be used in combination with knowledge of the aggregate angularity, roughness, and engineering judgment to provide guidance during the mix design procedure.

Graziani et al. (2012) evaluated the concepts, methodology and parameters of the Bailey Method by applying them in the European mix design practice. They redesigned two of their gradations by applying the Bailey Method. They concluded that the European practice for aggregate grading design allows the application of the Bailey Method criteria's and also confirming the authenticity of its basic principles. Moreover they found that compaction slope was associated to the Bailey aggregate ratios (CA, FA_c, and FA_f) that confirms the overall legitimacy of this grading evaluation method.

2.7 Mix Design Methods

The design of asphalt mixtures has been studied since the early 1900's. There has been many a lot of development in mixture design methods over the previous century. For designers the main concern is to understand the interaction of aggregates, asphalt, and the voids created during compaction. Almost every mix design methodology includes specimen preparation and compaction to find out the mixture composition and volumetric properties. Following are two famous mix design methods.

- Marshall Mix Design
- Superpave Volumetric Mix Design

2.6.1 Marshall Mix design

Marshall Mix design method was at first developed by Bruce Marshall of the Mississippi Highway Department around in 1939 that was afterwards polished by the U.S. Army (Asphalt Institute MS-2, 1993). American society of testing and materials standardized it as ASTM D-1559. The Marshall Mix design method provides sufficient assistance in selection of the suitable component materials for hot mix asphlat mixes, where as the choice of the design aggregate gradations is still left to the experience of the mix designer (Asphalt Institute, 2001).

Marshall Mix design includes several major steps. Compaction method, volumetric analysis and the Marshall Stability and flow test of the compacted specimens are the important features of this mix design method. The process of heating, mixing and compacting the mixture of aggregates and binder are well defined by Marshall Method.

Prepared specimens were then subjected to a stability-flow test and a density-voids investigation (Garber and Hoel, 2002).

It is mentioned in standard that specimens should be of 63.5 mm height and 100mm diameter should be used. These specimens are to be prepared using standard procedure of heating mixing and compaction of asphalt binder and aggregate mixture. In order to achieve the required compaction standard hammer is used to apply impact force on the specimen. Number of blows is related to the expected traffic conditions with 35, 50, and 75 for low, medium and high traffic respectively. Marshall Stability and flow test are to use as a performance measure for Marshall Mix design. Marshall Method defines Stability as the maximum load the sample can bear after placing it water bath at 60^{o}C for 30 minutes. Whereas Marshall flow is the vertical deformation of the sample in 0.01 inch taking place at the point of highest load. To satisfy the minimum stability and flow values we select the asphalt binder content at a required density (Asphalt Institute MS-2, 1993).

Now the next phase in Marshall Mix design is to work out the volumetric parameters of the specimens. These volumetric include the air voids, Voids in the Mineral Aggregate, and Voids filled with Asphalt. Finally the design asphalt content is determined based up on:

- Stability
- Flow value
- Air void
- VMA
- VFA

One of the major advantages of this method is that equipment required are relatively inexpensive and portable. It can be conducted rapidly with little effort and testing time is relatively short. The volumetric analysis also addresses to some extent the durability and safeguard against environmental effects by defining a range of volumetric parameters that were developed by experience. Some deficiencies of the method are that the mode of compaction use in this method does not replicate mixture densification as it occurs in a real pavement. Moreover, the shear strength of HMA cannot be effectively estimated using Marshall Stability test. Few attempts were also made to improve the Marshall method. Baladi et al. (1988) recommended a customized method to obtain the optimum asphalt content by rationalizing few of its parameters such as stability and flow. Moreover he also defined a new terminology called equivalent Marshall Stiffness as follows:

$$ES = \frac{S}{2[F0.5(s)]} \qquad (2\text{-}5)$$

Where,

ES = equivalent stiffness (pound/inch)

S = Marshall Stability (pounds)

F0.5(s) = flow at half the value of Marshall Stability (inches)

Baladi et al (1988) concluded that the mixture resilient modulus is better co related with this new parameter ES. He suggested that to decide on the optimum asphalt content Marshall Stability should be replaced by the equivalent Marshall stiffness.

Lees (1987) suggested a new procedure of determining the design asphalt content as well. He used a "range" approach as an alternative of the method of taking average. Like the original method selected parameters are plotted in opposition to the asphalt content. Graph is drawn and the midpoint of the common overlie of all ranges is taken as the design binder content. Following parameters are used Lees's method: Stability, Flow, Marshall Stiffness, air voids, and voids filled with asphalt.

2.6.2 Superpave Mixture Design

Superpave was introduced as the result of research carried out by Strategic Highway Research Program (SHRP) in 1993 (Roberts, 1996). The Superpave mix design method was designed to replace the Hveem and Marshall methods. The basis of volumetric in Superpave system is common to Hveem and Marshall Methods. Along with traffic condition Superpave also considers the climate conditions. Gyratory compactor was new compaction device introduce to replace the Hveem and Marshall Compaction devices. The compaction effort in Superpave mix design is more practical in a sense that it is nearly creating same effect as in field. The main features included asphalt binder's new grading system named Performance Grading (PG) system, specifications of aggregate, change of compaction method, and mixture testing and analysis measures (McGennis 1995; Roberts et al. 1996).

In this new system of performance grading the binders are specified considering the climatic conditions and the selected level of consistency. Following are some new tests that were also anticipated to assess asphalt cement binder:

- Rolling Thin Film Oven Test (RTFO)
- Direct Tension Test (DTT)
- Rotational Viscometer (RV)
- Bending Beam Rheometer (BBR)
- Dynamic Shear Rheometer (DSR)
- Pressure Aging Vessel (PAV)

The basic requirements remained same for the physical properties of binders; however the temperature at which the bitumen is likely to attain the properties varies depending on the climatic conditions (McGennis, 1995). A new form i.e. PG X-Y are use to specify the binders. The first number 'X' explains the high temperature grade that would be the average of the 7-day maximum pavement temperature in ^{o}C. The second number '-Y', describes the lowest temperature at which this bitumen is likely to perform .For example, PG 80-25 can be used for climate where maximum temperature of the pavement would be 80°C and the minimum temperature would be -25°C.

In order to consider different traffic levels the Superpave method also explains few of the aggregate properties related to pavement construction. These aggregate properties are flat and elongated particles, Coarse Aggregate Angularity, Fine Aggregate Angularity, and clay material. Adequate bond among the aggregate and binder would be achieved by introducing the restrictions on the amount of clay in aggregates (McGennis, 1995).

A advance feature of the Superpave method is compaction procedure, which is established to be very successful in simulating the compaction in the field .It guarantee that the properties of the mix placed in the field are to similar to same degree to the samples compacted in laboratory. Moreover it is also proficient of monitoring the rate of densification for the period of compaction. The design number of gyrations required is decided based upon the traffic level for which the mix is designed as shown in Table 2.5.

Table 2.5 Superpave Gyration Levels (Adopted from SP-2 Manual Third Edition, 2001)

	No. of Gyrations		
Design ESALs in Millions	N_{ini}	N_{des}	N_{max}
<0.3	6	50	75
0.3 to < 3.0	7	75	115
3.0 to < 30.0	8	100	160
≥ 30.0	9	125	205

Three levels of compaction and percent of theoretical maximum specific gravity are used for the investigation of the compacted samples. These levels are (D'Angelo, 1995):

- N_{ini}.
- N_{des}.
- N_{max}.

$\mathbf{N_{ini}}$ represents the number of gyrations used as a measure of mixture compactability for the duration of construction.

$\mathbf{N_{des}}$ is the design number of gyrations necessary to fabricate a sample with the same density as that likely in the field.

$\mathbf{N_{max}}$ is the number of gyrations essential to generate a laboratory density that must never be exceeded in the field.

The existing method of understanding of the SGC results and the design criteria are prejudiced toward the performance under traffic. However, the constructability of mixtures does not adequately consider. The use of the SGC curve helps to evaluate the constructability of the mixtures as well (Bahia et al. 1998). He explained the concept of compaction and traffic density indices (CDI, TDI) that are used to relate to construction and in-service response of Hot Mix Asphalt mixes. Bahia suggested that by controlling these indices it is likely that the optimization of hot mix asphalt construction and traffic needs can be attained. Figure 2.14 explains the idea of the compaction indices.

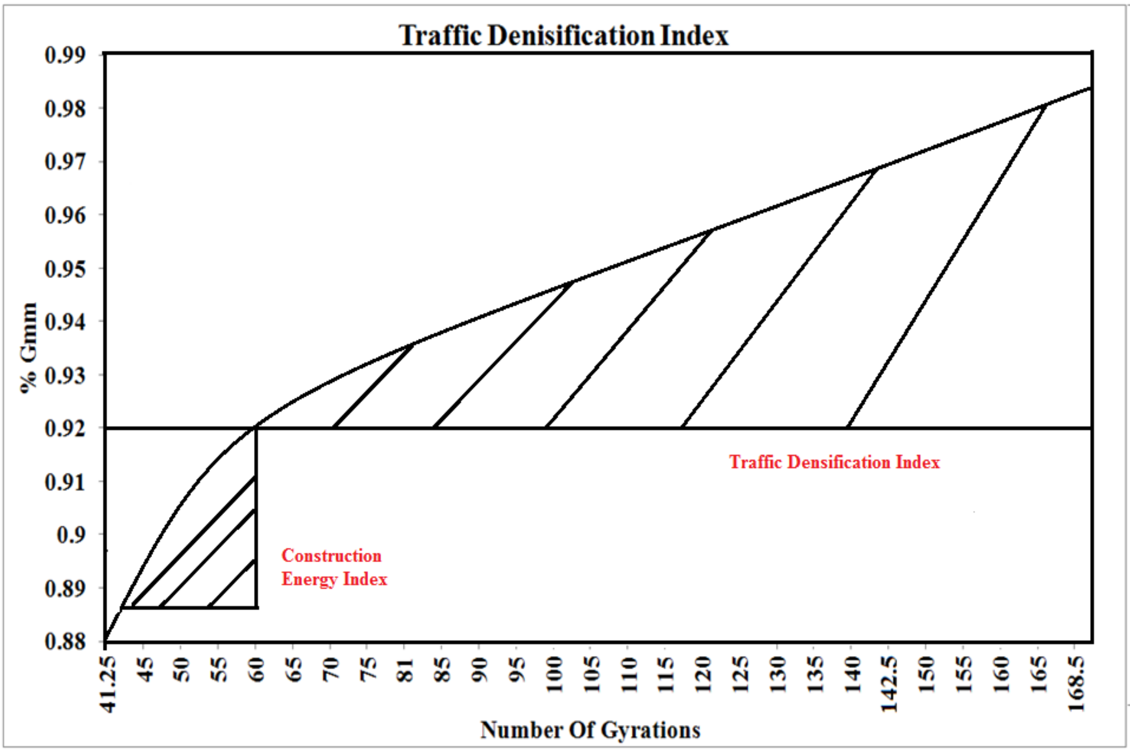

Figure 2.14 Energy Indices from the Superpave Gyratory Compactor

Two sets of criteria: volumetric and densification were finally use to find out the optimum asphalt binder content. Volumetric include: Total Mix air voids (VTM), Voids in Mineral Aggregate (VMA) and Asphalt filled voids (VFA) keeping in view the traffic and NMPS in the mix design (D'Angleo 2001). VMA and VFA requirements are presented in Table 2.6 & Table 2.7 respectively.

Table 2.6 Superpave Requirements for VMA (Adopted from SP-2 Manual Third Edition, 2001)

NMAS (mm)	Minimum % VMA
37.5	11.0
25.0	12.0
19.0	13.0
12.5	14.0
9.5	15.0

Table 2.7 Superpave Requirements for VFA (Adopted from SP-2 Manual Third Edition, 2001)

Design ESALS in Millions	Design % VFA
<0.3	70-80
0.3 to < 3.0	65-78
3.0 to < 10.0	65-75
10.0 to < 30	65-75
≥ 30	65-75

Now considering densification, the Superpave method requires that the designed mixture, have a density of 96 % of Gmm or 4% air voids at designed number of gyrations (Ndes). The mixture cannot attain a density of above 89 % of Gmm at the initial stage of compaction (Nini) (Alshamsi, 2006). Superpave densification criteria are presented in Figure 2.15.

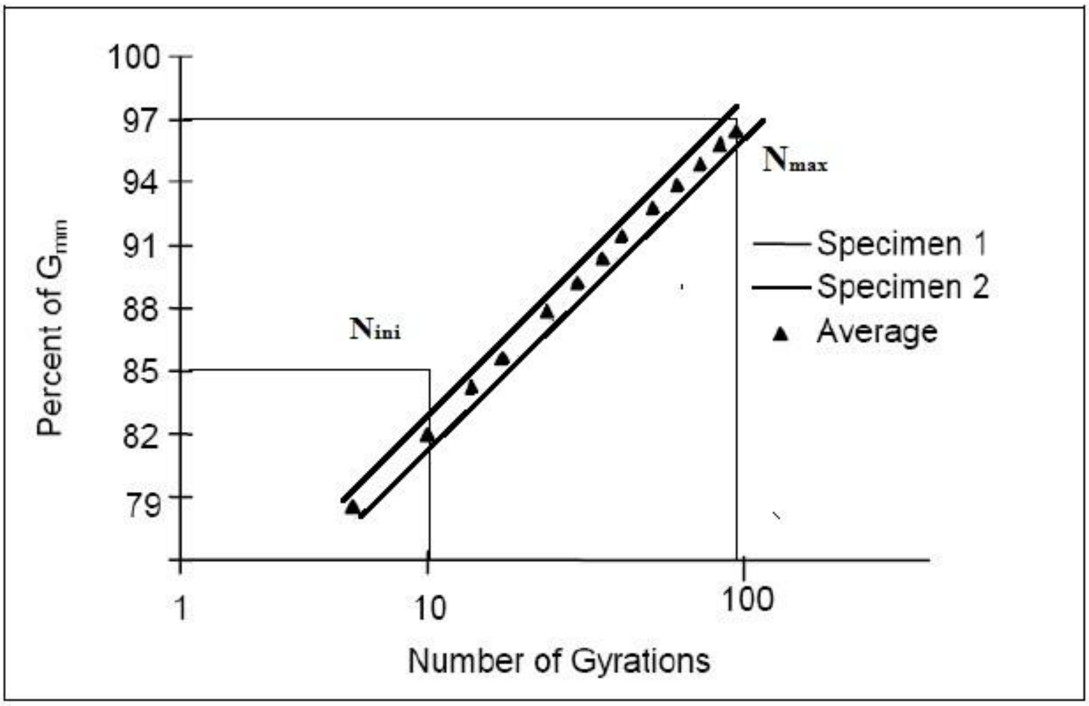

Figure 2.15 Superpave Densification Requirements

2.7 Rutting Susceptibility of HMA

The Strategic Highway Research Program (SHRP) recognized rutting as a most important reason of distress of flexible pavements. It is a permanent deformation in HMA pavements that results in a loss of serviceability of the HMA pavement. It can also create certain safety risks as well. It is observed that Binder and aggregate properties is two of the main causes that affect the rutting susceptibility of flexible pavements.

2.7.1 Literature Review on Rutting Behavior of HMA

Kandhal et.al (2001) suggested that stiff binders having large aggregates normally are more defiant to rutting than mixes containing finer aggregates and higher binder contents. An appropriately designed HMA mixture with bitumen of adequate stiffness can considerably decrease a pavement's rutting vulnerability. Normally as we increase number of load applications it develops rutting in paving materials.
As the wheel load applications increases, a common distress known as rutting develops that normally emerges as a longitudinal depression along the wheel path. In asphalt concrete layers it is observed that dense graded mixture are suitable to ease the effects of rutting. Proper compaction can produce mixtures with fewer voids in dense and continuous gradation as compare to open and gap gradations. t (Sousa et al. (1991). Mixtures that are made from angular aggregates are steadier than mixtures made from rounded aggregates. Also Lower viscosity asphalts are more vulnerable to rutting due to mixtures less stiffness. They also concluded that the binder content has a great impact on the mixture's capability to oppose permanent deformation.

Brown and Cross (1992) found in their study that there are more chances to increase the likelihood for premature rutting for in place air voids less than 3.0%.so to decrease the possibility of premature rutting a value of 3.0% or slightly above it should be used. Therefore, the HMA mixture must be laid with an air void content of extensively above 3.0% and consequently a reasonably high compactive effort is required to guarantee that the voids in the mix keep on above 3.0% later on.

Eisemann and Hilmar (1987) studied deformation in asphalt pavement using wheel tracking device. They calculated the average rut depth as well as the volume of displaced materials. They concluded that in the initial phase, traffic compaction or densification is the primary mechanism of rut development. After that primary phase, the volume decrease under the tires is roughly equal to the volume increase in the nearby disturbance zones. According to them, shear deformation is the most important means of rutting for the greater part of the life of the pavement.

2.7.2 Wheel Tracker Device for Rutting susceptibility

In order to determine the rutting behaviour in HMA pavements a number of laboratory test methods have been established. Few of those methods have been in use for many years, while others are still in stage of development. The Hamburg Wheel Tracker Device (HWTD) has been used for over thirty years now to evaluate the performance of flexible pavements (Aschenbrener and Currier 1993).It is use to evaluate the design mixes for their behaviour under traffic load and varying environmental circumstances. Samples are subjected to wheel-tracking devices that apply repeated loadings by a moving wheel. It estimates the expected permanent deformation in the pavement. However, some highway agencies have avoided using the HWTD as a requirement for acceptance due to its lack of repeatability in its results. According to them the problem is the lack of consistency in the procedures used to prepare the samples. There is a standard procedure for testing, but no process exists for preparing the test sample. The testing procedures are being addressed in AASHTO T324: Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA) addresses, but it does not address the preparation of the specimen. Figure 2.16 presents the output graph obtained from wheel tracking test report.

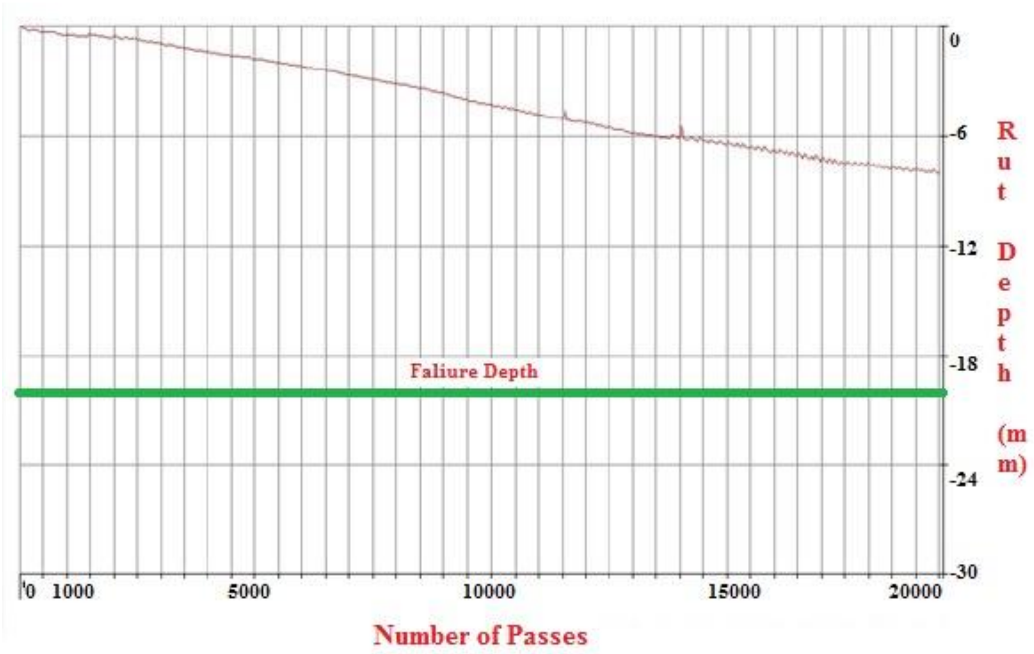

Figure 2.16 Output of Wheel Tracker Test (Number of Passes Vs Rut Depth)

According to Mogawer and Stuart (1995) Hamburg Wheel Tracking Device was at first developed in Germany with the aim to observe the rutting susceptibility of flexible pavements. Ever since then number of U.S departments have utilised it to check the rutting potential of HMA. Texas Department of Transportation has also accepted that this device can be used to envisage the moisture damage propensity of hot mix asphalt. Moreover, they found that the presence of soft limestone in mix increases rutting due to severe abrasion and degradation, when tested in wheel tracking device.

Cooley (2000) described the background history of humburg Wheel Tracker. According to him, Helmut Wind finalized the test method and developed specification requirements to measure rutting and stripping vulnerability. Pass/fail criteria is mentioned to decide the susceptibility to rutting and moisture damage.

Yetkin et al. (2007) mentioned in his study that the load of the wheel passing on the sample applies a force of 158lb and whereas the average contact stress is around 0.73 MPa with a contact area approximately 38 inches. They explained that rut depth increases as the contact area increases, and thus the contact stress is inconsistent.

Hafeez et al. (2012) performed statistical analysis and developed a regression model to look at the effect of size of aggregate on the rutting susceptibility of the mix. Least square regression analysis was run on entire data using the Microsoft Excel Solver tool and regression coefficients were derived. The model was also evaluated on the basis of the goodness-of-fit parameters.

2.8 Summary

This chapter includes background of hot mix asphalt (HMA) in brief and a review of the researches and studies already carried out at the packing characteristics of aggregates. Furthermore it includes the role of binder, aggregate and aggregate gradation in behavior of HMA. The focus of studies, Bailey Method of gradation of aggregate is discussed in detail. Literature review related to Bailey Method is carried out in this chapter. The reason behind literature review was to become familiar with previous studies on the area under discussion i.e. aggregate gradation adjustment. The effect that bailey parameters have on VMA is also discussed in this chapter. Some overview on different mix design method is also discussed. The two mix design methods that are used in this research is explained in detail. Past studied carried out to evaluate rutting susceptibility and rutting prediction models are presented at the end.

Chapter 3

RESEARCH METHODOLOGY AND MATERIAL TESTING

3.1 Introduction

This chapter includes the methodology adopted during the study to attain the stated objectives. It includes the detailed information on the materials acquisition, material characterization, specimen preparation, testing and analyzing the significance of various factors. This research is conducted to evaluate the applicability of Bailey method of gradation adjustment. Therefore the testing was performed in three phases. In the first part the material characterization of selected mineral aggregate and binder was performed, in which the required aggregate and asphalt properties were tested according to their reference standard specifications. In second phase the selected gradations were adjusted using the Bailey volume blending spread sheets (VBS) and optimum bitumen content is calculated using the Marshall Mix design Method. In third phase Superpave Gyratory Compacter (SGC) specimens were prepared that were then transformed into samples of required size for Hamburg wheel tracker testing. This study was carried out on four (04) different wearing course gradation i.e. NHA-A, NHA-B, SP-1 and MS-2 with aggregate source of Margalla quarry and bitumen source of ARL of 60/70 pen grade. For each type of mix, 9 numbers of samples of 4 inch diameter using 3 trial bitumen were prepared and using average values volumetric against each trial bitumen content were determined. Similarly for the performance testing triplicate specimens were fabricated for each mix type. The analysis was then carried out for the control and adjusted gradations that is explained in next chapter.

3.2 Frame Work of Research Methodology

To achieve the stated objectives, four different gradations were selected i.e. NHA-A, NHA-B, SP-1, MS-2. Aggregate collected from Margalla quarry was brought to laboratory for testing. Bitumen grade 60/70 PEN from ARL is selected as binder. After adjusting the selected gradations through the bailey method optimum bitumen content is calculated through Marshall Mix design method. The results of Marshall

Parameters and volumetric for control gradations were obtained from a research already carried out in laboratory at national institute of transportation (NIT). Specimens were then prepared for both control and adjusted gradations, in laboratory under controlled conditions for performance testing using Superpave gyratory compactor .samples were transformed into required size for Hamburg wheel tracker device that were tested for rutting susceptibility. Using extracted data analysis was performed using statistical software. Finally the conclusions and recommendations were made that will be described in next chapters. Figure 3.1 shows the research methodology adopted for the study.

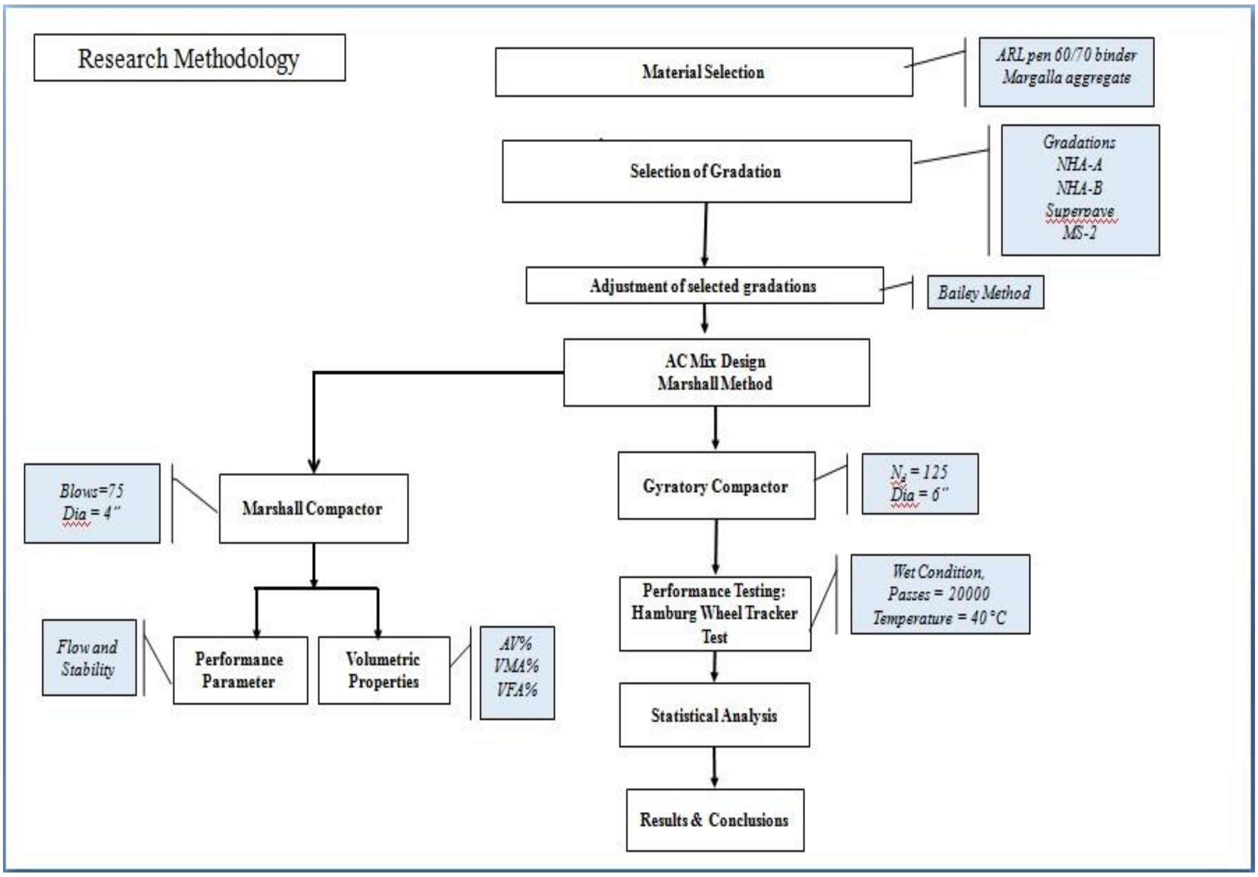

Figure 3.1 Flow Chart for Research Methodology

3.3 Materials Selection and Laboratory Characterization

Asphalt pavement or the HMA is primarily consisting of aggregate mineral and bituminous binder. Normally aggregate makes up about 95 % of the mixture and remaining 5% is the asphalt binder. Laboratory testing of aggregate and binder is essential for proper selection of materials, in order to meet the standard requirements for hot mix asphalt mixes. In the light of ASTM and BS standards and specifications for material characterization, required tests were performed on aggregate and asphalt binder.

3.3.1 Selection of Materials

In this study the aggregates were obtained from Margalla quarry. Aggregates consist of coarse aggregates; fine aggregates and filler material and it was obtained in form of three stockpiles i.e. 0-5, 5-10 and 10-20 mm.

The bitumen source used in sample preparation was Attock Refinery Limited (ARL) having pen grade 60/70 that is suitable for colder to modest temperature regions and is mostly used in Pakistan for road construction.

3.3.2 Aggregate Testing

The main portion of the resistance to permanent deformation of the mixture is provided by the aggregate skeleton. They are anticipated to offer a well-built stone skeleton to resist repetitive loads. To find out the fundamental aggregate properties such as specific gravity, loose and rooded unit weights, gradation e.t.c, and detailed laboratory assessment procedures of individual stockpiles were performed. Tests performed in the laboratory include:

1. Shape Test
2. Unit Weight Test
3. Specific Gravity and Water Absorption Test

All of above tests were performed using three samples and then average is taken which were used in further process.

3.3.2.1 Shape Test Results

Particle shape has a significant role to participate in workability, strength of the asphalt mix. It also influences the compactive effort crucial to gain the required density. Therefore the quantity of flat and elongated aggregate particles was determined using Shape test. Flakiness of aggregate particles is classified as flaky, when they have smaller dimension of less than 0.6 of their mean sieve size, whereas elongated a when they have a length of more than 1.8 of their mean sieve size (ASTM D4791). The results of flakiness and elongation index for coarse aggregate is depicted in Table 3.1.

Table 3.1 Results of Flat and Elongated Particles in Aggregates

	SAMPLE NO				Test Standard and Specification
	1	**2**	**3**	**Average**	
Flat Particles (%)	10.93	14.62	13.211	**12.924**	ASTM D4791 ≤15
Elongated Particles (%)	5.817	1.736	3.180	**3.578**	ASTM D4791 ≤15

3.3.2.2 Unit Weight Test

It is necessary to know the unit weight of aggregate to determine the volumetric as well as weight to volume relationship. Different volume related quantities are VMA, VFA and VA. In addition to determine the packing characteristics of aggregates by utilizing Bailey's method, unit weight is very important to be known. This property of aggregate is one of the inputs of Bailey volume blending spread sheets (VBS).

The loose unit weight is determined on each coarse aggregate and fine aggregate stock pile i.e. 10-20, 5-10 and 0-5. Table 3.2 presents the LUW and loose voids test results performed in lab.

Table 3.2 Loose Unit Weight and Loose Voids Results

	LUW			
	10-20	**5-10**	**0-5**	**Test standard**
LUW(Kg/m^3)	1402.95	1387.95	1650.752	ASTM C29
Loose voids (%)	48.03	45.38	39.84	

The quantity of aggregate that fills a unit volume with compactive effort applied is known as rodded unit weight (RUW).the volume of voids in aggregate decreases with increasing compactive effort whereas grain to grain contact increases. Rodding procedure mentioned in AASHTO T-19 was followed to determine the RUW. Table 3.3 shows the RUW and loose voids test results performed in lab.

Table 3.3 Rodded Unit Weight and Loose Voids Results

	RUW			
	10-20	**5-10**	**0-5**	**Test standard**
RUW(Kg/m^3)	1510.95	1458.95	1900	ASTM C29
Loose voids (%)	43.63	43.92	34.69	

3.3.2.3 Aggregate Specific Gravity

Weight volume characteristics of aggregate material are represented by its specific gravity. Coarse and fine aggregate specific gravities were determined independently. According to definition coarse aggregate is the aggregate that are retained on the No. 4 sieve whereas those passing No. sieve are fine aggregates.

- *Coarse Aggregate Specific Gravity*

Three types of specific gravities were determined: saturated surface dry (SSD), bulk and specific gravity by applying the specific gravity test on coarse aggregate. The percentage absorption test is also performed to calculate the water absorption which is an input value in bailey aggregate blending sheet (VBS). Specific gravity and water absorption were calculated using the equipment and procedures mentioned in ASTM C 127. The test is performed for both of the coarse graded stock piles i.e. 10-20 mm and 5-10 mm .The results of test conducted in laboratory are presented in Table 3.4 & Table 3.5.

- *Fine aggregate specific gravity*

Specific gravity test was performed on fine aggregate to find out the value of bulk, SSD and apparent specific gravities. ASTM C128 was adopted for determining the specific gravity and water absorption for fine aggregate. Specific gravity test results for fine aggregates are presented in Table 3.6.

Table 3.4 Specific Gravity of Course Aggregate (10-20) mm

Course Aggregate (10-20) mm					
	Sample 1 (gm)	Sample 2 (gm)	Sample 3 (gm)	After 24 hours	Test standard
Air Weight (WA)	3000	3000	3000	3000	
Weight in Water (WC)	1880	1881	1878	1880	
Weight SSD (WB)	3016.3	3015.6	3016.7	3022	ASTM C127
Specific Gravity	2.64	2.64	2.63	2.63	
Average	2.636				
% Water Absorption	0.73				

Table 3.5 Specific Gravity of Course Aggregate (5-10) mm

Course Aggregate (5-10)					
	Sample 1 (gm)	Sample 2 (gm)	Sample 3 (gm)	After 24 hours	Test standard
Air Weight (WA)	2000	2000	2000	2000	
Weight in Water (WC)	1266.1	1268.9	1273.2	1266	
Weight SSD (WB)	2038.4	2041.5	2040	2049	ASTM C127
Specific Gravity	2.59	2.59	2.61	2.55	
Average	2.602				
% Water Absorption	2.45				

Table 3.6 Specific Gravity of Fine Aggregate

Fine aggregate (0-5) mm				
	1	2	3	Test standard
Wt. of bottle(W1)	597.5	393.5	597.5	
Wt. of water + bottle (W4)	1331	1112	1322	
Wt. of bottle +sample(W2)	1097.5	893.5	1095	ASTM C128
Wt. of water +bottle + sample(W3)	1633	1424	1622	
specific gravity	2.52	2.65	2.51	
Average		2.567		

3.3.3 Asphalt Binder Testing

According to Asphalt Institute MS-4 manual three properties of asphalt are important for engineering and construction purposes, i.e. consistency, purity and safety. Change in temperature also affects the consistency of asphalt cement binder. Therefore, in order to compare the consistency of one asphalt binder to another the use of standard temperature is necessary. Viscosity test or a penetration test commonly used to find out the consistency of bitumen binder (Asphalt Institute MS-4, 2003). Additional information and confidence toward consistency is provided some other tests like ductility and softening point. So following tests were performed in laboratory to characterize the asphalt binder.

1. Bitumen Penetration Test

2. Bitumen Softening Point Test

3. Bitumen Ductility Test

3.3.3.1Penetration Test

Penetration test determines the penetration of asphaltic materials. The method includes needles and containers having specimen. Higher values of penetration indicate softer binder. According to AASHTO T 49-03 temperature, load, and time for the test are 25°C, 100 g, and 5s, respectively until unless the conditions are not specifically mentioned. Penetration tests were conducted by using two specimens of ARL 60/70 and taken five values from each specimen. All penetration values satisfied the necessary criteria of penetration test as per specifications. Penetration test result is presented in Table 3.7.

Table 3.7 Results of Penetration Test

Asphalt Binder	**ARL 60/70**		
Penetration (0.1mm)	Sample 1	Sample 2	Test specification
1	68	61	ASTM D5/ AASHTO T49 (60-70)
2	62	64	
3	60	65	
4	61	68	
5	65	60	

3.3.3.2 Softening Point Test

Bitumen's are visco-elastic material so as the temperature rises they gradually become softer and less viscous. Softening point is the temperature at which a bitumen standard size sample cannot uphold the weight of 3.5 gm steel ball. Softening point of bitumen is the average temperature at which the two disks of bitumen soften enough to let the balls to fall a distance of 25 mm. Ring and ball apparatus were used to determine the softening point of asphalt as per AASHTO T 53 specifications. Table 3.8 shows the outcome of softening point test.

Table 3.8 Results of Softening Point Test

Binder	**ARL 60/70**				
Softening Point (°C)	1	2	3	Average	Test specification
Right	47.5	48.5	48.5	48.1	ASTM D36
Left	48.2	49.0	48.2	48.5	
Difference	0.7	0.5	0.3	0.4	
Average	47.8	48.7	48.3	48.2	

3.3.3.3 Ductility Test

Ductility is a substantial property of bitumen which is considered an important factor in case of performance of HMA mix. It is a sign of behavior of bitumen under various temperatures. By definition it can be explained as the "distance to which it will lengthen prior to breaking when two ends of specimen of the material, are pulled away from each other at a particular speed i.e. 5 cm/min and at a particular temperature of 25 ± 0.5 °C (AASHTO T 51-00). Standard specifications and lab results for ductility tests for asphalt binder is shown in Table 3.9. All samples had seen fulfilling the minimum criteria of ductility as 100cm.

Table 3.9 Results of Ductility Test Binder

	ARL 40/50	**Test specification**
Specimen No.	Ductility (cm)	
1	101	ASTM D113
2	101	(≥100)
3	100	

3.4 Experimental Blends

Asphalt mixture with changed gradation and prepared from aggregates of same source with the same physical and chemical properties will result different responses. It has been a long continuous issue about the choice and effect of gradation on the performance of HMA. Different agencies around the world have different gradations for HMA mixtures keeping in view the maximum aggregate size. To observe the effect of gradation on rutting, this research uses four mix designs i.e. NHA-A (NHA gradation), NHA-B (NHA gradation), Superpave-1 (Super pave Gradation) and MS-2 (Asphalt Institute Gradation) for asphalt wearing course. These four gradations are named as control gradation for this research. Among selected four control gradations NHA-A and NHA-B were coarse gradations having the nominal maximum size (NMPS) of aggregate 19 mm. The other two gradations Superpave-1 & MS-2 were fine mixes with the nominal maximum size of aggregate of 12.5 mm. Four selected asphalt wearing coarse gradation are presented in Table 3.10.

Table 3.10 Asphalt Wearing Course Control Gradations

Sieve Size mm	Cumulative Passing Percentage (%)			
	NHA Gradation WClass-A	NHA Gradation WClass-B	Superpave Gradation WClass-A (1)	Asphalt Institute WMS-2
37.5	100	100	100	100
25.4	100	100	100	100
19	95.0	100	100	100
12.5	76.0	82.0	94.0	95.0
9.0	63.0	70.0	87.0	82.0
6.4	51.5	59.0	74.0	69.0
4.75	42.5	50.0	65.0	59.0
2.36	29.0	30.0	37.0	43.0
1.18	20.0	20.0	21.0	30.0
0.6	13.0	15.0	14.0	20.0
0.3	8.5	10.0	9.0	13.0
0.15	6.0	7.0	7.0	8.5
0.075	5.0	5.0	5.0	6.0

Among the above four wearing course gradations NHA-A, NHA-B and Superpave-1 satisfies the Superpave criteria of control point and passes through the defined limits. One of the gradations i.e. MS-2 passes through the Superpave restricted zone but as per NCHRP Report No. 464 gradations that go against the restricted zone perform similar to or better than the mixtures having gradation passing outside the restricted zone. Figures 3.2 & 3.3 presenting the plots of gradations along with the maximum density line, control points and restricted zone.

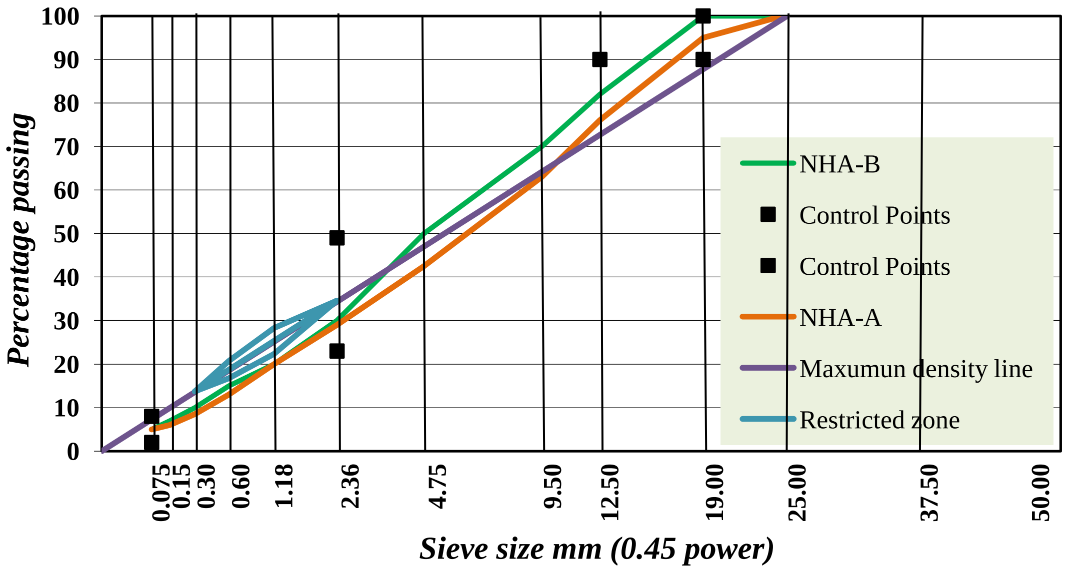

Figure 3.2 Gradation Plots of NHA-A & NHA-B Control

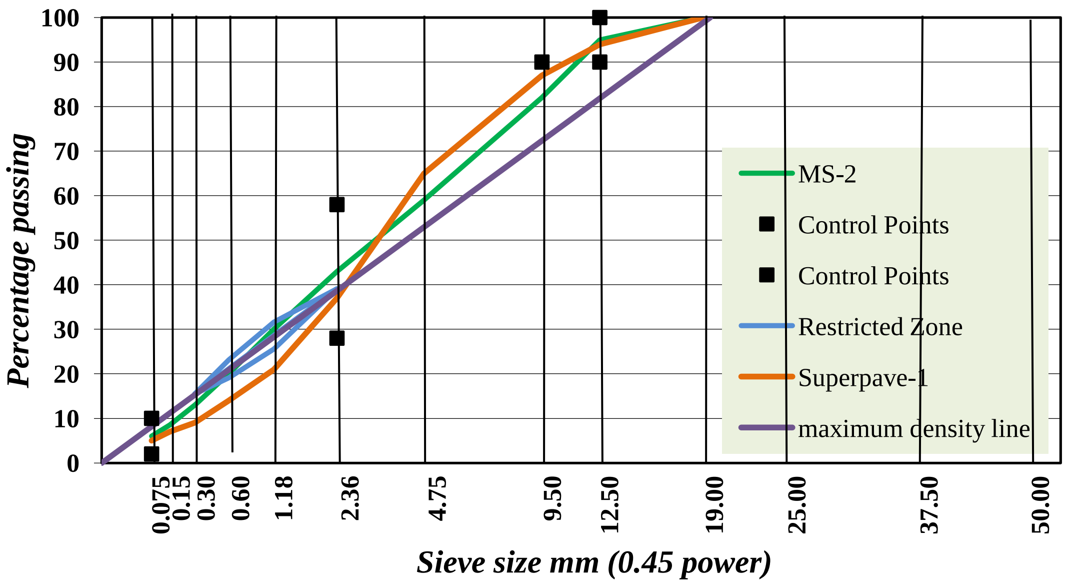

Figure 3.3 Gradation Plots of Superpave-1 & MS-2 Control

3.5 Application of Bailey Method

Vast amount of extensive calculations and iterations are required to fully make use of the Bailey method. To adjust the desired blend by selecting a percentage chosen unit weight (% CUW) involves a trial process. For that reason, an Excel spreadsheet was developed by the Heritage Research Group (HRG).The Bailey Method of Gradation Selection calculations were performed using HRG blending sheets for all the four selected gradations.

3.5.1 Stockpile Gradation

Aggregate stockpile gradation plays important role in performance of mix design. Moreover as this research uses volume blending spreadsheets that requires stockpile gradation as an input, to calculate the optimum gradation so the aggregate from the quarry stockpiles were sieved to obtain the average stockpile gradation. Aggregates were sampled from aggregate source in accordance with AASHTO T-29. The material obtained is in form of three aggregate stockpiles i.e. 0-5, 5-10 and 10-20.Sieveing is performed to determine the percentage of aggregate required from each stockpile according to ASTM-C136 specification standard. The passing percentage of the aggregate through the selected sieves is obtained by taking weights retained on individual sieves. If the maximum particle size is too small, the blend may be unbalanced and in case it is too large, workability and segregation may be setback. The curve with subjected to the sample grade were produced from the graph percent passing percent sieve size to the power of 0.45 with lower and upper bound. Finally the mass reserved were calculated via the percent passing for every sample size. Table 3.11 presents the average gradation for each stockpile at Margalla quarry.

Table 3.11 Average Gradation of Margalla Quarry

Sieve Size (mm)	38	25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
20-38	100	29.0	4.9	0.6	0.5	0.3	-	-	-	-	-	-
10-20	-	100	97.4	48.6	18.4	1.6	0.8	-	-	-	-	-
5-10	-	-	-	100	93.0	14.5	0.8	0.6	-	-	-	-
0-5	-	-	-	-	100	98.9	69.9	42.8	26.6	18.6	13.2	9.3

3.5.2 Volume Blending Spread Sheet

The selected gradations were adjusted using the volume blending spread sheet developed by Heritage Research Group (HRG). The first page on volume blending spread sheets provides step-by-step direction on how to use the spreadsheets. The second sheet is the main mix design calculation or blending worksheet. There are quite a few input values for the Bailey calculations that must be chosen by the designer. The user interface of the HRG Excel worksheet is shown in Figure 3.4

Heritage Research Group

A Heritage Group Company

7901 W. Morris Street • Indianapolis, IN 46231 U.S.A.
317-243-0811 • 486-2985 (FAX)

Design Number:	Initial Blending Example
Design Date:	Today
Mix Producer Name:	Hot Mix, Inc.
Mixture Name/Code:	9.5mm Coarse-graded Virgin blend

Aggregate	#1-CA	#2-CA	#3-CA	#4-CA	#1-FA	#2-FA	#3-FA	#4-FA	MF	Hyd Lime	AC
Code	Coarse				Natural				Bag		Black
Source Id	Aggregate				Sand				House		Magic
Name	Chips								Fines		PG XX-XX
Location											
Agg %'s (P)	64.2	0.0	0.0	0.0	32.7	0.0	0.0	0.0	3.1	0.0	100.0

Sieve, mm	#1-CA	#2-CA	#3-CA	#4-CA	#1-FA	#2-FA	#3-FA	#4-FA	MF	Hyd Lime	BLEND	Percent Passing By Volume
19.0	100.0				100.0				100.0		100.0	100.0
12.5	100.0				100.0				100.0		100.0	100.0
9.5	96.9				100.0				100.0		98.0	98.0
4.75	30.8				99.8				100.0		55.4	55.8
2.36	7.7				86.8				100.0		38.1	38.3
1.18	4.9				70.2				100.0		29.2	29.3
0.600	4.1				51.2				100.0		22.5	22.6
0.300	3.7				16.7				100.0		10.8	10.6
0.150	3.5				1.7				99.0		6.9	6.7
0.075	3.0				0.9				88.0		4.9	4.8

CA	0.434	0.436
FA_c	0.623	0.620
FA_f	0.261	0.252

	#1-CA	#2-CA	#3-CA	#4-CA	#1-FA	#2-FA	#3-FA	#4-FA	MF	Hyd Lime
% CA LUW	100.0						% FA RUW	100.0		
LUW	1422.2									
CHOSEN UW	1422.2	0.0	0.0	0.0	1722.8	0.0	0.0	0.0		
RUW	1580.9				1722.8					
Bulk Spec Gr	2.630				2.680				2.800	
Apparent Gr									2.800	
% Absptn.										
Loose Voids	45.9									
Rodded Voids	39.9				33.2					

Enter the multiplication factor to be used with the Bulk Specific Gravity of the Aggregates according to the values entered for the Unit Weights (e.g. 62.4 lbs./ft³ or 1000 kg/m³)	1000.0

Desired Blends by VOLUME									Total Volume %'s
Coarse Agg's	100.0				100.0	← MUST TOTAL 100.0%			54.1
Fine Agg's	MUST TOTAL 100.0% →			100.0	100.0				45.9

% AC	Gmb	VCAmix
4.5	2.332	45.8
5.0	2.351	45.7
5.5	2.363	45.7
6.0	2.374	45.7

Enter the percent passing the 0.075mm sieve desired in the Combined Blend	6.00

Combined Bulk Specific Gravity of the Aggregates (Gsb)	2.618

Figure 3.4 Bailey Method Volume Blending Worksheet (HRG)

All the required information for each stockpile was entered on this worksheet. The data that was entered includes the gradation of each stockpile, loose and rodded unit weight for each stockpile, specific gravity of each aggregate stockpile, multiplication factor for specific gravity and percentage water absorption. After putting all the required fields in the spreadsheet different trials were performed by changing the input parameters i.e. % CUW, desired blend by volume and percentage passing 0.075 sieves to get the final blend. The target was to adjust the gradations in such a way that they remain in their

permissible gradation envelops. The aim values for each of the Bailey weight ratios i.e. CA, FA_c, and FA_f were set in between the recommended limit for each or ratio.
Initially the procedure is carried out for the original mixes to back calculate the % CUW and the three aggregate ratios. The process is repeated and several attempts were made to bring this ratio within limits for the adjusted gradations. In case of control gradation CUW is a back calculated value while for the redesigned mixtures it is a chosen value. The desired blend by volume was also in tune to create a best possible mixture. This is performed by varying the final amount in percentage of each aggregate to be used in the mixture.

3.5.3 Bailey Adjusted Gradations

Four mixtures were chosen for redesign with the Bailey Method; they are NHA-A, NHA-B, Superpave-1 and MS-2 for asphalt wearing course. For clarity the Bailey Redesign gradations will be called as NHA-A Bailey, NHA-B Bailey, Superpave-1 and MS-2 Bailey in this study. Among the selected four gradations NHA-A and NHA-B were originally course gradation while SP-1 and MS-2 were fine graded. Three gradations NHA-A, NHA-B and SP-1 mixtures were redesigned to be "coarse" mixtures according to the Bailey Method, meaning the CUW was chosen to be in the 95%-105% range. While several attempts were made to bring MS-2 gradation within acceptable values of CA, FA_c and FA_f ratios by designing it as course graded, but no combination of input values achieved an acceptable combination. So the mix is redesigned as fine graded mix. Table 3.12 shows the four asphalt wearing course adjusted Bailey gradations.

Above Table shows the four asphalt wearing course adjusted Bailey gradations. Among the above four wearing course gradations, NHA-A Bailey, NHA-B Bailey and Sp-1 Bailey satisfies the Superpave criteria according to which aggregate gradation must pass through the control points. One of the gradations i.e. MS-2 Bailey passes through the Superpave restricted zone like the original control MS-2 gradation. Figures 3.5 and 3.6 are presenting the plots of adjusted Bailey gradations along with the maximum density line, control points and restricted zone.

Table 3.12 Asphalt Wearing Course Adjusted Bailey Gradations

Sieve Size Mm	Cumulative Percentage Passing (%)			
	NHA gradation WClass-A	NHA gradation WClass-B	Superpave gradation WClass-A(1)	Asphalt institute WMS-2
37.5	100.0	100.0	100.0	100.0
25.4	100.0	100.0	100.0	100.0
19	98.9	100.0	100.0	100.0
12.5	77.4	78.1	90.2	89.9
9.0	62.6	63.3	82.0	82.7
6.4	50.5	53.0	67.5	75.5
4.75	38.4	38.2	48.1	60.6
2.36	25.5	28.6	34.7	46.6
1.18	16.1	17.8	21.2	28.5
0.6	10.6	11.5	13.1	17.6
0.3	7.9	8.4	9.1	12.3
0.15	6.1	6.4	6.5	8.8
0.075	4.8	4.9	4.6	6.2

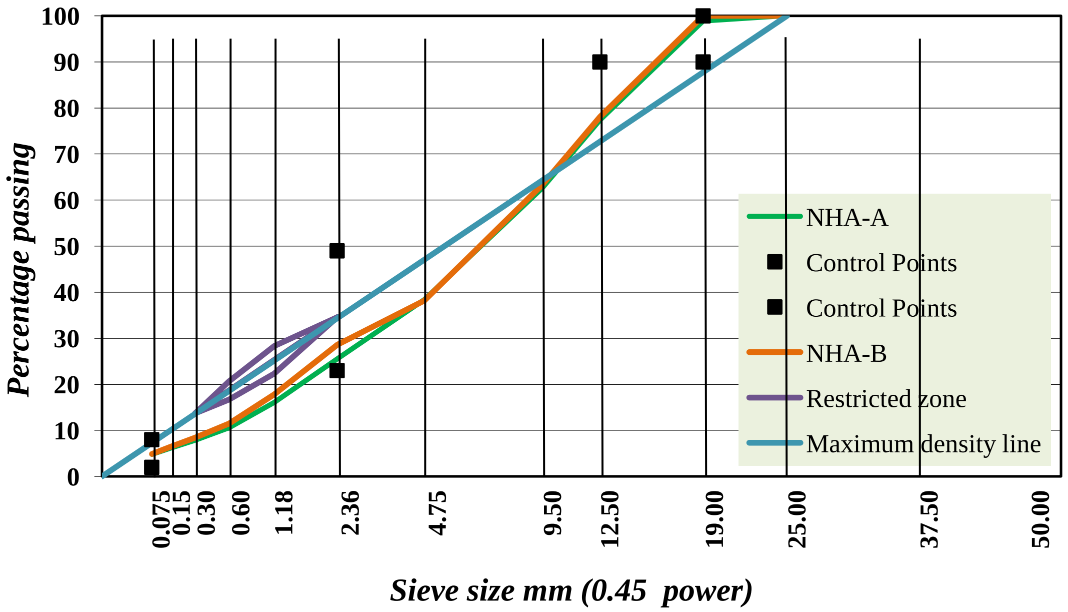

Figure 3.5 Gradation Plots for NHA-A & NHA-B Bailey Adjusted

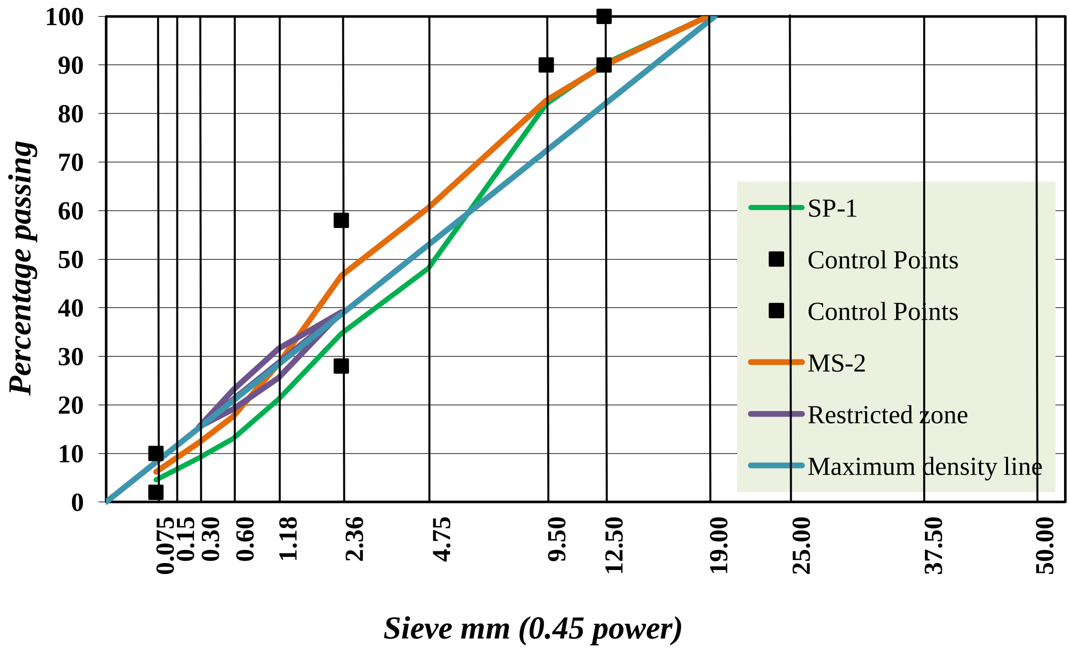

Figure 3.6 Gradation Plots of Superpave-1 & MS-2 Bailey Adjusted

3.6 Determination of Optimum Binder Content

After setting the selected gradations next step is to calculate the optimum bitumen content for each mix. For determination of optimum bitumen content, standard practice for mixture preparation was carried out using Marshall Apparatus. The whole procedure is described in following paragraphs.

3.6.1 Specimen Preparation

According to the standard procedure it was one of the requirements to determine volumetric properties, stability and flow of HMA at optimum asphalt content (OBC) before preparation of specimens for performance testing using SGC. Therefore standard practice for the preparation of HMA samples as per ASTM D6926 was followed to find out the optimum bitumen content using Marshall Apparatus. For each type of mix, 9 numbers of samples of 4 inch diameter using 3 trial bitumen were prepared and using average values volumetric against each trial bitumen content were determined. Total numbers of samples prepared for each type of gradation for calculation of OBC is shown in Table 3.13. A confirmation sample was prepared for each mixture type on the calculated optimum bitumen content to verify the volumetrics.

Table 3.13 Number of Samples for Calculation of OBC

Sr. No.	Binder	Gradation	Number of samples for OBC	Number of Samples for Confirmation
1	ARL 60/70	NHA-A	9	1
2		NHA-B	9	1
3		Superpave-1	9	1
4		MS-2	9	1

According to ASTM D 6926 the amount of aggregates required for 4 inch diameter sample is 1200 gm. So for this purpose amount of aggregates against each sieve size was calculated and was dried in oven at temperature 105 C^o to 110 C^o. The quantity of bitumen required for each sample was obtained from Equations 3-1 and 3-2.

$$W_A + W_B = W_T \qquad (3\text{-}1)$$

$$W_B = p/100 \times W_T \qquad (3\text{-}2)$$

Where,

p = Percentage of Binder

W_A = Aggregate Weight

W_B = Bitumen Weight

W_T = Total Mix Weight

After calculating the aggregate for each sieve and bitumen the mixing of aggregates and bitumen, is carried out in mechanical mixing machine (ASTM D 6926). The mixing was performed at temperature between 160 °C to 165 °C. Now to avoid honey combing aggregate and bitumen mix was putted in the Marshall 4 inch mold in two equal increments. Compaction was done with design criteria of heavy traffic 75 numbers of blows on each end of specimen using mechanical hammer. The mold was detached from the holder after completion of blows. Specimen was then extracted using extraction jack. The samples were then allowed to cool by placing it on the flat surface.

3.6.2 Testing of Specimen

Marshall Test is mainly engaged to find the optimum mix design for hot mix asphalt that best fits the criteria of stability, flow, density .So following tests and analysis were performed on each compacted specimen.

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

ASTM D6927-06 is followed to determine the Stability and flow test values. While ASTM D2041 and ASTM D2726 standards were followed to determine theoretical maximum specific gravity (Gmm) and Bulk specific gravity respectively. After determination of above mentioned tests and performing analysis, separate graphical plots for all values were drawn in such a way that a smooth curve is obtained that "best fit" for all values. Subsequent graphs were used to find out the optimum bitumen content (OBC) of the mix design:

- AC vs. Stability.
- AC vs. Flow
- AC vs. Unit Weight of Total Mix
- AC vs. VA
- AC vs. VFA
- AC vs. VMA

The ultimate mix design obtain is normally the most rational that will accomplish all the guidelines for Marshall Mix Design. Usually, the standards of mix design produce a narrow range of sufficient asphalt contents that accomplishes all the requirements. Figure 3.7 shows the plots which were used to find out the OBC.

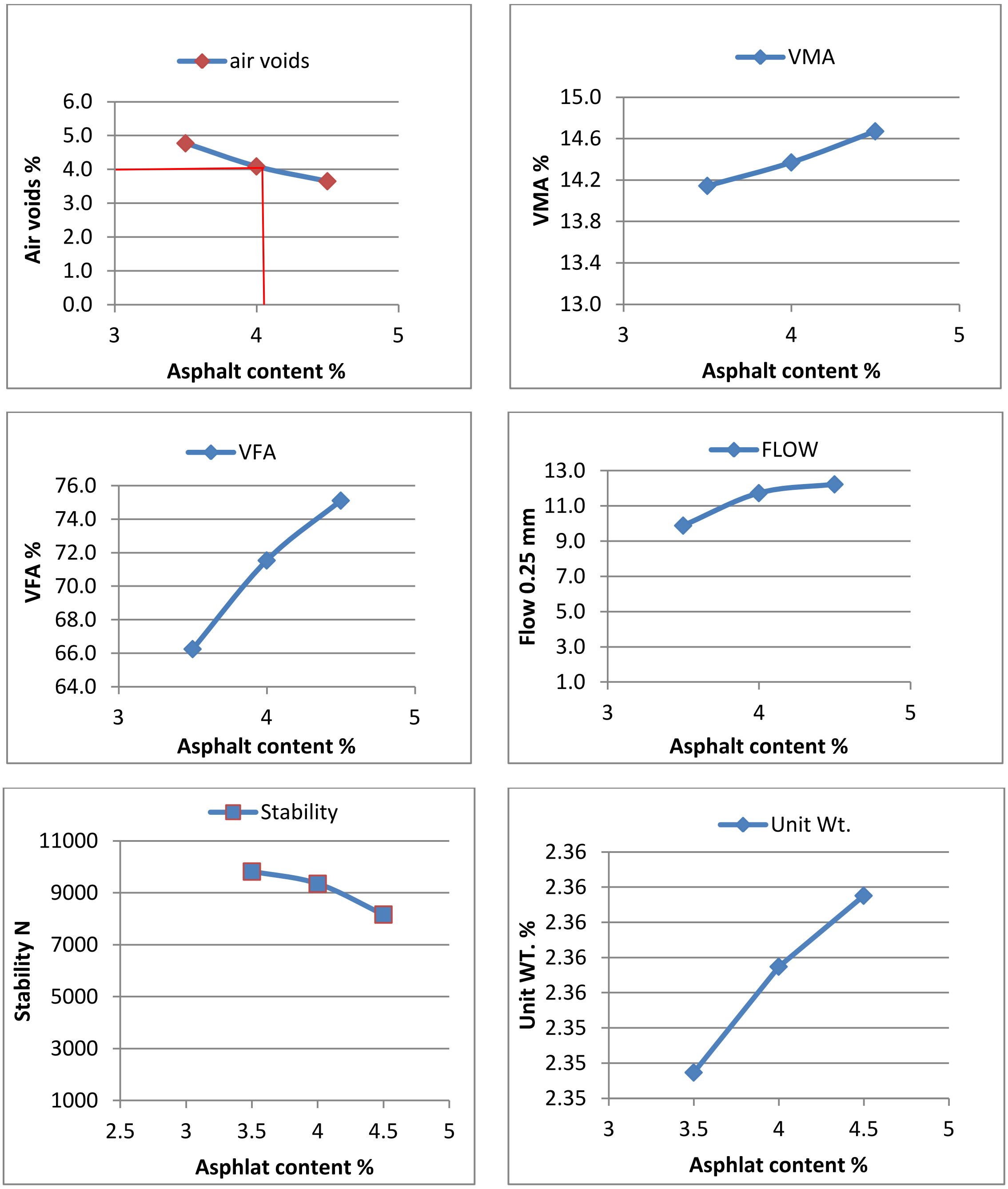

Figure 3.7 Plots to Determine Optimum Bitumen Content at 4% Air Voids

For all the selected mixes, optimum bitumen content (OBC) is calculated on a condition of 4% air voids. Optimum bitumen content was determined against the 4% air voids and then using that bitumen content other properties of the mixtures were determined by using the graphs shown in Figure 3.7.The volumetric properties Specific Gravity determination, Stability and Flow Test for wearing course mixes for control gradations and adjusted gradations are illustrated in Table 3.14 & Table 3.15.

The data for the control gradations optimum calculation were obtained from the study name “Improvement of asphalt mix design technology for Pakistan” carried out at National Institute of Transportation (NIT), NUST Islamabad. It can be seen from Table 3.14 and Table 3.15 that OBC for NHA-A and NHA-B mixes are less as compared to SP-1 and MS-2 mix for the reason that these are coarser gradations and for coarser particles bitumen necessity is low as well as the optimum bitumen content (OBC). The results obtained are also well within limits set by MS-2 manual for Marshall Mix design.

Table 3.14 Control Gradations Volumetric Properties Results

Optimum Bitumen Content Results (Control Mixes)									
Mix Type	**AC (%)**	**Gsb**	**Gmb**	**Gmm**	**Air Voids (%)**	**VMA (%)**	**VFA (%)**	**Stability (Kg)**	**Flow (0.25mm)**
NHA-A	3.5	2.614	2.382	2.513	5.22	12.07	56.77	1330	9.63
	4.0	2.614	2.399	2.500	4.04	11.90	66.01	1451	11.35
	4.5	2.614	2.417	2.481	2.58	11.70	77.91	1276	12.95
	4.0	**2.614**	**2.392**	**2.498**	**4.24**	**12.15**	**65.08**	**1362**	**12.03**
NHA-B	3.5	2.611	2.330	2.503	6.91	13.89	50.22	1499	12.14
	4.0	2.611	2.360	2.483	4.96	13.23	62.54	1471	13.38
	4.5	2.611	2.399	2.468	2.81	12.27	77.09	1531	14.38
	4.1	**2.611**	**2.370**	**2.482**	**4.51**	**12.95**	**65.16**	**1291**	**12.65**
SP-A	4.5	2.604	2.312	2.467	6.28	15.21	58.68	1247	14.47
	5.0	2.604	2.335	2.448	4.62	14.82	68.83	1544	12.53
	5.5	2.604	2.348	2.418	2.90	14.79	80.42	1409	14.62
	5.0	**2.604**	**2.338**	**2.449**	**4.53**	**14.70**	**69.18**	**1424**	**13.55**
MS-2	4.5	2.606	2.308	2.470	6.55	15.41	57.52	1609	12.35
	5.0	2.606	2.350	2.448	3.99	14.32	72.12	1836	11.77
	5.5	2.606	2.369	2.411	1.73	14.08	87.74	1876	15.89
	4.8	**2.606**	**2.340**	**2.455**	**4.68**	**14.52**	**67.73**	**1554**	**13.12**

Table 3.15 Bailey Adjusted Gradations Volumetric Properties Results

Optimum Bitumen Content Results (Adjusted Mixes)									
Mix type	**AC (%)**	**Gsb**	**Gmb**	**Gmm**	**Air voids (%)**	**VMA (%)**	**VFA (%)**	**Stability (kg)**	**Flow (0.25mm)**
NHA-A	3.5	2.643	2.351	2.469	4.77	14.14	66.25	1280	9.9
	4.0	2.643	2.357	2.458	4.09	14.37	71.54	1534	11.7
	4.5	2.643	2.362	2.451	3.65	14.67	75.11	1311	12.2
	4.1	**2.643**	**2.353**	**2.452**	**4.00**	**14.47**	**72.30**	**1470**	**11.6**
NHA-B	3.5	2.627	2.324	2.496	6.92	14.64	52.74	1293	9.6
	4.0	2.627	2.362	2.485	4.95	13.66	63.81	1344	11.4
	4.5	2.627	2.383	2.459	3.09	13.36	76.84	1128	14.2
	4.2	**2.627**	**2.364**	**2.471**	**4.20**	**13.50**	**69.92**	**1306**	**11.9**
SP-A	4.5	2.590	2.320	2.468	6.02	14.46	58.36	1310	12.07
	5.0	2.590	2.333	2.440	4.37	14.42	69.71	1570	12.44
	5.5	2.590	2.343	2.408	2.75	14.52	81.06	1420	11.36
	5.1	**2.590**	**2.334**	**2.440**	**4.34**	**14.48**	**70.06**	**1464**	**11.98**
MS-2	4.5	2.585	2.304	2.463	6.45	14.88	56.62	1630	9.91
	5.0	2.585	2.345	2.444	4.04	13.82	70.57	1674	9.51
	5.5	2.585	2.368	2.441	1.79	13.43	86.69	1811	12.53
	5.0	**2.585**	**2.340**	**2.445**	**4.30**	**14.02**	**69.33**	**1585**	**11.10**

3.8 Wheel Tracker Sample Preparation

Samples for performance testing were prepared for both control and adjusted gradations, after determination of OBC for each mix type using Gyratory Compactor.

AASHTO T 324-04 was applied to prepare the required number of samples. Triplicate samples were prepared for each mix of control and adjusted wearing course mixes.
The prepared specimens were compacted by means of Superpave gyratory compactor (SGC), at a temperature of 135 ºC as shown in Figure 3.8. Gyratory compactor mould was cleaned and placed in oven at 100 ºC for 30 minutes after that compaction of specimen was done. Filter paper was placed on both sides of mould on top and at bottom in which batch of mix was transferred. After the required gyrations and compaction was achieved, the specimen was extracted from mould by means of mechanical sample extruder as shown in Figure 3.9.

Figure 3.8 Superpave Gyratory Compactor

Samples obtain after extraction having approx. height of 160mm and diameter of 150 mm is shown in Figure 3.10. All the samples were labeled according to their gradation, with suffix of "C" for control and "B" for Bailey. Total of 125 numbers of gyrations were applied on samples as specified in Superpave mix design for traffic loading ≥ 30 million ESALs.

Figure 3.9 Extraction of Compacted Specimen

Figure 3.10 Specimens Prepared Using Gyratory Compactor

Compacted sample from superpave gyratory compactor were then cutted into 1.5” depth from the upper and lower surfaces to obtain two equal sizes of cakes of the surface layers and were then cut to the size of silicon mould of the wheel tracker tray. The samples were placed in the mould and extra spaces left were filled with plaster of Paris to stop the dislocation of specimen with wheel movement as shown in Figure 3.11. The steel tray along with the specimen mounted in it was placed under the wheel and bolts were tightened to fix the tray at its place.

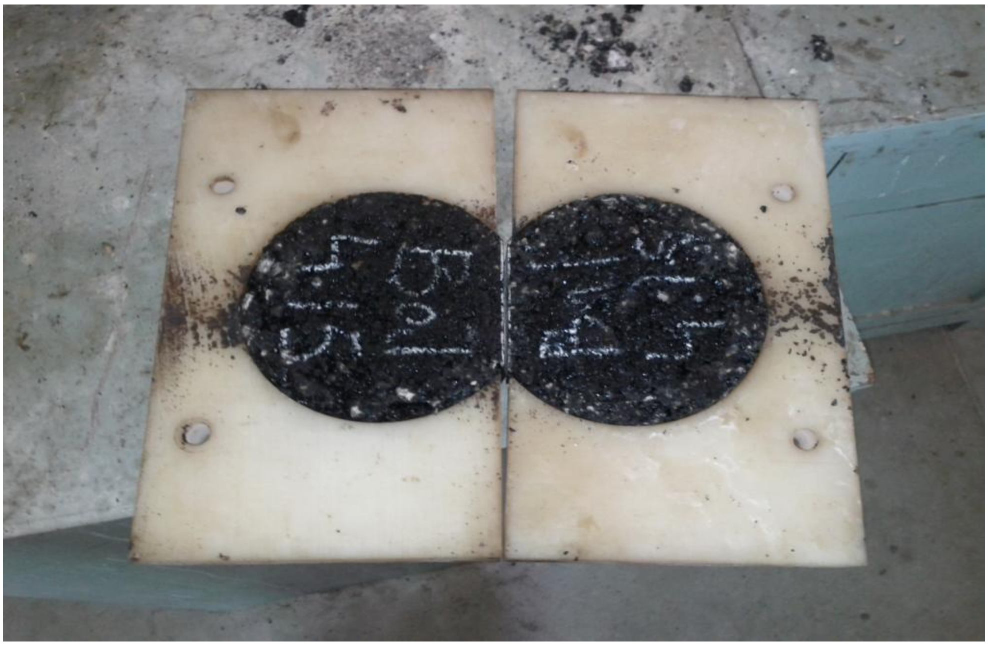

Figure 3.11 Wheel Tracker Sample in Mold

Triplicate samples were prepared for each mix which was tested at same temperature and conditions. Three replicates samples for each gradation and sum of twenty four samples were prepared that consist of eight samples for control gradations and remaining eight for the adjusted gradations.

As this research was performed for wet condition at 40 ^{0}C so the machine is filled with water up to the marked level. The wheel tracker device was switched on and the details of specimen were entered in the software. The speed of the wheel and number of passes were fixed to 50 ppm (passes per minute) and 200000 respectively. Wet mode of wheel tracker device was selected with test temperature fixed to 40 ^{0}C. By giving the required temperature the heater of the wheel tracker turns on and water start heating.

Figure 3.12 Performing test on PMW Wheel Tracking Machine

Finally the test starts when the set temperature is achieved and wheel started moving to and fro on the specimen. Numbers of passes were visible on the LCD of the system attached with machine. The LVDT measures the rut impression in millimetres, at the same time with the motion of wheel. After completing given number of passes the machine stopped. wheel tracker software generate two types of data outputs, a Graph which shows number of passes verses rut depth in mm and an Excel spreadsheet that displays numerical data of the rut depth at 11 points of the wheel path.

The test results of rut depth obtained is in the form of excel sheets were then analysed. Average is taken of the 11 Liner variable displacement Transformers (LVDT) points to simplify the rut depths obtained. This makes it easy to plot the graph among number of passes and the rut depth in millimetres by simplification of the data. This process is repeated for all the samples output. Figure 3.13 shows the average rut profile drawn for one of the gradation.

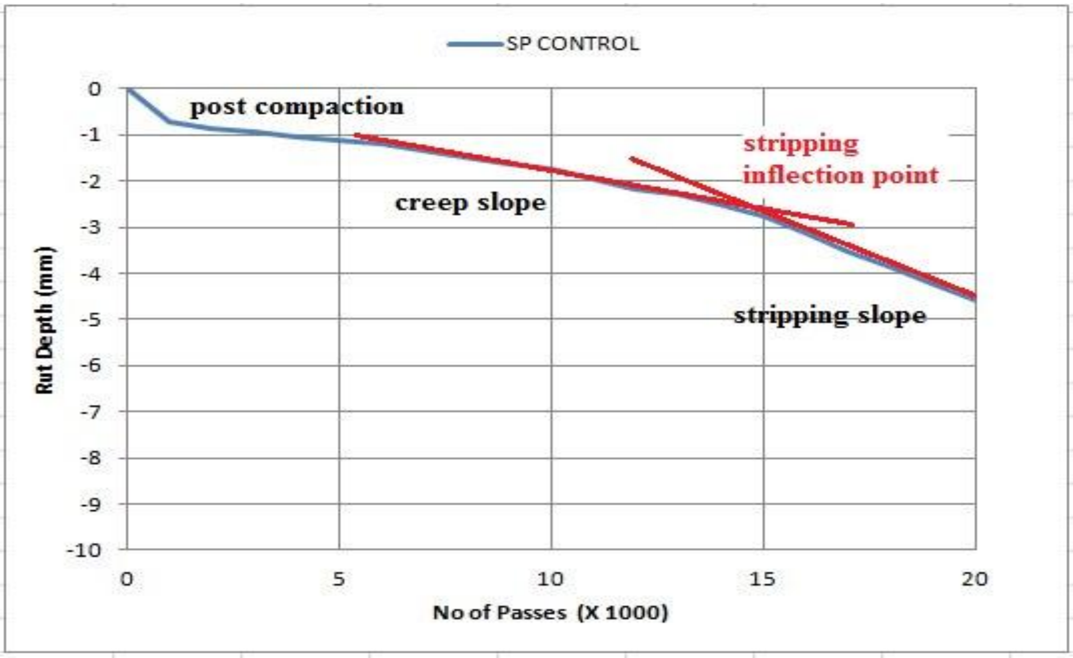

Figure 3.13 Rut Profile Drawn For SP Control Gradation

3.9 Summary

This chapter includes the detail of methodology adopted for the study in form of flow chart. In this chapter detailed of the mix design selected for the study is also included in detail. Volume blending spread sheet (VBS) developed by HRG is also explained using screenshot of the user interface. The input and output of the spread sheet is also explained. Four different types of wearing course mixes were prepared first for the original gradations and after adjusting the experimental blends the process is repeated for the new mixes. The type of gradation used in this research study is also is presented in form of Table. The mixes have NMPS of 19 mm and 12.5 mm. This chapter includes the material characterization for the HMA mixture preparation and important test on binder and aggregate is performed that were related to study. The study is carried out on only one aggregate source i.e. Margalla quarry. The pen grade of ARL 60/70 was used as binder.

The test samples were prepared using Superpave gyratory compactor for performance testing and mechanical hammer for Marshall Samples. The specimens extracted from gyratory compactor were then transformed into the size required for the wheel tracker by cutting into 1.5” thickness from the upper and lower surface to get two cakes of the surface layers to conform AASHTO T 324-04 specification.

For each type of gradation optimum bitumen content was determined using standard ASTM procedures. Same procedure is repeated every time for each mix and volumetric properties were presented in tabular form in this chapter. Wheel tracker rut test is performed using Hamburg wheel tracker all eight gradation samples four control and four adjusted gradations. The testing is carried out at 40 c^{o} under wet condition. The Hamburg wheel tracker software details and software output is also discussed herein. The output results are then arranged using spreadsheet and graphs were plotted to conclude the results.

Chapter 4

RESULTS AND ANALYSIS

4.1Introduction

This chapter primarily contains wheel tracker test results and based on obtained results, statistical analysis was performed, that is also presented herein. The chapter includes in detail the Bailey method and its parameters. A major portion of analysis is based on the results of the bailey adjustment to the selected gradations. The chapter also includes various factors affecting the rutting susceptibility like NMPS, Bailey parameters and mixture properties are also discussed in detail. Effect of bailey parameters i.e. CA, FA_c and FA_f on VMA is also studied in detailed. The gradation curves and rutting profiles are analysed to see the improvement in rut depth. Two statistical models were also developed using PASW 18 statistical software that are included in this chapter.

4.2 Wheel Tracker Test Results

Permanent deformation is use as a performance measure and is evaluated by comparing the specimen's resistance to rutting with and without modification in selected gradations. Hamburg Wheel tracking (HWT) is used to calculate the permanent deformation for controlled specimens first and then for modified specimens for each aggregate gradation separately. Controlled and adjusted specimens of NHA-A, NHA-B, SP-1 and MS-2 were tested against rutting in wet mode of wheel tracker .A total of 16 specimens were tested for with and without gradation modification. For both control and modified gradations the test temperature was $40c^{o}$ and numbers of passes were 20,000. Triplicate wheel tracker samples were tested for every mix type, a total of three for each mix .All the controlled and adjusted gradation specimens passed the wheel tracker test but the Bailey modified specimen's resistance to rutting was greater than the controlled specimens. The results of wheel tracker test for each mix presented in appendix-A. Figure 4.1 shows the average rut depth plotted against 20,000 numbers of passes. It is clear from Figure that the rut depth obtained after 20,000 numbers of passes for Bailey adjusted mixtures is greater than the rut depth obtained with control mixes. The maximum rut depth obtained for MS-2 controlled specimens is 7.09 mm whereas the minimum rut depth obtained is for NHA-A bailey mix i.e. 4.83.The maximum and minimum rut depth are understandable because NHA-A is a courser gradation with NMPS of 19mm where as MS-2 is a finer gradation. The rut depths obtained for controlled and RAP containing mixtures were well in acceptable range as the failure depth was set at 20 mm.

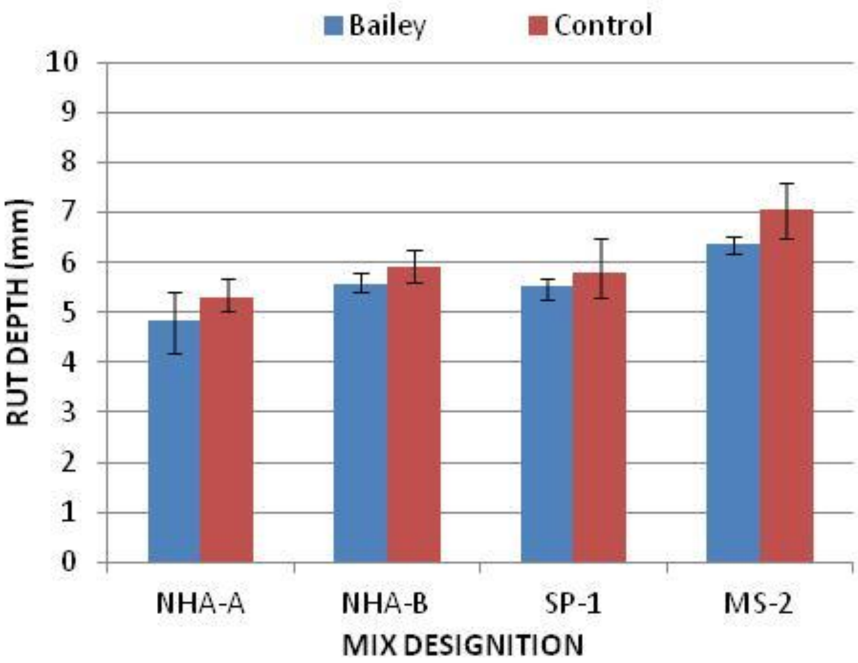

Figure 4.1 Average Rut Depths for All Mixes

Now the percentage improvement in resistance to rutting for all selected four mix types were calculated using the rut depth values for 20,000 passes. Percentage improvement in rutting with and without adjustment of blends is shown in Table 4.1. From Figure 4.1 it is clear that there is enhancement in resistance to rutting for all the selected gradations. Error bars on each bar showing the upper and lower values. The highest improvement is observed in MS-2 gradation with percentage of 10%.

Table 4.1 Percentage Improvement in Resistance to Rutting

Mixtures	Rutting Controlled Mixtures (mm)	Rutting Adjusted Mixtures (mm)	Improvement in Rut Depth (%)
NHA-A	-5.30	-4.83	**9%**
NHA-B	-5.92	-5.56	**6%**
SP-1	-5.79	-5.51	**5%**
MS-2	-7.05	-6.36	**10%**

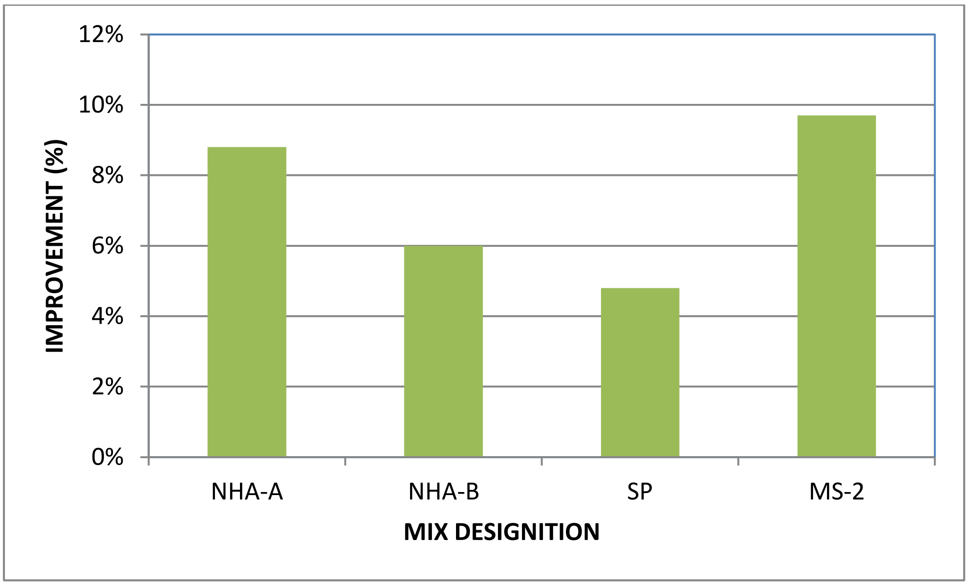

Figure 4.2 Percentage Improvement in rut depth for all mixes

4.3 Gradation Evaluation

From test results, it can be observed that there is some improvement in resistance to rutting for bailey mixes. So the gradations of bailey mixes are drawn against controlled mixes to study the variation in each gradation. Figure 4.3 shows the percentage passing gradation chart for NHA-A control and NHA-A bailey. We can witness in graph that NHA-A bailey is finer then the NHA-A control gradation. The percentage passing for 19mm is more for NHA-A bailey then NHA-A control where as the percentage passing for sieves smaller than 4.75 is more for NHA-A control. So packing of aggregate is improved by reducing larger size aggregates and increasing smaller size aggregates. Both the original and redesign gradation are within the permissible limits of NHA specifications as shown by the control point on the graph.

The percentage passing gradation chart for NHA-B control and NHA-B bailey in shown in Figure 4.4. We can see in graph that NHA-B control is much finer then the NHA-A bailey gradation. Therefore the gradation is redesigned to improve the percentage of coarser particles. The plot of bailey blend shows it a coarser gradation then the original gradation.

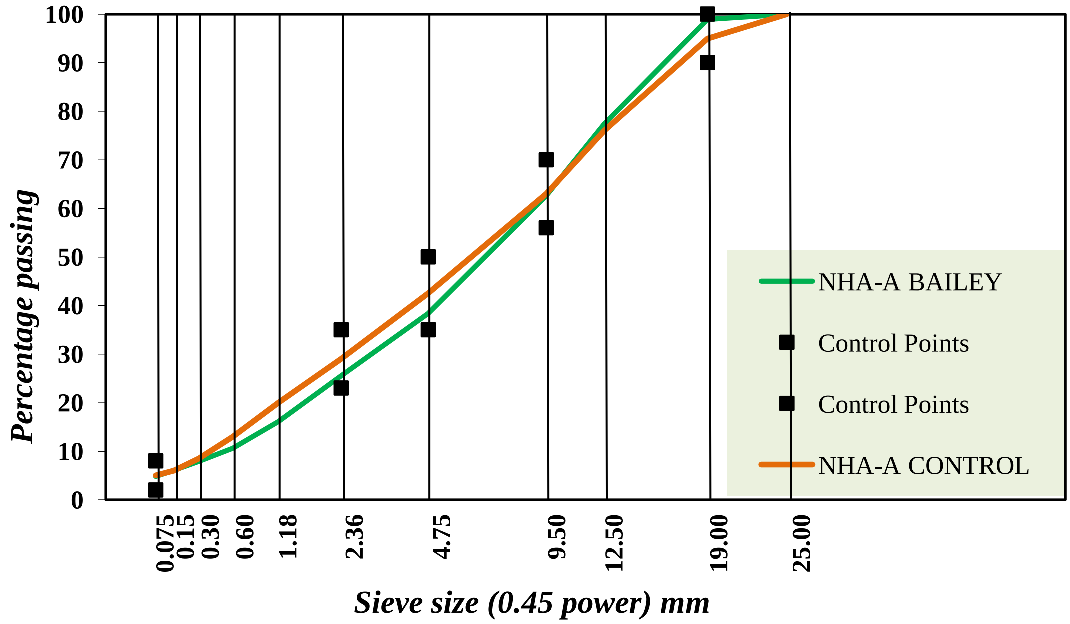

Figure 4.3 Gradation Plot of NHA-A Control vs. NHA-A Bailey

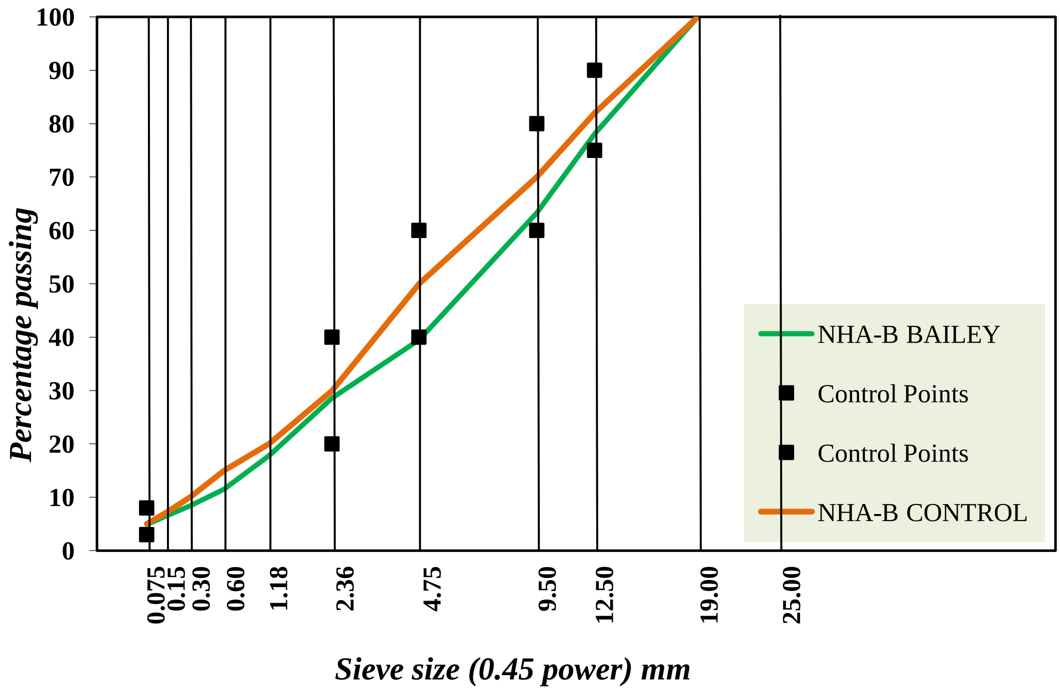

Figure 4.4 Gradation Plot of NHA-B Control & NHA-B Bailey

Figure 4.5 shows the gradation plot for SP-1 control and SP-1 Bailey along with the control points and restricted zone for Superpave mixes respectively. By analysing the graph we can find out that the original SP-1 gradation is finer then the adjusted bailey gradation. The percentage passing for the larger sieves are much more in control gradation then the bailey adjusted gradation. By redesigning the gradation using bailey method the retained material for larger sieves are increased.

Similarly the graph for the MS-2 control and adjusted gradations is shown in Figure 4.6 along with the control points. No big change in gradation was observed between the control and redesign gradation. Percentages passing of sieves are changed to just a few tenth of percentage still keeping the adjusted gradation within the allowed control points.

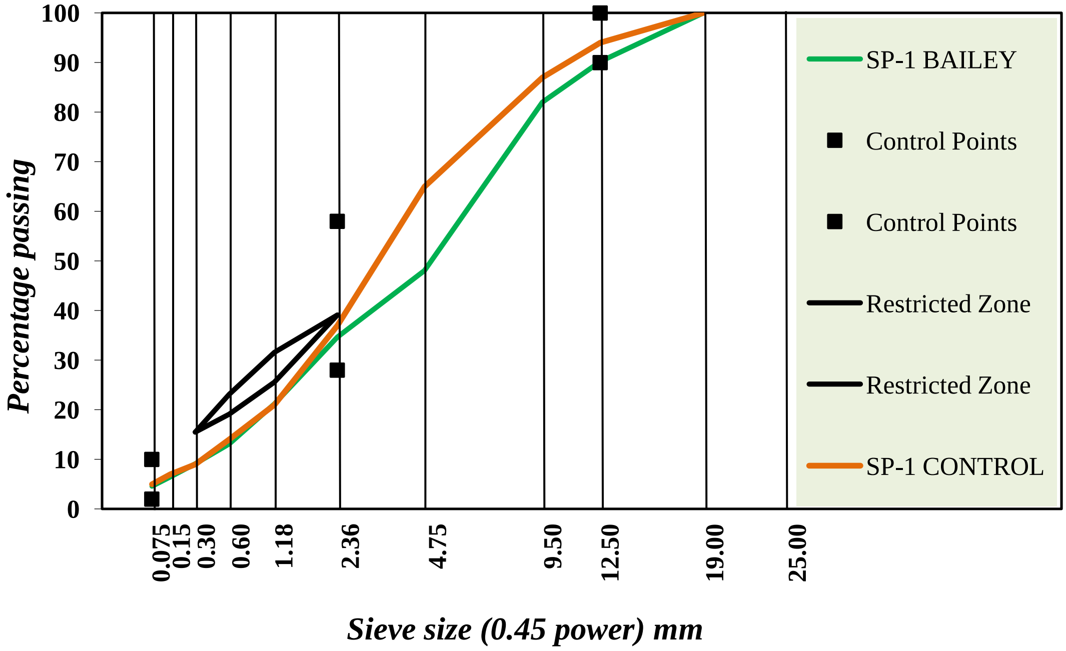

Figure 4.5 Gradation Plot of SP-1 Control vs. SP-1 Bailey

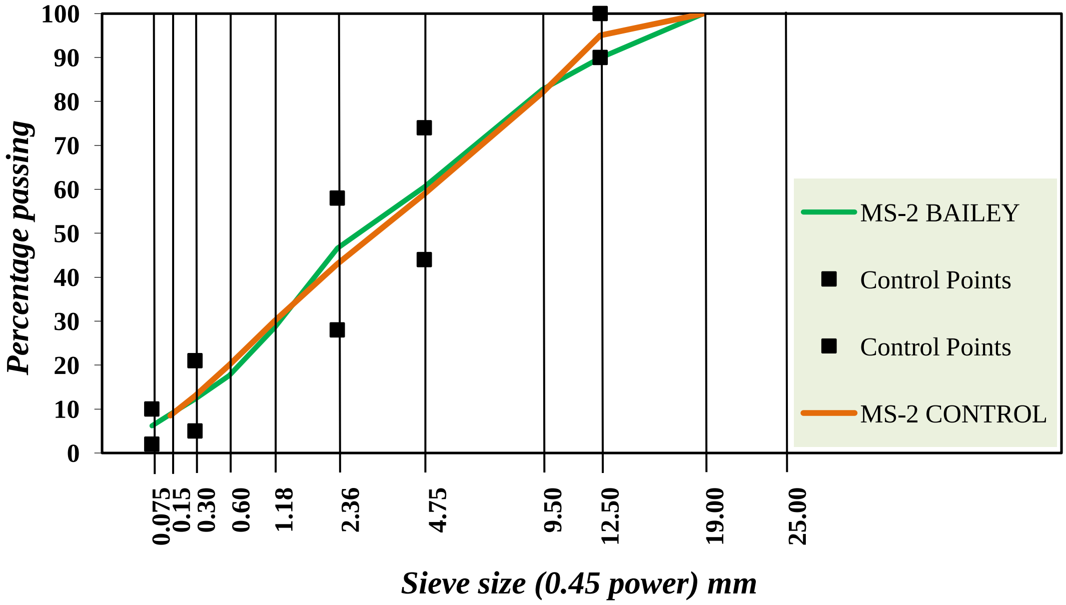

Figure 4.6 Gradation Plot of MS-2 Control vs. MS-2 Bailey

4.4 Bailey Parameters Analysis

The Bailey analysis was performed on the selected control mixes and the Bailey adjusted mixes to find out the aggregate ratios for each mix individually. The Bailey parameters for the original and redesigned mixtures are shown in Table 4.2.

The %CUW for the original mixtures is back calculated, while for the redesigned mixtures it is a selected value. For NHA-B and MS-2 mixtures, the original CUW value classifies the mixture as a "fine" mixture (CUW <85%) within the Bailey system. For NHA-A the original %CUW classifies the mix as border line case to coarse mixture with CUW as 91%.while for SP-1 the mix is classified as coarse graded(CUW 95%-105%) in Bailey system. Three of the mixtures i.e. NHA-A, NHA-B and SP-1 were redesigned to be "coarse" mixtures according to the Bailey Method, meaning the CUW were selected to be in the 95%-105% range. Whereas several attempts were made to design the MS-2 mix as course graded without letting the grading out of the recommended ranges of specification but no such combination was found satisfying. So that was redesigns as fine graded with %CUW 75. The target was to bring the values for each of the Bailey weight ratios, CA, FA_c and FA_f within the recommended limits. The optimum gradation for each mixture was then found such that the Bailey ratios were as close as possible to the target values and the gradation met the Superpave gradation control points and did not pass through the restricted zone.

For NHA-A 19 mm gradation FA_c and FA_f ratios were in range but CA ratio was outside the recommended range (0.6-1.0).so that was adjusted to satisfy the bailey recommended range of values. For NHA-B the original gradation was classified as fine graded as per bailey method that was redesigned as coarse graded with %CUW as 100.The NHA-B mix design had weight ratios close to its target values, but value for CA ratio was on higher side that was adjusted a bit on the middle of the recommended range.

Table 4.2 Bailey Parameters for Original and Redesign Mixtures

Mix	Bailey Parameters	Bailey Limits (Fine Mix)	Original Value	Bailey Redesign Value	Bailey Limits (Coarse Mix)
NHA-A (19mm)	CUW	<85%	91	100	95%-105%
	CA RATIO	0.6-1.0	0.475	0.647	0.6-0.75
	FA_c RATIO	0.35-0.50	0.424	0.419	0.35-0.50
	FA_f RATIO	0.35-0.50	0.467	0.491	0.35-0.50
NHA-B (19mm)	CUW	<85%	76	100	95%-105%
	CA RATIO	0.6-1.0	0.705	0.684	0.6-0.75
	FA_c RATIO	0.35-0.50	0.468	0.466	0.35-0.50
	FA_f RATIO	0.35-0.50	0.467	0.472	0.35-0.50
SP-1 (12.5 mm)	CUW	<85%	95	100	95%-105%
	CA RATIO	0.6-1.0	0.7	0.585	0.5-0.65
	FA_c RATIO	0.35-0.50	0.377	0.378	0.35-0.50
	FA_f RATIO	0.35-0.50	0.493	0.496	0.35-0.50
MS-2 (12.5 mm)	CUW	<85%	81	75	95%-105%
	CA RATIO	0.6-1.0	0.598	0.602	0.5-0.65
	FA_c RATIO	0.35-0.50	0.509	0.5	0.35-0.50
	FA_f RATIO	0.35-0.50	-	-	0.35-0.50

SP-1 12.5mm control gradation was define as coarse graded in Bailey system with %CUW value of 95.The recommended CA ratio for 12.5mm NMPS and for coarse graded mix is 0.5-0.65.But for the original SP-1 gradation the value of CA ratio was 0.7, that was outside the suggested value. So that value was brought to 0.585.simlarly the original MS-2 gradation was defined as fine graded as per bailey method. Now for an original NMSA of 12.5mm, as in case of MS-2 the fine tertiary control sieve (TCS) would need openings 0.033 mm in diameter. Since the smallest sieve used for asphalt engineering is the #200 with 0.075 mm openings, the TCS and the FA_f ratio were ignored in the fine graded analysis for the 12.5 mm calculations. The other two ratio were adjusted just a few points to improve the packing of mixture.

4.5 Performance Modelling

The performance of a pavement can be used to measure its behavior against different factor like weather, temperature and loading e.t.c. According to the newly developed AASHTO 2002 M-EPDG it is vital to predict pavement performance at design stage of HMA for durability and long service life. It focuses on the development of distress models like cracking, fatigue etc.

4.5.1 Rutting Prediction Model

In this study rutting is used as a performance measure to observe the improvements made in gradations using Bailey method. So rutting is performance indicator and depends on the bailey parameter and NMPS. Rut depth observed for both control and adjusted gradations for 20000 wheel passes were modeled using PASW Statistics 18.

$$\text{Rutting} = f\,(\text{Bailey parameter, Nominal Maximum Particle Size})$$

Initially X-Y scatter plots were generated for rutting verses its affecting variables to conform the best relation between dependent and independent variables. The scatter plot for rutting against the four Bailey parameters and other variables were plotted to observe the relation among dependent and independent variables. Only the FA_c among the Bailey parameters and NMPS are showing some relationship. So multiple linear regressions was at first used to generate linear model but it does not give healthy vale of R^2, and also the co-efficient were not significant in the model. So non-linear regression was adopted, which appropriately give better results and fit the data. Functional forms like polynomial and logarithmic emerges as good by iterating process but the R^2 values were on lower side. So finally a functional form known as Cobb-Douglas is applied. This functional form is generally used when the input independent variables and dependent variable have more than one functional form and also in cost based pragmatic studies. The general generic functional form of Cobb-Douglas model is:

$$y = a * {X_i}^{b_i} \qquad (4\text{-}1)$$

Where i=Number of Variables = 1,2,3……n

Functional form can be rewritten for this study as Rut depth in mm is a function of FA_c and NMPS.

$$D_R = \alpha * {FA_C}^{\beta_1} * NMAS^{\beta_2} \qquad (4\text{-}2)$$

Whereas

D_R=Rut depth in millimeters

FA_c=coarse portion of fine aggregate (%)

NMAS= Nominal maximum aggregate size

α , β_1 , β_2 = Regression Coefficients

Table 4.3 Rutting Model Summary

Parameter	Estimate	Std. Error	T-stat	R^2 (%)	95 % Confidence Interval	
					Lower Bound	Upper Bound
α	23.46	6.676	3.51		6.30	40.62
β_1	.679	.173	3.92	83.8	.235	1.123
β_2	.-0.308	.093	3.31		-0.548	-0.068

Table 4.3 shows the parameter estimates and other model statistics for the pavement rutting model. The t-statistics of the model parameters value suggest that at 95% confidence level, both of the selected variables are statistically significant as their t-stat values are greater than critical value of t-stat at 95% confidence level i.e. 2.308. The coefficient of determination (R^2) value of the developed model also shows a good fit. As the value of R^2 is approximately 84 % so we can conclude that model is capturing 84

percent of variation in rutting using FA_c and NMPS as predictors. Model output is presented in Appendix B.

4.5.2 Model Validation

In model building sequence, model validation is an important step. A high R^2 value individually does not assure that the model fits the given data well. A number of model validation methods are available but for this study, mean absolute percentage error (MAPE) is applied on the data. It can be defined as the mathematical difference among observed and fitted data value and the answer is divided by corresponding observed value. Finally taking average of all this gives mean absolute error and if it is multiplied by that will yield error in percentage.

$$\mathrm{MAPE} = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{\mathrm{A_t}-\mathrm{F_t}}{\mathrm{A_t}}\right| \tag{4-3}$$

Where,

F_t = Fitted value

A_t = Actual value

The MAPE of rutting model is 6.6%.Validation plot for rutting model is shown in Figure 4.7. According to this method the more data values close to 45^o line better the model predictive potential would be. We can observe from Figure that the majority of the data values are close to line except few of the values, which shows that model is good.

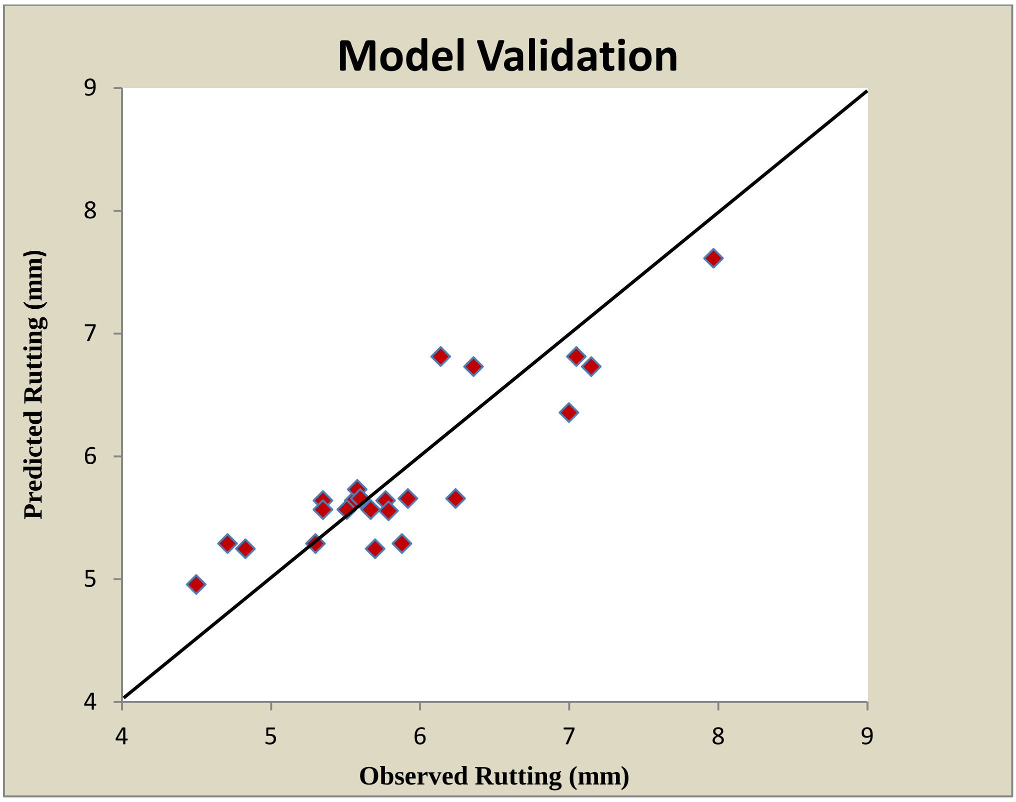

Figure 4.7 Validation Plot for Rut Model

4.5.3 VMA Prediction Model

One of the objectives of this study was to evaluate the predicting capability of Bailey method in terms of change in voids in mineral aggregate (VMA). So for this purpose, laboratory asphalt concrete samples were fabricated and volumetric were calculated for both control and adjusted mixes. The values for VMA were then analyzed versus the bailey principles. The data acquired from laboratory testing and gradation adjustment, using volume blending spread sheet (VBS) is used for development of statistical model to predict the VMA. In this case (VMA) was predicted that depends on the Bailey parameters i.e. %CUW, CA, FA_c and FA_f.

$$\text{Voids in mineral aggregate} = f\,(\%CUW, CA, FA_c, FA_f)$$

X-Y scatter plot were drawn to conform the best relation of VMA and the factors affecting it. The scatter plot for VMA against the three Bailey parameters shows some relation i.e. CA, FA_c and FA_f.Whereas there was nothing considerable observed in VMA vs. %CUW. The trend of the plots between VMA and Bailey parameters shows non linear relationships. So non-linear regression was adopted and cob Douglas functional form is selected to develop the model that perfectly fits the data.

This functional form for VMA model can be rewritten for this study as

$$VMA = \alpha * CA^{\beta_1} * {FC_A}^{\beta_2} * {FA_F}^{\beta_3} \qquad (4\text{-}4)$$

Where,

VMA = Voids in mineral aggregate (%)

CA = Coarse Aggregate

FA_c = Fine portion of coarse aggregate

FA_f = Fine portion of fine aggregate

α, β_1, β_2, β_3= Regression Coefficients

PASW 18 is to perform the Non-linear regression. The general model for voids in mineral aggregates was developed incorporating the Bailey parameters as variable and model output is presented in Appendix B. Table 4.4 presents the parameters statistics for VMA predicting model using Bailey parameters.

Table 4.4 VMA Model Summary

Parameter	Estimate	Std. Error	T-Stat	R^2 (%)	95 % Confidence Interval	
					Lower Bound	Upper Bound
A	33.674	2.587	13.01	91.8	28.277	39.071
β_1	.304	.035	8.68		.231	.378
β_2	-.088	.035	2.51		-.162	-.015
β_3	1.120	.088	12.72		.936	1.305

It can be seen from the above Table that VMA predicting model is capturing 91 percent of variation in VMA whereas all the independent variables are significant in the model as well. The value of t-stat at 95% confidence level is 2.308 and all parameters have t -stat greater than this value.

4.5.4 Model Validation

The MAPE for VMA model is 1.5%. The validation plot for VMA model is shown in Figure 4.8. It is clear from Figure that the majority of the data values are close to line which shows that model is good.

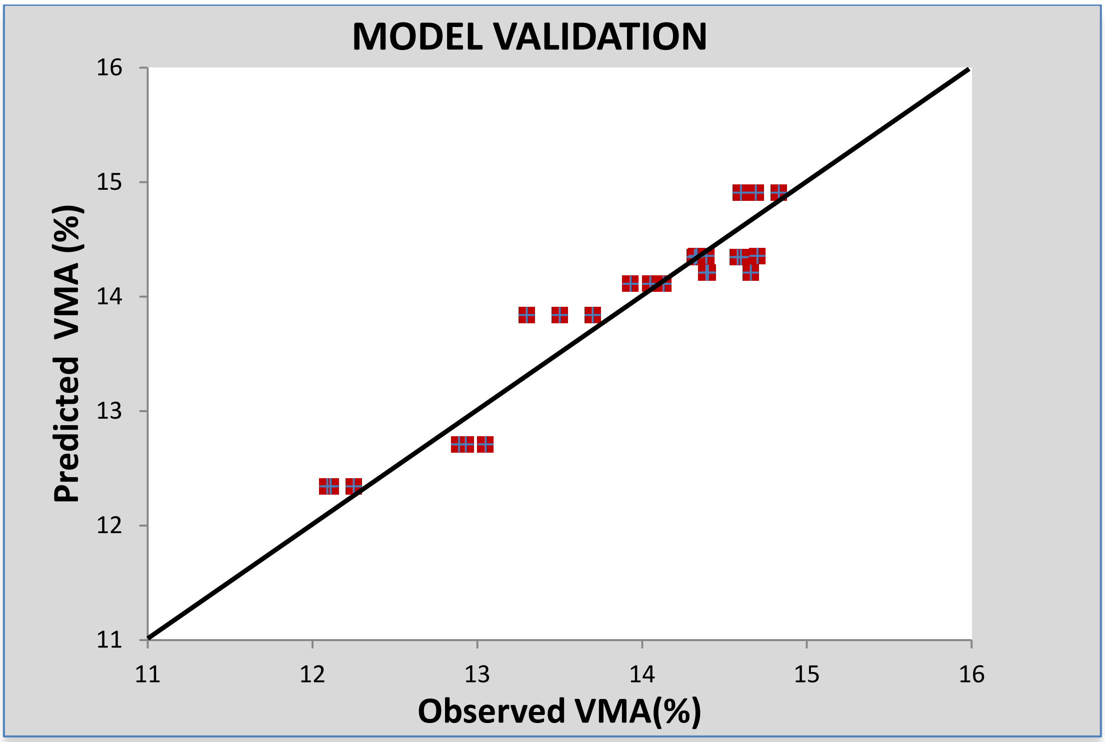

Figure 4.8 Validation plot for VMA model

4.6 Summary

The laboratory test results obtained for wheel tracker device using are presented herein plots and Tables. Improvement is observed in all of the adjusted mixes especially for NHA-A and MS-2. The gradation evaluations for different mixes were carried out to analyse the changes in percentage passing different sieves and its effect on nature of the mix. The change in VMA as described by Bailey Method is determined for each parameter i.e. changes in chosen unit weight (%CUW), CA ratio, FA_c ratio, and FA_f ratio. Finally an overall net change due to all the parameters was determined to predict the change in VMA as per variation in gradation of the mix. The change in VMA according to bailey method were plotted against the original change in VMA. The results shows better prediction in case of 12.5mm NMPS mixes rather than 19mm.

Statistical analysis was also performed to find out the effect and interaction of different parameters that influences VMA and Rutting susceptibility separately. Three bailey parameters CA, FA_c and FA_f were considered for VMA predicting model. Whereas the fourth bailey parameter i.e %CUW is not showing any significance in prediction of VMA. On the other hand for rutting predicting model one of the bailey parameter i.e. FA_c is considered along with NMPS. The result of the statistical analysis is also presented in tabular form. Model predictive ability is verified by calculating the mean absolute percentage error (MAPE) and plotting the observed data to fitted data.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Four wearing coarse gradation were selected to be adjusted using Bailey method of aggregate gradation selection. The optimum calculation for both the control and adjusted gradations were obtained from the laboratory including Marshall Stability, Flow and mix volumetrics. The Superpave gyratory specimens were prepared based on optimum results for each gradation and after extraction, wheel tracker samples of 1.5 inch height were obtained using saw cutting machine. The performance testing is carried out using wheel tracker test on four control wearing course mixes and four modified wearing course mixes.

The Hamburg wheel tracker (HWT) was used to test the permanent deformation i.e. rutting on three replicate specimens at test temperature of 40^{o}c.The process is first carried out for the original selected gradation and is then repeated for the Bailey adjusted gradations. Laboratory obtained Wheel tracker and volumetric results were analyzed separately.

5.2 Conclusions

The objective of this research project was to assess the applicability of the Bailey Method to wearing coarse mixtures commonly in use across Pakistan. For this purpose four of the wearing coarse mixtures were chosen for redesign with the Bailey Method. NMAS values of 19 mm and 12.5 mm were chosen as representative of most mixtures. The Bailey parameters for the original mixtures were calculated and the gradations were redesigned to fall within the recommended ranges. Specimens for each of the mix design were fabricated in the laboratory and performance testing is carried out using the Hamburg wheel tracker under wet conditions at a target test temperature of 40^{o} C. Average rut depths were calculated and comparisons among the various mixtures were done. Following were the conclusions drawn.

a. Two of the control gradations NHA-B and MS-2 classified as a “fine mixture” (CUW <85%) while for SP-1 the mix is classified as coarse graded (CUW 95%-105%) within the Bailey system. Whereas for NHA-A the original CUW classifies the mix as border line case to coarse mixture with CUW as 91% in the Bailey system.

b. Three of the mixtures i.e. NHA-A, NHA-B and SP-1 were redesigned to be “coarse” mixtures, Whereas MS-2 mix was redesigns as fine graded with %CUW as 75.

c. In this study the response of the redesigned mixtures were also evaluated with respect to rutting susceptibility. The results show that the NHA-A and MS-2 redesigned mixture were significantly better performing than the original mixture. Improvement is also observed in the other two mixes but that was not very major. The highest rut depth is obtained for MS-2 control gradation having value of 7.09 mm whereas least value is observed in NHA-A Bailey i.e. 4.83.

d. Overall the rut depth for gradations with 12.5 mm NMPS is greater than the mixture with 19mm NMPS which is obvious because of lager aggregate particles in 19 mm NMPS gradations.

e. Two Statistical models were also developed using the data obtained from the laboratory results. Both the models were developed using Cobb-Douglas formulation.

f. First model is use to predict VMA, incorporating three of bailey parameters CA, FA_c and FA_f as independent variables. Whereas the fourth bailey parameter i.e. %CUW does not show a significant influence on the VMA. The R_2 for this model is 91.8% showing that most of the variation in VMA is explained by variation in Bailey parameters.

g. The second model was developed to predict the rutting, using one of the bailey parameter and NMPS of the aggregate. The results shows that model is capturing 84% of the variation in rutting and all the independent variables are significant as their t-stat are greater than critical value of t-stat at 95% confidence level. Among four of the Bailey parameters only FA_c shows some significant relation with rutting. FA_c is the sieve size near to PCS that is a major break point between coarse and fine particles. The other parameter used in model to predict rutting is NMPS which is also an important factor regarding gradation of mix.

h. Overall, this research project showed that the Bailey Method would be a constructive and handy tool in the evaluation and design of mixtures. The Bailey Method should not be used exclusively, but can be used in combination with knowledge of the aggregate angularity, roughness, and engineering judgment to provide guidance during the mix design procedure and improve mixture performance.

5.3 Recommendations

Following are the recommendation for future studies and application of the adjusted gradations:

a. In this research only one of the performance testing is utilized i.e. the rutting susceptibility using Hamburg wheel tracker, other performance tests like dynamic modulus, indirect tensile strength and flow number & flow time etc should also be carried out to completely characterize and observe the behaviour of the mixtures used in this study.
b. The gradations were adjusted with goal to adjust the bailey parameters values within the suggested limits. It is recommended that gradations should be adjusted at mid point values of the Bailey parameters.
c. The adjustments made in selected gradation using bailey method shows improvement in rutting resistance, so to completely apply the adjusted gradations in field other performance tests should be carried out to check other HMA properties. Suggested testing would include contrast of different aggregate and binder sources commonly used in Pakistan.

REFERENCES

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

AASHTO T 19-00 (2004) "*Standard Method of Test for Bulk Density ("Unit Weight") and Voids in Aggregate*" by American Association of State Highway and Transportation Officials, Washington, DC USA

AASHTO T 49-06 (2011) "*Standrad Method for Penetration of Bituminious Material*" by American Association of State Highway and Transportation Officials, Washington, DC USA

AASHTO 51-08 (2008): "*Standard Method of Test for. Ductility of Bituminous Materials*" by American Association of State Highway and Transportation Officials, Washington, DC USA

AASHTO T 53 (2007) "*Standard Method of Test for Softening Point of Bitumen (Ring-and-Ball Apparatus)"* by American Association of State Highway and Transportation Officials, Washington, DC USA

Alshamsi, K., Mohammad, L. N., Wu, Z., Cooper, S., and Abadie, C., (2006). *Compactability and Performance of Superpave Mixtures With Aggregate Structures Designed Using the Bailey Method. Journal of Association of Asphalt Paving Technology.*

Alshamsi, K. (2006). *Development of a Mix Design Methodology for Asphalt Mixtures with Analytically Formulated Aggregate Structures. Journal of Association of Asphalt Paving Technology.*

Aschenbrener, T. and G. Currier(1993). *Influence of Testing Variables on the Results from the Hamburg Wheel-Tracking Device.* Report CDOT-DTD-R-93-22, Colorado Department of Transportation, Denver, Colorado.

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

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

Asphalt Institute (2003). *"The Asphalt Handbook"*, Manual Series No.1 (MS-4), Pennsylvania State University.

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

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

Aurilio, V., William, J. P. and Lum, P. (2009). "*The Bailey Method Achieving Volumetric and HMA Compactability*", *Course Materials and Handouts.*American

Baladi, G. Y., Lyles R. W. and Harichandran, R. S., (1998), "*Asphalt Mix Design: An Innovative Approach*". *The 67th Annual Meeting of the Transportation Research Board, National Research Council, Washington, D. C.,* January 11-14.

D.Angelo, J., Harman, T.P., Paugh, C.W. (2001) .*Evaluation of Volumetric Properties and Gyratory Compaction Slope for the Quality Control of Hot Mix Asphalt Production*., *Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions*, Vol. 70, pp. 729-761.

Denneman, E., Verhaeghe, B.M.J.A. and Sadzik, E.S. (2007). "*Aggregate Packing Characteristics of Good and Poor performing asphalt Mixes*". 26th Annual Southern African Transport Conference and Exhibition, Pretoria, South Africa, pp. 213-224

Eisenmann, J. and Hilmar, A. (1987), *Influence of wheel load and inflation pressure on the rutting effect of asphalt pavements - Experiments and theoretical investigations*, Proceedings of the Sixth International conference on structural design of asphalt Pavements, Vol. 1, Ann Arbor, Michigan.

Garber, N. J., and Hoel, L. A. (2002). *Traffic and highway Engineering*. (3rd ed.) United States of America: Brooks/Cole.

Graziani, A., Ferrotti, G., Pasquini, E., Canestrari, F. (2012). "*An Application to the European Practice of the Bailey Method for HMA Aggregate Grading Design*". Procedia - Social and Behavioural Sciences journal, vol. 53, pp. 991-1000.

Guler M., Bahia H. U., Bosscher P, J., Plesha M. E., "*Device for Measuring ShearResistance of Hot-Mix Asphalt in Gyratory Compactor*". Transportation

Research RecordNo. 1723, Transportation Research Board, Washington, DC, 2000.

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

John, P. Z. and Craig M. *An Evaluation of the Bailey Method to Predict Voids in the Mineral Aggregate* .Department of Civil and Environmental Engineering Morgantown, West Virginia.

Jo Sias, D., and Felix, R. (2009). "*Application of the Bailey Method to New Hampshire Asphalt mixtures"* .U.S Department of Transportation, Washington, D.C: FHWA-Nh-Rd-13733, Final Report.

Kandhal, P. S., Foo, K. Y., and Mallick, R. B., (1998). *Critical Review of the Voids in Mineral Aggregate Requirements in Superpave*. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1609*, TRB, National Research Council, pp. 21–27.

Kandhal, P. S., and Mallick, R. B., (2000), "*Effect of Mix Gradation on Rutting Potential of Dense Graded Asphalt Mixtures*", *80th annual meeting of the Transportation research Board, Washington, D. C*.

Khedaywi, TS and Tons, E. *Aggregate Rugosity And Size Effect on Bituminous Mixes*, Transportation Research Record, 1998, pp 26-36.

Khosla, N.P. and Sadasivam, S., 2005. *Determination of optimum gradation for resistance to permeability, rutting and fatigue cracking*. Department of Civil Engineering North Carolina State University.

Lavin, P. G., (2003). *Asphalt Pavements: A Practical Guide to Design, Production, and Maintenance for Engineers and Architects*: London: Spon Pess National Asphalt Pavement Association (NAPA)."A Guide for Hot Mix Asphalt Pavement". *Information Series 131*, 2002.

Lees G. "*Asphalt Mix Design for Optimum Structural and Tyre Interaction Purposes*",Sixth International Conference on the Structural Design of Asphalt Pavements,University of Michigan, Ann Arbor - July 13-17, 1987.

Mamat, B. R., (2008). "*Evaluation of Marshall Properties of Asphalt Mixtures with Aggregate Gradations Designed Using the Bailey Method*". Master's Thesis, University of Technology, Malaysia.

McGennis, R. B.; Anderson, R. M.; Kennedy, T. W.; Solaimanian, M. "*Background of SUPERPAVE Asphalt Mixture Design and Analysis*". U.S Department of Transportation,Federal Highway Administration, Report No. FHWA-SA-95-003, 1995.

Mogawer, W. S., and K. D. Stuart. (1995) "*Effect of Coarse Aggregate Content on Stone Matrix Asphalt*",Transportation Research Record 1492, TRB, National Research Council, Washington, D.C., Pages 1-11,.

Roberts, F., Mohammad, L., and Wang, L. (2002). "*History of Hot Mix Asphalt Mixture Design in the United States*." *J. Mater. Civ. Eng.*, 14(4), 279–293.

Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y., and Kennedy, T. W., (1996).*Hot Mix Asphalt Materials, Mixture Design and Construction*. (2^{nd} Ed.) NAPA Research and education Foundation: Lanham, Maryland.

Sousa, Jorge B., Craus, J., Monismith, Carl L. (1991). "*Summary Report on Permanent Deformation in Asphalt Concrete*." *SHRP-A/IR-91-104 Institute of Transportation Studies University of California Berkeley, California Strategic Highway Research Program National Research Council, Washington, D.C.*

Vavrik, W. R., Pine, W. J., Huber, G. A., Carpenter, S. H., and Bailey, R., (2001). The Bailey Method of Gradation Evaluation: The Influence of Aggregate Gradation and Packing Characteristics on Voids in the Mineral Aggregate. Journal of the Association of Asphalt Paving Technologists, Vol. 70, pp. 132–175.

The Asphalt Institute. (1993). *Mix Design Methods for Asphalt Concrete and Other Hot- Mix Types*. Manual Series No. 2 (MS-2). (6th Ed.). Lexington, KY.

Thompson, G., (2006*). Investigation of the Bailey Method for the Design and Analysis of Dense Graded Hot Mix Asphalt Concrete Using Oregon Aggregate*: Final Report, SPR 304-311.

Tons, E., and Goetz, W. H., (1968), "*Packing Volume Concepts for Aggregates*," Highway Research Record 236, pp. 79 – 96.

Vavrik, W. R., Pine, W. J., Huber, G. A., Carpenter, S. H., and Bailey, R., (2001). *The Bailey Method of Gradation Evaluation: The Influence of Aggregate Gradation and Packing Characteristics on Voids in the Mineral Aggregate*. Journal of the Association of Asphalt Paving Technologists, Vol. 70, pp. 132– 175.

Vavrik, W. R., Huber, G. A., Pine, W. J., Carpenter, S. H., and Bailey, R., (2002). *Bailey Method for Gradation Selection in HMA Mixture Design. Transportation*

Research Circular E-C044. Bailey Method for Gradation Selection in Hot-Mix Asphalt Mixture Design, TRB, National Research Council, Washington, D.C.,

Vavrik, W. R. (2000). "Asphalt Mixture Design Concepts to Develop Aggregate Interlock". Ph.D.thesis. University of Illinois at Urbana–Champaign,.

APPENDICES

APPENDIX A-WHEEL HAMBURG TRACKER TEST RESULTS

Number of passes verses the rutting for both adjusted and control mixes

	BAILEY ADJUSTED GRADATIONS				CONTROL GRADATIONS			
Pass No	**NHA A**	**NHA B**	**SP 1**	**MS 2**	**NHA A**	**NHA B**	**SP 1**	**MS 2**
5	0	0	0	0	0	0	0	0
20	-0.26508	-0.0478	-0.06997	-0.02863	-0.04618	-0.00831	-0.12631	-0.08613
40	-0.55603	-0.07343	-0.09744	-0.05288	-0.07989	-0.02309	-0.21913	-0.13231
60	-0.74099	-0.11753	-0.15101	-0.07135	-0.09698	-0.02725	-0.27201	-0.1554
80	-0.85713	-0.13254	-0.17526	-0.07574	-0.10668	-0.02956	-0.30388	-0.17665
100	-0.97236	-0.15009	-0.20412	-0.09098	-0.12446	-0.03094	-0.34613	-0.20366
120	-1.11783	-0.16487	-0.22606	-0.10576	-0.13139	-0.04018	-0.37338	-0.21936
140	-1.19011	-0.17157	-0.24777	-0.11153	-0.14501	-0.0351	-0.40594	-0.22883
160	-1.24668	-0.17988	-0.26347	-0.11499	-0.15286	-0.04711	-0.43134	-0.25746
180	-1.29679	-0.19165	-0.28079	-0.12608	-0.15863	-0.04941	-0.45674	-0.26762
200	-1.31965	-0.20736	-0.30572	-0.13831	-0.16602	-0.05126	-0.47498	-0.27201
220	-1.33858	-0.21544	-0.31565	-0.13878	-0.17826	-0.05634	-0.50107	-0.30503
240	-1.37553	-0.22721	-0.3332	-0.14501	-0.1845	-0.05911	-0.51885	-0.30896
260	-1.40601	-0.22999	-0.32489	-0.14709	-0.18681	-0.05865	-0.54056	-0.31635
280	-1.42125	-0.23091	-0.34105	-0.16025	-0.19858	-0.05588	-0.56088	-0.33182
300	-1.43325	-0.24199	-0.35629	-0.17364	-0.21197	-0.06419	-0.58074	-0.33043
320	-1.47897	-0.25192	-0.37084	-0.17688	-0.21244	-0.06881	-0.58974	-0.35468
340	-1.48428	-0.25492	-0.3877	-0.17803	-0.22052	-0.0762	-0.61006	-0.35606
360	-1.49052	-0.25954	-0.38631	-0.18611	-0.23045	-0.08082	-0.62276	-0.36784
380	-1.52839	-0.2727	-0.40155	-0.19396	-0.24061	-0.08913	-0.63223	-0.37338
400	-1.52423	-0.28356	-0.42025	-0.20181	-0.24592	-0.08913	-0.64308	-0.38377
420	-1.53347	-0.28079	-0.40525	-0.21267	-0.25007	-0.08775	-0.65763	-0.40224
440	-1.55817	-0.28379	-0.42303	-0.22167	-0.25238	-0.09375	-0.69088	-0.3997
460	-1.56487	-0.29418	-0.44242	-0.2226	-0.25931	-0.0956	-0.68211	-0.41564
480	-1.57111	-0.29118	-0.4415	-0.22514	-0.26693	-0.10483	-0.69989	-0.41656
500	-1.59974	-0.29695	-0.45143	-0.23022	-0.26901	-0.10807	-0.7082	-0.43203
520	-1.58404	-0.3048	-0.45143	-0.23553	-0.27663	-0.11176	-0.71859	-0.43619
540	-1.61636	-0.30688	-0.46459	-0.24245	-0.27825	-0.12053	-0.72205	-0.44681

560	-1.61659	-0.32166	-0.48953	-0.24823	-0.28448	-0.12839	-0.7299	-0.44843
580	-1.61983	-0.31127	-0.47683	-0.25816	-0.29141	-0.12608	-0.73868	-0.44866
600	-1.62583	-0.32373	-0.49946	-0.26439	-0.2981	-0.133	-0.76639	-0.47637
620	-1.62699	-0.32974	-0.49207	-0.26762	-0.30226	-0.13577	-0.76569	-0.46297
640	-1.65908	-0.33528	-0.5147	-0.26762	-0.30203	-0.14132	-0.77147	-0.48514
660	-1.64823	-0.34429	-0.50708	-0.27363	-0.30757	-0.14409	-0.78371	-0.48029
680	-1.67201	-0.33828	-0.5274	-0.28032	-0.31473	-0.14547	-0.78301	-0.49045
700	-1.65677	-0.35167	-0.5274	-0.28148	-0.32327	-0.15055	-0.80379	-0.51193
720	-1.69141	-0.34821	-0.5267	-0.29187	-0.3242	-0.15194	-0.79779	-0.502
740	-1.67247	-0.3556	-0.54079	-0.2981	-0.33159	-0.15332	-0.80633	-0.51447
760	-1.70965	-0.35144	-0.53617	-0.30873	-0.33736	-0.15979	-0.81049	-0.53317
780	-1.68795	-0.36668	-0.55903	-0.31635	-0.34544	-0.16533	-0.83173	-0.52301
800	-1.72581	-0.35675	-0.55811	-0.32004	-0.35075	-0.16487	-0.82989	-0.53525
820	-1.70549	-0.3683	-0.55187	-0.32281	-0.36114	-0.16164	-0.83797	-0.55257
840	-1.72558	-0.36969	-0.57843	-0.32258	-0.36738	-0.16718	-0.84374	-0.54264
860	-1.70896	-0.37615	-0.57035	-0.33066	-0.3683	-0.17087	-0.85136	-0.55834
880	-1.73228	-0.37638	-0.58997	-0.33297	-0.3616	-0.17549	-0.85621	-0.57242
900	-1.75168	-0.39001	-0.59251	-0.33967	-0.37246	-0.17919	-0.85921	-0.56388
920	-1.72789	-0.38262	-0.58674	-0.34683	-0.37592	-0.18196	-0.86845	-0.56411
940	-1.76784	-0.39393	-0.60521	-0.35006	-0.38192	-0.18565	-0.88415	-0.59113
960	-1.74867	-0.39462	-0.60775	-0.35421	-0.38654	-0.2032	-0.87838	-0.59344
980	-1.76184	-0.40201	-0.60729	-0.35791	-0.38862	-0.20874	-0.88346	-0.58813
1000	-1.77708	-0.40709	-0.63015	-0.37292	-0.39624	-0.21059	-0.89962	-0.60175
1050	-1.78908	-0.41125	-0.63338	-0.3877	-0.41633	-0.21752	-0.90101	-0.61283
1100	-1.81125	-0.41771	-0.6537	-0.40501	-0.41564	-0.22075	-0.91024	-0.65278
1150	-1.82280	-0.43549	-0.65393	-0.42141	-0.43203	-0.22721	-0.92733	-0.65786
1200	-1.83480	-0.44242	-0.67541	-0.4378	-0.44358	-0.23876	-0.94557	-0.68095
1250	-1.82972	-0.45166	-0.68211	-0.45443	-0.44981	-0.25631	-0.96566	-0.69642
1300	-1.84935	-0.4632	-0.70981	-0.47267	-0.46667	-0.27755	-0.97051	-0.71928
1350	-1.84242	-0.47406	-0.71928	-0.48699	-0.47452	-0.28125	-0.97559	-0.74214
1400	-1.85697	-0.46967	-0.71651	-0.50107	-0.48768	-0.28633	-0.97882	-0.75253
1450	-1.89576	-0.48121	-0.74768	-0.52185	-0.49969	-0.31219	-0.9936	-0.78902

1500	-1.91424	-0.49438	-0.75346	-0.53502	-0.514	-0.31681	-1.0063	-0.81395
1550	-1.91262	-0.50708	-0.76962	-0.54818	-0.51631	-0.34683	-1.01508	-0.83312
1600	-1.90038	-0.51516	-0.77493	-0.57104	-0.54056	-0.35514	-1.01877	-0.86475
1650	-1.93040	-0.53548	-0.78648	-0.59182	-0.53409	-0.37961	-1.02685	-0.88115
1700	-1.94218	-0.5334	-0.79387	-0.61006	-0.54679	-0.40917	-1.01808	-0.89824
1750	-1.94449	-0.54333	-0.8068	-0.6283	-0.56503	-0.43041	-1.0354	-0.93033
1800	-1.93132	-0.55003	-0.81811	-0.63939	-0.56342	-0.46413	-1.03886	-0.97305
1850	-1.98397	-0.55903	-0.89639	-0.66017	-0.57312	-0.47798	-1.05595	-0.99984
1900	-1.95695	-0.57127	-0.8606	-0.68719	-0.59228	-0.49553	-1.06472	-1.02662
1950	-1.97497	-0.57866	-0.86614	-0.70681	-0.60775	-0.53709	-1.05456	-1.05572
2000	-2.00152	-0.58443	-0.87815	-0.72459	-0.60267	-0.54033	-1.0638	-1.08343
2050	-1.98489	-0.59805	-0.89847	-0.74791	-0.60406	-0.56757	-1.07188	-1.12199
2100	-2.02577	-0.61029	-0.89454	-0.77101	-0.62161	-0.60498	-1.0982	-1.13492
2150	-2.03916	-0.62022	-0.92479	-0.78879	-0.641	-0.62669	-1.08989	-1.15685
2200	-2.00775	-0.6253	-0.93611	-0.81511	-0.66132	-0.64147	-1.08689	-1.20835
2250	-2.04216	-0.6447	-0.95966	-0.83982	-0.66687	-0.65855	-1.09797	-1.22405
2300	-2.03477	-0.64447	-0.96566	-0.85667	-0.67195	-0.66363	-1.11529	-1.24829
2350	-2.05786	-0.65024	-0.96705	-0.8823	-0.6761	-0.68903	-1.1206	-1.28663
2400	-2.05047	-0.67679	-0.97698	-0.89108	-0.67472	-0.72321	-1.11391	-1.3081
2450	-2.07495	-0.6731	-0.99268	-0.92964	-0.68719	-0.74584	-1.11875	-1.3365
2500	-2.04909	-0.68349	-0.99984	-0.94119	-0.69273	-0.77863	-1.14392	-1.37229
2550	-2.08580	-0.70427	-1.03309	-0.97259	-0.7015	-0.81049	-1.13723	-1.39492
2600	-2.10427	-0.71559	-1.02985	-0.99522	-0.70843	-0.83312	-1.14	-1.41339
2650	-2.08280	-0.71951	-1.04717	-1.01069	-0.71951	-0.88531	-1.14785	-1.45681
2700	-2.13452	-0.73614	-1.05479	-1.03401	-0.72875	-0.94719	-1.16609	-1.48613
2750	-2.10427	-0.74861	-1.06057	-1.0541	-0.74168	-0.96566	-1.14739	-1.50414
2800	-2.12413	-0.75854	-1.0698	-1.09359	-0.74099	-0.98321	-1.16217	-1.53254
2850	-2.11513	-0.77008	-1.09428	-1.10605	-0.75323	-1.02524	-1.17625	-1.55841
2900	-2.11790	-0.78717	-1.10421	-1.11598	-0.76177	-1.06449	-1.17879	-1.56233
2950	-2.16916	-0.8068	-1.12591	-1.1587	-0.7717	-1.07188	-1.16886	-1.60228
3000	-2.13383	-0.81395	-1.13099	-1.16078	-0.78555	-1.12176	-1.1841	-1.6256
3050	-2.16177	-0.82919	-1.14254	-1.18479	-0.80403	-1.15501	-1.19703	-1.65608

3100	-2.17285	-0.82989	-1.1557	-1.20234	-0.81626	-1.20996	-1.19172	-1.67386
3150	-2.15692	-0.84305	-1.16355	-1.23559	-0.83289	-1.26492	-1.18433	-1.67848
3200	-2.18071	-0.86291	-1.18179	-1.25314	-0.83843	-1.28986	-1.21135	-1.73505
3250	-2.18325	-0.8666	-1.1908	-1.27439	-0.84605	-1.28755	-1.21435	-1.72882
3300	-2.18671	-0.88207	-1.20281	-1.29194	-0.84721	-1.34851	-1.20488	-1.78493
3350	-2.21881	-0.89339	-1.20765	-1.31849	-0.85436	-1.39146	-1.20996	-1.78239
3400	-2.17378	-0.90424	-1.22266	-1.33304	-0.85136	-1.42286	-1.2319	-1.82049
3450	-2.19294	-0.91786	-1.22174	-1.35313	-0.86198	-1.42887	-1.22474	-1.83642
3500	-2.21927	-0.93357	-1.2476	-1.37714	-0.86152	-1.49491	-1.22012	-1.87567
3550	-2.20149	-0.94904	-1.26677	-1.3903	-0.87838	-1.52169	-1.23813	-1.86944
3600	-2.20149	-0.95412	-1.26423	-1.43395	-0.88507	-1.5554	-1.23767	-1.92901
3650	-2.22804	-0.96728	-1.28409	-1.43926	-0.8987	-1.60159	-1.23121	-1.91354
3700	-2.27030	-0.97998	-1.28824	-1.45773	-0.90978	-1.63345	-1.24853	-1.97058
3750	-2.22412	-0.99522	-1.35243	-1.47389	-0.90632	-1.64223	-1.24298	-1.97335
3800	-2.23913	-1.00168	-1.3051	-1.49098	-0.91047	-1.71796	-1.23721	-2.0126
3850	-2.24975	-1.01831	-1.32403	-1.53832	-0.92595	-1.69672	-1.25984	-2.04424
3900	-2.25321	-1.02939	-1.34435	-1.56164	-0.94557	-1.74429	-1.24714	-2.0387
3950	-2.24213	-1.03655	-1.34251	-1.57849	-0.94257	-1.77107	-1.25915	-2.11467
4000	-2.27007	-1.06241	-1.35775	-1.61105	-0.9585	-1.79185	-1.28316	-2.13245
4050	-2.29501	-1.06772	-1.35705	-1.6069	-0.95435	-1.82695	-1.26007	-2.11582
4100	-2.25760	-1.07373	-1.35913	-1.62375	-0.96497	-1.8736	-1.26954	-2.17401
4150	-2.27191	-1.09382	-1.38753	-1.63276	-0.98044	-1.89623	-1.27439	-2.18555
4200	-2.30101	-1.10167	-1.38453	-1.63992	-0.98806	-1.91008	-1.27577	-2.1784
4250	-2.29501	-1.11899	-1.40601	-1.68587	-0.98483	-1.93456	-1.3051	-2.23659
4300	-2.27099	-1.13607	-1.42032	-1.69787	-1.00977	-1.97243	-1.28201	-2.29385
4350	-2.29062	-1.14854	-1.4194	-1.7205	-1.04279	-1.98905	-1.29933	-2.26776
4400	-2.32110	-1.15824	-1.44226	-1.73574	-1.03009	-1.98212	-1.28663	-2.29824
4450	-2.32017	-1.16909	-1.45565	-1.75329	-1.01646	-2.05232	-1.30048	-2.33888
4500	-2.29431	-1.1938	-1.47943	-1.77685	-1.05271	-2.05925	-1.30394	-2.33264
4550	-2.31579	-1.18964	-1.47828	-1.79947	-1.0608	-2.08095	-1.29748	-2.33726
4600	-2.34973	-1.21112	-1.48313	-1.82557	-1.04833	-2.06802	-1.31572	-2.40723
4650	-2.32041	-1.20627	-1.48359	-1.84058	-1.06195	-1.82372	-1.31087	-2.41069

4700	-2.31025	-1.22821	-1.51038	-1.86759	-1.07188	-2.01076	-1.33604	-2.38899
4750	-2.32687	-1.24945	-1.51961	-1.91331	-1.0698	-2.07079	-1.31711	-2.42662
4800	-2.36220	-1.24506	-1.52169	-1.92601	-1.1109	-2.08511	-1.33927	-2.49543
4850	-2.30147	-1.27254	-1.55171	-1.94195	-1.10698	-2.1396	-1.32634	-2.50305
4900	-2.33149	-1.26561	-1.5337	-1.97958	-1.09451	-2.19687	-1.3395	-2.49105
4950	-2.34742	-1.28362	-1.55356	-1.99921	-1.13399	-2.18948	-1.34343	-2.49913
5000	-2.37444	-1.30325	-1.56857	-2.00752	-1.13376	-2.21257	-1.34181	-2.56448
5050	-2.33218	-1.31203	-1.57018	-2.01283	-1.11437	-2.22319	-1.35982	-2.57625
5100	-2.32341	-1.31872	-1.59443	-2.02438	-1.14508	-2.27723	-1.33812	-2.60235
5150	-2.34973	-1.33235	-1.59881	-2.04124	-1.16286	-2.27261	-1.37553	-2.59034
5200	-2.35412	-1.33812	-1.60736	-2.06848	-1.17717	-2.3017	-1.35313	-2.60073
5250	-2.37767	-1.36721	-1.61567	-2.10012	-1.17533	-2.33449	-1.38545	-2.62798
5300	-2.42801	-1.37553	-1.64292	-2.15138	-1.15732	-2.34973	-1.35728	-2.68547
5350	-2.36659	-1.38014	-1.62953	-2.1336	-1.21366	-2.38668	-1.39492	-2.70672
5400	-2.37328	-1.39469	-1.65931	-2.12829	-1.1871	-2.39822	-1.37391	-2.71272
5450	-2.37051	-1.40577	-1.68194	-2.14676	-1.18479	-2.40838	-1.39769	-2.6827
5500	-2.43124	-1.40693	-1.68379	-2.14515	-1.23883	-2.39314	-1.38245	-2.69563
5550	-2.44417	-1.42032	-1.67917	-2.17655	-1.21112	-2.43748	-1.41478	-2.73119
5600	-2.45872	-1.44895	-1.72073	-2.19456	-1.25199	-2.44995	-1.394	-2.76606
5650	-2.45018	-1.44572	-1.70942	-2.22643	-1.24783	-2.4952	-1.42563	-2.80508
5700	-2.44694	-1.45935	-1.72605	-2.26337	-1.29448	-2.51137	-1.40462	-2.84896
5750	-2.44925	-1.47759	-1.72628	-2.292	-1.25014	-2.53631	-1.43348	-2.83164
5800	-2.44417	-1.48313	-1.74313	-2.28369	-1.30949	-2.52892	-1.41432	-2.88452
5850	-2.44533	-1.49721	-1.75029	-2.29431	-1.32219	-2.52014	-1.43464	-2.91338
5900	-2.47581	-1.51107	-1.78031	-2.32364	-1.29517	-2.58433	-1.42494	-2.92446
5950	-2.51091	-1.52769	-1.79855	-2.35481	-1.33789	-2.59219	-1.44895	-2.96533
6000	-2.54670	-1.5427	-1.81356	-2.38437	-1.3432	-2.64853	-1.43371	-2.98311
6050	-2.53700	-1.55956	-1.81772	-2.4354	-1.34227	-2.60881	-1.4732	-2.96372
6100	-2.49867	-1.56533	-1.82303	-2.42547	-1.34759	-2.65037	-1.45704	-2.94802
6150	-2.52060	-1.56626	-1.84404	-2.43355	-1.37899	-2.66885	-1.4732	-2.99304
6200	-2.51691	-1.58542	-1.85882	-2.46357	-1.36306	-2.67901	-1.46258	-3.01613
6250	-2.51691	-1.58381	-1.85281	-2.49636	-1.42286	-2.71688	-1.48705	-3.04361

6300	-2.54993	-1.60482	-1.85951	-2.54092	-1.3716	-2.75567	-1.48775	-3.05262
6350	-2.58110	-1.61082	-1.85512	-2.55131	-1.43348	-2.73581	-1.51777	-3.0547
6400	-2.57671	-1.61313	-1.89045	-2.54623	-1.41593	-2.74043	-1.50853	-3.07525
6450	-2.57002	-1.63345	-1.88745	-2.57879	-1.43741	-2.73766	-1.53093	-3.08471
6500	-2.59957	-1.65008	-1.90292	-2.57441	-1.43833	-2.79308	-1.52769	-3.12212
6550	-2.63560	-1.64546	-1.91793	-2.63075	-1.48405	-2.79354	-1.53693	-3.15168
6600	-2.61020	-1.68702	-1.94818	-2.65037	-1.45727	-2.83833	-1.54039	-3.15052
6650	-2.65823	-1.67617	-1.9491	-2.68963	-1.48013	-2.80924	-1.5367	-3.17454
6700	-2.60604	-1.6831	-1.96065	-2.72958	-1.51015	-2.79077	-1.5524	-3.1563
6750	-2.60604	-1.70688	-1.96319	-2.71849	-1.47574	-2.85635	-1.55079	-3.22072
6800	-2.63698	-1.72304	-2.00845	-2.73096	-1.51084	-2.87205	-1.57203	-3.25605
6850	-2.62959	-1.72304	-1.97981	-2.7402	-1.50253	-2.8702	-1.55563	-3.28307
6900	-2.64021	-1.73851	-2.00775	-2.79908	-1.54086	-2.89837	-1.5778	-3.32024
6950	-2.63167	-1.76022	-2.03292	-2.81178	-1.55032	-2.87944	-1.56764	-3.30662
7000	-2.66977	-1.76253	-2.03085	-2.84826	-1.52608	-2.92977	-1.59674	-3.31909
7050	-2.63975	-1.76645	-2.05163	-2.87159	-1.56764	-2.9307	-1.57942	-3.36758
7100	-2.66631	-1.78701	-2.05301	-2.90645	-1.5681	-2.97272	-1.60805	-3.39252
7150	-2.67277	-1.81171	-2.08511	-2.84803	-1.56141	-2.96857	-1.59905	-3.38097
7200	-2.69656	-1.82395	-2.08927	-2.90668	-1.61429	-2.97873	-1.62768	-3.37774
7250	-2.69148	-1.8221	-2.10035	-2.96649	-1.58819	-2.99489	-1.60921	-3.38189
7300	-2.69840	-1.84519	-2.13245	-2.96811	-1.6353	-2.9815	-1.64361	-3.42438
7350	-2.71757	-1.86598	-2.13799	-2.97388	-1.62629	-3.04153	-1.62398	-3.42415
7400	-2.71549	-1.90408	-2.17978	-2.96349	-1.64292	-3.04477	-1.63807	-3.45117
7450	-2.71688	-1.89369	-2.16154	-3.03022	-1.63992	-3.06509	-1.63322	-3.47911
7500	-2.73650	-1.91123	-2.18255	-3.05377	-1.67986	-3.05631	-1.66347	-3.50751
7550	-2.73627	-1.95003	-2.2165	-3.08656	-1.66278	-3.07201	-1.65677	-3.52783
7600	-2.73604	-1.93456	-2.21095	-3.09141	-1.72304	-3.12697	-1.67755	-3.5366
7650	-2.76560	-1.93987	-2.21603	-3.07502	-1.67617	-3.15329	-1.67455	-3.58879
7700	-2.76329	-2.00291	-2.26222	-3.11496	-1.72397	-3.1048	-1.70365	-3.64836
7750	-2.76745	-1.97127	-2.25044	-3.14221	-1.73805	-3.17177	-1.69233	-3.64536
7800	-2.77668	-2.00129	-2.25229	-3.20663	-1.71011	-3.18608	-1.72351	-3.67122
7850	-2.78361	-2.02438	-2.28046	-3.1937	-1.7713	-3.14406	-1.71404	-3.68531

7900	-2.79746	-2.02184	-2.30078	-3.15861	-1.71727	-3.20871	-1.74336	-3.73311
7950	-2.80439	-2.04886	-2.29177	-3.19463	-1.76622	-3.22626	-1.72281	-3.71186
8000	-2.80508	-2.07426	-2.33772	-3.26482	-1.781	-3.18839	-1.7556	-3.71879
8050	-2.78269	-2.06179	-2.32664	-3.24612	-1.80709	-3.24889	-1.74082	-3.75089
8100	-2.80855	-2.0798	-2.32318	-3.24751	-1.80571	-3.23781	-1.76692	-3.74419
8150	-2.81686	-2.08649	-2.35181	-3.26759	-1.87152	-3.2512	-1.75422	-3.77167
8200	-2.82402	-2.11074	-2.37582	-3.28029	-1.81356	-3.29461	-1.77777	-3.80007
8250	-2.83857	-2.12483	-2.38852	-3.34657	-1.88191	-3.32417	-1.76992	-3.78599
8300	-2.84619	-2.13014	-2.41346	-3.38628	-1.89207	-3.30108	-1.79601	-3.82224
8350	-2.84896	-2.19872	-2.43055	-3.29738	-1.83157	-3.33109	-1.79255	-3.82039
8400	-2.84249	-2.16593	-2.41716	-3.36919	-1.92393	-3.35603	-1.83042	-3.83055
8450	-2.86651	-2.14953	-2.4287	-3.40937	-1.91147	-3.3722	-1.80779	-3.89959
8500	-2.85173	-2.21603	-2.44856	-3.40522	-1.89807	-3.38975	-1.84381	-3.90791
8550	-2.86535	-2.18879	-2.45202	-3.4768	-1.95511	-3.38559	-1.82441	-3.89705
8600	-2.88821	-2.20218	-2.46357	-3.47126	-1.92763	-3.39021	-1.86228	-3.91045
8650	-2.88175	-2.25229	-2.4825	-3.43454	-1.95973	-3.40221	-1.8445	-3.97833
8700	-2.89006	-2.2673	-2.50398	-3.4738	-1.92624	-3.42207	-1.86113	-3.98364
8750	-2.92516	-2.2576	-2.49982	-3.52945	-1.97681	-3.46456	-1.84519	-3.98018
8800	-2.93555	-2.29916	-2.49936	-3.53337	-1.9812	-3.45902	-1.87614	-4.02197
8850	-2.94409	-2.29016	-2.53007	-3.58648	-2.06063	-3.49504	-1.85882	-4.06308
8900	-2.95702	-2.31509	-2.57002	-3.55623	-1.98374	-3.53429	-1.89022	-4.06515
8950	-2.96441	-2.34396	-2.54139	-3.52298	-2.0925	-3.50659	-1.89646	-4.05915
9000	-3.01152	-2.32456	-2.53977	-3.59479	-2.06802	-3.5112	-1.91262	-4.06977
9050	-3.02560	-2.33357	-2.58387	-3.63451	-2.09504	-3.53476	-1.92901	-4.09356
9100	-3.05193	-2.39545	-2.6229	-3.61049	-2.10012	-3.55	-1.93202	-4.14851
9150	-3.03946	-2.37121	-2.58664	-3.69362	-2.10774	-3.58787	-1.92578	-4.14251
9200	-3.04915	-2.35643	-2.60558	-3.66984	-2.11721	-3.59433	-1.9364	-4.19539
9250	-3.05955	-2.42431	-2.63098	-3.62458	-2.17355	-3.60311	-1.96157	-4.14343
9300	-2.97434	-2.45341	-2.67139	-3.65783	-2.16731	-3.59433	-1.94472	-4.16537
9350	-3.07594	-2.41508	-2.66585	-3.66476	-2.16523	-3.63035	-1.97104	-4.19723
9400	-3.05077	-2.45503	-2.64945	-3.55438	-2.21719	-3.64097	-1.97266	-4.20278
9450	-3.06971	-2.45664	-2.67393	-3.73311	-2.22088	-3.63959	-2.01307	-4.20024

9500	-3.10019	-2.4892	-2.71295	-3.73957	-2.22365	-3.65899	-2.02553	-4.24319
9550	-3.10249	-2.5116	-2.70625	-3.75712	-2.24952	-3.67561	-2.02253	-4.30415
9600	-3.10804	-2.49613	-2.7245	-3.73911	-2.31463	-3.67423	-2.05625	-4.28221
9650	-3.17177	-2.48735	-2.71688	-3.75712	-2.23543	-3.67792	-2.03015	-4.31454
9700	-3.15399	-2.54577	-2.73697	-3.78183	-2.30747	-3.69362	-2.04701	-4.32031
9750	-3.18932	-2.50629	-2.74528	-3.78345	-2.30886	-3.69362	-2.03569	-4.32146
9800	-3.18147	-2.54115	-2.76537	-3.83863	-2.33772	-3.70609	-2.07033	-4.32169
9850	-3.21703	-2.57949	-2.77045	-3.86796	-2.3562	-3.73057	-2.09111	-4.38381
9900	-3.18747	-2.5624	-2.78961	-3.73749	-2.39407	-3.71948	-2.09435	-4.38381
9950	-3.20179	-2.58757	-2.82748	-3.88066	-2.38367	-3.68947	-2.12298	-4.38866
10000	-3.19601	-2.61481	-2.80416	-3.87258	-2.35712	-3.76428	-2.10866	-4.45585
10050	-3.23711	-2.63121	-2.8164	-3.82478	-2.44856	-3.75735	-2.1142	-4.44385
10100	-3.28122	-2.6132	-2.84341	-3.8451	-2.38344	-3.71902	-2.15323	-4.4383
10150	-3.28607	-2.62798	-2.83279	-3.9213	-2.45572	-3.77906	-2.14769	-4.47964
10200	-3.30962	-2.63906	-2.84803	-3.92153	-2.45987	-3.78321	-2.18763	-4.48726
10250	-3.32671	-2.67323	-2.88198	-3.9818	-2.51298	-3.80076	-2.17655	-4.50827
10300	-3.28422	-2.68409	-2.87944	-4.00189	-2.48273	-3.80815	-2.19802	-4.59117
10350	-3.31470	-2.69286	-2.89675	-4.01251	-2.51645	-3.79984	-2.21742	-4.52813
10400	-3.31770	-2.70856	-2.91684	-3.9818	-2.53099	-3.87281	-2.19248	-4.53598
10450	-3.29646	-2.7021	-2.93116	-3.93446	-2.49982	-3.84417	-2.23312	-4.58701
10500	-3.29784	-2.72473	-2.9277	-3.99288	-2.60512	-3.87696	-2.22804	-4.57223
10550	-3.32555	-2.74967	-2.96418	-3.99588	-2.61135	-3.88112	-2.24582	-4.62742
10600	-3.32578	-2.76929	-2.95425	-3.99034	-2.55986	-3.88528	-2.25691	-4.69738
10650	-3.37635	-2.76375	-2.97965	-4.05938	-2.63421	-3.91299	-2.25183	-4.64035
10700	-3.39229	-2.77391	-2.99073	-4.08917	-2.63213	-3.93192	-2.28946	-4.64866
10750	-3.39136	-2.79862	-2.99466	-4.04483	-2.64576	-3.8862	-2.27399	-4.67106
10800	-3.38097	-2.83857	-3.00967	-4.10695	-2.67485	-3.95871	-2.30517	-4.68445
10850	-3.36827	-2.85635	-3.02491	-4.13697	-2.71133	-3.86265	-2.31417	-4.74241
10900	-3.39529	-2.86512	-3.02883	-4.10972	-2.68386	-3.95593	-2.31255	-4.75603
10950	-3.43708	-2.88359	-3.07502	-4.17091	-2.74066	-3.96471	-2.36081	-4.80406
11000	-3.42184	-2.89237	-3.06971	-4.18015	-2.78615	-3.9818	-2.33357	-4.73872
11050	-3.42346	-2.89906	-3.08379	-4.15498	-2.71295	-4.0229	-2.37444	-4.77035

11100	-3.46802	-2.9404	-3.10157	-4.22702	-2.82702	-3.96563	-2.37236	-4.77405
11150	-3.46595	-2.97111	-3.09741	-4.26258	-2.78592	-3.9878	-2.38367	-4.80822
11200	-3.43708	-2.98773	-3.14267	-4.25981	-2.83025	-3.96471	-2.3936	-4.82969
11250	-3.46918	-2.99605	-3.13251	-4.24919	-2.83695	-4.04091	-2.40469	-4.84724
11300	-3.48049	-2.98796	-3.13667	-4.23764	-2.83279	-4.04737	-2.44371	-4.85117
11350	-3.47380	-2.99974	-3.15399	-4.30438	-2.86766	-4.0797	-2.44694	-4.87611
11400	-3.47865	-3.0256	-3.17546	-4.29468	-2.86951	-4.0991	-2.45872	-4.85948
11450	-3.50266	-3.05631	-3.17477	-4.28798	-2.9434	-4.05245	-2.4384	-4.89019
11500	-3.47611	-3.08264	-3.18123	-4.35356	-2.8448	-4.11388	-2.4414	-4.87334
11550	-3.55046	-3.08148	-3.21218	-4.33209	-2.94178	-4.11619	-2.49313	-4.91975
11600	-3.56131	-3.11912	-3.2288	-4.31592	-2.915	-4.11988	-2.48828	-4.94007
11650	-3.51190	-3.09187	-3.22303	-4.37804	-2.94779	-4.11203	-2.5116	-4.89319
11700	-3.61811	-3.1018	-3.20802	-4.11873	-2.95333	-4.14851	-2.53377	-4.98902
11750	-3.53406	-3.11635	-3.24104	-4.3501	-2.98427	-4.15636	-2.54877	-4.98948
11800	-3.54376	-3.13621	-3.23342	-4.35402	-3.01082	-4.16929	-2.59657	-5.01304
11850	-3.58071	-3.16115	-3.27475	-4.39628	-2.99189	-4.19054	-2.56748	-4.99987
11900	-3.54723	-3.21518	-3.29184	-4.37319	-3.02883	-4.15867	-2.62313	-5.05691
11950	-3.61858	-3.20733	-3.27475	-4.43276	-3.08241	-4.17853	-2.59957	-5.04329
12000	-3.60080	-3.21564	-3.28353	-4.43091	-3.07733	-4.19885	-2.65084	-5.02112
12050	-3.55969	-3.23758	-3.28076	-4.41614	-3.0637	-4.24549	-2.6356	-5.08462
12100	-3.67653	-3.23919	-3.29184	-4.47941	-3.13043	-4.2007	-2.66238	-5.07954
12150	-3.62758	-3.26898	-3.32555	-4.45816	-3.11889	-4.21825	-2.6259	-5.07954
12200	-3.60911	-3.26759	-3.33179	-4.47179	-3.12605	-4.24319	-2.68155	-5.10586
12250	-3.65691	-3.25559	-3.33525	-4.5272	-3.11658	-4.28383	-2.65268	-5.16151
12300	-3.61719	-3.29415	-3.34195	-4.53529	-3.17408	-4.24411	-2.68547	-5.18045
12350	-3.70378	-3.30985	-3.36111	-4.53159	-3.21218	-4.26351	-2.68155	-5.18091
12400	-3.67907	-3.30154	-3.34911	-4.51704	-3.20225	-4.29352	-2.73835	-5.20469
12450	-3.61350	-3.34564	-3.38905	-4.58516	-3.24704	-4.31985	-2.70833	-5.204
12500	-3.68531	-3.37404	-3.38721	-4.58101	-3.20317	-4.30876	-2.79469	-5.20469
12550	-3.66753	-3.39598	-3.44978	-4.56346	-3.24012	-4.33924	-2.75775	-5.26542
12600	-3.76059	-3.37751	-3.41076	-4.57061	-3.26529	-4.28198	-2.80508	-5.24787
12650	-3.70447	-3.39344	-3.45186	-4.63388	-3.27822	-4.27136	-2.77968	-5.27512

12700	-3.71948	-3.40175	-3.44678	-4.64312	-3.32763	-4.34201	-2.83302	-5.24718
12750	-3.74281	-3.4103	-3.46456	-4.64127	-3.36573	-4.33416	-2.79608	-5.27997
12800	-3.70955	-3.43685	-3.45809	-4.62165	-3.34911	-4.36695	-2.84665	-5.33077
12850	-3.80423	-3.46341	-3.50035	-4.62996	-3.35973	-4.39697	-2.82587	-5.27927
12900	-3.71648	-3.53453	-3.51859	-4.61864	-3.39136	-4.32077	-2.86951	-5.36009
12950	-3.79545	-3.51559	-3.51559	-4.69531	-3.39552	-4.40621	-2.85842	-5.33654
13000	-3.79245	-3.50243	-3.48142	-4.68307	-3.42115	-4.42514	-2.84688	-5.36379
13050	-3.76821	-3.50058	-3.50936	-4.75072	-3.45325	-4.40713	-2.85496	-5.3781
13100	-3.81693	-3.54053	-3.52529	-4.69438	-3.43177	-4.45839	-2.86397	-5.33238
13150	-3.78645	-3.57378	-3.56708	-4.72925	-3.46964	-4.46901	-2.95217	-5.36471
13200	-3.82686	-3.60518	-3.60426	-4.75257	-3.46225	-4.46578	-2.90484	-5.37603
13250	-3.79730	-3.61858	-3.57701	-4.77682	-3.4985	-4.48056	-2.95656	-5.41089
13300	-3.85803	-3.62089	-3.58117	-4.78051	-3.48627	-4.46717	-2.90207	-5.46308
13350	-3.80307	-3.61835	-3.57678	-4.832	-3.50266	-4.49857	-2.98473	-5.41528
13400	-3.88043	-3.64698	-3.60495	-4.79275	-3.50497	-4.45793	-2.9778	-5.49725
13450	-3.87766	-3.68115	-3.67815	-4.87033	-3.5179	-4.5055	-2.98519	-5.49564
13500	-3.85041	-3.66684	-3.62943	-4.88881	-3.59803	-4.54291	-2.97827	-5.47509
13550	-3.86773	-3.66684	-3.65737	-4.89689	-3.54469	-4.53505	-2.99443	-5.52104
13600	-3.89867	-3.67792	-3.64513	-4.89412	-3.5657	-4.53783	-3.02468	-5.47093
13650	-3.89867	-3.7054	-3.66383	-4.89458	-3.55023	-4.61125	-3.0196	-5.51942
13700	-3.88505	-3.72918	-3.70494	-4.90266	-3.56893	-4.57015	-3.07017	-5.56422
13750	-3.90329	-3.77998	-3.7151	-4.90751	-3.59387	-4.62927	-3.05585	-5.55036
13800	-3.88366	-3.76543	-3.7465	-4.89273	-3.61488	-4.61356	-3.10388	-5.54574
13850	-3.98503	-3.76936	-3.73588	-4.8955	-3.64282	-4.66113	-3.11496	-5.58431
13900	-3.91021	-3.77329	-3.7622	-4.91121	-3.53845	-4.64681	-3.09834	-5.58477
13950	-3.95847	-3.76313	-3.74803	-4.91213	-3.66568	-4.64774	-3.1145	-5.60463
14000	-3.93792	-3.80169	-3.77805	-4.90751	-3.66915	-4.68792	-3.09049	-5.56745
14050	-3.98965	-3.8354	-3.79745	-4.93383	-3.67169	-4.69069	-3.16576	-5.64596
14100	-3.96633	-3.90306	-3.84826	-4.92575	-3.66545	-4.66298	-3.14845	-5.57645
14150	-3.97325	-3.87073	-3.83141	-4.99941	-3.69547	-4.7304	-3.17731	-5.61479
14200	-4.00142	-3.86727	-3.84203	-4.95277	-3.70771	-4.6639	-3.21333	-5.61756
14250	-3.93238	-3.85133	-3.83326	-5.00103	-3.73934	-4.7438	-3.20964	-5.66628

14300	-4.00489	-3.86473	-3.8492	-5.01904	-3.75066	-4.73456	-3.22234	-5.65242
14350	-4.01135	-3.90583	-3.87946	-5.02389	-3.72733	-4.76689	-3.18655	-5.68845
14400	-4.03375	-3.91922	-3.8947	-5.02019	-3.73911	-4.76873	-3.23665	-5.69699
14450	-4.00396	-3.96586	-3.94343	-5.03128	-3.77282	-4.76088	-3.2385	-5.7404
14500	-4.04414	-3.9564	-3.92819	-5.08831	-3.813	-4.80984	-3.31401	-5.70184
14550	-4.02082	-3.98411	-3.93651	-5.14835	-3.79822	-4.74056	-3.29253	-5.72701
14600	-4.07347	-3.97718	-3.9282	-5.15805	-3.7689	-4.81723	-3.29715	-5.65843
14650	-4.05453	-3.99842	-3.94322	-5.17537	-3.81577	-4.80984	-3.30085	-5.75056
14700	-4.13397	-4.01782	-3.9737	-5.14627	-3.83101	-4.81353	-3.31955	-5.74479
14750	-4.05430	-4.05153	-3.99218	-5.20354	-3.82293	-4.90174	-3.35488	-5.76303
14800	-4.16906	-4.08825	-4.02821	-5.17952	-3.82178	-4.86895	-3.39991	-5.78104
14850	-4.06677	-4.07116	-4.01343	-5.23979	-3.89474	-4.91744	-3.41007	-5.75264
14900	-4.15405	-4.07855	-4.02037	-5.21231	-3.91783	-4.83662	-3.37543	-5.8009
14950	-4.13119	-4.07439	-4.01922	-5.28274	-3.92522	-4.90682	-3.38582	-5.78589
15000	-4.13096	-4.1118	-4.05201	-5.31229	-3.88112	-4.88234	-3.40568	-5.81106
15050	-4.15036	-4.12611	-4.06726	-5.22871	-3.93331	-4.95669	-3.41376	-5.85054
15100	-4.14020	-4.19146	-4.11437	-5.23355	-3.96148	-4.93222	-3.46502	-5.83877
15150	-4.17207	-4.17322	-4.09682	-5.29405	-3.98549	-4.95115	-3.49158	-5.84893
15200	-4.13119	-4.10764	-4.10399	-5.35063	-3.96355	-4.95346	-3.50174	-5.85932
15250	-4.19539	-4.16675	-4.12154	-5.31368	-4.02959	-4.97655	-3.49596	-5.90712
15300	-4.14759	-4.18569	-4.13932	-5.35293	-4.02936	-5.01627	-3.53152	-5.82884
15350	-4.26027	-4.1977	-4.15503	-5.31437	-4.00997	-5.04629	-3.54238	-5.82907
15400	-4.15636	-4.24041	-4.1996	-5.37002	-4.04737	-5.03012	-3.5373	-5.87987
15450	-4.25819	-4.22887	-4.18737	-5.41251	-4.07162	-5.04352	-3.56131	-5.87756
15500	-4.21455	-4.23972	-4.19638	-5.43167	-4.05638	-5.05691	-3.55254	-5.89049
15550	-4.24642	-4.24803	-4.20562	-5.39935	-4.0707	-5.0292	-3.61234	-5.88633
15600	-4.26374	-4.25219	-4.20886	-5.3975	-4.11411	-5.08785	-3.65021	-5.98817
15650	-4.24549	-4.27736	-4.23611	-5.3945	-4.12865	-5.05737	-3.64836	-5.94037
15700	-4.26027	-4.29976	-4.25898	-5.4543	-4.12935	-5.10725	-3.64282	-5.7785
15750	-4.28798	-4.32793	-4.2726	-5.4924	-4.14874	-5.11325	-3.6068	-5.8898
15800	-4.27343	-4.33255	-4.27677	-5.4289	-4.191	-5.09432	-3.64028	-5.93552
15850	-4.22818	-4.32862	-4.28739	-5.41782	-4.17391	-5.08924	-3.66891	-5.93367

15900	-4.27759	-4.34963	-4.29363	-5.51203	-4.20347	-5.14789	-3.73565	-5.93921
15950	-4.26812	-4.3912	-4.32989	-5.48802	-4.21571	-5.15204	-3.75943	-5.97939
16000	-4.29260	-4.43646	-4.38393	-5.49771	-4.23049	-5.12618	-3.71025	-5.96577
16050	-4.26120	-4.41521	-4.35484	-5.47093	-4.22079	-5.12757	-3.70378	-6.00895
16100	-4.33601	-4.41798	-4.36062	-5.55336	-4.27343	-5.213	-3.73357	-6.05213
16150	-4.27875	-4.42768	-4.37286	-5.53073	-4.30969	-5.207	-3.82224	-6.04197
16200	-4.39997	-4.4928	-4.41004	-5.57599	-4.27875	-5.18714	-3.78229	-6.00133
16250	-4.28267	-4.50735	-4.44076	-5.5753	-4.33763	-5.15851	-4.04045	-6.03897
16300	-4.39928	-4.52028	-4.44469	-5.57969	-4.37665	-5.21393	-3.9057	-6.08838
16350	-4.29352	-4.50434	-4.43176	-5.58361	-4.30576	-5.26149	-3.91892	-6.05998
16400	-4.41706	-4.52697	-4.4604	-5.53581	-4.3718	-5.19869	-3.976	-6.11909
16450	-4.31477	-4.57777	-4.49296	-5.594	-4.40413	-5.24764	-3.98875	-6.13987
16500	-4.38935	-4.56807	-4.51421	-5.61871	-4.36233	-5.32199	-4.02551	-6.13687
16550	-4.33024	-4.575	-4.52599	-5.6194	-4.40321	-5.28736	-4.05142	-6.10062
16600	-4.40852	-4.59671	-4.55278	-5.62864	-4.48495	-5.2735	-4.05193	-6.0766
16650	-4.33001	-4.59879	-4.54055	-5.66789	-4.42722	-5.26057	-4.10325	-6.05559
16700	-4.45516	-4.60756	-4.55557	-5.64596	-4.45308	-5.28043	-4.10099	-6.1117
16750	-4.35795	-4.64197	-4.59506	-5.68337	-4.45562	-5.30029	-4.15207	-6.10524
16800	-4.45354	-4.62834	-4.57659	-5.64249	-4.43576	-5.27858	-4.1692	-6.15049
16850	-4.35587	-4.69623	-4.61215	-5.6829	-4.51589	-5.21901	-4.1614	-6.18883
16900	-4.43738	-4.67175	-4.61608	-5.70068	-4.48379	-5.30213	-4.20925	-6.24217
16950	-4.38381	-4.67452	-4.62417	-5.67875	-4.51266	-5.41159	-4.24555	-6.30451
17000	-4.46417	-4.71193	-4.65281	-5.68821	-4.52905	-5.38388	-4.27354	-6.31513
17050	-4.40367	-4.72555	-4.67221	-5.71269	-4.5145	-5.35986	-4.30407	-6.29435
17100	-4.47132	-4.73248	-4.68168	-5.74779	-4.56438	-5.41112	-4.34453	-6.29504
17150	-4.43553	-4.73364	-4.68677	-5.69468	-4.59163	-5.46516	-4.35866	-6.37355
17200	-4.50042	-4.73271	-4.69416	-5.79189	-4.56161	-5.37787	-4.35617	-6.41373
17250	-4.43576	-4.75211	-4.70271	-5.78104	-4.62649	-5.45453	-4.40148	-6.39988
17300	-4.52420	-4.79598	-4.74082	-5.81775	-4.62165	-5.46608	-4.43178	-6.38371
17350	-4.44777	-4.78213	-4.72443	-5.79074	-4.60548	-5.50995	-4.42906	-6.3567
17400	-4.52790	-4.85025	-4.76045	-5.79743	-4.65697	-5.50303	-4.50415	-6.44052
17450	-4.48310	-4.82254	-4.76346	-5.78843	-4.66344	-5.44622	-4.51551	-6.47007

17500	-4.60964	-4.84032	-4.77132	-5.79235	-4.66829	-5.55152	-4.51995	-6.43451
17550	-4.48125	-4.87541	-4.8115	-5.84038	-4.70431	-5.54089	-4.56295	-6.44005
17600	-4.61125	-4.90197	-4.83783	-5.78404	-4.68445	-5.52889	-4.60179	-6.3246
17650	-4.53482	-4.90012	-4.84014	-5.81729	-4.72925	-5.50857	-4.59145	-6.44906
17700	-4.58678	-4.88211	-4.84938	-5.85747	-4.35564	-5.57784	-4.6229	-6.47331
17750	-4.54013	-4.90382	-4.85031	-5.89234	-4.71008	-5.5626	-4.66313	-6.40796
17800	-4.58447	-4.91305	-4.86348	-5.90065	-4.69646	-5.57415	-4.70313	-6.47053
17850	-4.60317	-4.96732	-4.90205	-5.84639	-4.76689	-5.62125	-4.71357	-6.56451
17900	-4.54406	-4.98948	-4.91683	-5.91081	-4.75696	-5.65543	-4.74086	-6.55736
17950	-4.64381	-4.98325	-4.91683	-5.91012	-4.77405	-5.5372	-4.7707	-6.53911
18000	-4.57131	-4.98556	-4.91822	-5.98078	-4.8066	-5.6074	-4.77236	-6.60215
18050	-4.69831	-5.04236	-4.94455	-5.91035	-4.76412	-5.66882	-4.79828	-6.60608
18100	-4.56438	-5.03705	-4.97181	-5.90365	-4.8006	-5.64896	-4.82696	-6.60977
18150	-4.67822	-5.05252	-4.98567	-5.99047	-4.85625	-5.6194	-4.83301	-6.56105
18200	-4.60756	-5.04652	-4.99121	-5.96761	-4.87287	-5.58292	-4.88548	-6.62524
18250	-4.64104	-5.0359	-4.99076	-6.0138	-4.86156	-5.70623	-4.90377	-6.56475
18300	-4.67914	-5.08623	-5.02286	-5.92374	-4.89897	-5.65496	-4.9082	-6.60654
18350	-4.61518	-5.12433	-5.05196	-5.97962	-4.92252	-5.64804	-4.9385	-6.94251
18400	-4.68191	-5.13057	-5.05589	-6.0325	-4.87126	-5.70253	-4.97942	-6.6832
18450	-4.62696	-5.12433	-5.05497	-6.01103	-4.9463	-5.69283	-5.02358	-6.72246
18500	-4.73502	-5.13426	-5.06306	-6.00733	-4.9082	-5.68914	-5.01624	-6.7467
18550	-4.65051	-5.15897	-5.1007	-5.97408	-4.93984	-5.7404	-5.0724	-6.7885
18600	-4.69184	-5.17513	-5.11756	-6.05536	-4.96085	-5.76164	-5.06182	-6.7534
18650	-4.71539	-5.16844	-5.12172	-6.05628	-4.97586	-5.68267	-5.10066	-6.72707
18700	-4.66991	-5.19915	-5.13904	-6.11193	-4.94122	-5.79767	-5.14574	-6.78827
18750	-4.79552	-5.21	-5.1342	-6.11666	-4.98417	-5.73163	-5.14279	-6.81898
18800	-4.74079	-5.23702	-5.16653	-6.05767	-5.00611	-5.70438	-5.16939	-6.8072
18850	-4.69415	-5.23563	-5.16608	-6.11483	-5.02204	-5.7972	-5.22255	-6.80859
18900	-4.77266	-5.26103	-5.20649	-6.07639	-5.00703	-5.74271	-5.2256	-6.83722
18950	-4.75580	-5.28713	-5.21827	-6.11831	-5.06707	-5.76811	-5.25221	-6.86631
19000	-4.78767	-5.2862	-5.20973	-6.09418	-5.05137	-5.75287	-5.27927	-6.82914
19050	-4.82046	-5.32638	-5.24945	-6.14603	-5.10494	-5.51827	-5.33382	-6.85315

19100	-4.74079	-5.31114	-5.26308	-6.1547	-5.09039	-5.75749	-5.32601	-6.82752
19150	-4.84286	-5.30606	-5.2266	-6.1666	-5.11579	-5.72516	-5.35146	-6.89818
19200	-4.83362	-5.35501	-5.2848	-6.14409	-5.04721	-5.83784	-5.37345	-6.89379
19250	-4.77104	-5.36125	-5.30143	-6.21095	-5.12295	-5.77919	-5.43169	-6.93466
19300	-4.90497	-5.33354	-5.27927	-6.17597	-5.12988	-5.78012	-5.42365	-6.93951
19350	-4.80683	-5.41574	-5.33053	-6.21558	-5.1622	-5.84385	-5.47912	-6.96168
19400	-4.81030	-5.43283	-5.3407	-6.20185	-5.14027	-5.83369	-5.47271	-6.92773
19450	-4.93337	-5.40905	-5.32893	-6.23523	-5.15505	-5.83369	-5.50347	-6.94321
19500	-4.88096	-5.43722	-5.35733	-6.23027	-5.17906	-5.82953	-5.53169	-6.94736
19550	-4.81053	-5.39935	-5.36103	-6.29158	-5.18183	-5.90481	-5.59385	-6.92312
19600	-4.93360	-5.455	-5.39429	-6.2476	-5.22617	-5.84431	-5.58628	-6.97253
19650	-4.89273	-5.46239	-5.3936	-6.31538	-5.24741	-5.91081	-5.62327	-7.2517
19700	-4.82692	-5.5275	-5.44856	-6.2781	-5.22062	-5.89834	-5.63071	-7.03903
19750	-4.95046	-5.52404	-5.44349	-6.30709	-5.22709	-5.89095	-5.65916	-7.02218
19800	-4.90959	-5.51988	-5.44072	-6.28043	-5.22524	-5.89557	-5.698	-7.06905
19850	-4.83847	-5.56514	-5.48945	-6.33781	-5.28851	-5.963	-5.72369	-7.06559
19900	-4.97494	-5.5723	-5.49938	-6.37581	-5.27027	-5.89649	-5.74844	-7.05681
19950	-4.86779	-5.55059	-5.48808	-6.32744	-5.29705	-5.94545	-5.76373	-7.06813
20000	-4.83685	-5.56814	-5.51694	-6.37097	-5.30052	-5.92236	-5.7998	-7.0582

APPENDIX B-VMA AND RUTTING MODEL OUTPUTS

Nonlinear Regression for VMA

Iteration Record						
Iteration No.		Residual Sum of Squares	Parameter			
			a	b	C	d
	1	4621.999	0.0	0.0	0.0	0.0
	1.1	17.705	13.851	.000	.000	.000
	2.0	17.705	13.851	.000	.000	.000
	2.1	207.872	25.753	.301	-.093	1.086
	2.2	10.686	15.250	.165	-.118	.165
	3.0	10.686	15.250	.165	-.118	.165
	3.1	9.756	19.437	.231	-.159	.538
	4.0	9.756	19.437	.231	-.159	.538
	4.1	3.950	21.927	.240	-.161	.665
	5.0	3.950	21.927	.240	-.161	.665
	5.1	4.394	26.957	.274	-.124	.906
	5.2	2.920	24.114	.253	-.148	.769
	6.0	2.920	24.114	.253	-.148	.769
	6.1	2.811	28.553	.281	-.115	.960
	7.0	2.811	28.553	.281	-.115	.960
	7.1	1.582	30.871	.291	-.104	1.032
	8.0	1.582	30.871	.291	-.104	1.032
	8.1	1.506	33.553	.305	-.088	1.120
	9.0	1.506	33.553	.305	-.088	1.120
	9.1	1.448	33.674	.304	-.088	1.120
	10.0	1.448	33.674	.304	-.088	1.120
	10.1	1.448	33.674	.304	-.088	1.120
Derivatives are calculated numerically.						
a. Major iteration number is displayed to the left of the decimal, and minor is to the right.						
b. Run stopped after 22 model evaluations and 10 derivative evaluations.						

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	33.674	2.587	28.277	39.071
b	.304	.035	.231	.378
c	-.088	.035	-.162	-.015
d	1.120	.088	.936	1.305

Correlations of Parameter Estimates

	a	b	c	D
a	1.00	.395	.432	.896
b	.395	1.00	.048	.192
c	.432	.048	1.00	.052
d	.896	.192	.052	1.00

ANOVA[a]

	Sum of Squares	Degree of freedom	Mean Squares
Regression	4620.551	4	1155.138
Residual	1.448	20	.072
Uncorrected Total	4621.999	24	
Corrected Total	17.705	23	

Dependent variable: VMA

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .918.

Non-linear Regression for Rutting

Iteration Record

Iteration No.	Residual Sum of Squares	Parameter		
		a	b	c
1.0	273.795	.000	.000	.000
1.1	3.164	5.816	.000	.000
2.0	3.164	5.816	.000	.000
2.1	51.284	14.402	.716	-.325
2.2	2.559	6.692	.156	-.010
3.0	2.559	6.692	.156	-.010
3.1	2.098	8.702	.367	-.052
4.0	2.098	8.702	.367	-.052
4.1	1.428	10.870	.472	-.097
5.0	1.428	10.870	.472	-.097
5.1	1.769	15.223	.586	-.200
5.2	1.033	12.563	.516	-.132
6.0	1.033	12.563	.516	-.132
6.1	.949	15.935	.587	-.205
7.0	.949	15.935	.587	-.205
7.1	.621	17.689	.605	-.228
8.0	.621	17.689	.605	-.228
8.1	.603	21.163	.657	-.283
9.0	.603	21.163	.657	-.283
9.1	.515	22.930	.674	-.302
10.0	.515	22.930	.674	-.302
10.1	.512	23.466	.679	-.308
11.0	.512	23.466	.679	-.308
11.1	.512	23.466	.679	-.308
12.0	.512	23.466	.679	-.308
12.1	.512	23.466	.679	-.308

Derivatives are calculated numerically.

a. Major iteration number is displayed to the left of the decimal and minor iteration to the right.

b. Run stopped after 26 model evaluations and 12 derivative evaluations

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	23.466	6.676	6.305	40.627
b	.679	.173	.235	1.123
c	-.308	.093	-.548	-.068

Correlations of Parameter Estimates

	a	b	c
a	1.00	.456	-.870
b	.456	1.00	.036
c	-.870	.036	1.00

ANOVA[a]

	Sum of Squares	Degree of freedom	Mean Squares
Regression	273.283	3	91.094
Residual	.512	5	.102
Uncorrected Total	273.795	8	
Corrected Total	3.164	7	

Dependent variable: RUT

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .838.