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**Effect of Gradation of aggregates on the rutting performance
of hot mix asphalt**

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A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for Degree of Masters of Science in Civil Engineering (Road and Transport Engineering)

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any other University, and that all sources of materials used for the thesis have been duly acknowledged.

I

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Abstract

High proportion of asphalt mixes is made of mineral aggregates. Therefore, most of the performance problems are directly or indirectly related to the physical and chemical properties of aggregates.

Various studies have shown that the variation in gradation of aggregate have significant effect on the performance of asphalt concrete pavements. This study was intended to investigate the effect of gradation of aggregate (sourced from basalt) in the rutting performance of hot-mix-asphalt.

Using different percentage of the mineral aggregates to be retained on different standard sieve sizes, a number of trial mixes have been prepared using Asphalt Institute and Bailey method of Gradation specification by the standard Marshal Mix design procedure to arrive at asphalt concrete mixtures that fulfill the Marshal criteria.

The effects of each gradation type on Marshal Properties of the asphalt mixtures at their respective optimum asphalt content were evaluated and possible causes for such difference in properties and relationships in between the studied properties was discussed.

Performance tests chosen to measure the permanent deformation of asphalt mixes is wheel tracking tests and Relationship between rutting and factors affecting rutting were studied. Relationships have been developed to predict the impact of Hot Mix Asphalt properties on its permanent deformation behavior.

Changing percentage passing values of different sieves to tolerances value has shown significant change in the rutting performances of HMA. In addition to this, it has been revealed that mixes with coarser gradation showed better resistance against rutting.

When compared to conventional mix by AI gradation, Bailey method of gradation has given good result in rutting performance. Moreover, the CA ratio used in Bailey method has a good R^2 value to forecast the rutting performance.

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Acronyms and Abbreviations

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AI	Asphalt Institute
ASTM	American Society for Testing Materials
D10	Particles at 10% passing
D60	Particles at 60% passing
DSR	Dynamic Shear Rheometer
ERA	Ethiopian Roads Authority
GLWT	Georgia Loaded Wheel Test
HMA	Hot Mix Asphalt
MDL	Maximum Density Line
MEPDG	Mechanistic Empirical Design Guide
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
OGFC	Open Graded Friction Course
SMA	Stone Matrix Asphalt
SUPERPAVE	Superior Performing Pavement
VMA	Voids in Mineral Aggregate
VFA	Voids Filled with Asphalt
VCA	Voids in Coarse Aggregate

1. Background of the study

A conventional flexible pavement consists of a prepared subgrade or foundation and layers of subbase, base and surface courses. The layers are selected to spread traffic loads up to a limit that the carrying capacity of the subgrade is not passed. The surface course consists of a mixture of mineral aggregates cemented by a bituminous material.

HMA wearing courses are the most critical layer in a pavement structure and must be of high quality and have predictable performance.[1]

In hot tropical areas like Ethiopia, where the daily temperature variation is high and traffic flow and loading rate of pavements is more than the capacity it is designed for, problems of rutting and other performance problems should be solved so that the pavement serves the design life. There are several reasons put behind the causes of rutting such as gradation, binder grade, aggregate shape, angularity of fine aggregate, filler type, compaction level, surface temperature, etc. from all these reasons, gradation comes first as it comprises 95% by weight and 85% by volume of HMA.[6]

Rutting of the pavement is basically due to the decrease in thickness of component layers. About 91% of the rutting occurs in the pavement itself: 32% in the surface, 14% in the base, and 45% in the Subbase. Thus, only 9% of the surface rut could be accounted for by the rutting of the embankments. Data also showed that changes in thickness of the component layers were caused not by the increase in density but primarily by lateral movement of materials [34].

Apart from the normal procedure for Marshall Mix design, The Bailey Method is introduced to this research which was originally developed by Mr. Robert Bailey (retired) of the Illinois Department of Transportation. It is a systematic approach to blending aggregates that provides aggregate interlock as the backbone of the structure and a balanced continuous gradation of particles to complete the blend. The method uses dry rodded unit weights of the various materials to estimate the void space between the particles. This available space is then filled with the appropriate size and amount of material without disrupting the “rock on rock” contact of the larger stone which are supposed to bring a rut resistant mixes.[20]

Rut resistant mixes are obtained by making gradation of the mix to the coarser side of the MDL as the stone to stone contact of the aggregate will be highly increased up on increasing the percentage of coarse aggregate fractions in the mix. Moreover, gradation has the highest effect when the general shape of gradation is changed from coarse to fine.

True prediction of HMA behaviors and their precise selection on the basis of performance can be one of the solutions towards this performance problem. At higher

temperatures i.e. 40°C and above, the rutting susceptibility of asphalt mixes needs to be studied in the laboratory before it's laying at site.[13]

1.1 Statement of the problem

Rutting is the main mode of failure in most Ethiopian roads especially those roads associated with extra large axle loads beyond what the road is designed for together with localities exposed to high variation of surface temperature. To solve such problems, which kind of mixes produced by AI or Bailey aggregate specification are more rut resistant mixes? Moreover, does violating the gradation band put by AI specification have a significant effect on the volumetric properties and rutting resistance of HMA?

Gradation specifications are violated from the job mix design in the actual plant mix. However, tolerances are put in the TRL manual for different sieve sizes to conform to the actual job mix design. Does this varying gradation to tolerance value has tolerable change in rutting performance?

Several causes are put to the reasons behind the rutting resistance of hot mix asphalt. Can aggregate structure have a good relationship with the rutting performance of hot mix asphalt at the needed and higher air void percentage in the mix?

As rutting of hot mix asphalt is the major mode of distress in pavement life, it is necessary to pay extra attention to material selection, mixture design and rutting measurement techniques. The questions of what factors of aggregate gradation are best related with development of permanent deformation need to be addressed. Analysis of gradation is generally limited to plotting the percent passing the sieves on the gradation band specified and subsequent adjustments are based on moving this curve to increase or decrease Voids in Mineral Aggregate (VMA). While this goal is generally achieved, it does not address the quality of the mix created related to performance problems.

1.2 Objective of the study

The general objective of the study is to improve the rutting resistance of hot mix asphalt using quality aggregates according to the ERA specification and to study the effect of varying the gradation of aggregates in the rutting performance of hot mix asphalt.

The specific objectives of the study are

- 1) To investigate the effect of varying gradation in the stability, flow and volumetric characteristics of Marshall Mix design and see the effect of these parameters on the rutting performance.
- 2) To develop the relationship between rutting resistance of HMA and different factors of gradation of aggregates as percentage passing values of control sieves, CA ratio in Bailey mixes and gravel to sand ratio.
- 3) To know the effect of gradation envelopes on the rutting performance of AC mix.
- 4) To study the effect of tolerances on percentage passing value of different sieves on the rutting performance of HMA.
- 5) To determine whether there is a potential for the Bailey Method to improve the rutting resistance of Marshall Mixes designed with aggregates commonly available in Addis Ababa. Furthermore, since the primary purpose of the Bailey Method is to create relatively dense HMA mixtures with a high degree of coarse aggregate interlock, such mixes may be well suited for use in intersections where rutting and shoving is a common mode of failure. If mixtures created in this research perform well in rutting performance, then further research into the use of the Bailey Method to create Marshall Mixes specifically for intersections may be justified.
- 6) To suggest a method for selection of gradation for HMA taking advantage of the international research rather than following the traditional criteria such that the selected gradation could be used to predict the properties of asphalt mix before making trials for the job mix.

2. Literature Review

2.1 Introduction

About 85% of hot mix asphalt by volume and 95% by weight consists of mineral aggregate. Hence most of the performance problems are directly or indirectly related to the physical and chemical properties of aggregates [6]. Aggregates are characterized by tests as gradation test, flakiness index, durability, soundness; percent crushed particles of aggregates, unit weight, absorption and voids. [6]

Consensus aggregate properties and source properties are the two SUPERPAVE aggregate quality criteria. Consensus Aggregate properties sited in Superpave mix design method, including coarse aggregate angularity, flat and elongated particles, fine aggregate angularity and sand equivalent were chosen to ensure the aggregate quality. They are sufficient to provide satisfactory HMA performance for the design traffic level.

The specification values for the source properties, including LA abrasion, sulfate soundness, and deleterious materials, are put in the specification of every contract which is supposed to vary according to the properties of locally available materials [6].

From all these tests to characterize the nature of aggregates, gradation comes first as it affects almost all the important properties of HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. The mixture volumetric properties including asphalt content, VMA, and VFA have been identified as important parameters for durability and performance that are highly tied up with gradation of aggregates. However, the VMA is considered the most important parameter.

The link between aggregate gradation and asphalt mixture performance was recognized early in the development of mix design methods. Gradation is the main factor to limit the void space in the mix. VMA and voids in the mix is the main factor behind permanent deformation characteristics of HMA. Gradation should incorporate the most economical aggregates available that are of suitable quality.

2.2 Permanent deformation.

Permanent deformation is a kind of deformation where the pavement layers are not in their original position due to the failure of one or more part of the pavement layers. Viscous materials deform when stressed by external forces which they won't attain their original position when the external load is removed. Whereas, in elastic materials, they still deform when loaded but they return back to their original position when the load is removed. Bitumen is viscoelastic material. Degree of viscosity or elasticity depends on the temperature and period of loading. At high temperature or longer loading time they

behave as viscous liquid and in low temperature or short loading time they behave as elastic solids. [18]

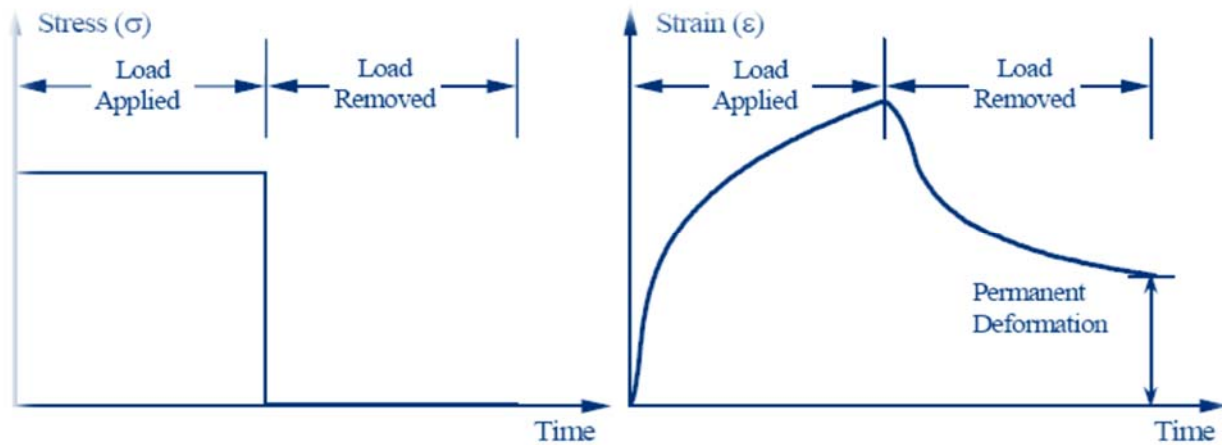


Figure 2.1: Permanent strain under load pulse. (After Gibb, 1996)

In such cases, small amounts of plastic strains are accumulated in the pavement layer. For a 100 penetration bitumen, at a loading time of 0.02sec (which represents vehicular speed of 50 km/hr) the stiffness modulus (S_t is defined as the ratio between the applied stress and the resulting strain at a loading time t) is approximately 10^7 Pa at 25°C but falls to approximately 5×10^4 Pa at 60°C. At low temperatures, the stiffness modulus is high and therefore permanent deformation doesn't occur. However, at high temperature and longer loading time (stationary traffic), stiffness modulus is highly reduced and under such circumstances permanent deformation is more likely to occur. [18]

In the dry season, asphalt pavement easily ruts under heavy or channelized traffic loads. This may cause traffic accidents if the rutting limits are passed. In recent research work, when the air temperature is more than 30°C, surface temperature of asphalt pavement may be up to 50°C or more, which may reach or exceed the softening point of asphalt. [21]

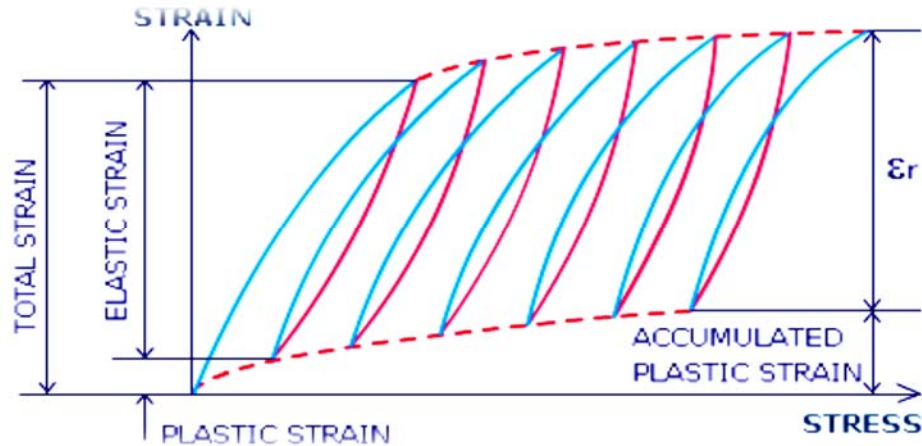


Figure 2.2: Accumulated Plastic strains in Pavements (Asphalt Institute, 1996)

When one thinks of HMA pavement distresses, the following are the most common modes: thermal cracking, rutting, fatigue cracking, raveling, and moisture-induced damage (stripping). Most of the distresses are due to design problems, deficiencies in quality of construction materials or improper maintenance [34].

From the lists of types of permanent deformation, rutting is the main mode of failure in most flexible pavements. Rutting is typically evidenced by a depression near the highest load concentration, i.e. wheel path, without an accompanying hump on either side. Plastic deformation is the result of shear failure within the HMA. It is typically evidenced by a depression where the load concentration is the highest accompanied by a slight hump on each side of the point of highest load concentration. Rutting occurs mainly due to high traffic loads or high surface temperature of the pavement. In many cases ruts are easily observed after a rainfall as it will be easy to see the deformation in the wheel path.

2.2.1 Types of Rutting

Based on different Experimental works and numerical modeling, shear stresses caused by vehicle tire loading produce significant amount of external energy to the mixture which leads to the permanent deformations. There are three different mechanisms that cause these deformations.

The first one is to reduce the friction between aggregates coated with bitumen. Friction resistance in these aggregates like all granular materials is related to their mineral components, roughness, angularity and also bitumen properties.

The second mechanism is defeating the interlock between aggregates that it pushes the aggregates away from each other. Increasing air-void in asphalt mixture is the result of this kind of dilatatory behavior. Quantity of expansion depends on gradation, angularity and the shape of the aggregates.

The third mechanism is the loss of adhesion between aggregate and bitumen in asphalt mixture usually by polarity problem of the bitumen. It is expected that the effect of each mechanism depends on mix design and pavement layer thickness. [10]

Based on the origin of rutting, it may be classified as originating from the surface or the underlying layers. At one extreme, when it is restricted to the uppermost asphalt layer or layers, termed surface rutting. At the other extreme, the main component of deformation arises in the subgrade, and this is termed as structural deformation [17]

2.2.1.1 Rutting by densification

Densification rutting is usually observed when there is additional compaction in the pavement surface or in any of the underlying layers (base, subbase or subgrade) after the road is open to traffic. This may be due to inadequate compaction during the construction phase of the pavement, illegal traffic in unopened roads and traffic loading in the service life as well. Densification, in general, may not be a problem if the asphalt surface is uniformly compacted by traffic as the overall cross-section of the pavement will be to the same finished grade level. However, with the common type of traffic flow where vehicles travel in channelized manner, most of the densification occurs in the wheel path, creating longitudinal ruts.

2.2.1.2 Rutting by raveling

This is a type of rutting caused by the loss of material in the wheel path. Dislodgement of individual aggregate particles under the action of tires occurs mainly due to loss of adhesion between the aggregates and the asphalt binder, when there is inadequate compaction, low asphalt content or excessive aging of the asphalt binder. Ruts caused by raveling tend to be dry and non-uniform.

Rut resulting from the loss of surface material may also be due to abrasion. In this situation aggregate particles wear out if traffic conditions are too abrasive or the aggregates are soft and fail to fulfill the project specification. These ruts are continuous with more resistant aggregates particles exposed and sticking out in the wheel paths.

2.2.1.3 Rutting by shoving

At low air void contents (less than 3%) shear deformation may occur within the asphalt mixture under traffic loading. In this situation pavement material is laterally displaced along shear planes within the mixture, which shows signs of mixture instability or total structural failure. The deformation is usually seen as depression in the loaded area in the wheel path and ridges appear along both edges of the wheel paths. Shear deformation is usually caused by lack of resistance to shear stresses generated in the pavement surface from tire pressures which is mainly due to inadequate load bearing capacity of the pavement by poor aggregate skeleton structure.[27]

Rutting has always been considered as a matter of concern of HMA pavements' performance due to repeated loadings. The rate and depth of rutting depend on external and internal factors. External factors include load and volume of truck traffic, tire pressure, temperature and construction practices. Internal factors include thickness of pavement, bitumen, aggregate and mixture properties.

Thus, finding an exact equation to represent rut depth could be difficult due to the dependence of rutting on several physical, rheological and environmental factors. Also, previous researches illustrated that there is nonlinear relationship between rut depth and time at the beginning of pavement life (first phase), and this trend alters to a linear relationship during the rest service time. [28]

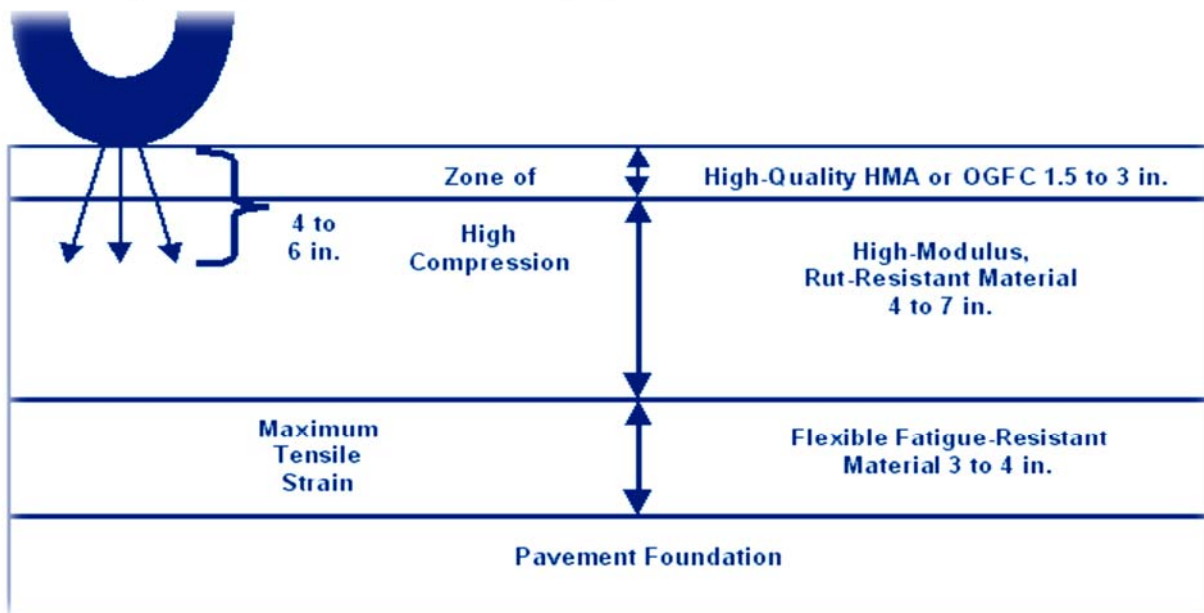


Figure 2.3: Pavement layers and permanent deformation zones.[17]

Rutting may occur in the failure of any of the pavement layers but usually by the lateral movement of surface course. In most areas pavements are susceptible for rutting during winter season when high pavement temperatures are expected and makes the asphalt binder to be less viscous leading most of the traffic load to be carried by the aggregates in the surface course.

Under a given set of material, load and environmental conditions, Mechanistic-Empirical Design Guide (MEPDG) has defined three distinct stages for the permanent deformation behavior of pavement asphalt materials. These are:

- 1) Primary stage has high initial level of rutting, with a decreasing rate of plastic deformations, predominantly associated with volumetric change.

2) Secondary stage has small rate of rutting exhibiting a constant rate of change of rutting that is also associated with volumetric changes; however, shear deformations increase at increasing rate.

3) Tertiary stage has a high level of rutting predominantly associated with plastic (shear) deformations under no volume change conditions as shown in the figure 1.4 [14]

The critical rut depth is generally set at 10 mm, if this depth is reached in the primary phase or in the first part of the secondary phase, the functional life of the Hot Mix Asphalt (HMA) layer is reduced drastically.[34]

In the study made on rutting it was concluded that the load carrying capacity of the asphalt mixtures would depend on different factors related to the aggregate gradation and properties such as the friction of angular particles, aggregate interlock and bonding between bitumen and aggregates in addition to aggregate stiffness. As a result, it can be concluded that the aggregate gradation has a critical role in rutting resistance due to the fact that aggregate structure is the main load carrying component of mixtures [10].

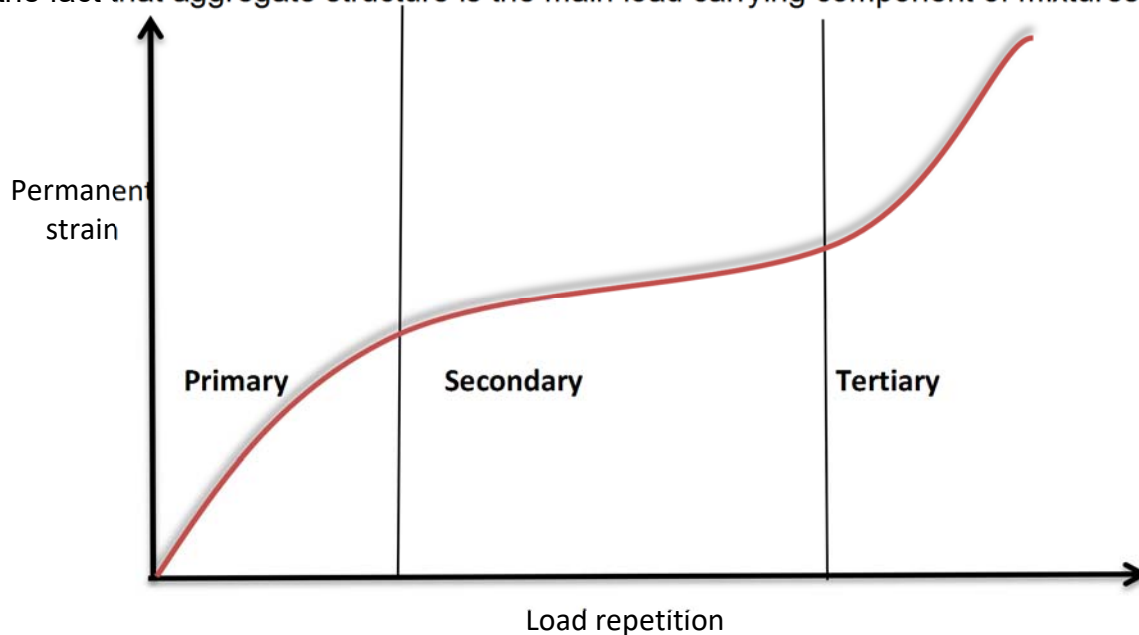


Figure 2.4: Typical Repeated Load Permanent Deformation Behaviors of Pavement materials (AASHTO Design Guide, 2002)

Rutting and moisture-induced damage are not only dependent on the asphalt content but on the characteristics of the aggregates in the mixture as well, and thus a proper selection of aggregates can reduce rutting and moisture induced damage to HMA. For example, rutting can be reduced by the use of large aggregates, and/or angular rough coarse and fine aggregates [32].

Rutting from traffic loading is due to densification and plastic flow of the HMA mixture at high temperatures. Factors such as asphalt content, asphalt grade, air voids and aggregate characteristics, construction practices, temperature, and increase in traffic load/repetitions all have an influence on the rutting potential of a mixture. Although all these factors are important, the effect of aggregates, which comprise up to 90% by volume of the mixture, plays a significant role in controlling permanent deformation.

Kandhal and Parker evaluated the properties of nine coarse aggregate sources. Nine tests were performed to evaluate coarse aggregate shape, angularity, and texture and Rut testing was performed on the nine mixtures using the Super pave Shear Tester and Georgia Loaded Wheel Tester (GLWT). From all the tests made the uncompacted voids in coarse aggregate (VCA) produced the best relationships with the rutting parameters from all nine mixtures [6]

There are several wheel path rutting classifications, one of which was provided in 1979 by the Federal Highway Administration, which classified rutting into three levels of severity:

1. Low, from 6 to 12.5 mm (0.25 to 0.5 inches),
2. Medium, from 12.5 to 25 mm (0.5 to 1.0 inches), and
3. High, over 25 mm (1 inch).

For normal cross slope values, a rut depth of 12.5 mm (0.5 inch) is typically accepted as the maximum allowable rut depth in the design life of the pavement [34]

2.3 Significance of Aggregate characterization

The design of asphalt mixtures has been studied since the 1860's when tar was used in the first bituminous pavements. In the early 1900's Clifford Richardson examined the mixtures and realized the importance of material selection as they comprise high percentage of hot mix asphalt mixture. He pointed out the significant role of aggregate, and VMA in the design of mixes.

Older method for selection of aggregate gradation was initially only used to determine the asphalt demand of the mixture. The need for minimum amount of asphalt binder was recognized and formulas were applied to the gradation for the determination of this amount of asphalt binder to provide adequate durability.

2.3.1 Mineral Aggregates characterization

Aggregates are produced when rocks are broken by a forces on the weak joints formed usually in the weathering process. For quarried aggregates, the crushing process begins with the blast or drilled outputs of hammering machines that turns solid rock into particles of a size range that can be accepted by the primary crusher called "shot rock." Additional crushing of shot rock or gravel is performed

- (1) To reduce the aggregate to product size;
- (2) To improve the aggregate shape; and

(3) In the case of gravel for HMA, to create fractured faces. [6]

Aggregate analysis is dependent to some degree on the source and method of production of aggregates. In smaller operations, aggregates are produced as single aggregate or major aggregates in which fillers may be added; in such instances, uniformly sized aggregates are produced and blended to the needed gradation as per the specification which minimizes wastage. In large scales aggregates from different crusher sites should be blended in trial and error way to fulfill the needed gradation written on the specification. [5]

For good performance of the mix aggregates should be clean and durable. Although aggregates constitute approximately 95% by weight of an HMA mixture, there is no performance grading of aggregates in the Marshall Mix design method. As to many ASTM and AASHTO index tests, ERA manuals also characterizes the qualities of aggregates needed for HMA mixtures; they measure size and gradation, aggregate cleanliness, toughness/hardness, durability soundness, surface texture, particle shape, absorption, and affinity for asphalt. [11]

Table2.1 Specifications of aggregates for surface course of different sources

Property	Test	ERA	UK transport department (1994)	South Africa Manual
Cleanliness(%)	Sedimentation	< 5	>40(SE)	>35(SE)
Particle shape(%)	Flakiness index	<45	<35	<30
ACV(%)	Ten percent fine value	<25	<25	<25
AIV(%)	Aggregate impact test	<25	<25	<25
Abrasion(%)	Los Angeles abrasion	<30	<30	<30
Polishing(%)	Polished stone value	50-75	>45	>50
Durability(%)	Soundness test	12-18	13-17.5	<12
Water absorption(%)	Water absorption	<2	<2	<1
Bitumen affinity(%)	Coating and stripping	>95	>95	>95

The investigation made by National Center for Asphalt Technology (NCAT) in the state of the practice of aggregate characterization, as obtained from a review of specifications from 45 states of America, Aggregate tests for HMA have been categorized as follows. [22] Particle Shape and Surface Texture, Porosity or Absorption, Cleanliness and Deleterious Material, Toughness and Abrasion Resistance, Durability and Soundness, Expansive Characteristics and Polishing and Frictional Characteristics.

The survey of tests and specifications indicates considerable variation. Most of the aggregates tests and/or related specifications have been developed over a period of time. Therefore, there are no standards which are acceptable on a national basis.

According to Irving Kett manual, Specific gravity and absorption tests for fine and coarse aggregate, Los Angeles Abrasion test, Sieve analysis, clay lumps and friable

materials test, density of fillers, sand equivalent value of fine aggregates, shape and texture of aggregates, flat and elongated particle tests are recommended to be conducted. [15]

Coarse aggregates should also fulfill source of aggregates to be sound, unweathered rock or natural gravel. Aggregates must be crushed to produce at least two fractured faces on each particle. Hydrophilic aggregates which have a poor affinity for bitumen in the presence of water should also be avoided. They may be acceptable only where protection from water can be guaranteed. However quarry sites for aggregates can't be obtained as specified to be sound source where the distribution of sound aggregate sources (as basalt and lime stone) is too scarce. In spite of this fact, fulfilling such specification is major task to contractors even in place where such sources are readily available. These tests however, do not give any clear indication of the performance of the aggregates in HMA with respect to permanent deformation. [11]

Clearly, aggregate selection based on the results of proper aggregate tests is necessary for attaining desired performance. Many of the current aggregate tests were developed to empirically characterize aggregate properties without, necessarily, strong relationships to the performance of HMA incorporating an aggregate. There is a need to identify and recommend tests which are related to HMA performance.

2.3.2 Mineral fillers characterization.

Mineral fillers are fine materials added to dense-graded HMA paving mixtures to fill the voids in the aggregate skeleton, to make asphalt mastic that increases the cementitious property of the bitumen and to reduce the voids in the mixture. When asphalt binder is mixed with aggregate, the fines mix with the asphalt binder to form a fines-asphalt mortar. The additions of fines to the asphalt binder can have three main effects: extend the asphalt binder, or stiffen the asphalt binder, or both. This modification to the binder that may take place because of the addition of fines could, in turn, affect HMA properties.

Mixtures prepared with fillers of volcanic-cinder at higher filler contents (5% - 8%), higher optimum asphalt content values were required to fulfill the Marshal requirements which makes them to be uneconomical from practical point of view. Whereas, mixtures prepared with limestone or crushed stone filler, optimum asphalt content are relatively the same. For both types of filler content in the mixture less or equal to 2%, the effect due to filler type is less as the percentage volume of the filler material will be small. [35]

Table 2.2 Recommended aggregates tests (Khandal and Parker 1998).

Aggregate properties	Fatigue cracking	Permanent deformation	Raveling	Stripping
Gradation and size	X	X		
Un compacted void content of coarse aggregate	X	X		
Un compacted void content of fine aggregates		X		
Micro-deval tests			X	
Magnesium soundness			X	
Particle size analysis of P200 materials		X		X

2.4 HMA Mixture Properties

Hot-mix asphalt is a mixture composed of large mass of aggregates and asphalt binder. Theoretically, in the design life of the pavement, traffic loads are carried in the aggregate structures. Such aggregate structure made by cohesion force of aggregate interlock. To support the cohesive force are the asphalt binder as a bonding material to keep the aggregate skeleton together. However, the asphalt binder must be sufficiently strong to resist excessive shear loads generated between the aggregate particles. If the binder is not strong enough, especially in hot weather, rolling tires can dismantle aggregate particles and shear deformation may easily occur. [27]

One can have the image of the effect of aggregate properties on shear strength of mixtures by considering their effect on cohesion and angle of internal friction as illustrated in Figure 1.5.

For a given level of stress, temperature and rate of loading, the shear strength depends on the cohesion and angle of internal friction. The cohesion is affected by the viscosity of asphalt binder and the proportion of fines. The angle of internal friction is obtained from aggregate interlocking. [14]

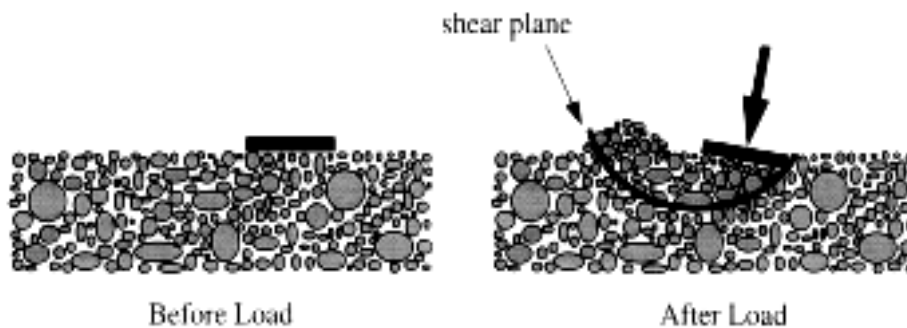


Figure 2.5: Shear Loading Behavior of Aggregate (After Asphalt Institute, 2003)

Many factors can affect the shear resistance of a mix, especially the asphalt binder. Binder film thickness should be adequate for coating the aggregate and providing cohesion, but too much binder can actually have a lubricating effect, reducing the effectiveness of the aggregate skeleton and creating an unstable mix that is prone to premature rutting. A binder content that is too low can leave the aggregates thinly coated, making the HMA susceptible to durability problems.

Binder grade can also affect rutting performance. In general, the higher the binder grade, the stiffer the binder, and the greater the rutting resistance.

Aggregate properties are important as well. In fact, it has been shown that the rutting resistance of a mix may be enhanced more by strengthening the aggregate gradation than by changing the grade or amount of binder. Natural (rounded) sands increase a mixture's susceptibility to rutting. Additionally, the nominal maximum aggregate size can affect wheel tracking results; typically mixes with larger aggregates are more resistant to rutting.

Compaction characteristics, characterized by the rate of densification during laboratory compaction, can also provide information relative to a pavement's resistance to permanent deformation. In theory, the greater the compactive effort required to compact a sample, the greater its shear resistance. Compaction criteria have been specified by Superpave mixture design methods in order to avoid tender mixes and mixes prone to rutting. As a specimen approaches the maximum allowable density at the end of the compaction process, rutting may be more pronounced.

Fibers and polymers can absorb a certain amount of distresses imposed by repetitive traffic loading during service life of pavement. Also, they provide three-dimensional networking effect on the surface of aggregate particles and prevent aggregates from any movement. [28]

Though many factors are known to contribute to rutting, the precise relationships between aggregate-binder interactions and rutting characteristics are still unknown.

2.5 Relation between aggregate gradation and permanent deformation.

The particle size distribution or gradation of an aggregate is one of the most important characteristics in determining how an aggregate will perform as a pavement material. In HMA, gradation helps to determine almost every important property including stiffness, stability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage. [25]

In marshal mix design, Trial aggregate gradation is mixed with varying percentages of asphalt cement and then compacted at a specified temperature level, fixed by the viscosity temperature relationship for the asphalt cement. The voids developed in the compacted samples are then determined and compared to the specification values. [5]

In current Super pave mix design, Asphalt binder testing was implemented to relate the performance of the binder to the climate and traffic level and gradations is from the chart with restricted zone to protect the mix from being tender mix. HMA mixture specifications, VMA (voids in mineral aggregates) requirements for compacted mixtures depend only upon the nominal maximum size of the aggregate in the mixture. Void structure in HMA is dependent upon aggregate gradation as well as nominal maximum aggregate size.

In the study made using different gradations in the gradation band of a specification, [9] reducing the air voids percentage and voids in mineral aggregate up to the certain amount, resilient modulus of the mixture will be increased and therefore deformation and non-recoverable strain will reduce. Gradation curves placed in the upper limit of asphalt mixture design gradation chart show the best performance against rutting while lower curves have the highest amount of permanent deformation.

In the study made using different aggregate source and gradations, study results and their analysis showed that all mixes had higher stability than the minimum acceptable value for mixes subjected to medium traffic. However, for heavy traffic, all mixes presented in the research achieved the minimum Marshall Stability except Basalt mixes with open or coarse gradations and Dolomite mixes with open gradation. Moreover, results showed that rutting resistance of asphalt paving mixes is affected by the mix gradation and type of aggregate. Coarser gradation had the highest resistance to rutting for all types of aggregate, while open graded mixes had the lowest resistance. Dolomite had the highest resistance for all types of gradations. Marshall Flow had the highest linear correlation with rutting, with coefficient of determination (R^2) of 0.74 [10].

The gradation-chart approach developed is a useful tool to evaluate the influence of gradation on HMA performance superior to the traditional approach, based on maximum diameter size and structure of aggregates. Data evaluated in the study made indicated that gravel-to-sand ratio has a marked influence on HMA performance, and also neither maximum-diameter size nor structure have such influence alone.

In an investigation to evaluate the effect of different aggregate gradations on the properties of asphalt mixtures using coarse, fine, and medium gradations and two poorly graded, it was concluded that: Variations in gradation have the greatest effect when the general shape of the gradation curve is changed (i.e., coarse-to-fine & fine-to-coarse gradations) and Fine gradation produced the highest Marshall stability, while the fine-to-coarse poorly graded gradation (with hump at sand sized) produced the lowest Marshall stability [20]

Gravel-to-sand ratio influence on HMA response was evaluated on considerations such as workability and resistance to rutting by means of data collected from related NCAT published works. Results indicate that:

1. Workability diminishes with gravel-to-sand ratio increase;
2. The larger the gravel-to sand ratio, the greater the resistance to rutting [12]

The type of gradation specifications put in to consideration is achieved by the trial and error method or Bailey method for Gradation which is supposed to bring different aggregate structures.

2.5.1 Trial and Error method:

In the trial and error method aggregate from 3 or 4 stockpiles manufactured from the corresponding crushers are mixed on weight basis to fulfill the job mix specification for the needed purpose.

The distribution of particle sizes in an aggregate must have just the right density so that the resulting HMA will contain the optimum amount of asphalt binder and air voids. Because the shape and texture of aggregate particles vary significantly depending on the aggregate type and the way it is mined and processed, specification limits for aggregate gradation tend to be very broad. [26]

The development and evolution of the Marshall Method is based on three criteria in the design mixture: asphalt content, density, and a structural test. Field performance will depend on the highest satisfactory asphalt content at an acceptable density achieved under traffic. In the laboratory the determination of this asphalt content under an appropriate design compactive effort is desired. The Marshall method was developed with a controlling idea that the voids achieved in the laboratory during design must correspond with the density achieved in the field under traffic. Hence, aggregate gradation is adjusted to fulfill such performance specification of the hot mix asphalt.

Generally, trial and error method is used to select the gradation by keeping the gradation curve in the middle of the specified envelope which varies from country to country. This approach sometime brings the gradation line parallel or very close to maximum density line which the gradation curve need to be kept away from the Maximum Density Line (MDL).[5].

2.5.2 Bailey method for Gradation:

Robert Bailey of Illinois Department of Transportation developed a method known as Bailey Method for adjusting the gradation of aggregates. It is a systemic approach to blend aggregates that also provides proper interlocking and packing within the aggregate particles.

The Bailey Method is a systematic method of aggregate blending that focuses on the importance of aggregate interlock and a balanced continuous gradation to create aggregate blends that will provide good performance in an asphalt mixture.

Interlock in the aggregate structure is important to the development of rutting resistance in asphalt mixtures. A continuous gradation allows for the aggregates to be packed tightly, so that a relatively dense aggregate skeleton is developed.

The gradation of the aggregate in an asphalt mixture is vital to both the development of the volumetric properties of the asphalt mixture as well as to the development of interlock within the aggregate structure. The Bailey Method utilizes the relationship between aggregate gradation and mixture volumetric to create aggregate blends that allow for these desired mixtures volumetric to be met as well as provide for the development of valuable coarse aggregate interlock.

He thoroughly elaborated the concept behind the Bailey method. It uses two principles that are the basis of the relationship between aggregate gradation and mixture volumetric:

- ❖ Aggregate packing
- ❖ Definition of coarse and fine aggregate

Bailey approach works based on nominal maximum aggregate size of aggregate (NMAS) to develop aggregate interlock and differentiating aggregate to coarse and fine portion by half sieve, primary control sieve (PCS), secondary control sieve (SCS) and tertiary control sieve (TCS) to develop the appropriate aggregate packing.

The Bailey Method breaks the overall aggregate blend down into two primary divisions, the coarse aggregate and the fine aggregate, based on whether the aggregate particles create voids or fill voids. The fine aggregate division of the blend is then considered separately as if it were a complete aggregate blend and further broken down into a coarse portion and a fine portion of the fine aggregate, again based on whether the aggregate particles create voids or fill voids. As per the definition, coarse aggregate is that portion of aggregate retained on PCS and fine aggregate is that portion passing PCS.

In the Bailey method, coarse-graded mix is defined as mixtures which have a coarse aggregate skeleton. Fine-graded mixtures do not have enough coarse aggregate particles to form a skeleton. The loose unit weight is the lower limit of coarse aggregate interlock. The rodded unit weight is generally considered to be the upper limit of coarse aggregate interlock for dense-graded mixtures. This value is typically near 110% of the loose unit weight. For dense-graded mixtures, the chosen unit weight is selected as a percentage of the loose unit weight of coarse aggregate. If the aim is to obtain some degree of coarse aggregate interlock (as with coarse-graded mixtures), the percentage used should range from 95% to 105% of the loose unit weight.[30]

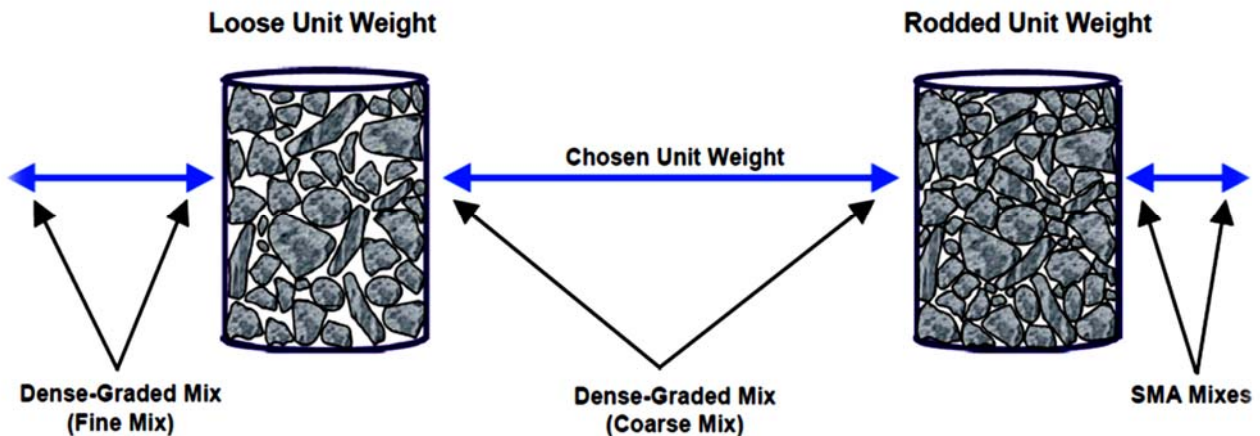


Figure 2.6: Selection of chosen unit weight of coarse aggregate (Vavrik, Pine, and Bailey; 2002)

In the Bailey Method, a particle size ratio is used to quantify particle size and packing. This particle size ratio is the ratio of the diameter of the fine aggregate particle that completely fills a void space to the diameter of the coarse aggregate particles that create the void space. Two - dimensional analyses of particles consisting of both round and flat faces have yielded the following particle size ratios:

- Particles with all round faces - 0.15 particle size ratio
- Particles with two round faces and one flat face - 0.20 particle size ratio
- Particles with one round face and two flat faces - 0.24 particle size ratio, and
- Particles with all flat faces - 0.29 particle size ratio.

The average of these four combinations of two-dimensional particle dimensions is 0.22. This ratio has been found to represent an average gradation relatively well and is considered to be a suitable representation of the randomly shaped particles contained in most aggregate blends for asphalt mixes. [8]

Bailey method of gradation works on the following three ratios, namely

- 1) CA Ratio—This ratio describes how the coarse aggregate particles pack together and, consequently, how these particles compact the fine aggregate portion of the aggregate blend that fills the voids created by the coarse aggregate.
- 2) FAc Ratio—This ratio describes how the coarse portion of the fine aggregate packs together and, consequently, how these particles compact the material that fills the voids it creates.
- 3) FAF Ratio—This ratio describes how the fine portion of the fine aggregate packs together. It also influences the voids that will remain in the overall fine aggregate portion of the blend because it represents the particles that fill the smallest voids created.

It has been determined that the best coarse aggregate structure results when the CA ratio is in the range of 0.40 - 0.80. As the CA ratio of an aggregate blend decreases below 1.0, fewer interceptors are available to limit the compaction of larger coarse aggregate particles, so compaction of the fine aggregate increases. Mixtures with a CA ratio lower than approximately 0.40 may require a stronger fine aggregate structure so that the desired volumetric properties can be attained. At a CA ratio less than 0.40, the resulting asphalt mixture may also become susceptible to segregation.

In this investigation, the Bailey Method generally resulted in gradations that were slightly more continuous in nature as well as located slightly closer to the maximum density line, as would be expected. However, the Bailey Method did not result in gradations that were exceedingly different from the conventional Superpave comparison mixes. This lack of considerable variation of the gradations is the probable reason behind the very similar rutting performance of the comparisons made. [8]

The Bailey Method Analysis Process, which uses three ratios (CA, FAc and FAf) to control the gradation for dense graded mixtures, has proven to be a useful tool. Moreover, the simple analysis process allows the mix designer to make rational decisions regarding adjustments to gradation to enhance the volumetric properties of mixes. [13]

On the study made using aggregates of trial and error and bailey type mix ,even though the Marshall stability of both methods doesn't vary much, the Bailey method predicted an increase in VMA for all the mixtures. But there was a significant decrease in VMA as the mix gets finer. Besides, at 60°C even though the performance of bituminous mix against rutting decreases, Bailey method of gradation showed a better performance than Conventional method of gradation [20]

Based on the results of research made on Bailey method, it appears that the Bailey Method of aggregate gradation selection may provide some degree of improvement to the rutting resistance of Superpave mixes designed with aggregates as they exist in stockpiles common in Arkansas. But, this improvement may be of marginal significance at best from a practical engineering perspective. [13]

2.6 Effect of VMA of mix in the rutting performance.

VMA is defined as the volume of inter-granular void space between the aggregate particles of a compacted asphalt paving mixture that includes the air voids and the effective asphalt content. VMA is calculated on the basis of the bulk specific gravity of the aggregate and is expressed as a percentage of the bulk volume of the compacted paving mixture.

VMA is one of the main criteria for both Marshall and Superpave mix design methods. This is due to the fact that varying the void space in the aggregates can vary the mix stability and durability to a high degree. And VMA is highly dependent on the gradation of the aggregates. The most important characteristic of a gradation is the resulting aggregate voids in the compacted mixture. In spite of this fact, the 'early' Marshall Mix design approach did not have a VMA requirement. Marshall believed no limits can be established for VMA, for universal application, because of the all-rounded application of bituminous materials to many types and gradations of aggregate.

The shift towards a minimum VMA requirement started by McLeod (1955) presented his initial analysis on "the voids properties of compacted paving mixtures", in which he laid out the basic principles of a minimum VMA requirement which he then presented the modified Marshall method that included the VMA requirement.

Hudson and Davis (1965) described an arithmetical method for computing VMA from the aggregate gradation. Using factors for the ratio of percent passing one sieve divided by the percent passing the next smaller sieve. Their procedure differentiated between rounded and angular aggregate. They reached on the conclusion that VMA depended on the following conditions:

1. Particle arrangement or degree of compaction,
2. Relationship between sizes of aggregate particles, in particular the ratio between percents passing adjacent sieves,
3. The range of size between fine and coarse materials, and
4. Aggregate shape. [7]

Volumetric properties of the asphalt mixture, such as voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA) affect the rutting performance of HMA in relation with aggregate interlock. By providing appropriate VMA, it is believed that rutting may be minimized, and mixture durability will be enhanced. However, studies have reported that increased values of VMA may actually have a negative impact on pavement performance with respect to rutting. Both VMA and VFA may be important characteristics, but it is important to remember that these values are functions of other, more fundamental, properties of the asphalt mixture.

Results show further experimentation into the development of asphalt mixtures with coarse aggregate interlock would provide a valuable improvement into the design of asphalt mixtures. Clear trends exist that show an increase in voids in an asphalt mixture with an increase in coarse aggregate. This trend is evident when the volume of coarse aggregate is near to the minimum value necessary for coarse aggregate interlock. [30]

It was found that the interlocking resistance provided by coarse aggregate is the best mechanism for resisting permanent deformation in an asphalt mixture. The interlocking resistance was found to increase with the volume concentration of coarse aggregate in the mixture. When a mixture contains small quantities of coarse aggregate these

particles can be considered to be solids moving in a liquid formed by the asphalt and fine aggregate material. He concluded that this type of mixture will have a decreased resistance to deformation. It was concluded that coarse aggregate affects the properties mainly through the quantity present in the mix, but not through the maximum particle size or gradation [33]

The VMA is considered to be the most important mix design parameter which affects the durability of the asphaltic concrete mix beyond the rutting performance. High VMA values allow enough asphalt to be incorporated into the mix to obtain maximum durability without the mix flushing. Additionally, such mixes have the following advantages compared to low VMA mixes:

1. Lower stiffness modulus at low temperatures. This is helpful in minimizing the severity of thermal and reflection cracking.
2. Lower susceptibility to variations in asphalt and fines content during production. Such variations can cause the mix to be too brittle or too rich. [7]

To investigate the effect of aggregate gradation (particularly the restricted zone) on VMA, 12 mixtures (four aggregate types and three gradations above the restricted zone, through the restricted zone, and below the restricted zone) were used. For river gravel, limestone, and rounded natural sand, HMA mixtures with the gradation passing above the restricted zone required the lowest asphalt content, and mixtures with the gradation passing below the restricted zone had the highest optimum asphalt content. For granite, mixtures with all three gradations required almost the same asphalt content. As expected, naturally round sand with coarse crushed river gravel yielded the lowest optimum asphalt content. [9]

The minimum VMA for the HMA mix used was calculated to be 15.6% to accommodate an optimum asphalt film thickness of 9 microns and 4% air voids. The corresponding Asphalt Institute or Superpave recommendation for minimum VMA is 14% for this mix (maximum nominal size of 12.5 mm). However, it may not be possible to achieve the desired VMA (15.6%) in some dense-graded HMA mixtures of similar gradation. [23]

Based on gradation analysis, it was found that by reducing the air voids percentage and voids in mineral aggregate up to the certain amount, resilient modulus of the mixture will be increased and therefore deformation and non-recoverable strain will reduce. However, for selected gradations in the study made, air voids percentage and VMA could not give a good estimation of rutting. [10]

2.7 Wheel tracking test.

Wheel-tracking tests, or loaded-wheel tests (LWTs), are the most common type of laboratory equipment used for the determination of rutting susceptibility. The LWT offers an excellent opportunity for quantitatively comparing the relative rutting susceptibility of one HMA mix with another. The two main advantages of the LWT are that

- 1) The stress state applied to the sample is somewhat similar to that which occurs in the field, as the lateral support of the mould represents the infinite lateral and longitudinal dimensions assumed in the Bossinesque theory. Moreover, 0.7MPa pressure of the wheel represents the pressure of the standard tandem axle load.
- 2) It is relatively inexpensive and easy to operate. The disadvantage is that no fundamental property, such as resilient modulus, is obtained from this test for use in mechanistic-empirical design models.



Figure 2.7 Wheel tracking test machine

All LWTs operate under the same general premise – a loaded moving wheel travels along the sample lengthwise while applying a load to the sample in order to simulate the actual wheel loads on flexible pavements.

Depressions, or ruts, are created in the sample. The magnitudes of the rut depths are measured and recorded. LWT data can be used to rank the performance of a variety of mixes, or pass/fail criteria can be applied for mixture acceptance. The parameters of air voids and test temperature are usually specified, while other parameters, such as sample type, pressure, load, and length of test can be variable and must be determined based on experience or manufacturer recommendations.[15]

”**Quan Zi Dong Che Zhe Shi Yan Yi**” Rutting analyzer machine is one of the wheel tracking test used to evaluate the rutting performance of HMA in this study. The HMA samples mixed in the laboratory were tested in the “Quan Zi Dong Che Zhe Shi Yan Yi.” The moulds for specimens of the test are made to 300mm width, 300mm length and 50, 80 or 100mm depth which allows variation for surface course, binder course and base course thickness. The sample in the mould will be compacted well enough to represent the field compaction by a kneading type of compactor. After being molded, the test piece together with the mould was laid at normal temperature for at least 12 hours for mixes with unmodified base bitumen. As for polymer modified bituminous mixtures, they should be laid at normal temperature for at least 48 hours, the polymer modified bitumen solidify sufficiently before it is used in rutting test, but the storage period at room temperature shall not be longer than one week.



Figure 2.8 Kneading type compactor used in the rutting test apparatus. [31]

Then the rut depth will be measured for the prevailing wheel load and temperature. The test temperature and wheel pressure in rutting test may be adopted according to relevant regulations and requirements, and the test temperature taken was 60°C and the wheel pressure was 0.7MPa to represent the ideal wheel pressure exerted by a representative axle load. As it is required, the test temperature may be 45°C at cold district and be 70°C at hot conditions. In principle, the dynamic stability shall be calculated 45min to 60min after the test starts.

In the Quan Zi Dong Che Zhe Shi Yan Yi wheel tracking test, there is a wheel to represent the actual wheel load. Test wheel: Rubber solid tyre, which is 200mm in outside diameter and 50mm in width, and the thickness of rubber layer, is 15mm. The hardness of rubber (international standard hardness) is 84 ± 4 at 20°C and is 78 ± 2 at 60°C. As for the test wheel, its traveled distance is $230\text{mm}\pm 10\text{mm}$, the reciprocating rolling velocity is 42 ± 1 per min (21 reciprocations per min).

It is permissible to activate the test bed (the test wheel does not move) with crank connecting link or activate the test wheel with chains (the test bed does not move).



Figure 2.9 wheel in Quan Zi Dong Che Zhe Shi Yan Yi apparatus [31]

The repetition and load of this wheel will be adjusted based on the design of the road. In the equipment the temperature is also adjusted based on the actual temperature of the road to be constructed. The temperature transducer and thermometer that automatically detect and record the temperature at test piece surface or in thermostatic chamber, which are accurate to 0.5°C The testing equipment is connected to a computerized device for tabulation of the results.[31]

2.8 Summary

As aggregates comprise 95% by weight of the HMA, gradation of aggregates is taken as the main reason behind performance problems. Different factors that are supposed to change with varying gradation are thoroughly discussed in this chapter. Such factors include filler content, different mixture properties as Marshall Stability and VMA.

Two types of gradations selection methods are studied in this section. The AI and Bailey methods of gradation and the effect of varying gradation on the rutting performance is clearly visualized in this section.

Different mechanisms and modes of rutting are clearly discussed in this section. these includes: rutting by breaking the interlock, reduction of friction and breaking adhesion forces and of these factors surface ruts mainly happen by lateral movement of materials by breaking the interlock keeping all the underlying pavement layers are in their original position. Even though gradation of aggregates is the main factor that affects performance of HMA, rutting is a complex phenomenon in which a single factor is not fully in charge to the rutting action. Instead, one major factor (gradation) triggers the effect of other factor that aggravates the rutting action.

3. Research Methodology

3.1 Introduction

This study involves investigating the relationship between Marshall Mix volumetric properties, gravel to sand ratio, gradation curve structures and the rutting performance of hot mix asphalt designed in Marshall Mix using aggregates of different gradation specifications.

The study involves preparing several types of mixes using the same type of Asphalt binder, varying gradation and percentages of fine and coarse aggregates and the same type of natural filler materials.

Sample of aggregate for the intended surface mix design is to be obtained from Addis Ababa in Lebu site for the construction of Megenagna Tor Hayloch LRT project. The site is selected in this study for it can represent the rock source for good quality basalt aggregates. In addition, roads susceptible to rutting can be observed in the vicinity where axle loads are supposed to be high and slow moving or stationary traffics are observed due to traffic congestion and turning traffics exert extra shear force on the road in round about which leads to deformations. Filler materials are selected to be produced from natural aggregates and collected from the same Quarry site (Lebu). Bitumen of grade 85/100 penetration grade is selected in the study and obtained from CRBC in the same project.

These ingredient materials were subjected to various laboratory tests in order to determine their physical properties whether they can meet common specification limits. These quality assurance tests conducted on the aggregates include: Los Angeles abrasion, soundness, flakiness, aggregate crushing value, specific gravity and water absorption tests. The tests carried out on the asphalt cement sample include: penetration, flash point, ductility, durability, purity and specific gravity. The results obtained are indicated in the subsequent sections.

Test specimens are then prepared with various gradation for Marshall Mix design in order to find the optimum bitumen content.

Using the obtained optimum bitumen content and varying the gradation to the finer and coarser side of aggregate specification band and leaving all other ingredients to the mix to be constant, the effect of aggregate gradation on the rutting performance is studied using rutting analyzer machine.

3.2 Characteristics of materials

It is recommended that the physical properties of component material of the hot mix asphalt meet all the requirements (which varies based on different specifications) to ensure the material has good performance.

3.2.1 Mineral Aggregates

Typically the qualities required of aggregates are described in terms of shape, hardness, durability, cleanliness, bitumen affinity and porosity. As a general guideline, the coarse aggregates used for making HMA should be produced by crushing sound, unweathered rock or natural gravel. Gravel should be crushed to produce at least two fractured faces on each particle, be clean and free of clay and organic material; be angular and not excessively flaky; be strong; be resistant to abrasion and polishing when exposed to traffic; be non absorptive; and have good affinity with bitumen. To investigate the physical properties of the aggregates and their suitability in road construction, various tests were conducted and the results are indicated in Table 3.1

Table 3.1 Test results and specifications for aggregate characterization

SN	Test Description	Test Method	Result	Specification
1	Cleanliness& deleterious material (%)	AASHTO T176	48	>40
2	Los Angeles Abrasion (%)	AASHTO T96	13	<30
3	Durability and Soundness (%)	AASHTO T104	2	<12
4	Bulk specific gravity Coarse Aggregate	AASHTO T85	2.63	-
	Fine Aggregate	AASHTO T84	2.57	-
5	Ten Percent Fine Value TFV (KN) dry	BS812 part111	240	>140
6	Aggregate crushing value ACV (%)	BS812 part110	12	<25
7	Water Absorption (%)	ASTM C127	1.27	<2
8	Affinity for asphalt (coating and stripping) (%)	AASHTO T182	99	>95

The coarse and fine aggregate particles were separated into different sieve size. Proportioning is done first by drying aggregates to constant weight at 105°C to 110°C and separated by dry sieving to desired size fractions to meet the needed gradation for bituminous mixtures of 12.5mm nominal maximum aggregate size surface course. The recommended sieve size fractions according to the crusher output are:

Less than 3 mm
3 to 6 mm
6 to 14 mm
14 to 25 mm

And

The test is carried out for five types of mixes which are believed to show the gradation variability to study its effect in rutting performance. These are

- 1) Dense Graded Mix
- 2) Coarser Dense Graded Mix
- 3) Finer Dense Graded Mix
- 4) Finer Dense Graded Mix (Bailey Type)
- 5) Coarser Dense Graded mix (Bailey Type)

A dense-graded mix is a well-graded (even and continuous distribution of aggregate particles from coarse to fine). Properly designed and constructed dense HMA mixtures are relatively impermeable. Aggregate gradation specification for dense graded hot mix asphalt is prepared in two approaches.

3.2.1.1) Asphalt Institute (AI), 1994 specification:

Particle size distributions recommended by the Asphalt Institute for wearing course layers is shown in Table 3.2

Table 3.2 Gradation specification for dense graded mix [1]

test sieve mm	ASTM D3515	South Africa manual
25	100	100
19	100	100
12.5	90-100	90-100
4.75	44-74	54-75
2.36	28-58	38-57
0.3	5-21	13-23
0.075	2-10	4-10

Dense-graded mixes can further be classified as either fine-graded or coarse-graded. Simply put, fine-graded mixes have more fine sand size particles than coarse-graded mixes. Table 3.3 can be used to define whether a dense mix is coarse or fine-graded.

Table 3.3 classification of dense graded mix for different NMAS

NMAS	Coarser Dense graded		Finer Dense Graded	
	Control sieve(mm)	Percentage passing	Control sieve(mm)	Percentage passing
37.5	4.75	<35	4.75	>35
25	4.75	<40	4.75	>40
19	2.36	<35	2.36	>35
12.5	2.36	<40	2.36	>40
9.5	2.36	<45	2.36	>45

Based on findings cited in the literature review of this paper, coarseness of a mix is best suited for rut resistance. The coarser a mix becomes the best potential of rut resistance it will attain. Four different types of mixes are prepared to study the effect of degree of coarseness on the rutting performance of HMA based on the above definition for coarseness.

Four different types of aggregate gradations are selected in this study. From the gradations three of them are coarse type gradation and the remaining one is fine graded mix based on the classification scheme presented in table 3.3. Coarse1 mix type is middle line of gradations envelopes specified by AI.coarse2 and coarse 3 are obtained by rearranging percentage passing values of AI aggregate gradation specifications. Coarse 4 is middle line of Superpave aggregate gradation that passes just below the restricted zone.

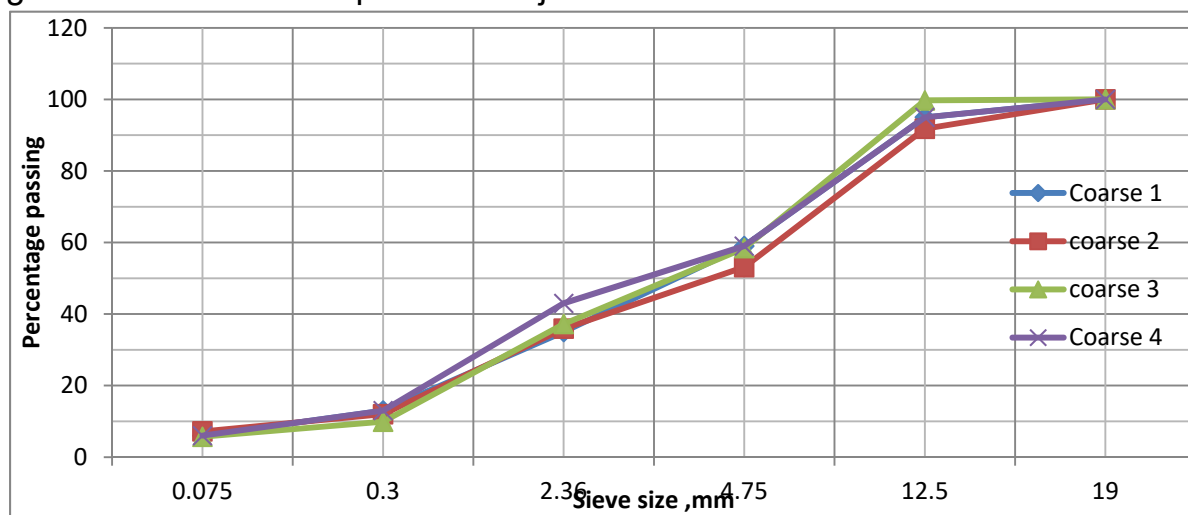


Figure 3.1 Gradation curves of aggregate for conventional mixes

Table 3.4 variations of aggregate gradation for dense graded mixes

Sieve size (mm)	Coarse 1 dense mix (percent finer)	Coarse 2 dense mix (Percent finer)	Coarse 3 dense mix (percent finer)	Coarse 4 dense mix (percent finer)
19	100	100	100	100
12	95	91.8	99.7	95
4.75	59	53.1	58.4	59
2.36	35	35.9	37.2	43
0.3	13	12	9.9	13
0.075	6	7.2	5.7	6

After establishing the job mix design from the specification envelopes in the plant mix design, tolerances are usually put to the composition of the plant produced. It is required to fulfill the Marshall and volumetric properties over the tolerances provided by making gradation charts coincide or be parallel with the intended job mix or original mix.

Table 3.5 Tolerances put for percentage passing of aggregates on different sieves (1)

test sieve mm	Percentage passing
>12.5	±8
9.5	±7
4.75	±7
2.36	±6
0.3	±5
0.075	±3

Taking the coarse 1 mix as a base mix and varying the percentage passing values for each sieve within the tolerance in table 3.5 and by keeping the new gradation curve to be nearly parallel to the base mix curve, the gradation for the trial mixes are tabulated as below. Rutting test Results from the modifications of the gradation are correlated with the test results of the base mix and the effects are thoroughly studied in the next chapter.

Table 3.6 Variation of aggregate gradation with tolerances in different sieves and with the same optimum bitumen content.

Sieve size (mm)	Base mix	Coarse 1-1	Coarse 1-2	Coarse 1-3	Fine 1-1
	Percentage finer				
25	100	100	100	100	100
19	100	100	100	100	100
12	95	93	93	97	97
4.75	59	55	57	63	65
2.36	35	31	33	39	41
0.3	13	9	11	17	18
0.075	6	4	6	9	9

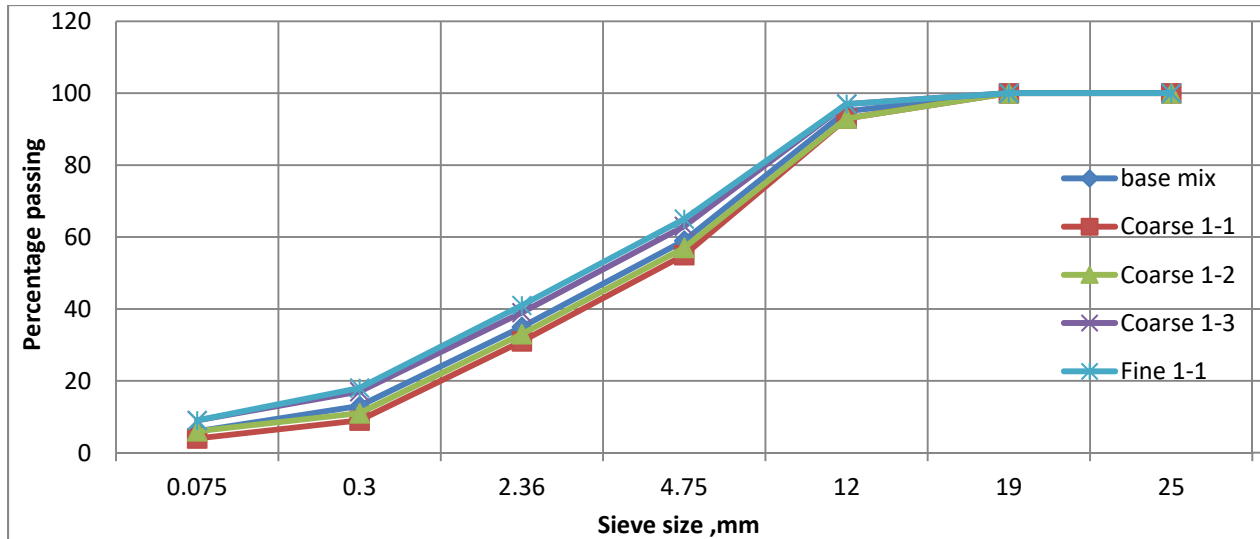


Figure 3.2 Gradation curves by varying percent passing to tolerance value

3.2.1.2 Bailey method for Gradation.

Bailey approach works based on Nominal Maximum Aggregate Size of aggregate(NMSA) to develop aggregate interlock and differentiating aggregate by half sieve, Primary control sieve(PCS), Secondary control sieve (SCS) and Tertiary control sieve (TCS) to develop the appropriate aggregate packing.

NMAS is defined as one sieve-size larger than the first sieve size to retain 10% or more of the total aggregate by mass.

$$\text{NMSA} = 12.5\text{mm}$$

$$\text{Half Sieve} = 0.5 * \text{NMSA} = 4.75\text{mm} \text{ ****}$$

$$\text{PCS} = \text{NMSA} * 0.22 = 2.36\text{mm}$$

$$\begin{aligned} \text{SCS} &= \text{PCS} * 0.22 && = 0.6\text{mm} \\ \text{TCS} &= \text{SCS} * 0.22 && = 0.15\text{mm} \end{aligned}$$

**** The nearest “typical” half sieve for a 12.5 NMPS mixture is 6.25mm. However, the 4.75mm sieve actually serves as the break point. Interpolating the percent passing value for 6.25mm sieve for use in CA Ratio will provide a more representative ratio value.

The packing within the aggregate is evaluated by following three ratios:

- **Coarse Aggregate ratio (CA Ratio) = (% Passing Half Sieve - % Passing PCS) / (100 - Passing half Sieve).....3.1**
- **Fine Aggregate Coarse Ratio (FAc Ratio) = % passing SCS / % passing PCS.....3.2**
- **Fine Aggregate Fine Ratio (FAf Ratio) = % passing TCS / % passing SCS.....3.3**

The specification for the bailey criteria is presented in the table

Table 3.7 Ratio guideline for coarse graded dense mix [30]

NMAS(mm)	37.5	25	19	12.5	9.5	4.75
CA Ratio	0.8-0.95	0.7-0.85	0.6-0.75	0.5-0.65	0.4-0.55	0.3-0.4
FAc Ratio	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5
FAf Ratio	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5

Table 3.8 Ratio guideline for fine graded dense mix [30]

NMAS(mm)	37.5	25	19	12.5	9.5	4.75
CA Ratio	0.6-1	0.6-1	0.6-1	0.6-1	0.6-1	0.6-1
FAc Ratio	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5
FAf Ratio	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5	0.35-0.5

Maximum Density Line (MDL) is an important parameter that needs to be watched carefully and bailey gradation curves are prepared relative to this line. Maximum density line involves particle arrangement where smaller particles are packed between the larger particles which reduce the void between particles

producing more particle to particle contact. A widely used equation to describe the maximum density gradation is given by:

$$P = (d/D)^n \dots\dots\dots 3.4$$

Where

p= Percentage finer than the sieve

d= Aggregate size being considered

D= maximum aggregate size of aggregate used

n= Parameter that adjusts curves for fineness and coarseness for maximum density n= 0.45 is used by Federal High Way Administration.

Table 3.9 The maximum density line for aggregate gradation

Sieve(mm)	0.075	0.15	0.6	2.36	4.75	12.5	19
MDL (%)	8.3	11.3	21.1	39.1	53.6	82.8	100

With this MDL as a reference, Bailey trial mix of aggregate is prepared to study the effect of varying gradation in relation with the Asphalt Institute gradation specification.

Table 3.10 Aggregate gradation for Bailey trial mix 1

Bailey Trial mix 1						
Sieve(mm)	Percentage passing	Slope of MDL	Slope of trial mix	CA ratio	FAC Ratio	Faf Ratio
19	100	2.65	2			
12.5	90	3.77	3.24	0.975	0.425	0.423
4.75	61.9	6.07	9.16	Needed specification		
2.36	40	10.22	13.07	0.575	0.425	0.425
0.6	17	21.78	21.77			
0.15	7.2	40	29.33			
0.075	5					

In the trial mix 1 the gradation curve is made in which the coarser sieves are on fine side of MDL and finer sieves on coarser side and crosses the MDL somewhere near the boundary of the coarse and fines making an S-curve. The gradation fits the Asphalt Institute gradation specifications but violates the CA ratio of Bailey Gradation Specifications as coarse aggregates retained in interceptors(Aggregates passing half sieve but retained on PCS) are much in percentage.

The regression line fit to the gradation curve is 4th degree polynomial function

$$y = -0.0022x^4 + 0.1125x^3 - 2.1171x^2 + 19.815x + 4.3731 \dots \dots \dots \mathbf{3.5}$$

Where y= Percentage passing value and X= Sieve size (mm)

Finding the percentage finer value for x= sieve size= 6.25mm, y=69.62

And the corresponding CA ratio= (69.62-40)/ (100-69.62) = 0.975

Table 3.11 Aggregate gradation for Bailey trial mix 2

Bailey Trial mix 2						
Sieve(mm)	Percentage passing	Slope of MDL	Slope of trial mix	CA ratio	F _{Ac} Ratio	F _f Ratio
19	100	2.65	1.54			
12.5	90	3.77	3.77	0.66	0.611	0.654
4.75	60.8	6.07	6.07	Needed specification		
2.36	46.3	10.22	10.23	0.575	0.425	0.425
0.6	28.3	21.78	21.78			
0.15	18.5	40	113.33			
0.075	10					

Trial mix 2 is prepared to study the effect of gradation curve parallel to the maximum density line on volumetric properties and rutting performance. This value doesn't fulfill the criteria for Bailey's principle though they fit the gradation band of the Asphalt Institute specification.

The regression line fit to the gradation curve is power function

$$y = 33.001x^{0.3929} \dots \dots \dots \mathbf{3.6}$$

Where y= Percentage passing value and X= Sieve size (mm)

Finding the percentage finer value for x= sieve size= 6.25mm, y=67.8

And the corresponding CA ratio= (67.8-46.3)/ (100-67.8) =0.66

Table 3.12 Aggregate gradation for Bailey trial mix 3

Bailey Trial mix 3						
Sieve(mm)	% passing	Slope of MDL	Slope of trial mix	CA ratio	FAC Ratio	Faf Ratio
19	100	2.65	3.08			
12.5	80	3.77	1.94	0.75	0.5	0.491
4.75	65	6.07	7.95	Needed specification		
2.36	46	10.22	13.07	0.575	0.425	0.425
0.6	23	21.78	26			
0.15	11.3	40	44			
0.075	8					

Trial mix 3 is prepared to fulfill FAC and Faf ratio of the bailey’s criteria but slightly higher value of CA ratio which leads the mix to be finer Bailey mix. Besides, this gradation curve doesn’t fulfill the asphalt institute gradation specification. Here the gradation is made to be vice versa of the criteria for best bailey mix i.e. to be on the coarser side of MDL for the coarser sieves and finer side of the MDL for the finer sieves.

The regression line fit to the gradation curve is 4th degree polynomial function
 $y = -0.0043x^4 + 0.2003x^3 - 3.2383x^2 + 23.276x + 7.8191$**3.7**

Where y= Percentage passing value and X= Sieve size (mm)

Finding the percentage finer value for x= sieve size= 6.25mm, y=69.14

And the corresponding CA ratio= (69.14-46)/ (100-69.14) = 0.75

Table 3.13 Aggregate gradation for Bailey trial mix 4

Bailey Trial mix 4						
Sieve(mm)	% passing	Slope of MDL	Slope of trial mix	CA ratio	FAC Ratio	Faf Ratio
19	100	2.65	2			
12.5	87	3.77	4	0.582	0.436	0.441
4.75	56	6.07	7.11	Needed specification		
2.36	39	10.22	12.5	0.575	0.425	0.425
0.6	17	21.78	21.11			
0.15	7.5	40	33.33			
0.075	5					

In the trial mix 4(ideal bailey gradation), the gradation curve is made in which the coarser sieves are on fine side of MDL and finer sieves on coarser side and crosses the MDL somewhere near the boundary of the coarse and fines making an S-curve. The percentage finer value for 12.5 sieve is made to be out of the Asphalt Institute gradation band to study the effect on volumetric properties and rutting performance in comparing bailey and the Asphalt Institute specification

The regression line fit to the gradation curve is 4th degree polynomial function $y = -0.0057x^4 + 0.2277x^3 - 3.1174x^2 + 21.131x + 4.2705$3.8

Where y= Percentage passing value and X= Sieve size (mm)

Finding the percentage finer value for x= sieve size= 6.25mm, y=61.64

The corresponding CA ratio = $(61.46-39) / (100-61.46) = 0.582$.

The gradation curves for the four trial mixes are prepared in the graph below.

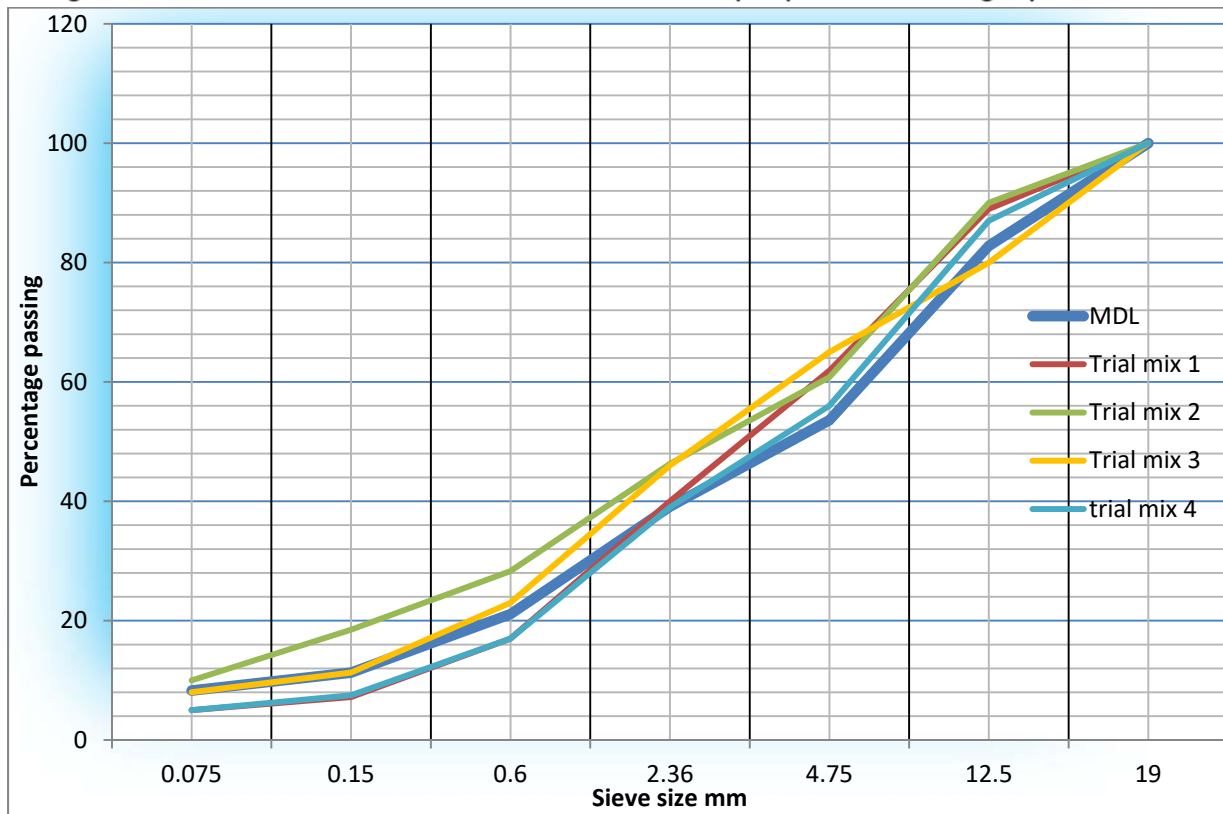


Figure3.3 Gradation curves for different Bailey trial mixes

3.2.2 Mineral Fillers

Mineral fillers are the part of mineral aggregates, they fill voids and provide contact points between larger aggregates particles and thereby strengthen the mixture. Utmost efforts were made to ensure less organic material passing sieve no. 200 (75µm) having plasticity index (PI) less than 4 and test result showed that filler material are totally non plastic (NP).

The mineral fillers used in the current study namely crushed stone is all materials passing No. 200 sieve. The physical property, which is believed to be major suspects of affecting the bituminous mixture property, such as plasticity index, was determined.

3.2.3 Bitumen properties

An asphalt binder of grade **85/100** penetration was used in the preparation of the trial mixes since it is widely used and acceptable for temperature condition of colder regions of Ethiopia like Addis Ababa. It was then tested in the laboratory to determine its physical properties, where the summary of test results obtained are as shown in table 3.14

Table 3.14 Test results and specifications for bitumen

SN	Test description	Test Method	Specification	Test Result
1	Penetration	AASHTO T49	85-100	90
2	Flash point (°C)	AASHTO T48	232	320
3	Ductility (cm)	AASHTO T51	100 min	100+
4	Durability (%)	AASHTO T179	1 max	0.2
5	Purity (%)	AASHTO T44	99	99.8
6	Specific Gravity	AASHTO T228	-	1.01
7	Softening point	AASHTO T53	42-51	48

3.3 Marshal Mix design for hot mix asphalt.

Marshal Mix Design method was used to determine the optimum asphalt content and evaluate the stability of the mixtures in the laboratory. In Marshall Mix design a series of five test specimens were prepared by increasing the bitumen content by 0.5% for each specimen with two specimens above and two specimens below the expected design bitumen content. The “expected design bitumen content” depends upon the experience with the particular aggregate which was estimated by the empirical formula

$$\text{DBC} = 0.035a + 0.04b + Kc + F [5] \dots \dots \dots 3.8$$

Where, DBC = approximate design bitumen content, per cent by total weight of mix

a = per cent of mineral aggregate retained on the 2.36mm sieve

b = per cent of mineral aggregate passing the 2.36mm sieve and retained on the 0.075mm sieve

c = per cent of mineral aggregate passing the 0.075mm sieve

K = 0.15 for 11-15% passing the 0.075mm sieve; 0.18 for 6-10% passing the 0.075mm sieve; 0.20 for 5% or less passing the 0.075mm sieve;

F = 0-2%. Based on absorption of bitumen. In the absence of other data, a value of 0.7 is suggested.

The amount of aggregate required for each sample was that mass of aggregate that will be sufficient to make compacted specimens 63.5 ± 1.27 mm high. This was normally approximately 1.2kg and for the whole test 25 kg and one gallon of bitumen was prepared.

Reference was made to the Temperature-Viscosity Chart, ASTM Designation D2493, for the AC being used. The temperatures selected for both mixing and compaction were those that allow the asphalt viscosities of (a) mixing, 170 ± 20 centistokes; and (b) compacting, 280 ± 30 centistokes. The aggregates were dried to a constant weight and heated to 163°C . As per the ASTM D2493, the mixing and compaction temperatures are 135°C and 125°C respectively.

Equipments (molds, hammers, and other tools) used in the preparation of the specimens were kept clean and maintained at a temperature of 93°C to 149°C (100°C in this case) and were compacted using a 75 blows on either sides of the specimen to simulate vehicular compaction by heavy traffic load. After compaction, the specimen were allowed to cool and removed from the mold by means of an extrusion jack.

The specimens were heated in a constant temperature water bath for 30 to 40 minutes at 60°C . It was then placed in a Marshall testing machine, where reading of stability and flow are simultaneously taken.

Table 3.15 mix property result evaluation for Marshall Mix [5]

Traffic condition	Light traffic		Medium Traffic		Heavy Traffic	
	Min	Max	Min	Max	Min	Max
No. of blows by Marshall compaction hammer	35		50		75	
Stability (N)	3336		5338		8006	
Flow (0.25mm)	8	18	8	16	8	14
Air void (%)	3	5	3	5	3	5
VFA (%)	70	80	65	78	65	75
VMA(%) for 4% air void & 12.5mm NMA	14	---	14	---	14	---

After selecting the optimum bitumen content using Marshall Mix design procedure, the aggregate gradation is allowed to vary within the limit listed in the table 3.3 and prepared for rutting analyzer testing machine accordingly. In the same manner, optimum bitumen contents for bailey trial mixes are calculated as per the specifications in the table 3.15 and volumetric property, stability, flow and density of the mix at optimum bitumen content are evaluated and calculated for further correlation between rutting, volumetric properties and gradation of aggregates results are checked if they meet specifications or not.

3.4 "Quan Zi Dong Che Zhe Shi Yan Yi" Rutting analyzer machine

The moulds for specimens of the test are made to 300mm width, 300mm length and 50mm thickness for wearing coarse. The sample in the mould will be compacted well enough to represent the field compaction by a kneading type of compactor with 12 passes on both sides for wearing course. After being molded, the test piece together with the mould was laid at normal temperature for at least 12 hours.

Then the rut depth will be measured for the prevailing wheel load and temperature. The test temperature and wheel pressure in rutting test may be adopted according to relevant regulations and requirements, and the test temperature taken was 60°C and the wheel pressure was 0.7MPa to represent the ideal wheel pressure exerted by a representative axle load. In principle, the dynamic stability shall be calculated 45min to 60min after the test starts.

In the Quan Zi Dong Che Zhe Shi Yan Yi wheel tracking test, there is a wheel to represent the actual wheel load. Test wheel: Rubber solid tyre, which is 200mm

in outside diameter and 50mm in width, and the thickness of rubber layer, is 15mm. The hardness of rubber (international standard hardness) is 84 ± 4 at 20°C and is 78 ± 2 at 60°C . As for the test wheel, its traveled distance is $230\text{mm}\pm 10\text{mm}$, the reciprocating rolling velocity is 42 ± 1 per min (21 reciprocations per min).

3.5 Conclusion

Asphalt concrete mixes with aggregates from the same source (the same physical and chemical properties) and bitumen of 85/100 penetration was prepared with varying gradation by changing the percentage passing of different sieves.

Both conventional gradation types with varying percentage passing in different sieves and bailey type gradation were prepared in the study and the mix is prepared in the Marshall method of mix design. The optimum bitumen content for the different gradation type was obtained and the result was taken to prepare samples for the evaluation of the rutting performances of the corresponding mix types.

4. Results and Discussions

4.1) General

In this study twelve different types of aggregate gradations are gone through to study the effect of gradation on the rutting performance of hot mix asphalt. From these mix types, the first four mixes are prepared by Asphalt Institute type gradation and variation is made to coarse and fine type of gradation by varying the cumulative percentage passing value of the representative sieve size for the corresponding nominal maximum aggregate size. The rutting performances and Marshall Properties are compared and the strength of the relationships in between is evaluated.

The next four gradation types are made by varying the cumulative percentage passing values of each sieve of a base mix to tolerance values with the same optimum bitumen content to study the effect of gradation on the rutting performances of bituminous mixtures.

The last four mixes are prepared by Bailey type gradation and variations are made to the three ratios CA, FAc and FAF mainly the CA ratio to study the effect these ratios have on the rutting performance in comparison to the Asphalt Institute gradation.

4.2) Asphalt Institute aggregate gradation.

4.2.1) Effect of Aggregate gradation on the Marshall Properties

After preparation of the four types of aggregate gradation, Marshall Tests are conducted on the bituminous mixtures with calculation of volumetric properties which the results are obtained in the appendix A. The specification's median air void value was ascertained which is normally 4 percent. Considering this as the optimum asphalt content, values from the graph plotted for Marshall stability, flow, VMA, VFA and bulk specific gravity of the mix are compared against the specification tabulated in table 3.15. For results beyond the specifications, mix design procedures are repeated until the needed result tabulated in table 4.1 is attained.

Mixture properties that are supposed to show good relationships with the variation of gradation and rutting performances are presented in the subsequent sections. The study of the relationship between these factors and gradation can be a basis for predicting the rutting performance from aggregate gradations.

Table 4.1 Test result for mix design of conventional mixes

Mix type	Percent passing sieve# 8	Optimum Bitumen content (%)	Stability (KN)	Flow (mm)	VMA (%)	VFA (%)	Bulk sp. Gravity	Air void (%)
Coarse 1	35	5.52	11.0	2.70	16.26	72.5	2.305	4.2
Coarse 2	35.9	5.4	10.9	2.70	15.90	69.1	2.322	4.6
Coarse 3	37.2	5.5	9.7	2.86	15.13	75.2	2.281	4.0
Coarse 4	43	5.54	9.5	3.40	15.25	76.1	2.265	4.2

4.2.1.1 Effect of gradation on Optimum Bitumen Content.

The relationship between the percentage passing value of sieve 2.36 as per table 3.3 and optimum bitumen content is presented in the figure 3.1 below. Though a poor linear relationship exists between the two parameters ($R^2 = 0.258$), it can be seen from the graph that as the gradation type changes from coarse to fine, the optimum bitumen content increases. This is due to the fact that as a gradation changes from coarse to fine, the percentage passing value of sieve no. 8 increases. This increases the percentage retained values of the lower sieve sizes (0.3 and 0.075mm) that increases the blend's surface area. And this in turn increases the amount of bitumen needed to coat the surface area and make it's durability to an acceptable range. Removing the relatively high optimum bitumen content from the graph (5.52%), gives a good logarithmic relationship with R^2 value of 0.7006 which strengthens the trend in the effect of percentage passing value of sieve 2.36mm on the OBC.

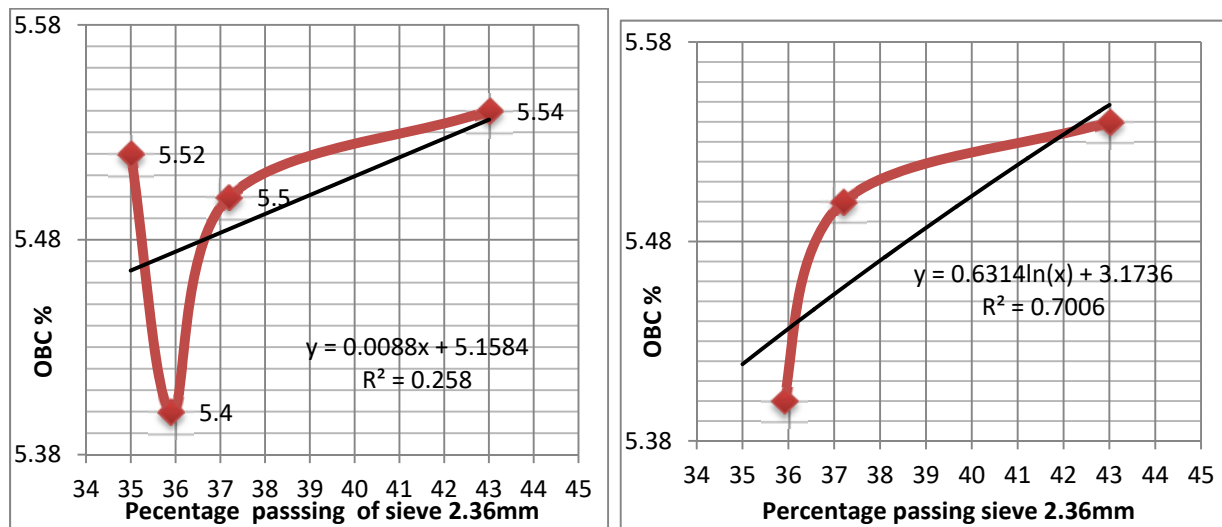


Figure 4.1 Effect of percentage passing sieve 2.36mm on OBC

4.2.1.2 Effect of gradation on Marshall Stability of the mix.

Figure 4.2 demonstrates the effect of gradation on the stability of bituminous mixtures. As the degree of fineness of gradation of aggregate increases, the Marshall stability of the mix will decrease to boundary that a mix for high traffic load is specified to have.

The stability of a mix depends on internal friction and cohesion. Internal friction among the aggregate particles (inter-particle friction) is related to aggregate characteristics such as shape, size and surface texture. Cohesion results from the bonding ability of the binder. As aggregate sizes are getting bigger, the internal friction between the particles increases due to a relatively higher aggregate to aggregate contact. Hence, the reason for such graph lies in the fact that the coarser a mix becomes, the more there will be larger aggregate fraction to bear the load exerted by an external force. The load bearing aggregates are coarse aggregate fractions retained on sieve 2.36mm.

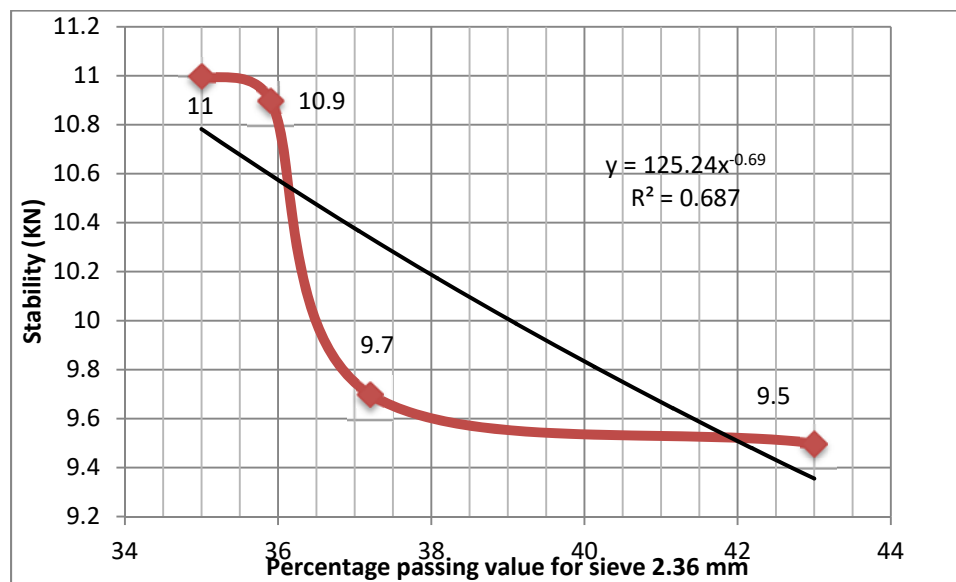


Figure 4.2 Effect of percentage passing sieve 2.36mm on Marshall Stability

4.2.1.3 Effect of gradation on VMA

The effect of gradation of aggregate on the VMA of hot mix asphalt is demonstrated in figure 4.3. VMA (Voids in mineral aggregate) defined as the volume of inter-granular void space between the aggregate particles of compacted paving mix that includes the air void and effective asphalt content.

As it can be seen from the figure, VMA usually decreases as gradation of aggregate changes from coarse to relatively finer gradation up to some point then starts to increase. In a coarser graded aggregate, voids are created in between aggregate particles which are to be filled by fine aggregate fractions. In spite of this fact, there will be voids left unfilled by fine aggregate as aggregate won't pack 100% on mixing and compaction. As the aggregate becomes finer, they are closely packed in such a way that the void space left unfilled by filler particles will be minimized. This will minimize the VMA of the mixture up to a point and then as the aggregate becomes finer, the mix's coarse fractions float in fine aggregate matrix which leads particles to slide one another instead of increasing the compaction level. This fact leads to an increased VMA.

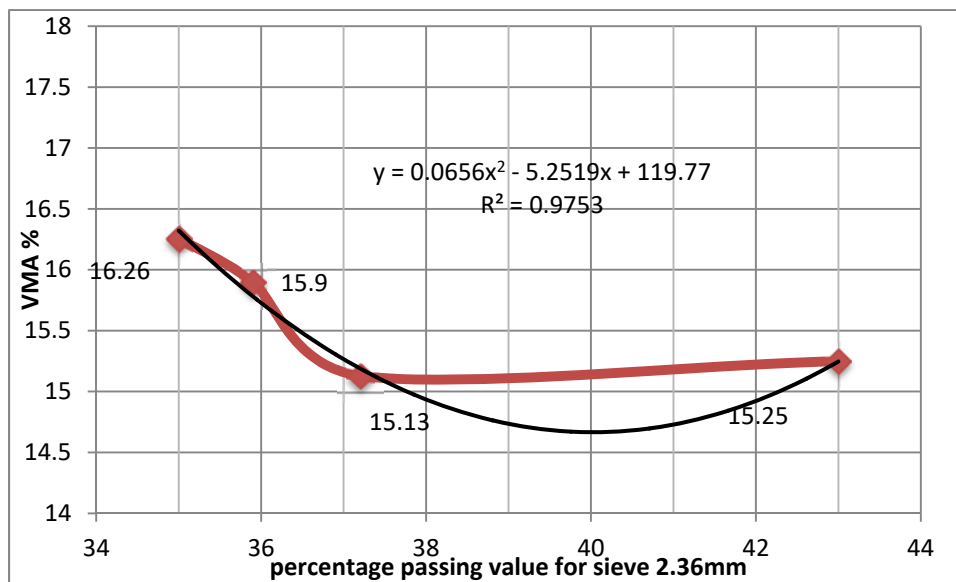


Figure 4.3 Effect of percentage passing of 2.36mm on VMA

4.2.1.4 Effect of gradation on Bulk Specific Gravity

The effect of gradation of aggregate on the Bulk specific gravity of hot mix asphalt is demonstrated in figure 4.4. As it can be seen from the figure, bulk specific gravity of the mix decreases as gradation of aggregate changes from coarse graded to relatively finer gradation up to some point then starts to fall down as aggregate gradation changes to finer values. This is due to the fact that as the mix becomes finer, almost all the main components of the mix become finer graded aggregate particles. This fact makes fine aggregate to fill the voids created by very small percentage of coarse aggregates and the remaining fine aggregate structures. In such case, fine aggregates start to slide one another as

Fine aggregates can't fill the voids created by another fine aggregate. Therefore, aggregate arrangements and packing in the mixtures will be affected and the density of the mix will be highly minimized.

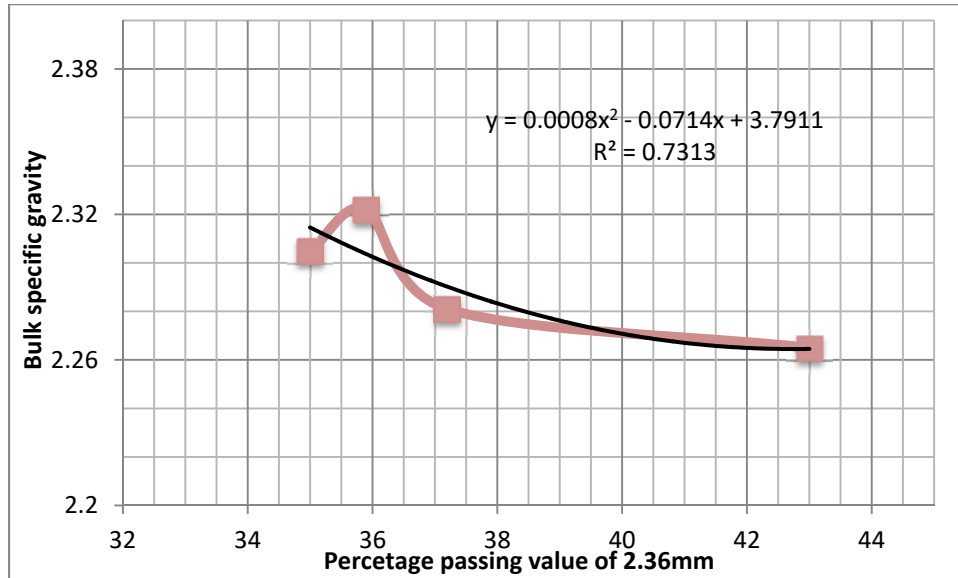


Figure 4.4 effect of percentage passing sieve 2.36mm on bulk specific gravity.

4.3 Rutting test results.

Rutting deformations are read from the graph that is automatically plotted by the rutting analyzer machine. Rut deformation d_1 and d_2 at 45min (t_1) and 60min (t_2), which are accurate to 0.01mm are automatically read from the graph and put under the table as presented in appendix B

When the deformation exceeds and reaches 25mm before 60min, the time when it reaches 25mm (d_2) is (t_2), the time 15min before t_2 is (t_1) and the amount of deformation at this time is (d_1).

Dynamic stability of bituminous mixtures shall be calculated according to the equation below. Dynamic stability expresses the ability of asphalt concrete pavements to support rutting. It expresses the number of passes needed to produce 1mm rut depth.

$$DS = \frac{(t_2 - t_1) * N * C_1 * C_2}{(d_2 - d_1)} \quad [31] \dots \dots \dots 4.1$$

Where: DS---Dynamic stability of bituminous mixtures, passes per mm;
 d_1 ---Amount of deformation corresponding to time t_1 , mm;
 d_2 ---Amount of deformation corresponding to time t_2 , mm;
 C_1 ---Correction coefficient for types of testing machine, which is 1.0 for the movement with variable speed of test piece activated by crank connecting link, and is 1.5 for the movement with constant speed of test piece activated by chain;

C_2 ---Coefficient of test piece, which is 1.0 for the test piece prepared in laboratory with width of 300mm, and is 0.8 for the test piece cut from the pavement with width of 150mm;
 N ---the rolling velocity of test wheel in reciprocation, which is 42 per min.

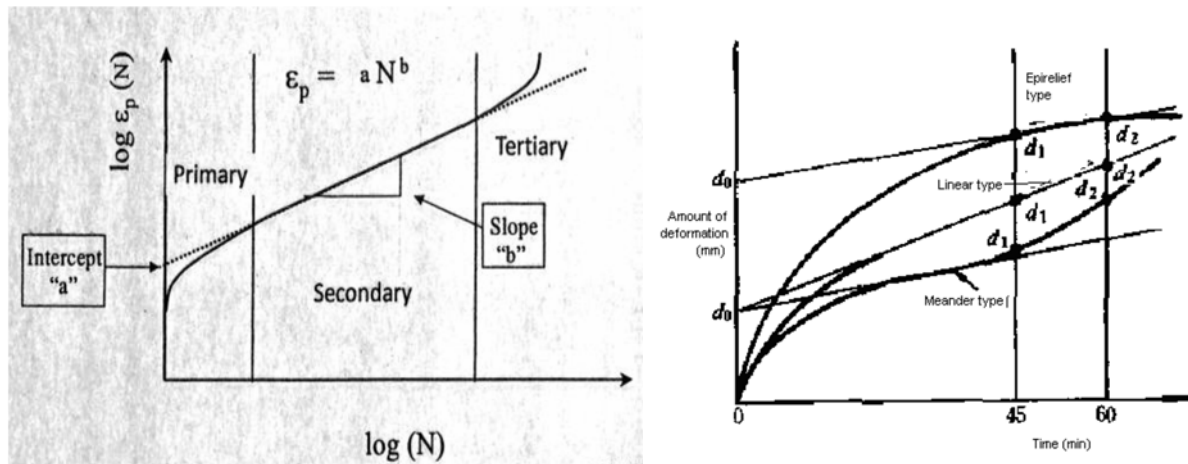


Figure 4.5 Self-recorded Deformation Curve in Rutting Test[31]

The use of the permanent strain accumulation model developed at Ohio State University predicts total rutting expressed in the following equation:

$$\epsilon_p = aN^b \quad [13] \dots\dots\dots 4.2$$

This power model can be expressed in the following form;

$$\text{Log } \epsilon_p = b \text{ Log } N + \text{Log } a \quad \dots\dots\dots 4.3,$$

- Where
- ϵ_p = permanent strain, rut depth
 - N = number of load application
 - a = Experimental constant (depends on material type and stress state)
 - b = Experimental constant (depends on material type)

When changed to log-log scale, the power model will generally fit to straight line in which the slope and intercept of the line equation is good indicator of the rutting resistance of the hot mix asphalt. [14]

4.3.1 Effect of aggregate gradation on the rutting performance of AI gradation types.

Here, the percentage passing value of each sieve size is varied to such an amount that the effect of the control sieve in different Marshall Properties and performances can easily be identified. By slightly varying the percentage passing value of the control sieve (2.36mm), Marshall Stability, flow values, all volumetric

properties and optimum bitumen content has shown considerable variations. Especially, the effect of control sieve can be seen in coarse1 and coarse 4 mixes as the percentage passing values of sieves other than the control sieves are exactly alike. All subsequent results of the two mix types can show us the control sieve put in the table as divide line between coarse and fine mix is a good classification mechanism.

The time frame and the loading condition provided for the rutting analyzer machine is in such a way that the linear relation in equation 4.3 holds true for the given time gap i.e., between 45 and 60 minutes of testing. The slope and intercept of this line equation can be extrapolated to load repetition that is found by actual traffic count (AADT) of the specific route selected. [31]

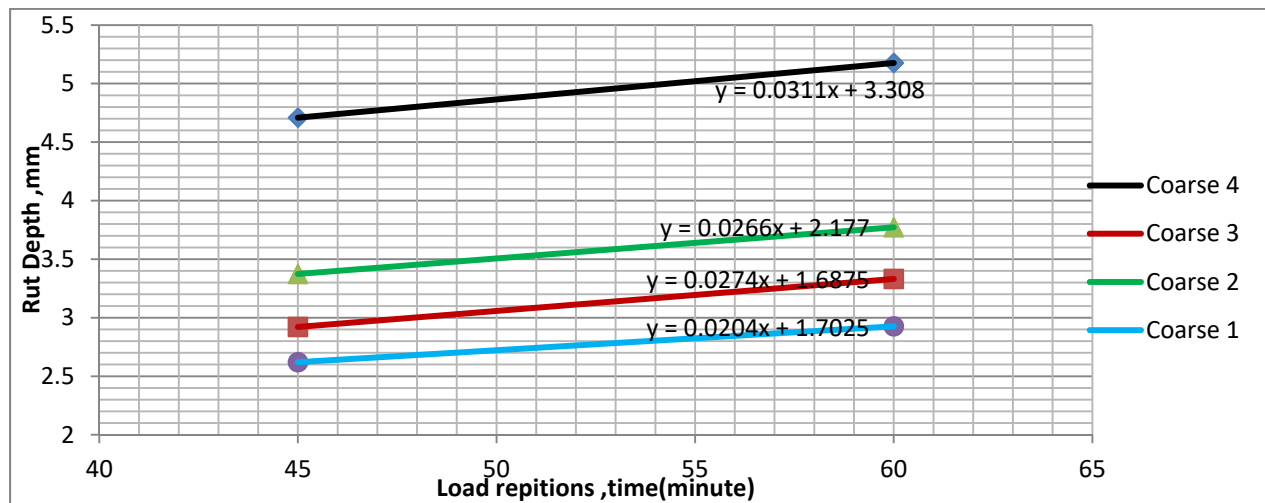


Figure 4.6 graph on the relationship between rut depth and load repetitions

The slope (Log a parameter) and Y intercept (b parameter) of the linear relationships can further be plotted against the gradation as percentage finer value of sieve 2.36mm. From the graph, a good linear relationship of Y intercept with $R^2=0.8353$ and relatively weak linear relationship of slope with $R^2=0.7216$ are noted with increasing the percentage finer values. Keeping all other characterization and source properties of aggregate to be constant, such values are a good indication of slope and Y intercept of rut depth Vs load repetition graph for aggregate gradation curves that fall in between the gradation curves selected for this study.

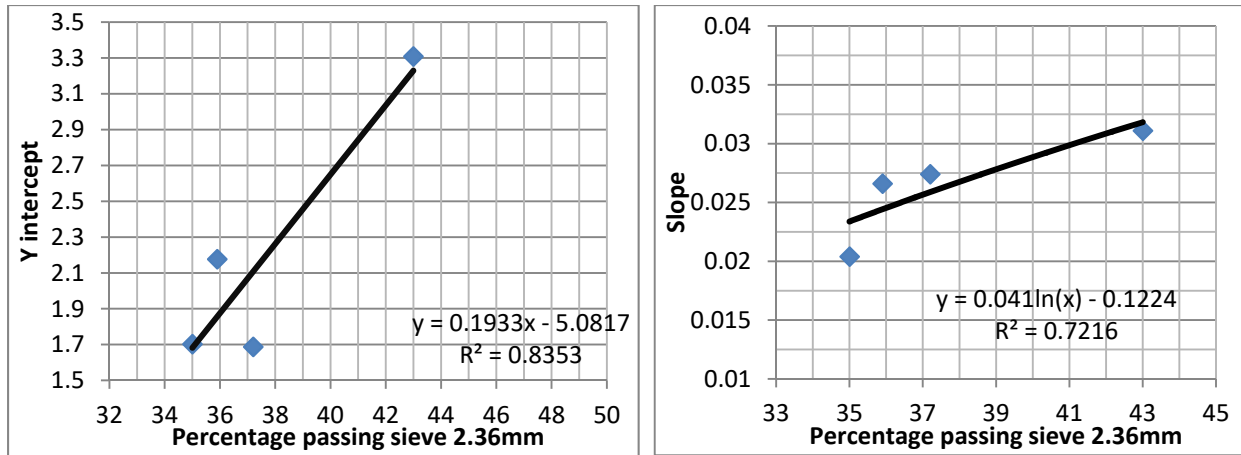


Figure 4.7 Graph showing slope & Y intercept of rut depth Vs load repetitions

The relationship between the gradation of aggregate expressed by the cumulative percentage passing value of sieve 2.36 as per table 3.3 of chapter two and Rutting values expressed in dynamic stability is presented in the figure4.8 below.

As it can be seen from the graph, power regression line is made to fit the relationship between gradation of aggregate and Dynamic Stability of bituminous mixtures. Power relationship with $R^2 = 0.6934$ shows as a mix becomes finer with increasing the percentage passing value of sieve 2.36mm, the dynamic stability of the mix decreases with a power regression model. As the mix becomes coarser the load bearing capacity of the mix increases as the main load bearing component of the mix becomes larger aggregate particles.

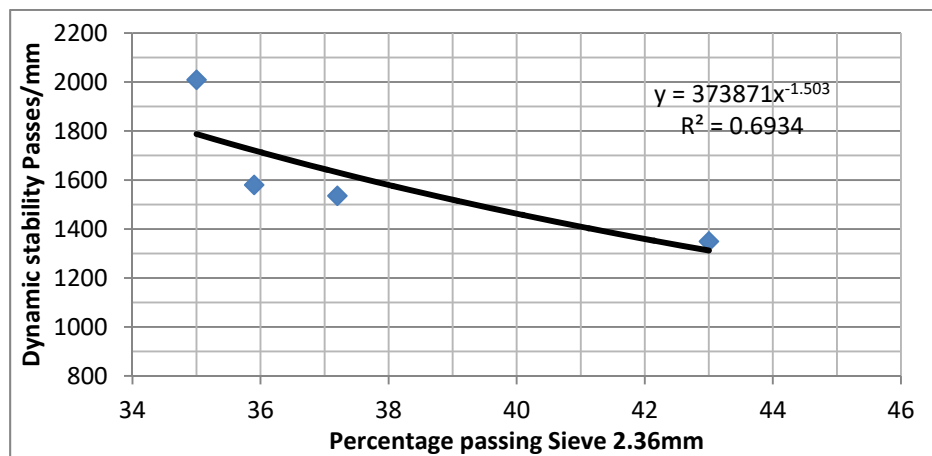


Figure 4.8 the relationship between percentage passing sieve 2.36mm and dynamic stability.

4.3.2) Varying aggregate gradation to tolerance values and its effect on rutting performance.

Based on aggregate gradation specified in table 3.6 of chapter 3, the gradation curves for the selected four aggregate gradations are made to be nearly parallel to the original gradation (base mix). With the same optimum bitumen content(5.52%), the percentage passing values of different sieve sizes are allowed to vary to tolerance values and Rutting tests are conducted on these four gradation variation to tolerance values and results are tabulated as below.

Table4.2 Dynamic stability for mixes with different AI gradation types.

Mix type	Base mix(C1)	C1-1	C1-2	C1-3	F1-1	C2	C3	C4
Dynamic Stability(Passes/mm)	2009.55	631.9	677.42	1055.28	891.09	1536.13	1349.66	1488.65

The objective of this experiment is to evaluate if changing the percentage passing values of different sieves to tolerance values has effect on the rutting performance of the base mix. To evaluate this, a statistical hypothesis testing is conducted on the test results. Null hypothesis (Ho) is the hypothesis that is initially stated and the reality is not proven. Alternative hypothesis (Ha) is a contradictory idea to the null hypothesis forwarded to accept or reject the null hypothesis.

The objective of a statistical test of H0 is not to explicitly determine whether or not Ho is true but rather to determine if its validity is consistent with the resultant data. Hence, with this it seems reasonable that H0 should only be rejected if the resultant data are very unlikely. This can be investigated by specifying a value α (Significance level) which leads the test to have the property that whenever H0 is true its probability of being rejected is never greater than α .

T-test is conducted for we had unknown variance and mean of the normally distributed samples with 5% level of significance. The null hypothesis of this test is “The average value of dynamic stability of the base mix is equal to dynamic stability of mixes obtained by varying percentage passing of different sieves.”

Ho: $\mu = \mu_0$4.4

Ha: $\mu \neq \mu_0$4.5

$$S_p^2 = \frac{(n-1)S_x^2 + (m-1)S_y^2}{n+m-2} \dots\dots\dots 4.6$$

$$S_x^2 = \frac{\sum_{i=1}^n (x_i - X)^2}{n-1} \dots\dots\dots 4.7$$

$$S_y^2 = \frac{\sum_{i=1}^m (y_i - Y)^2}{m-1} \dots\dots\dots 4.8$$

$$T = \frac{X - Y}{\sqrt{(S_p^2 (\frac{1}{n} + \frac{1}{m}))}} \dots\dots\dots 4.9$$

Table 4.3 T test for different mix with gradation changed to tolerance values.

	Base mix(C1)	Mixes with gradation changed to tolerance
Dynamic Stability Value(Passes/mm)	2025.72	631.90
	1909.91	677.42
	2093.02	1055.28
	-	891.09
Sample mean	2009.55	813.92
Sample Variance	8578.73	38657.68
Sp²	26626.10	
T	9.59	

With this analysis, the null hypothesis is rejected if the calculated value of T is far above t-value read from the table for n+m-2 degree of freedom and $\alpha/2$ level of significance = 0.025 as both sides of the normal distribution are tested. With this information, $t_{\alpha/2, n + m - 2}$ is read from the table whose value is 2.571. This shows the calculated T is by far greater than the $t_{\alpha/2, n + m - 2}$ value.

This enables to reject the null hypothesis. Hence, at 5% level of significance, by changing the percentage passing values of different sieves to tolerance values, considerable rutting variation from the base mix is observed.

The same T-test at 5% level of significance is conducted on the null hypothesis that varying aggregate gradation has significant effect on the rutting performance of HMA.

The null hypothesis is the average value of the dynamic stability of the base mix is equal to the dynamic stability of mixes obtained by varying aggregate gradation. $H_0: \mu = \mu_0$, and the alternative hypothesis $H_a: \mu \neq \mu_0$

Table 4.4 T test for mixes of different gradation.

	Base mix(C1)	Mixes with percentage passing value of sieve 2.36mm changed
Dynamic Stability(passes/mm)	2025.72	1580.15(C2)
	1909.91	1536.13(C3)
	2093.02	1349.66(C4)
Sample mean	2009.55	1488.65
Sample Variance	8578.73	14972.41
Sp²	11775.57	
T	5.88	

With this analysis, the null hypothesis is rejected if the calculated value of T is far above t-value read from the table for $n+m-2$ degree of freedom and $\alpha/2$ level of significance = 0.025 as both sides of the normal distribution are tested. With this information, $t_{\alpha/2, n + m - 2}$ is read from the table whose value is 2.776. This shows the calculated T is by far greater than the $t_{\alpha/2, n + m - 2}$ value.

This enables to reject the null hypothesis. Hence, it can be reached on the conclusion that at 5% level of significance, by changing aggregate gradation, considerable rutting variation from the base mix is observed.

4.4) Bailey types aggregate gradation

4.4.1) Bailey type aggregate gradation and Marshall Properties.

Bailey type aggregate gradation is a method for adjusting the gradation of aggregate so that proper packing and interlocking of aggregate is achieved. To achieve this packing model of aggregate, bailey method uses three ratios as a guide line. These are

Four types of Bailey mixes are chosen to be investigated in the study. These are Bailey1, Bailey 2, Bailey 3and Bailey 4 type mixes. The effect of the above mentioned three ratios on the rutting performance and Marshall Properties of the hot mix asphalt is studied in the subsequent sections.

Table 4.5 Test result for mix design of different Bailey mixes.

Mix type	CA Ratio	FAc Ratio	FAf Ratio	Optimum Bitumen content (%)	Stability (KN)	Flow (mm)	VMA (%)	VFA (%)	Bulk sp. Gravity	Air void (%)
Bailey 1	0.975	0.425	0.423	5.5	8.0	2.70	15.80	62.0%	2.290	6.0
Bailey 2	0.660	0.611	0.654	4.2	11.0	2.32	14.20	71.8%	2.312	4.0
Bailey 3	0.750	0.500	0.491	5.2	9.7	2.63	15.81	74.7%	2.286	4.0
Bailey 4	0.582	0.436	0.441	5.2	9.0	2.78	15.61	74.4%	2.290	4.0

4.4.1.1 Bailey 1 type gradation

In the Bailey 1 type gradation the gradation curve is made to be on the fine side of the MDL for coarser sieves and coarse side of the MDL for finer sieves. Moreover, the gradation curve fits the gradation envelopes put by the Asphalt Institute specification but violates one of the ratios specified in Bailey gradation. The CA ratio= 0.975 where as the FAc and FAf ratios are within the needed margin. As the CA ratio goes above the needed margin and approaches 1, the interceptor size aggregate will be much in quantity in the mix. The small quantity of pluggers in the mix makes the interceptors to be the main load bearing components of the mix. In such circumstances, when the ratio of pluggers to interceptors is highly minimized, the mix will become unbalanced and pluggers are made to float in the interceptors' matrix. This causes the mixture to move during compaction. This result is easily observable in stability values of table 3.4 at relatively high optimum bitumen content, the air void in the mix is beyond the margins specified but needed to fulfill the minimum stability of the mix. Due to such variations, such kind of variation should be avoided as it can't satisfy the stability and air void requirement of the mix.

4.4.1.2 Bailey 2 type gradation

In the Bailey 2 type gradation, the gradation curve is made to be nearly parallel to the maximum density line and the effect on the Bailey ratios is clearly visualized. The CA ratio is 0.66, FAc is 0.611 and FAf is 0.654 which all are above the specified limit. Following a gradation curve parallel or exactly the same to the

MDL will surely give the maximum packing arrangements that a mixture will attain. This can be seen in bulk specific gravity of 2.312.

The optimum bitumen content is relatively lower than the estimated value. This can be described as aggregate are in their densest packing state that with small insertion of bitumen, the needed Marshall specifications are fulfilled. Relatively higher stability value shows the strength of the aggregate structure with relatively lower bitumen content. This is categorized as dry mix with poor workability.

As it can be seen in table4.5, almost all the Marshall requirements are met except the VMA requirements. Here, the bottom of U shaped VMA curve falls below the minimum requirement of VMA (14%). This is a good indication that the VMA of the mix should be increased to a considerable amount basically by changing the gradation in such a way that the dense packing of aggregates is minimized to afford voids in the mixture.

4.4.1.3 Bailey 3 Type gradation

In the Bailey 3 type of gradation, the gradation curve is made to be on the coarser side of the maximum density line for coarser sieves and finer side of the maximum density line for finer sieves. This is vice versa of the gradation requirement of the best Bailey gradation. Here, the FAc and FAf requirements are exactly met but slightly higher value of CA (0.75) is obtained. This leads to a finer Bailey mixes where the fractions of interceptor sized aggregate is marginally higher than the bailey's specifications.

Here all the Marshall requirements and all the volumetric properties are exactly met as in the specifications

4.4.1.4 Bailey 4 type gradation

In the Bailey 4 type gradation, the gradation curve is made to be on the finer side of the MDL for coarser sieves and finer sieves to be on the coarser side of the MDL and crosses the MDL somewhere near the boundary of the coarse and fine making an S-curve. Here, all the Bailey criteria are met to an optimum value.

4.4.2 Rutting performances of Bailey type Gradations

Rutting performances in the form of Dynamic stability for the four types of the Bailey mixes is presented in table 4.6

Table 4.6 Dynamic stability of Bailey type mixes.

Mix type	Bailey 1	Bailey 2	Bailey 3	Bailey 4
Dynamic Stability(passes/mm)	316.03	1571.23	471.39	2692.31

As it can be seen from the table, the dynamic stability of Bailey 1 type mix is the least from the four types of mixes studied. This is basically due to imbalance in proportion of pluggers and interceptor sized aggregates. This imparts the floating of pluggers in the interceptor's matrix. Hence, such kind of mixes will be susceptible to poor stability and poor rutting performance as well.

In Bailey 2 type mix where the gradation curve is parallel to the MDL, the dynamic stability is an intermediate value. The good rutting resistance is developed by the dense packing of aggregate and relatively dry mix with insufficient film thickness and workability problem. Such good rutting performance can't be a guarantee for an overall good performance of the mix as lower VMA imparts durability problem.

In Bailey 3 type mix, even though all the Marshall and volumetric properties are good indication of the mix, the dynamic stability of the mix is highly deteriorated. This result is a good indication that when gradation curve is finer on the finer sieves and coarser for coarser sieves, there will be an imbalance to the mix that gives poor rutting performance. Such kind of mix will be too fine which increases the workability of the mix but increases the fine portion of the aggregate matrix which drastically reduces the rutting performance of the mix.

In Bailey 4 type mix, which is an ideal type Bailey mix where all the requirements of Bailey ratios are met in the mid line of the specifications, the dynamic stability of the mix is very high compared to any types of mixes in this study. The good nature of the mix is due to good proportioning of aggregates in different sieves. This mix is classified as coarser dense graded mix as per the classification scheme in table 3.3. However, an increase in the coarseness of the mix(by simply decreasing percentage passing value of sieve 2.36mm can't imply the good rutting performance of the mix. Rather, the structure in the aggregate packing is the main reason behind as more coarse dense graded mixes fail to be better in their dynamic stability values when compared to Bailey 4 type mixes.

4.5 CA ratio and Dynamic Stability

As per the ratio guideline put in the table 3.7 and 3.8, from the three Bailey ratios that characterize the Bailey mix, CA ratio is the main factor to change the mix from fine to coarser graded dense bailey mixes. Hence, in the study the FAF and FAc ratios are made to be nearly within the margin of the specifications to study the effect of CA ratio on the rutting performance.

As it can be seen from the graph below, power regression line with R² value of 0.8847 fits the relationship between dynamic stability and CA ratio. From the graph, good relationship supports the fact that as the CA ratio increases and goes out of margin, the dynamic stability decreases drastically and approaches zero as the CA ratio goes above 1.

As CA ratio goes out of margin and approaches 1, there will be unbalanced ratio of large sized coarse aggregate (pluggers) and small sized coarse aggregate (interceptors) which entails pluggers will float in interceptors' matrix and voids created by coarse aggregate will be highly minimized and fine aggregates will get hardly any space created by coarse aggregate. Hence, the fine aggregate structure will be widely dispersed and with high VMA values. Such things lead to an overall disturbed aggregate structure with minimum dynamic stability value.

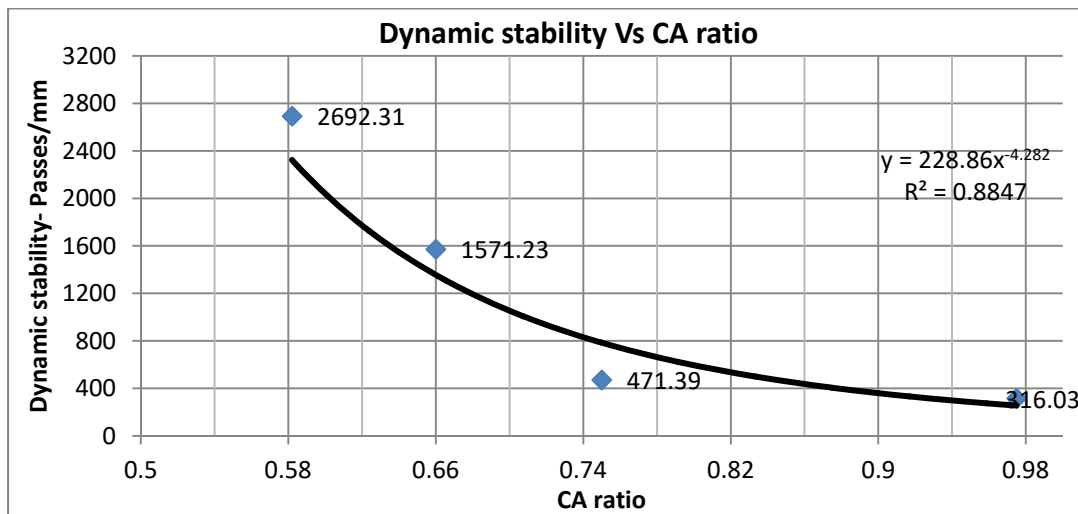


Figure 4.9 Relationship between CA ratio and Dynamic stability of Bailey mixes.

CA ratio can be determined to conventional mix with asphalt institute aggregate gradation by estimating the percentage passing values of the needed sieve sizes from the gradation curves and calculating the CA ratio. Results tabulated below

will not be accurate as the gradation curve is drawn based on the sieve sizes that the bailey method of gradation doesn't specify. Hence as per the result below, the CA ratio of all the mixes are beyond the Bailey specification which are supposed to be poor mixes with low dynamic stability as per the relationship of the CA ratio and dynamic stability. But the reality is that all the four mixes are good in rutting performance in decreasing order. This is because The CA ratio is used to determine how well the coarse portion of the aggregate gradation packs together as well as how much void space results from the coarse aggregate packing. For the conventional mixes, gradation is prepared not by packing theory. Fine aggregate may still pack to bring the needed overall strength of the mix. In so doing, the rutting performance of conventional mixes with AI type gradation can't be as high as that of Bailey Gradation as it fails to fulfill the packing theory.

Table 4.7 CA ratios for conventional mixes.

mix type	Percentage passing sieve 6.25	Percentage passing sieve 2.36	CA ratio
Coarse 1	69.85	35	1.16
Coarse 2	65.48	35.9	0.86
Coarse 3	71.85	37.2	1.23
Coarse 4	73.02	43	1.11

4.6 Percentage passing sieve 2.36 and Dynamic Stability.

As per table 3.3 of the classification scheme of dense graded mixes to fine and course type, the representative sieve varies based on the NMAS of the aggregate types. For NMAS of 12.5mm the representative sieve is 2.36mm. Percentage passing values of sieve 2.36mm of both AI gradation and Bailey type gradation are prepared and the relationship with the rutting performance is studied. For the bailey type gradation, Bailey 1 and Bailey 3 type are not considered in the table as they are made by wrong gradation patterns that are introduced to study the effect of wrong gradation patterns on the Bailey ratios.

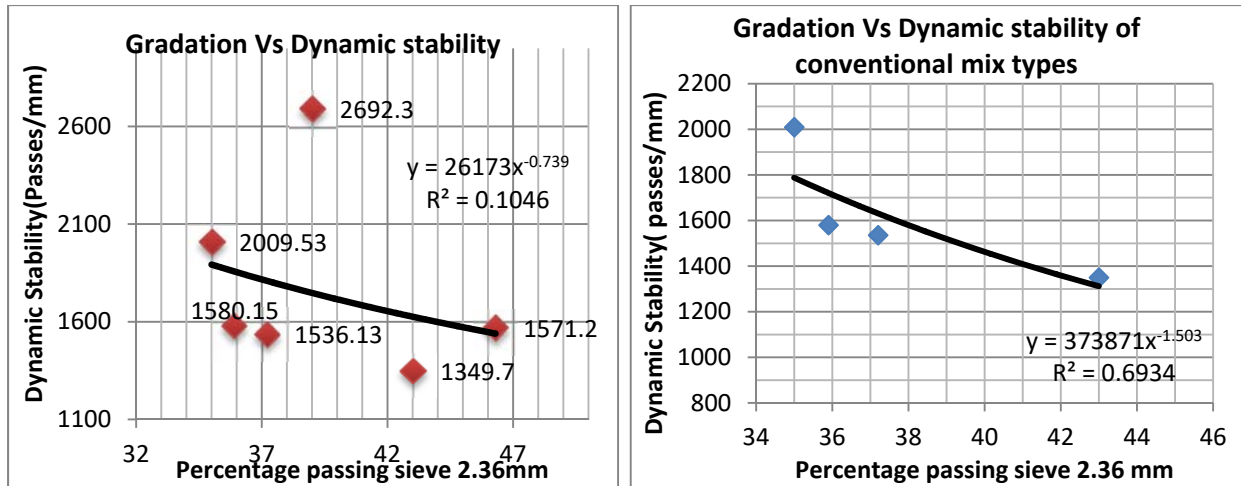


Figure 4.10 relationship between percentage passing of sieve 2.36mm and Dynamic stability.

The relationship between percentage finer value of sieve #8 and dynamic stability has shown stronger relation with power regression line of $R^2=0.6934$. Generally, the dynamic stability decreases the gradation of aggregate changes from coarse graded to fine graded. Such a strong relationship can't hold true if Bailey gradations are introduced to the graph ($R^2 = 0.104$) due to the fact that the cause of good rutting performance is not only changing the percentage finer values of sieve #8. Rather, appropriate aggregate packing can mean a lot in giving good rutting performance which can even be seen in the margin of coarse and fine graded mix as for Bailey-4 mix.

Hence, percentage finer value of sieve #8 can't by its own characterize the gradation of aggregate as it must be jointly presented with other factors to produce strong relationships with rutting performances of hot mix asphalt.

4.7 Marshall properties and Dynamic Stability.

As it can be seen from the figure, weaker power relationship holds between the Marshall Stability and dynamic stability of HMA and very poor relationship at low and high flow values exists between flow values and dynamic stability. This is a good indication of the fact that a good Marshall Stability result is not a guarantee for the mix to have good rutting performance. Rather, it supports the fact presented in section 4.6. i.e., even though different factors have the influence on the rutting performance in different circumstances, they must be jointly put with aggregate packing factors in the form of the three bailey ratio. As of section 4.6, the dynamic stability of Bailey 4 mix humps out of the good trend formed by other

mix types. This is good indication that good rutting performance of Bailey 4 type mix is entirely based on the aggregate packing though this mix doesn't have strong Marshall Properties.

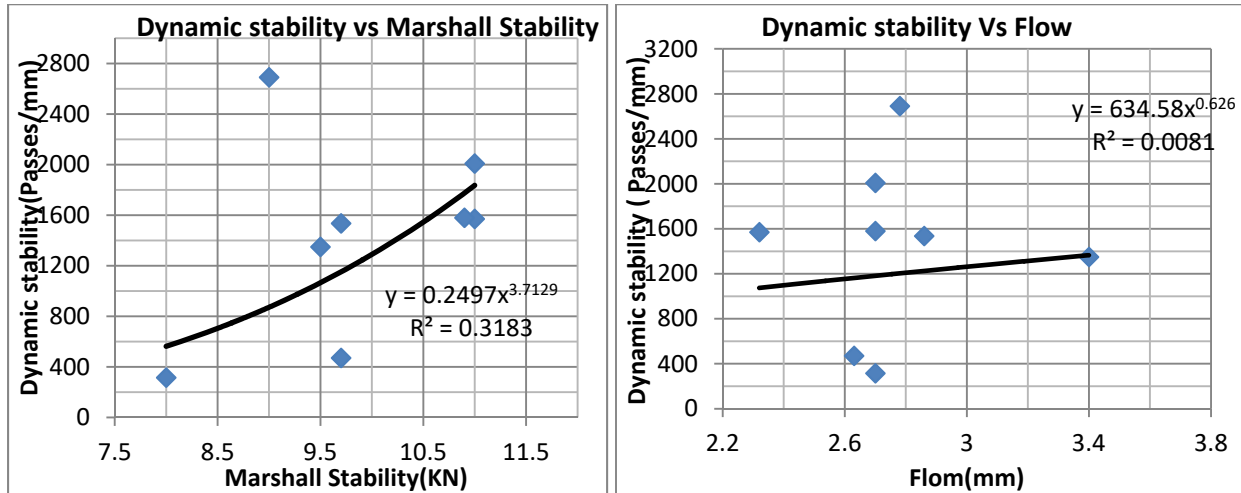


Figure 4.11 relationships between Marshall Properties and Dynamic stability.

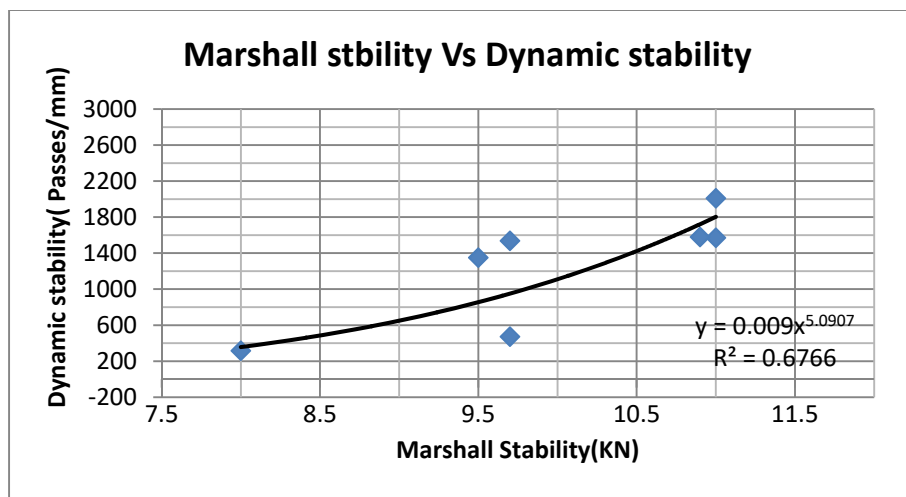


Figure 4.12 Relationship between Marshall Stability and dynamic stability.

4.8 Gravel to Sand ratio and Dynamic Stability

As per the study made on different sources of aggregate ,results indicated that gravel-to –sand ratio has a marked influence on HMA performance, and also neither maximum diameter size nor structure have such influence alone[2].

Hence gravel to sand ratio is compared with the rutting performance as in the figure below. From the figure, poor power relationship holds as of section 4.6. From the graph, the relatively higher dynamic stability result of Bailey 4 type

gradation is the main reason for such weaker power relationship. This strengthens the fact that without the existence of Bailey 4 type gradation, the relationship will be stronger. Hence some stronger factor makes the Bailey4 type gradation to be the best in the rutting performance that is aggregate packing.

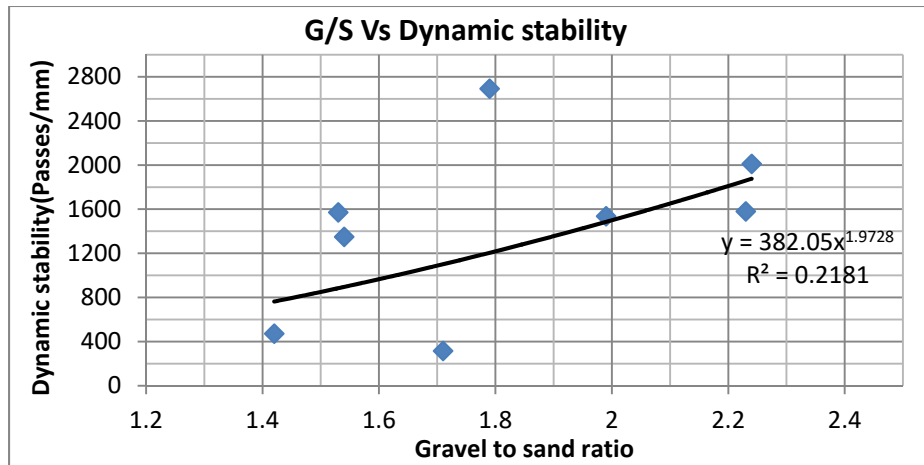


Figure 4.13 Relationship between gravel to sand ratio and dynamic stability.

5/ Conclusions and Recommendations.

5.1) Conclusions.

- Without considering the DS result of Bailey 4 type gradation, a relatively stronger relationship exists between G/S Vs DS, Marshall Stability Vs DS and Percentage passing sieve # 8 (Gradation) Vs DS when compared to the Bailey 4 inclusive relationships. The R^2 values of the relationships without Bailey 4 are 0.267, 0.6766 and 0.3457 respectively and with Bailey 4 inclusive are 0.2181, 0.3183 and 0.1046 respectively. Similar trends are followed by changing factors of conventional mixes other than Bailey 4 type mix.
- There is significant difference in rutting performance by changing the percentage passing value of sieve # 8 in small percentages for the same NMAS. This can be clearly visualized in coarse 1 and coarse 4 mixes where the percentage finer value of all sieves other than sieve # 8 is exactly alike. The percentage passing values of sieve # 8 are 35 % and 43% respectively. Small variation of percentage passing value of sieve # 8 has considerable rutting value.
- Figure 4.13 indicates that the increase in gravel-to-sand ratio enhances rutting resistance. By increasing the gravel to sand ratio, there will be increased ratio of larger coarse aggregate size which increases the load bearing capacity of the mix that gives better rutting performance.
- Mid line of Superpave gradation specification (coarse 4) gives lower rutting potential than mid line of conventional AI gradation specification (coarse 1). As per the classification scheme in table 3.3, Superpave gradation gives a relatively finer dense graded mix.
- A gradation envelope has minor effect in controlling the gradation of aggregates. Bailey 4 mix can be an evidence to this conclusion as it marginally violates the gradation envelope used conventionally by the AI. The percentage passing value specified by AI for sieve size 12.5 mm is 90-100% and percentage passing value of Bailey 4 mix for 12.5mm sieve is 87%. Moreover, as per classification scheme put in table 3.3 for coarser dense graded mixes, the recommended percentage passing value of sieve #8 should be less than 40%. The actual percentage passing value of Bailey 4 mix is 39% which marginally fits the specification when compared to 35% passing of sieve #8 for coarse 1 mix. In spite of these facts, Bailey 4 gave us the best rutting performance. Hence, some other character gives Bailey 4 a good rutting performance. Namely aggregate interlock and good packing. When compared to conventional gradation methods, Bailey mixes are very close to the MDL as expected.
- Varying aggregate gradation by changing percentage passing of different sieves to tolerance values recommended by AI has significant effect on the rutting

performance of HMA when studied by the control sieves. The coarser the varied mix becomes, the higher will be the variation from the base mix. This is due to the fact that for the same optimum bitumen content, as the mix becomes coarser, the mix becomes over lubricated that makes the particles pass one another up on testing for rutting rather than the expected aggregate interlock.

- Varying aggregate gradation, expressed by varying percentage passing value of sieve 2.36mm, has significant effect on the rutting performance of HMA. And in conventional type of mix, as the mix becomes coarser, the rutting performance of the mix is highly improved.
- Using Bailey type aggregate gradation generally gives good aggregate packing expressed by good rutting performance. Moreover, the three bailey ratios namely CA, FAc and FAf ratios are good classification mechanisms to make proper aggregate gradations and CA ratio better forecasts the performance of the mix as The effect of varying such ratios can clearly be seen in Bailey1, Bailey2 and Bailey 3 type mixes. This will make bailey mixes be better in their aggregate packing and overall mix properties when compared to conventional mixes as there is no guide line mechanism to identify erratic gradation in conventional mixes.
- Gradation of Bailey 3 (inverted S curve) brings considerable variation in the rutting performance. Even though all the Marshall and volumetric properties are met in the mix, considerable loss of rutting potentials is seen in the mix that needs to be avoided from implementing. And by varying the general shape of the gradation curve (from S curve of Bailey 4 to inverted S of Bailey 3), considerable change in the rutting performance is observed.
- With almost all factors that rutting performance is related, the strength of the relationship in between is not satisfactory to conclude and rely on that trend for other mix types with the same aggregate and bitumen properties. I.e., CA ratio $R^2 = 0.884$, gradation $R^2 = 0.104$ and 0.6934 , Marshall Stability $R^2 = 0.318$ and 0.6766 , flow $R^2 = 0.008$ and Gravel to sand ratio with $R^2 = 0.218$.

5.2) Recommendations.

- The rutting performances of Bailey mixes are relatively better than that of conventional mixes as it outfits the trend lines that fits better to conventional mixes alone. Hence, it is recommended to use Bailey method of gradation specification to prevent the rutting problems of most Ethiopian roads. Especially, those roads in hotter part of the country, in intersections and roundabouts where roads are susceptible to stationary and rounding traffics with high shear forces.
- Percentage passing value of sieve 2.36mm (for NMAS of 12.5mm) is a good divide line between coarse and fine dense mixes.
- Gradation envelope put by the AI gradation is simply a guide line to mix preparations. It is not related to any performance of the mix as keeping in envelopes cannot be a guarantee for a good performance and violating the envelope doesn't mean poor performance. Hence, some other factor need to be jointly put to gradation specification of AI as CA , FAc and FAF ratios of Bailey mixes.
- Varying gradations to tolerances of control sieves has shown a high variation of rutting performance. There should be restriction that inhibits high variation in tolerances of control sieves.
- Sieve number 8 for conventional mix methods and CA ratio for Bailey mix types has shown good relationship with the rutting performance. Hence, these ratios can be used to forecast the rutting performance of mixes with gradation curves that fall in between curves in the study.

6) Limitation and Issues for future study

- Due to shortage of laboratory equipments those related to rutting analyzer, the sample size (number of tests) to each of the mix type is limited to 2 or 3 samples. But, had it been with the increased numbers of tests for the intended purpose, it would have been reached on stronger relationships with the different variables studied. I.e. the R^2 values will be improved.
- The bitumen type used in the study is bitumen of grade 85/100 which is suitable to roads of colder parts of Ethiopia like Addis Ababa. Effect of gradation on Varieties of bitumen grade need to be studied to address the rutting problems of roads of different parts of the country especially hotter regions.
- Quality aggregate types are used in the study. But in places where aggregate sources are not easily obtained or sources are very far from project areas in some parts of the country, there should be a means to use marginal materials that fulfills only some of the specifications. Hence a study needs to be made with such aggregate.
- Several reasons are put behind rutting problems. Of these factors, gradation is selected for this study for aggregates are major constituents of hot mix asphalt. Due to complicated nature of the rutting mechanisms, other factors like bitumen grade, optimum bitumen content, bitumen filler ratio, filler type, aggregate source type, aggregate source properties(flakiness, sand equivalent value, durability) , compaction level need to be jointly studied with gradation to develop models that better represents rutting mechanisms in hot mix asphalt.
- Nominal maximum aggregate size is one of the major factors affecting the rutting performance of HMA. In spite of this fact, only 12.5mm NMA is covered in the scope of this study. The effect of Larger NMA in the rutting performance need to be assessed in future studies. Moreover, Stone Matrix Asphalt (SMA) needs to be studied in minimizing the rutting of several roads in the country.
- The effect of bitumen content and film thickness with respect to rutting and aging needs to be studied well to Bailey type gradation.

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APPENDIX A

Mix Design Results

APPENDIX B

Rutting test results