



Addis Ababa University
Addis Ababa Institute of Technology
School of Civil and Environmental Engineering

**Experimental Investigation on Rutting Criteria of Asphalt Mix
Using Refusal Density and Wheel Tracking Tests**

*A Thesis Submitted to the School of Civil and Environmental Engineering Addis
Ababa University in Partial Fulfillment for The Requirement of Degree of
Master of Science*

Submitted by

by

Taye Demeke

Advisor: Dr. Abubeker Worake Ahmed

February 2022

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Undertaking

I, the undersigned, declare that this dissertation work titled “**Experimental Investigation on Rutting Criteria of Asphalt Mix Using Refusal Density and Wheel Tracking Tests**”, to the best of my knowledge and belief, is my original work. It has not been presented for a degree in this or any other universities and all sources of material for this dissertation has been fully acknowledged.

Taye Demeke

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Signature

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Abstract

Ethiopian Road Authority (ERA) has administered around 156 road projects in the years from 2017 to 2021. From those road projects, 94.87% of road projects has being constructed using the Marshal mix design procedure in the preparation of asphalt mixes. ERA manual recommends that the air void after refusal density test is used as a requirement for rutting resistance of the asphalt mixes for roads subjected to heavy traffic. In this study, twelve mixes were prepared with 19 mm and 12.5 mm nominal maximum aggregate size (NMAS) and using bitumen grades of 60/70 and 80/100 penetration grade. The mixes are commonly used for asphalt surfacing in most road projects. Mix designs were performed using the Marshall mix design procedure based on the Asphalt Institute and ERA manual guidelines. Following to the determination of optimum binder content of the mixes, the refusal density tests were conducted by applying further compaction effort using the Marshall hammer. The mixes were then subjected to the wheel tracking tests. The wheel tracking tests were conducted with 20,000 wheel passes and test temperatures of 46°C and 50°C for mixes with 80/100 and 60/70 bitumen penetration grade, respectively. Texas Hamburg Wheel test requirement was used to evaluate the mixes performance to rutting.

The test result indicated that most of the mixes did not fulfil the air void criteria after secondary compaction. From those mixes, more than 50% of the asphalt mixes does not fulfil the performance test requirements (after the wheel tracking test). Therefore, it is found that the percent refusal density (PRD) test may not be a reliable method to indicate the rutting resistance of the asphalt mixes. Thus, other performance tests are recommended to design asphalt mixes for roads subjected to high traffic.

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List of Symbols and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Material
DSR	Dynamic Shear Rheometer
ERA	Ethiopian Road Authority
ESAL	Equivalent Standard Axle Load
G_{mm}	Theoretical Specific Gravity
HMA	Hot Mix Asphalt
HWTD	Hamburg Wheel Tracking Device
MS	Manual Series
NCHRP	National Cooperation Highway Research Program
NMAS	Nominal Maximum Aggregate Size
PG	Performance Grade
PRD	Percent Refusal Density
RTFO	Rolling Thin Film Oven
UK	United Kingdom
VIM	Void in the Mix (air void)
VFA	Void Filled with Asphalt
VMA	Void in Mineral Aggregate

1 Introduction

1.1 Background

Permanent deformation (rutting) is one of the most important distress (failure) mechanisms in asphalt pavements. In recent years, the truck tire pressure has been increasing and rutting has become the dominant mode of flexible pavement failure [1]. Pavement rutting, which results in a distorted pavement surface, is primarily caused by the accumulation of permanent deformation in all or a portion of the layers in the pavement structure. Longitudinal variability in the magnitude of rutting causes roughness. Water may become trapped in ruts resulting in reduced skid resistance, increased potential for hydroplaning, and spray that reduces visibility. When the rutting is progressed, the asphalt pavement can lead to cracking and eventually to complete disintegration or failure. It accounts for a significant portion of maintenance and associated costs in both main highways and secondary roads [2].

The primary causes of rutting in flexible pavements are poorly designed asphalt paving mixture and weak sub-grade. Poorly designed asphalt mixes are expected to be the main cause of rutting. A poorly designed asphalt mix experiences plastic deformation under wheel loads in such a way that the mix flows and upheaves along the wheel path which forms rutting [3].

Asphalt mix design is challenging, especially, for roads expected to carry heavy truckloads with higher design traffic significantly exceeding one million equivalent single axle loads (ESAL). Ethiopian Road Authority Pavement Design Manual recommends refusal density mix test to indicate rutting to the secondary compaction under traffic and virtually no densification will occur outside of the wheel paths for sites categorized as severe.

The percent refusal density (PRD) has several deficiencies in its mode of compaction (not simulating actual field condition) and expected in losing its compaction temperature while compacting. It is found necessary to investigate whether it is conducive in designing rut resistance asphalt mixes. The investigation was conducting the performance test (wheel tracking test) of the asphalt mixes and compare the test result with PRD.

1.2 Statement of the problem

Some studies have recommended the refusal density design procedure for rutting performance of asphalt mix by supplementing it with a minimum air void criterion at refusal density for flexible pavement under heavy traffic.

In refusal density design ensuring that the composition of a mix is correct and that the VIM value will not fall below 3% after trafficking is a vital part of the design process. However, the degree of aggregate interlock and friction between particles also has an important bearing on the resistance of a bituminous mix to shear failure. For example, uncrushed rounded gravel could meet the minimum VIM requirement when compacted to the refusal in a mould, but such material will have little aggregate interlock and would be expected to suffer shear failure under heavy traffic [27].

Hence, percent refusal density has serious drawbacks such as its mode of compaction, which does not simulate the field condition as well as a poor methodology to identify mixes prone to plastic deformations. Due to its drawbacks, it was dropped from the American Standard Testing procedure in 1998 [38]. Following this, it is found necessary to evaluate the asphalt mix with the extended marshal compaction (refusal density) in comparison to the performance test method such as the wheel tracking test. Therefore, this paper evaluates the extended marshal compaction (refusal density) in the indication of the asphalt mixes for rutting criteria.

1.3 Objectives of the research

1.3.1 General objectives

The objective of the study is to check the extended Marshall compaction (percent refusal density) in indication of the rutting criteria of the asphalt mixes after secondary compaction.

1.3.2 Specific objectives

The specific objective of the research is:

- a. To evaluate the asphalt mixes designed with MS2 manual (75 blows) in fulfilling secondary compaction criteria.
- b. To check the effects of different aggregate structures on asphalt institute manual in the rutting performance of the asphalt mixes.
- c. To check the rut depth of the specimens using the wheel tracking test.

1.4 Research Questions

- Does a variable aggregate structure (blend) on the asphalt institute affect rutting performance of the asphalt mixes?
- Does asphalt mixes designed with 75 blows fulfil secondary compaction criteria?
- Does extended marshal compaction (percent refusal density) method address asphalt mix rutting problem?

1.5 Scope and limitations of the research

The limitations and assumptions of the research are: -

- The experimental tests for this research were limited to the available testing equipment in Addis Ababa University, and test machines which were available at the laboratory of the Modjo – Hawassa expressway project.
- The research was limited to twelve types of asphalt mixes.
- The research was limited to the laboratory only and no verification is conducted on the site.

1.6 Scope of the research

This research focused on the experimental investigation of asphalt mix design (with different aggregate structures) for rutting criteria using extended marshal compaction (percent refusal density) and the wheel tracking test. The mixes were prepared using Marshall mix design method with 19 mm and 12.5 mm NMAS along with bitumen type 60/70 and 80/100 penetration grade. A total of twelve (12) asphalt mixes were prepared in this study. From those asphalt mixes, six (6) mixes were prepared with NMAS 19 mm of which three (3) of them were with 60/70 penetration grade and the remaining three (3) were with penetration grade 80/100. The remaining six (6) mixes were prepared with 12.5 mm NMAS with 60/70 and 80/100 penetration grade. The asphalt mixes produced (which fulfils the criteria stipulated in the manual) were subjected to the extended marshal compaction (refusal density) and verification was done by conducting a performance test (wheel tracking test). Finally, determine the worthiness of Marshall refusal density in evaluating rutting resistance of asphalt mixtures.

1.7 Significance of the research

Marshall mix design is still the most commonly used procedure in Ethiopia. To evaluate rutting susceptibility, some studies including our local manual (ERA Pavement Design Manual Volume-I) have recommended a refusal density design procedure by supplementing it with a minimum void criterion at refusal density. However, serious drawbacks with Refusal Density design are its mode of compaction, which does not simulate the field compaction as well as a poor methodology to identify mixes prone to plastic deformations. This research was aimed at evaluating whether the extended Marshall compaction (percent refusal density) can be reliably used to develop rut-resistant asphalt mixes.

1.8 Outline and organization of the research

Section 1 gives the introduction inclining background, statement of the problem, research objective, and significance. **Section 2** focuses on a literature survey of past experimental investigations on similar/ related matters with the study area. **Section 3** views the methodology for experimental tests and the major process of the tests conducted. **Section 4** focuses on the results obtained from the experimental studies, discussions, and way of analysis. **Section 5** gives the conclusion and recommendation of the research.

2 Literature review

This section delivers a background of the study area and related subjects and identifies the connection of others works in the context of their contribution to the subject matter and tries to put the topic within the context of existing literature by specifying a case for why further study is required.

2.1 Asphalt mixes

Asphalt mixture consists of a combination of aggregate uniformly mixed and coated with asphalt binder, each having its particular characteristics suited to specific design and construction uses.

Mixes are classified as dense-graded, open-graded, and gap graded (stone mastic). Dense-graded asphalt mix has well distributed aggregate gradation throughout the entire range of sieves used. The open-graded asphalt mix is an asphalt mixture designed to have a large volume of air voids (typically 18 to 22 percent) which are used to provide skid resistance and water drain pavement surfaces. Gap graded or stone matrix asphalt (SMA) is an asphalt mixture with a high asphalt content (typically more than 6 percent), high coarse aggregate content (typically 70 to 80 percent), and high filler content [27].

This study focuses on the dense graded asphalt mixes and on hot mix asphalt (HMA) wearing course which is the most critical layer in a pavement structure. The mix design in the HMA wearing course need to possess high resistance to deformation, resistance to fatigue cracking, good workability, sufficient surface texture, durability.

2.2 Rutting in Asphalt mixes

Ruts are a surface depression that occurs in the pavement wheel path as a result of traffic loads. Rutting stems from a permanent deformation in any way of the pavement layers or the sub-grade, one usually caused by the plastic movement of the asphalt mix either in hot weather or from inadequate compaction during construction [15].

A pavement surface under rutting is characterized by longitudinal surface depression within the wheel path and may have associated transverse displacement, thereby reducing the serviceability and safety of the pavement. It can be the result of traffic densification (consolidation/ permanent reduction in volume) or permanent movement of material at constant volume (plastic deformation/ shear) or a combination of two [21].

Rutting occurs in two stages in asphalt mixtures. Densification of the asphalt mixture under traffic is the first stage. If the mix is properly designed, this initial rutting rate decrease considerably as the maximum density for a particular mixture is attained. After attaining the maximum the mixtures become unstable and failure occurs rapidly. The steps to minimize rutting are to construct the pavement close to the final density that will be obtained under traffic. Sufficient voids (typically 3-5 percent) are available in the mixture after traffic so that plastic flow does not occur during the design life of the pavement [16].

2.2.1 Cause and Types of Rutting [16]

There are three basic types of asphalt pavement rutting;

1) Structural

Affects all structural layers and is related to an appropriate pavement design and construction quality. Mostly it is a reflection of permanent deformation within granular base layers and sub-grade. The potential causes are weak sub-grade with poor drainage exposed to heavy traffic loading.

2) Surface Wear Rutting

This type of rutting forms only on the top layer of the asphalt layer. It is due to progressive loss of coated aggregate particles from the pavement surface which is caused by a combination of environmental and tire influences.

3) Instability Rutting

This type of rutting only forms on the asphalt layer and is related to asphalt mixtures' mechanical properties, air void content, and mixture resistance to rutting. Weak aggregate structures, excessive bituminous and moisture damage in general weak asphalt layers are potential causes due to low shearing capacity.

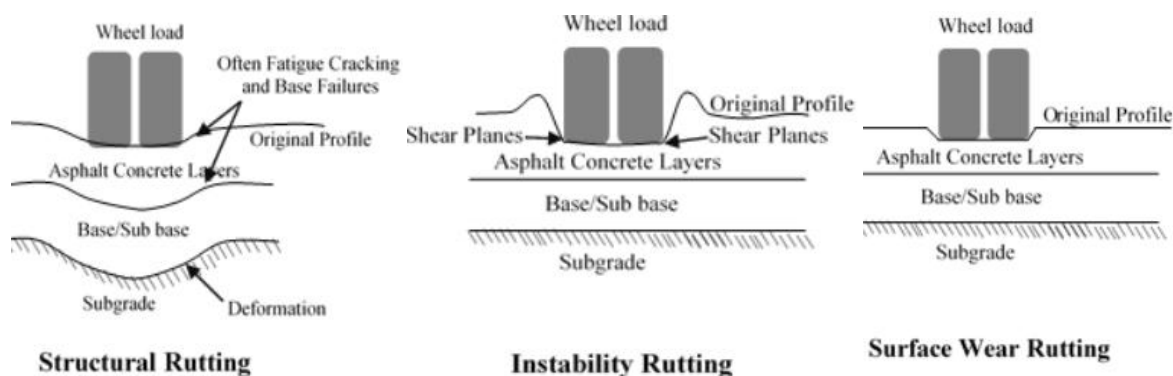


Figure 2.1 type of asphalt pavement rutting

2.3 Effects of Constituents of asphalt mix on Rutting

The three constituents of HMA are binder, aggregate, and air voids. Those can affect the rutting of an HMA pavement.

2.3.1 Aggregates

Aggregates represent major parts of asphalt concrete and it is responsible for the strength and toughness of the materials. The physical properties of aggregates significantly affect the performance of asphalt concrete pavement in service. From aggregate properties many authors singled out aggregate gradation, aggregate angularity and filler content have a significant influence on the rutting resistance of asphalt concrete.

Aggregate gradation

Gradation refers to the particle size distribution of the aggregates which is usually described in terms of particle size distribution curve (also known as gradation curve or gradation chart) determined from sieve analysis.

It is an important factor in the rutting resistance of asphalt mix especially bumps on the 0.45 power curve tend to give mixes that are tender [10].

Different researchers have come to different conclusions regarding the effects of aggregate gradation on the resistance of rutting of asphalt mixes. However, most of the authors agree that aggregate gradation is the key factor in the permanent deformation of asphalt mixes.

Aggregate Angularity

Aggregate particle shape and surface texture affect the bond with asphalt binder, the strength of aggregate particles, and the resistance to sliding of one particle over another. Rough-textured cubical-shaped aggregates perform better than smooth, rounded aggregates. The rougher texture and cubical shape aid in providing aggregate interlock which reduces the potential for rutting as a movement of aggregate under loading are reduced by the interlocking mechanism [8].

The shear strength of asphalt mixtures greatly depends on the degree of mechanical interlock of the aggregate structure and friction that develops at contact points.

The evidence indicates that aggregate angularity is an important factor to be considered in selecting materials for rut-resistant mixtures.

Mineral Fillers

Mineral fillers in asphalt mix are defined as material passing the #200 (0.075mm) sieve. It is added to paving mixtures to impart greater stability and strength. According to the theories developed to explain the effect of fillers, it serves to fill the voids between aggregate particles, thereby increasing the density & strength of the compacted mixtures. And also fillers become suspended in the asphalt binder forming mastic which absorbs binder components, thereby increasing the viscosity of the binder and, consequently the toughness of the mixes [4].

Several literatures indicates that the importance of fillers in improving the performance of asphalt concrete mixtures in resistance to permanent deformation. In addition to the influence on rut considerations such as susceptibility to cracking, moisture and workability may dictate the proportion and type of fillers to be used in asphalt mixtures.

Hot-mix asphalt is a material composed of aggregates and asphalt binders. The aggregate skeleton should be capable of supporting and carrying the traffic to the mixture if it is sufficiently contained and kept bonded together at all times. Since the aggregate particles are not very cohesive the asphalt binder acts as a glue or 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 dislodge aggregate particles and shear deformation may easily occur [23].

The selection of the right aggregate structure and the choice of the most appropriate binder having the required properties are therefore very important for HMA to resist rutting. Some of the aggregate properties that influence shear properties and therefore, rut resistance are particle shape, texture and crushed faces, and gradation. The viscosity or the stiffness is also a property of the asphalt binder that affects rut resistance; a higher viscosity or stiffer binder, especially at higher temperatures, results in higher rut resistance. Asphalt content, dust to asphalt ratio or percent of mineral filler, and film thickness are also some of the properties of the mixture that have been found to affect mixture rutting potential and performance [22].

2.3.2 Bitumen

Bitumen is another important component of asphalt mixture relating to rut resistance. It is visco-elastic material whose resistance to deformation under load is very sensitive to loading time and temperature. It combines viscus behavior, in which the material deforms constantly under applied loads, and elastic

behavior, in which it recovers to its initial state after removal of applied loads. Due to these rheological properties of the binder and bitumen amount used in the mix influences the resistance of asphalt mix.

Bitumen properties

The critical pavement distress mode in which binder plays an important role were fatigue cracking, thermal cracking, and rutting. Oxidative ageing and physical hardening were also considered as durability factors that cause a change in properties of binders and thus affect performance. When the design traffic exceeds 10 million ESALs, SUPERPAVE suggests that an increase in the high-temperature binder grade be considered to achieve better asphalt pavement performance. It can be noted that when the high-temperature grade is increased by one grade, the stiffness of the binder will approximately double [11].

Bitumen Content

Binder content in the asphalt mix has a significant influence on permanent deformation. The binder affects the volumetric properties of the asphalt mix i.e. void filled with asphalt and an increase in a void filled with asphalt leads to an increase in rut depth [6].

2.3.3 Air voids

The amount of void in asphalt mixture is the dominant factor to be considered in the preparation of rut resistance asphalt mixes. Low air content leads to rutting while high air content leads to permeability of air and water resulting in moisture damage, oxidation, raveling, and cracking. Asphalt mixtures with low voids in mineral aggregate and high asphalt content tend to have very low air void contents after densification by traffic and stability i.e. start to shove and rut after reaching a critical compaction level [19].

In general effects of HMA constituents on rutting resistance of asphalt mix are summarized in table 2.1 below [5].

Table 2-1 Effect of HMA constituent on the rutting of asphalt mix [5]

Factor		Change in factor	Rutting Resistance
Aggregate	Surface Texture	Smooth to rough	Increase
	Gradation	Gap to continuous	Increase
	Shape	Rounded to angular	Increase
	Size	Increase in Maximum Size ¹	Increase
Binder	Stiffness ²	Increase	Increase
Mixture	Binder Content	Increase	Decrease
	Air Void Content ³	Increase	Decrease
	Void in Mineral Aggregate ⁴	Increase	Decrease
	Method of Compaction ⁵ ⁵
Test of Field Conditions	Temperature	Increase	Decrease
	Load Repetition	Increase in tire contact pressure	Decrease
	State of Stress/Strain	Increase	Decrease
	Water	Dry to Weight	Decrease (if mixture is water sensitive)

1

1. Assuming constant layer thickness
2. Refers to stiffness at temperature at which rutting propensity is being determined
Modifier may be utilized to increase stiffness at critical temperatures, thereby reducing rutting potential
3. When air void contents are less than about 3 %, the rutting potential of mixtures increase
4. It is argued that very low (i.e. less than 10%) voids in mineral aggregate should be avoided
5. The method of compaction whether laboratory or field, may influence the structure of the system and therefore the propensity or tendency for rutting.

2.4 Refusal Density of Asphalt Mixture

Refusal density is a measure of the maximum degree of packing of aggregates in the asphalt mix that is possible without degradation of the aggregate. It also used to simulate the in-situ density to which an asphalt mix can be compacted under extreme condition of traffic loading which correlates mixes prone to rutting [32].

Rutting (permanent deformation) occurring in an asphalt mixture that densifies to a very low air void content is called tertiary flow in theological terms. The Superpave mix design system uses the ‘repeated shear test’ to analyse this property. Some highway agencies stipulate, as part of mix design procedure, carrying out wheel track test, to measure ruts created by the repeated passage of a wheel over asphalt concrete specimens of the designed mix. Deformation (rutting) is then measured by a relative percentage reduction in the thickness of asphalt concrete in the wheel path. On the other hand, refusal density testing is simply a procedure for asserting the air void level when the mix has achieved its maximum density under Marshall compaction (or any other type of compaction). The air void level after the refusal density test is then compared with the threshold lower limit of air voids (3 %) that has been recognized as an indicator of the tendency of the mix for rut resistance [17].

It was originally developed to assessing the effectiveness of field compaction of the asphalt designed to recipe specifications. The low voids in the PRD test correlated to mixes prone to rutting, hence the current use in the UK of the refusal density test as a design tool to identify mixes with potential for low in-situ voids. Percent Refusal Density of field cores usually indicates good performance and satisfactory material when the PRD of the compacted material falls in the range (ratio) 93% -97% of the bulk density of the field core before vibratory compaction of the heated core [30].

Bituminous mix design following the guideline of MS-2 specifications has been performing under heavy traffic conditions. 75 blows Marshall compaction is inadequate to represent the in-place density attained by the field mixes under heavy axle load. The propensity of a bituminous mix for rutting under secondary compaction due to heavy traffic was judged by studying the air voids levels under increased Marshall compaction up to refusal density [24].

A comprehensive review of international published literature [27] emphasized that all research and experience to date had confirmed that proper compaction of the asphalt is the most significant factor for achieving satisfactory service life of the asphalt surfaced pavement.

The deficiency of the empirical mix design methods such as Marshall are summarized in the book [26], that the method is restricted by the small sample size used and their compaction techniques, which do not simulate the compaction regime in-situ. They do not measure the mechanical properties of the mixtures so cannot be used for performance specifications or design procedures. Besides, it was indicated that void at refusal density in the extended Marshall design procedure is not a reliable parameter in determining the plastic deformation potential of asphalt mixes [26].

The Marshall mix procedure is empirical and has limitation of accuracy in determining the full effect of variations in environmental and traffic loading conditions, material properties and types on the pavement performance. The shear susceptibility of the asphalt mixes cannot be identified with this approach. The method of compaction also does not simulate the densification that occurs under traffic in a real pavement. Due to its drawbacks, it was dropped from the American Standard Testing procedure in 1998 [38].

In extended Marshall design (Refusal Density Design) ensuring that the composition of a mix is correct and that the VIM value will not fall below 3% after trafficking is a vital part of the design process. However, the degree of aggregate interlock and friction between particles also has an important bearing on the resistance of a bituminous mix to shear failure. For example, rounded gravel could meet the minimum VIM requirement when compacted to the refusal in a mould, but such material may have little aggregate interlock and would be expected to suffer shear failure under heavy traffic. Although the Marshall design method addresses these problems, it has been found that the correlation between measurements of stability and flow and subsequent performance in the road is not as good as desired. A better indication of the tendency for a mix to deform plastically under traffic is given by the 'Stiffness Quotient' i.e. maximum stability divided by the flow value. However, measurements of both these values usually have large variations and, therefore, Stiffness Quotient values tend to be unreliable [27].

It has also many other shortcomings and limitations, such as absence of simulating field conditions in the laboratory. To minimize the limitations of the Marshall mix design method, some studies provide a hybrid approach (designed the modified Marshall method) to integrate the effects of temperature and the asphalt performance grading in the AC-mix design and the level compaction [37].

Resistance to plastic deformation of asphalt mixture is mainly dependent on internal friction between the aggregate particles and binder viscosity. When VIM is reduced to a low value, stresses are progressively transferred to the bitumen which then forces the aggregate apart and allows the materials to deform plastically [9].

The plastic deformation of the asphalt is happened when the asphalt losses its plastic behaviour. The risk of plastic deformation increased dramatically when the in situ VIM decreased to less than 3%. At this level of VIM, bitumen hardening is quite rapid and this is likely to continue in the area of surface which are outside the wheel paths and therefore not subject to additional compaction. Such areas of surfacing with a difference of densities and different degrees of bitumen hardening and different susceptible to cracking [18].

The asphalt institute recommends that the asphalt mixtures are laid and compacted to air voids of 8%. This allows for the air voids to reach 3% - 5% after consolidation during trafficking. To make sure in-situ VIM never drops below 3% an additional procedure is needed, in which the samples are compacted to a refusal condition. This is by compacting the samples until they refuse to become any denser and the binder content is set corresponding to 3% air voids at refusal condition [12].

In Marshall's test compaction level, VMA reduces to a minimum and then increases as a bitumen content is increased. However, samples subjected to refusal density will have a sensibly constant value of VMA over a range of bitumen contents before the aggregate structure begins to become over filed and VMA increase. It will be a simple matter to determine the sensitivity of the mix to variations in bitumen content required to give a minimum of 3% at refusal density. The aggregate also can be adjusted to increase VMA which will reduce the sensitivity of the mix to change in bitumen content [31].

In the refusal density test procedure, trial mixtures with varying binder content are subjected to an extended Marshall compaction until no further densification of samples is obtained. The Marshall mix design procedure using 75 blows on each face should first be completed to check that Marshall requirements for the mix are met and to provide input to refusal density procedure. It is preferable to conduct a trial using the lowest binder content and compact samples using an increasing number of blows say, 200, 300, 400, etc. until no further increase in density occurs, usually, 500 blows to each face are found to be sufficient [35].

In addition, in modified asphalt mixtures show high air voids after marshal refusal compaction, which can be misleading as it gives a false impression that the mixture are resistant to densification, whereas the same mixtures are compacted using Nmax – gyration may fail the minimum air void requirement in super pave for Nmax. It is recommended to use superpave Nmax gyration criteria for identifying rut resistant mixtures asphalt mix design [26].

Method of compaction

There is two simple and inexpensive methods by which refusal density can be achieved. The first method is an extension of marshal compaction in which the sample is subject to 400 or more blows per face instead of 75. The second method uses an electrical vibrating hammer as described in BSI: 598 part 104 (BSI: 1989), which uses a 102 mm diameter foot to compact samples in a 152 mm split mould.

Some authorities have adopted the procedure using an increased number of blows of the marshal hammer to design surfacing which will require a minimum level of VIM after compaction by traffic. A vibrating hammer as described earlier is used as an alternative. Neither of these methods exactly reproduces the mode of compaction which occurs under heavy traffic; however, the later procedure is preferred because it allows a degree of kneading of the mix which is more representative of field compaction and it is relatively quicker method [17].

2.5 Wheel Tracking Test

The wheel track devices are used to measure the resistance to rutting of asphalt mixtures. The wheel tracking devices attempt to simulate field condition and traffic loading and they are used to evaluate the rutting and stripping of asphalt mixtures under various moisture and temperature condition. The three most commonly employed wheel tracking devices are, Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device, and French Rutting Tester. In these devices, an asphalt specimen is subjected to a repeated rolling load through a pressurized hose, or an inflated wheel, or a steel or rubber wheel. These devices measure the potential of rutting by rolling a loaded wheel device repeatedly across an asphalt mix specimen. The cumulative rut depth is then measured and used as rutting criteria [21].

Hamburg Wheel Tracking device (HWTD) is developed in the mid-1970s in Germany based on a similar British device that had a rubber tire. HWTD tests two slabs simultaneously two reciprocating solid steel wheels. The slabs are (320 mm long and 260 mm wide, the slab can be 38, 76, or 119 mm thick. The width and diameter of the wheels are 22.87 mm and 203 mm, respectively. Test specimens

are typically compacted to 7 ± 1 percent air voids using a linear kneading compactor. The test uses a water chamber as a means of obtaining the required test temperature which can be set from 25-70 °C with 50 °C being the most common test temperature [23].

The HWTD measures the combined effects of moisture damage (stripping) and rutting by rolling a steel wheel across the surface of an asphalt concrete slab that is immersed in hot water. The AASHTO T-324 specification permits the specimen set up to consist of either one slab specimen (rectangular specimen) or two adjacent cylindrical specimens to measure HMA rutting properties while submerged in water.

The Dyna – Track wheel tracker is also used to measure the resistance to rutting of asphalt mixtures. It is used to perform tests only on asphalt slabs according to the Standard EN12697-22 and user-defined procedures. The equipment allows the test to be performed in air and within the heated chamber up to 65°C. The equipment carries out the tests on compacted slabs obtained with roller compactor equipment (model 77-B3602) housed in relevant moulds (size 400×300mm or 320×260mm). The wheel has a diameter of 200mm and has an outer surface of hard rubber. It is mounted on a special arm at the end of which a weight is applied in which designed so that the wheel applies a load on the sample of 700 ± 10 N. The mechanical system consisting of the wheel system and the sliding table is housed in a thermostatic chamber which permits temperature in the range of 25 °C to 65 °C ± 1 °C [34].

A 25 × 0.1 mm displacement transducer measures the rut depth caused by tyre at the center of the test sample during the test. The equipment allows the test to be performed according to procedure A and procedure B of in the air and within the heated chamber up to 65 °C according to the standard UNIEN 12697-22 (Small Size device). In the standard, if the test specimen is tested in the air (procedure A or B), they are to be conditioned at the specified test temperature ± 1 °C for a period to the testing of:

- ✓ A minimum of 4 h for specimens with a nominal thickness equal to or less than 60 mm.
- ✓ A minimum of 6 h for specimens with a nominal thickness larger than 60 mm.
- ✓ A maximum of 24 h.

In procedure A, monitoring the rut development is with either an automatic displacement measuring device or a dial gauge and continuing tracking for 1000 cycles or until a rut depth of 15 mm reached whichever is the shorter. While in procedure B, the rut depth was monitored as set the machine in motion take readings at the vertical displacement of the wheel, and continues tracking until 10000 load cycles are applied or until a rut depth of 20 mm is reached whichever is the shorter [33].

2.6 Summary of Literature

Rutting is one of the major pavement distress in our country. Poorly design asphalt mixes are the main cause of rutting. The propensity of bituminous mixes for rutting under secondary compaction due to heavy traffic was judged by studying the air voids levels under increased marshal compaction up to refusal density. However, this approach (refusal density) is questioned on its mode of compaction which does not indicate the degree of aggregate interlock and friction between particles. Due to this its drawbacks, it was dropped from the American Standard Testing procedure in 1998.

On the other hand the wheel tracking test approach used to evaluate the rutting resistance of the asphalt mixes by simulating actual field and traffic loading. To verify the refusal density test approach, it is important to evaluate rut resistance of different asphalt mixes using extended marshal compaction (refusal density test) approach in comparisons of performance testing approach (wheel tracking test).

3 Research methods and materials

3.1 Introduction

The research methodology applied for this study was experimental. As it is stated before, the main objective of this study was to investigate the rutting criteria of asphalt mix after secondary compaction at heavy traffic condition that is based on the marshal mix design and performance test method (wheel tracking test). Therefore, it was necessary to conduct all the necessary experimental tests required to arrive at a reasonable conclusion point. The tests were conducted on asphalt mixtures using mostly used virgin binder and different mineral aggregates. The subsequent sections describe the types of materials used, the sample prepared, types of tests conducted, the purpose of the test, and related matters.

3.2 Experimental Program and Test Method

This section presents the materials used (i.e. aggregates and bitumen) and the asphalt mixture tests conducted in this study. Aggregates were sampled from three different sources and the bitumen sampled from the stock was ready for road construction. The sources of aggregate were located in a different location in which different properties of the aggregate are expected. The material quality test was conducted as per the required standard. After conducting material quality tests, different asphalt mixes were designed using the Marshall method. The refusal density test was also conducted with a Marshall hammer with more blows (400 and 450) due to the unavailability of a vibrating compactor. The same mixtures were subjected to the wheel tracking test to evaluate the rut depth of each mix. A single wheel tracking machine was used for the study due to the unavailability of the HWTD in our country. The required tests are mentioned in table 3.1 below.

Table 3-1 Experimental program and test method

Material Selection	
Aggregate Tests	Bitumen Tests
Gradation	Penetration
Specific gravity	Softening Point
Flat or elongated particles	Ductility
Clay content	Specific gravity
Toughness (LAA, ACV & TFV)	Flash Point
Soundness	Solubility test
	PG determination

Marshal mix design
Check the Volumetric Properties of the mixes
Refusal Density Test
Performance Tests
Wheel Tracking Test

3.3 Materials

The materials used for this study were bitumen and aggregates. Two types of bitumen grades (60/70 and 80/100) were used in this study. The aggregates used in the study were crushed type from three sources which are located in a different place. The difference of the sources is only the location which may have different aggregate properties. Both the bitumen and aggregates were sampled from the stock and crusher sites prepared for asphalt works on the road projects. A total of twelve mixes was prepared from those materials using marshal mix design to achieve the goals of the study. From those asphalt mixes, six types of aggregate blends were prepared in such manner that one aggregate blend was used for two mixes with different bitumen type.

3.3.1 Bitumen

The selection of binder grade depends on the air temperature range for the specific project and on the traffic volume which is then used to establish the corresponding design pavement temperatures. For this study, a penetration grade of 60/70 (PG 64-YY) and 80/100 (PG 58-YY) were used, which are the commonly used bitumen types in most regions of Ethiopia [36].

3.3.2 Aggregates

The aggregates used in this study were hard, tough, durable (sound), rough, strong, clean, cubical, low porosity, and hydrophobic surface. Even if the sources of aggregates were different, all sources of aggregates fulfilled the asphalt institute manual’s requirements for the preparation of the hot mix asphalt mixtures. Figure 3.1 shows the aggregates which were ready for the preparation of the asphalt mixtures.



Figure 3.1 Aggregate used for the asphalt mixes

The aggregates used in HMA affect the stiffness, stability, workability, fatigue resistance, fractural strength, durability, permeability, voids, and compatibility of the mixtures. Table 3.2 shows the material characteristics along with the standard test methods.

Table 3.2 HMA aggregates property and test method

HMA Aggregate Characteristics	Standard Test Method
Aggregate Gradation and Size	ASTM C117 /AASHTO T-30
Particle Shape and Surface Texture (Flat and Elongated Particles)	ASTM D-4791
Cleanness and Deleterious Material	AASHTO T-176
Toughness and Abrasion Resistance	AASHTO T 96 or ASTM C131
Durability and Soundness	AASHTO T 104 or ASTM C88
Bitumen Affinity	ASTM D1664
The specific gravity of aggregates	

For this specific study, a nominal aggregate size of 19 mm and 12.5 mm have been selected and considering the road subjected to heavy traffic (i.e. Design ESALs (million) > 30). The main purpose of

selecting this nominal aggregate size was by considering the lift thickness of most roads in our country (Ethiopia) which is 50 mm. In this regard, ERA 2013 Pavement Design Manual recommended that the thickness of the asphalt shall be lie between 2 and 4 times the maximum stone size of the mixture to achieve good compaction. Table 3.3 shows the required properties of aggregate for HMA.

Table 3-3 Required Properties for HMA Aggregates as per ERA Flexible Pavement Design Manual, 2013

Property	Test	Properties	
		Wearing Course	Binder Course
Cleanliness	Sand equivalent for < 4.75mm fraction		
	<1.5×10 ⁶ ESA	>35	
	>1.5×10 ⁶ ESA	>40	
	Material passing 0.425 sieve		
	Plastic Index ²	<4	
	Linear shrinkage %	<2	
Plastic shape	Flakiness Index ³	<35	
Strength	Aggregate Crushing Value(ACV) ⁴	<25	
	Aggregate Impact Value (AIV) ⁴	<25	
	10 FACT (dry) KN ⁴	>160	
	Los Angeles Abrasion (LAA) ⁵	<30	<35
Abrasion	Aggregate Abrasion Value (AAV) ⁴		
	<250 cv/lane/day	<16	
	>3250 cv/lane/day	<12	
Water Absorption	Water absorption ⁶	<2	
Sundeness ⁷ (5 cycles, % loss)	Sodium Sulphate Test		
	Coarse	<10	
	Fine	<16	
	Magnesium Sulphate Test		
	Coarse	<15	
	Fine	<20	
Bitumen Affinity	Immersion Mechanical Test: index of retained Marshal Stability	>75	
	Static Immersion Test ⁸	>95% Coating retained	
	Retained Indirect Tensile Strength ⁹	>79% (at 7% VIM)	

- Notes:-**
- | | |
|--|--------------------------------------|
| 1. AASHTO T176-86 | 6. British Standard 812, Part 2 1975 |
| 2. British Standard 812, Part 2 (1990) | 7. AASHTO T104 - 99 |
| 3. British Standard 812, part 105 (1990) | 8. D Whiteoak (1990) |
| 4. British Standard 812, Part 3 (1985) | 9. AASHTO T283 |
| 5. ASTM C131 and C535 | |

3.4 Bitumen Tests

Sample preparation

Two types of bitumen penetration grades (60/70 and 80/100) were prepared for this study so as to conduct the conventional tests.

3.4.1 Conventional Tests

The following conventional tests of bitumen under Table 3.4 have been conducted.

Table 3.4 Convectional Tests of bitumen

Test Type	Importance	Test Standard
Penetration	Measures the consistency (hardness or softness) of asphalt binder	ASTM D5 or AASHTO T 49
Softening Point	Used to know the temperature at which the asphalt starts flowing	ASTM D36
Ductility	Measures the adhesive property of bitumen and its ability to stretch.	ASTM D113
Purity	To determine the purity of the asphalt cement	ASTM D2042
Safety	Indicates the temperature to which asphalt cement may be safely heated without the danger of instantaneous	ASTM D92
Specific Gravity	Used in calculation of some asphalt mixtures property	ASTM D70

Specifications of Bitumen

Table 3.5 shows the required requirements of the asphalt property along with the standard test method for the 60/70 and 80/100 penetration grades [27].

Table 3-5 Requirement for penetration grade bitumen

Test		Test Method (ASTM)	Penetration Grade	
			60/70	80/100
Based on original bitumen				
Penetration at 25°C		D 5	60-70	80-100
Softening Point (°C)		D 36	46-56	42-51
Flash Point (°C)	Min	D 92	232	219
Solubility in trichloroethylene (%)	Min	D 2042	99	99
TFOT heating for 5h at 163°C				
Loss by Mass (%)	Max		0.5	0.8
Penetration (% of original)	Min	D 5	58	50
Ductility at 25°C	Min	D 113		75

3.4.2 Bitumen Super-pave Tests

Super-pave studies the rheological behaviour of the bitumen to evaluate the performance of the pavement. It used to study the bitumen property at its original state, after mixing and placing of the asphalt layer (short term ageing effect) and after its service/design life (long term ageing effect) considering different external factors. Figure 3.2 shows the DSR test machine.



Figure 3.2 DSR test machine.

PG Determination Test

This test is conducted at high temperatures to categorize the asphalt binder (bitumen), based on its temperature resistance. The purpose of the test is to determine the complex shear (G^*) modulus and phase angle (δ) of asphalt binders. Test performed on the original asphalt binder to represent the first stage of transport, storage and handling. The second stage indicate the asphalt binder during mixing, production, and construction and is simulated by ageing the asphalt binder using the rolling thin film oven (RTFO). The third stage occurs as the asphalt binder ages over a long period as part of the hot mix asphalt pavement layer. This stage is simulated for the specification by ageing using the pressure ageing vessel (PAV). In this study, the test was conducted up to the second stage due to that the unavailability of pressure ageing vessel (PAV). The diameter and the thickness of the sample were 25 mm and 1 mm respectively. Super-pave specification defines and places requirements on a rutting factor, $G^*/\sin \delta$ which represents a measure of high-temperature stiffness; and to minimize the rutting effect of the asphalt $G^*/\sin \delta$ should be a minimum of 1 kPa for un-aged binder and 2.2 kPa for short term aged binder. The phase angle and complex shear modules define the resistance to shear deformation of the asphalt binder in the linear viscoelastic region. The test is conducted as per the procedure found in AASHTO T 315. In this study, the PG determination test was used to determine the test temperature for the wheel tracking tests.

Mixing and Compaction Temperature

Determination of mixing and compaction temperature is one of the important parameters in the design of asphalt mixes. Viscosity tests such that kinematic and rotational viscosity tests are used to determine the mixing and compaction temperature of the asphalt mixes. In this study, neither of the above tests could be conducted due to the non-availability of test equipment. Instead, other methods were adopted which are conducted by using a DSR test machine. From these methods, the method based on the phase angle (Casola) of the binder was used to determine the specific mixing and compaction temperature of the asphalt mixes [7].

Based on the literature review and the guidance from the research panel (NCHRP), three candidate methods for selecting mixing and compacting temperatures were explored:

1. Steady shear rate viscosity, and

3. A new approach based on the phase angle of binders.

3. High shear rate viscosity,

The steady shear flow approach considers the shear rate dependency of binders. Flow profiles for shear-dependent binders show that viscosities tend to stabilize with increasing shear. The target shear stress of 490 Pascals was chosen by Reinke as a value where the viscosity measurements appeared more stable and within the capabilities of standard asphalt DSR. Although this approach requires viscosity-temperature data to be extrapolated to high temperatures outside of the range of most DSRs, the method is fairly simple and, based on a limited set of binders, appears to yield reasonable results for mixing and compaction temperatures.

The second candidate technique considers the non-Newtonian viscoelastic behaviour of binders as measured using standard asphalt DSR equipment. In dynamic testing, the phase angle is the measure of the time lag between the applied stress and the resulting measured strain. For dynamic shear rheology, the phase angle identifies the relatively elastic and viscous response to shear and can be easily measured over a range of temperatures and frequencies. Therefore, it was logical to explore the phase angle as an alternate consistency parameter that could be used to establish mixing and compaction temperatures. Although phase angle is a fundamental material property, its relationship to coating and lubricating aggregate particles is empirical. A phase angle of 86° is an identifiable transition point of the material exhibiting viscoelastic behaviour for comparison.

$$\mathbf{Mixing\ Temperature\ (^{\circ}F) = 325 \times w^{-0.0135}}$$

$$\mathbf{Compaction\ Temperature\ (^{\circ}F) = 300 \times w^{-0.012}}$$

Where $w = \text{Frequency in } \frac{\text{rad}}{\text{s}}$ at phase angle 86°

The high shear rate viscosity approach is based on the hypothesis that modified binders are shear thinning and that the reason Super-pave gyrator compaction is insensitive to binder viscosity or moduli because of the compaction process is a high shear domain for asphalt coatings on aggregates. The viscosity data generated with this method are easy to obtain and indicate the shear rate dependency of binders through typical mixing and compaction temperature ranges.

In this study, the second approach was used to determine the mixing and compaction temperature of the asphalt mixtures. This was selected due to that it was easy to conduct the tests with a standard DSR machine and also it takes short time for completion of the test.

3.5 Aggregate size distribution of the mixes

Aggregate particle size distribution is critical in the preparation of HMA which fulfils the volumetric parameter of the asphalt mixes. It is suitable for dense AC surfacing to produce a mix that will have sufficient VMA to accommodate enough bitumen (workable during construction), be durable in the service and retain a minimum of 3% VIM after secondary compaction by traffic. Table 3.6 shows the particle size distribution of aggregates for the AC wearing course.

Table 3.6 Recommended Particle size distribution for AC wearing Course as per Asphalt Institute, 1994

Sieve Size (mm)	Nominal Maximum Stone Size (mm)	
	Percentage Passing Sieve	
	19	12.5
25	100	
19	90 - 100	100
12.5	-	90 - 100
9.5	56 - 80	-
4.75	35 - 65	44 - 74
2.36	23 - 49	28 - 58
1.18	-	
0.6	-	
0.3	5 - 19	5 - 21
0.15	-	
0.075	2 - 8	2 - 10
Bitumen Content (%)	4 - 10	4 - 11

In this study, a NMAS of 19 mm and 12.5 mm were used for the preparation of the asphalt mixes. Figure 3.3 and 3.4 show the aggregate gradation curve for NMAS 12.5 mm and 19 mm respectively.

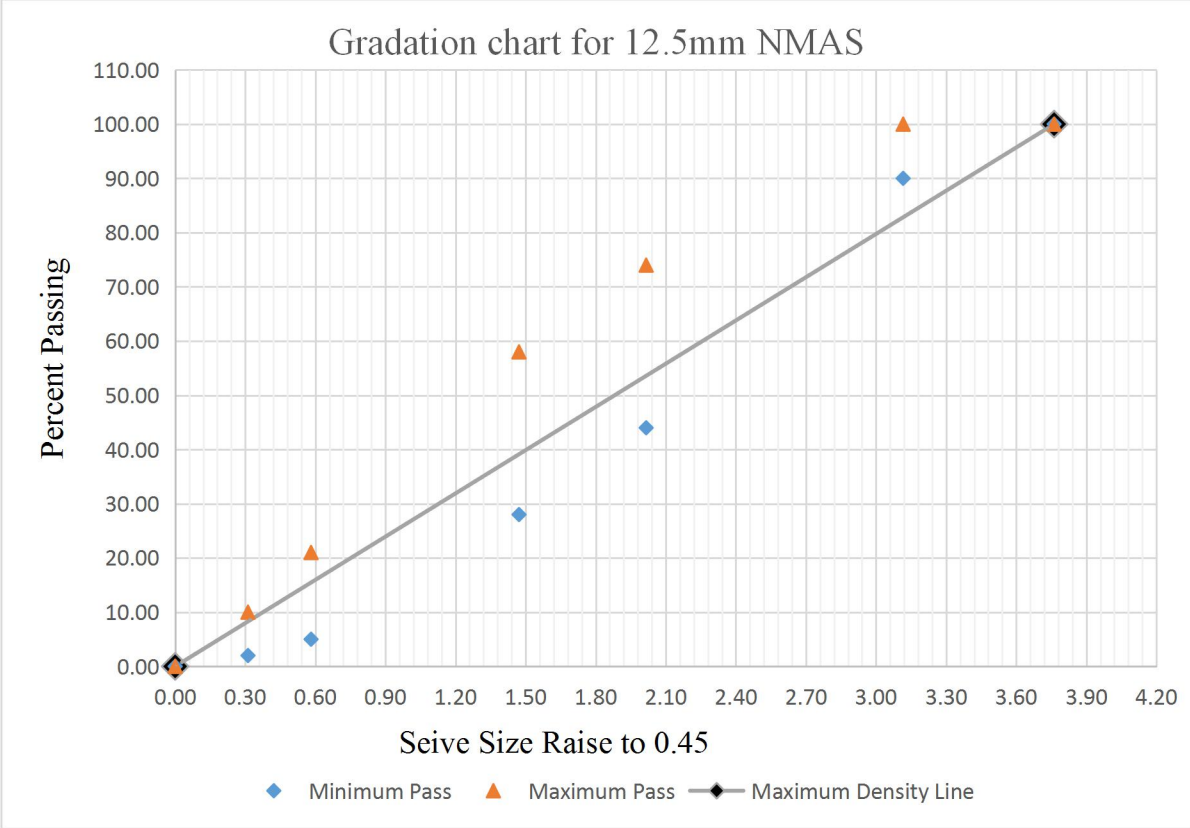


Figure 3.3 Maximum Density Line for 12.5mm NMAS

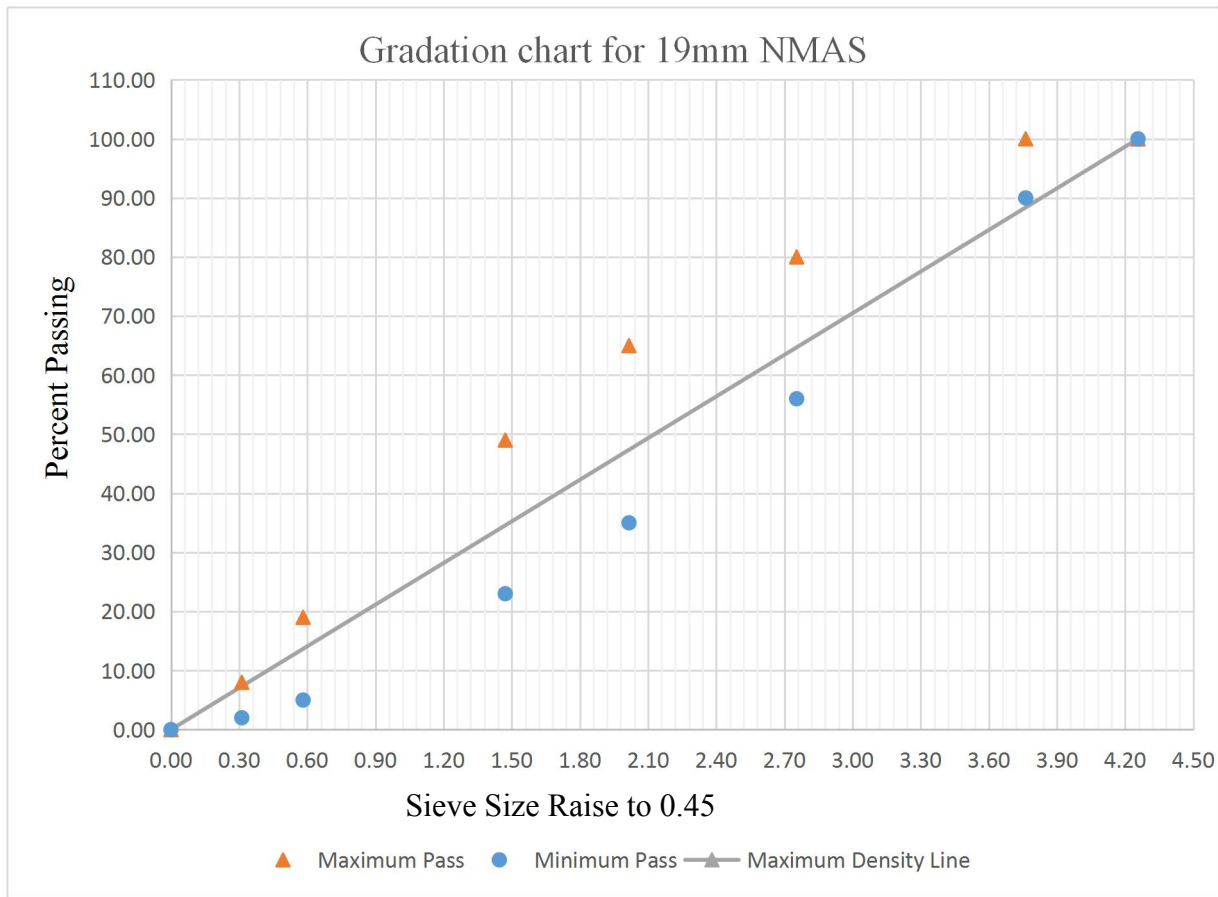


Figure 3.4 Maximum Density Line for 19mm NMA S

3.6 Asphalt Mix Design using the Marshal method

3.6.1 Determining the Optimum Binder Content

The binder content of mixtures generally varies based on gradation, maximum aggregate size, and aggregate properties. Aggregate absorption rate has a significant effect on the amount of asphalt needed to obtain the design air void content of the mixture. The initial value of bitumen content in preparation of HMA is recommended with the respective NMAS of the asphalt mixture. Table 3.7 shows the default binder content of the mixes along with the NMAS as per MS-2 standard.

Table 3.7 Default binder content of the mixes as per (MS-2, 7th edition)

NMAS (mm)	Trail Asphalt Binder Content (%)
37.5	3.5
25	4.0
19	4.5
12.5	5.0
9.5	5.5

Volumetric Design of Asphalt Mixes

The controlling factor in the design of the mixes for all traffic levels is the volume of each mix component. The basic parameters of the Volumetric design are;

- ✓ Air Void (VIM)
- ✓ Void in Mineral Aggregate (VMA)
- ✓ Void Filled with Bitumen (VFB)
- ✓ Effective Bitumen Content (P_{be})

Figure 3.5 illustrate the volumes in a compacted HMA specimen

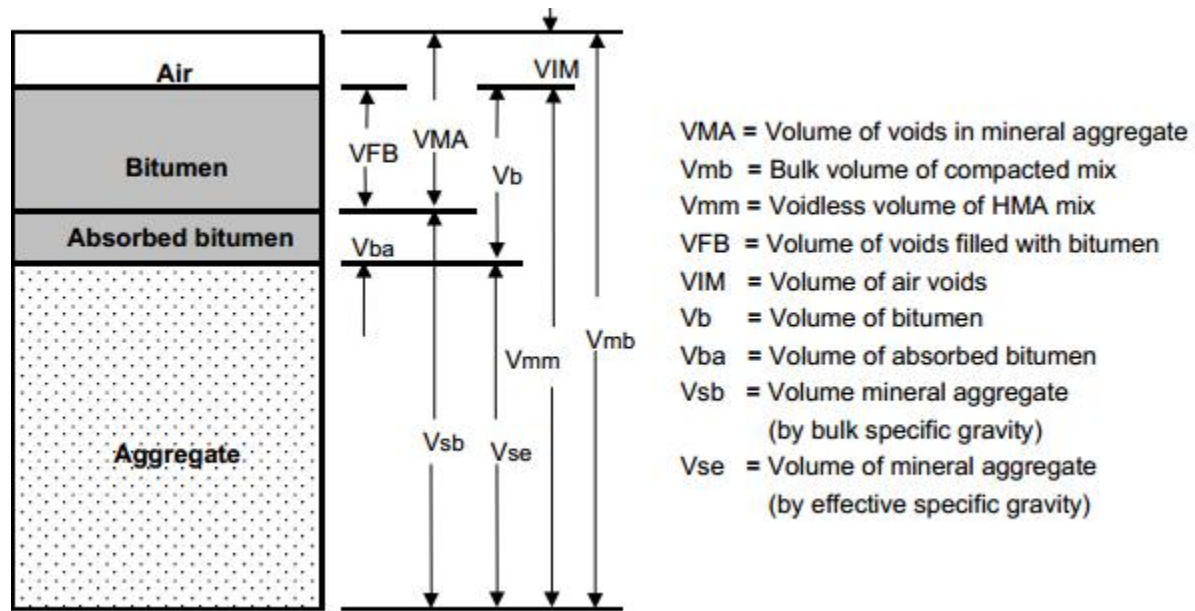


Figure 3.5 Volumes in a compacted HMA Specimen as per MS-2, 1994

Calculation of the Volumetric Properties

After the compaction, the air void contents, VMA contents, VFA contents, and specific gravity values are calculated according to the following equations;

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) * 100 \quad (3.1)$$

$$G_{mb} = \frac{W_d}{W_{ssd} - W_{sub}} \quad (3.2)$$

$$G_{mm} = \frac{W_{agg} + W_b}{V_{eff} + V_b} \quad (3.3)$$

$$V_{eff} = V_{agg} - V_{BA} \quad (3.4)$$

Where; V_a is the air void (%),
 G_{mm} is the theoretical Specific gravity ($g \text{ cm}^3/$),
 W_d is the dry weight (g),
 W_{ssd} is the saturated surface dry weight (g),
 W_{sub} is the weight submerged in water (g),

- Wagg is the weight of aggregate (g),
- Wb is the weight of binder (g),
- Veff is the effective volume of aggregate (cm³),
- V is the volume of binder (cm³),
- Vagg is the volume of aggregate (cm³),
- VBA is the volume of absorbed asphalt (cm³),

When the air voids are calculated the corresponding VMA and VFA values are calculated with the following equations;

$$VMA = 100 - \left(\frac{G_{mb} \times P_s}{G_{sb}} \right) \tag{3.5}$$

$$VFA = VMA - P_a \tag{3.6}$$

- Where;
- VMA is the voids in mineral aggregate (%),
 - P_s is the aggregate content by weight of mix (%),
 - G_{sb} is the bulk specific gravity of the aggregate (g cm³),
 - VFA is the voids filled with asphalt (%),
 - P_a percent of the air voids (%),

Accordingly, the design mix was selected considering the mixes at the optimum bitumen content that satisfies all volumetric properties and compaction characteristics.

The Marshall requirements confirmed for mixes designed for heavy traffic (>5 million ESAL) category. Table 3.8 shows Marshall requirement of the mixes for the traffic level >5 Million ESAL.

Table 3.8 Marshal Requirements for traffic level >5 Million ESAL

Category and design traffic (million ESA)	No. of blows of Marshall compaction hammer	Min. Stability (N)	Flow (mm)	VFB (%)	VIM at optimum bitumen content (%)
Very heavy (> 5)	75	9000	2 - 3.5	65-73	5

Figure 3.6 illustrates the test machines used for the mix design preparation and compacted asphalt specimens.



Figure 3.6 Marshal Test Machine and Compacted Specimens

Nomination of the asphalt Mixes used in the study

Twelve asphalt mixes were prepared in this study using 60/70 and 80/100 Pent. grade aggregates along with 12.5 mm and 19 mm NMA. Table 3.9 shows the nomination of the asphalt mixes used in exclusive of this study.

Table:- 3.9 Nomination of different mixes used in this study

Nomination	Bitumen Type	NMA	Source of Aggregates
M1	80/100	19mm	#1
M11	80/100	19mm	#3
M111	80/100	19mm	#3
M2	60/70	19mm	#1
M22	60/70	19mm	#3
M222	60/70	19mm	#3
M3	80/100	12.5mm	#3
M33	80/100	12.5mm	#2
M333	80/100	12.5mm	#1
M4	60/70	12.5mm	#3
M44	60/70	12.5mm	#2
M444	60/70	12.5mm	#1

From the above-nominated mix types, every two types of asphalt mixes had the same aggregate blends with different bitumen types. (i.e.M1 and M2, M11 and M22, M111 and M222, M3 and M4, M33 and M44, M333 and M444).

3.7 Refusal density test

After a Marshall requirement was satisfied, the mixes were subjected to the refusal density by increasing the compaction effort (number of blows) to the level that aggregates cannot be compacted any further. The number of blows was determined by the number of trail compaction that the number of blows at which the density of the specimen going to start constantly. After compaction of the mixture with the required compaction effort, the air voids of the mixes have checked whether it fulfils the minimum VIM requirement (3%). Figure 3.7 shows the Marshall hammer.



Figure 3.7 Marshal Hammer

3.8 Performance tests

As part of the study, after proper mixes with the required proportion of aggregate and bitumen were identified, further performance evaluation of the mixes was conducted through wheel tracking tests.

3.8.1 Wheel Tracking Test

For the wheel tracking test samples were prepared using a slab compactor with 25 numbers of passes to get VIM 7% considering the initial compaction of asphalt after placing. After conditioning the specimens for 24 hrs, it was subjected to a wheel tracking test with a wheel load of 700 ± 10 N and 10,000 cycles with a frequency of 53 passes per minute (i.e. the number of pass simulates heavy traffic

condition which exceeds 30 million ESAL). Figure 3.8 shows the wheel track test machine used in this study.

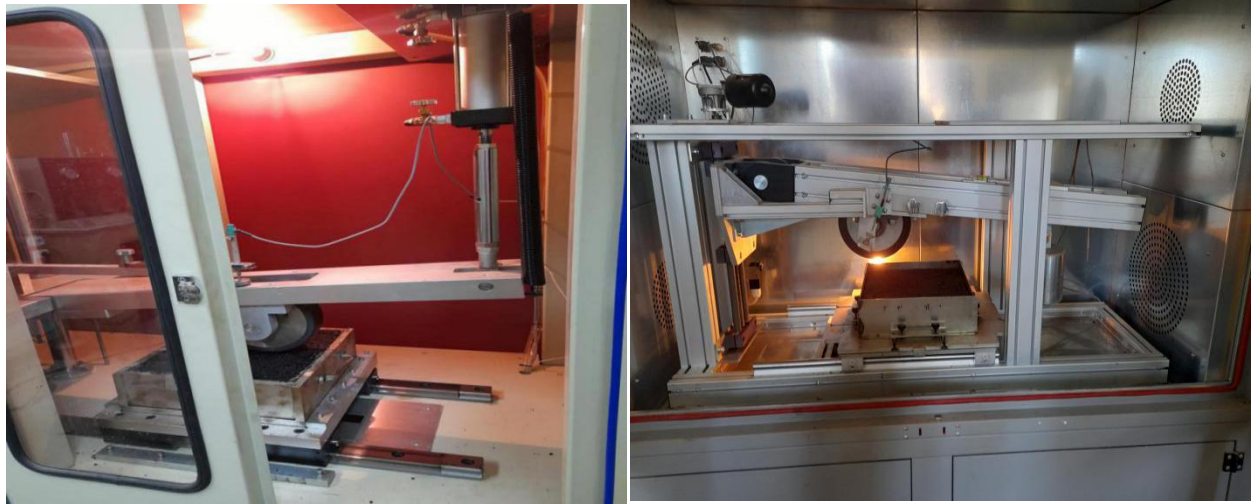


Figure 3.8 Single Wheel Track Test Machine

Temperature determination

Binder selection for the mixes focuses on the temperature of the project. This study uses two bitumen types which is used for different temperature locations. To evaluate the performance of the mixes, different testing temperatures were considered in the wheel tracking test. Test temperature for the HWTD test was revised to ensure the future HMA projects do not contain aggregate binder combinations that are susceptible to both rutting and moisture damage [2]. For the mixture intended to be used in a location where the recommended binder is PG 64-XX, a test temperature of 50°C is suggested. For mixtures intended to be used in a location where the recommended binder is PG 70-XX, the test temperature should be raised from 50°C to 54°C. On the other hand, the mixture made with a PG 58-XX binder will most likely fail the test at 50°C so a lower temperature of 46°C is recommended. In this study, the temperature for the wheel tracking test was determined based on the PG test results of the bitumen type used in the mixes.

Figure 3.9 shows the specimens after tests are conducted.



Figure 3.9 Asphalt specimens after wheel tracking test

4 Result and Discussion

This part of the research presents the study results in light of the conducted laboratory tests and interprets and describes how the results fit with the prevailing knowledge, what new comprehensions and findings with the prevailing theories.

4.1 Analysis and Interpretation Test Results

Almost all tests conducted were based on the Marshall test method except PG determination of the asphalt mix which is the Super-pave bitumen test method. Besides, the performance test was conducted using a wheel tracking test machine for the comparison of the percent refusal density and wheel tracking test which is the main objective of the study.

4.1.1 Conventional Tests of Asphalt

Table 4-1 shows the convectional test results of the bitumen type used in the study.

Table 4.1 Convectional test results of Bitumen

No.	Test method	Test results (Average of trails)	
		80/100	60/70
1	Penetration, 100gm, 5 sec at 25 °C (AASHTO T-49)	85	61
2	Ductility 5cm/min at 25 °C (AASHTO T-51) cm	100+	100+
3	Flash Point Cleavened Open Cup (AASHTO T-48) °C	292	296
4	Specific Gravity at 25 °C (AASHTO T-228)	1.012	1.023
5	Solubility in Trichloroethylene (AASHTO T-44) %	99.59	99.79
6	Softening Point (AASHTO T-53), °C	43	50
7	Loss on Heating (AASHTO T-47), %	0.05	0.06

As depicted in the table above, the test results of the binders for both 60/70 and 80/100 penetration grade fulfilled the specification requirement stipulated in the ERA 2013 Pavement Design Manual.

4.1.2 Super-pave tests of Asphalt

The basis for conducting Super-pave tests for the asphalt in this research was basically to determine the performance grade (PG) of the binders and also to determine the mixing and compaction temperature of the asphalt mixes.

Performance grade determination

In the case of performance grade determination using DSR, as the shear stress, (τ) is applied to the test samples, it measures the response (shear strain) of the asphalt. The relationship between the applied stress and the resulting strain provides information necessary to calculate the complex shear modulus (G^*) and phase angle (δ /delta). The test was conducted at different temperatures with 6°C increments until the sample fails to satisfy the required resistance for the provided temperature. The high temperature of the asphalt binder is the lowest temperature where $G^*/\sin \delta \geq 2.20$ kPa for aged and $G^*/\sin \delta \geq 1.00$ kPa for un aged binder respectively. Table 4.2 shows the PG test results of both un-aged binders types (60/70 and 80/100).

Experimental Investigation on Rutting Criteria of Asphalt Mix

Table 4.2 PG results of the unaged binders used in the study

Binder Type	Trail s	Temperature	Frequency	Phase Angle	Complex Modulus	Elastic Modulus	Viscous Modulus	Complex Viscosity	Shear Stress	Strain	Pass/Fail Temp	PG grade
		(°C)	(Hz)	(°)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)		
80/100	1	45.93	1.60E+00	84.36	5.66E-03	5.56E-04	5.63E-03	5.65E-04	6.81E-04	1.20E-01	58.5	58
		51.89	1.60E+00	85.42	2.45E-03	1.95E-04	2.44E-03	2.44E-04	2.94E-04	1.20E-01		
		57.91	1.60E+00	86.02	1.09E-03	7.52E-05	1.08E-03	1.08E-04	1.30E-04	1.20E-01		
		63.89	1.60E+00	86.15	4.92E-04	3.30E-05	4.91E-04	4.91E-05	5.88E-05	1.20E-01		
	2	45.99	1.60E+00	84.95	6.64E-03	5.84E-04	6.62E-03	6.62E-04	8.00E-04	1.20E-01	58.6	
		51.89	1.60E+00	86.45	2.78E-03	1.72E-04	2.78E-03	2.78E-04	3.34E-04	1.20E-01		
		57.98	1.60E+00	87.77	1.09E-03	4.24E-05	1.09E-03	1.09E-04	1.31E-04	1.20E-01		
		63.94	1.60E+00	88.34	4.66E-04	1.36E-05	4.66E-04	4.65E-05	5.60E-05	1.20E-01		
60/70	1	57.99	1.60E+00	84.17	2.74E-03	2.79E-04	2.73E-03	2.73E-04	3.29E-04	1.20E-01	65.2	64
		63.94	1.60E+00	85.94	1.18E-03	8.36E-05	1.18E-03	1.18E-04	1.41E-04	1.20E-01		
		69.94	1.60E+00	87.29	5.37E-04	2.54E-05	5.37E-04	5.36E-05	6.46E-05	1.20E-01		
	2	57.99	1.60E+00	84.16	2.53E-03	2.57E-04	2.52E-03	2.52E-04	3.04E-04	1.20E-01	64.9	
		63.93	1.60E+00	85.78	1.13E-03	8.30E-05	1.13E-03	1.13E-04	1.35E-04	1.20E-01		
		69.93	1.60E+00	86.8	5.16E-04	2.88E-05	5.15E-04	5.15E-05	6.19E-05	1.20E-01		

Table 4.3 PG results of the aged binders (RTFO) used in the study

Binder Type	Trail s	Temperatu re	Frequency	Phase Angle	Complex Modulus	Elastic Modulus	Viscous Modulus	Complex Viscosity	Shear Stress	Strain	Pass/ Fail Temp	PG grade
		(°C)	(Hz)	(°)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)		
80/100	1	46	1.60E+00	81.85	1.41E-02	1.99E-03	1.39E-02	1.40E-03	1.41E-03	1.01E-01	58.9	58
		51.97	1.60E+00	84.13	5.74E-03	5.87E-04	5.71E-03	5.73E-04	5.75E-04	1.00E-01		
		57.95	1.60E+00	85.69	2.35E-03	1.77E-04	2.35E-03	2.35E-04	2.35E-04	1.00E-01		
		63.95	1.60E+00	86.51	1.01E-03	6.13E-05	1.01E-03	1.01E-04	1.01E-04	9.99E-02		
	2	46	1.60E+00	81.9	1.32E-02	1.99E-03	1.50E-02	1.50E-03	1.55E-03	1.10E-01	59.3	
		51.89	1.60E+00	84.23	4.88E-03	5.07E-03	5.44E-03	6.25E-04	6.27E-04	1.00E-01		
		57.9	1.60E+00	85.89	2.27E-03	1.66E-04	2.46E-03	2.46E-04	2.46E-04	1.00E-01		
		63.98	1.60E+00	86.65	1.10E-03	7.80E-05	1.00E-03	1.00E-04	1.00E-04	9.00E-02		
60/70	1	57.99	1.60E+00	81.6	1.11E-02	1.56E-02	1.73E-02	1.73E-03	1.73E-03	1.10E-01	66.5	64
		63.94	1.60E+00	84.5	2.25E-03	2.36E-03	2.28E-03	2.28E-04	2.14E-04	1.10E-01		
		69.94	1.60E+00	87	1.12E-03	1.12E-04	1.21E-04	5.30E-05	5.29E-05	9.00E-02		
	2	57.99	1.60E+00	82	1.21E-02	1.28E-03	1.52E-03	1.25E-03	1.25E-03	1.10E-01	65.8	
		63.93	1.60E+00	85.8	2.25E-03	2.83E-03	2.13E-03	2.13E-04	2.35E-04	1.10E-01		
		69.93	1.60E+00	86.8	1.54E-03	1.29E-04	5.15E-04	5.15E-05	5.15E-05	9.90E-02		

PG grade is taken as the minimum value of the test results after testing the original binder and aged binder (after RTFO). Based on the above results, there is no significant difference of the PG result before and after ageing of the bitumen. Thus, the PG grade for 80/100 and 60/70 penetration grade was 58-XX and for 64-XX respectively.

Mixing and Compaction Temperature (Casola Test Method)

The transition from Newtonian to non-Newtonian behaviour makes for an easily identifiable threshold to rank the binder. A phase angle of 86°C is an easily identifiable transition point of the material exhibiting visco-elastic behaviour of the comparison at a reference temperature of 80°C. ERA 2013 Pavement Design Manual recommend atypical mixing temperatures with interval of 130°C - 165°C for 80/100 pen. grade, and 140°C - 170°C for pen. grade bitumen type. Table 4.3 shows the mixing and compaction temperatures of the asphalt mixes in the study.

Table 4- 4 Mixing and Compaction Temperature Computation using Casola Method

Bitumen Type	Sample	DSR Data Collected			Temperature (°F)		Temperature (°C)	
		Temperature (°C)	Phase Angle (°)	Frequency (rad/sec)	Mixing	Compaction	Mixing	Compaction
80/100	1	80	86	106.69	305.14	283.65	151.74	139.8
	2	80	86	50.54	308.24	286.21	153.46	141.23
	3	80	86	61.97	307.39	280.07	152.99	137.8
						Average	152.73	139.61
60/70	1	80	86	78.29	306.42	280.08	152.46	137.82
	2	80	86	64.96	307.19	285.34	153.01	140.74
	3	80	86	73.88	306.66	291.26	152.59	144.03
						Average	152.69	140.86

From the above result, the mixing and compaction temperatures of the asphalt mixtures were 152.73 °C and 139.61 °C for 80/100 pen. grade and also 152.69 °C and 140.86 °C for 60/70 pen. grade bitumen respectively.

4.2 Aggregate test results

Quality aggregates are critical to the overall performance of the mixed pavement service life. The summary of test results of aggregates from different sources that have been used for the mixes is presented in Tables 4.5 along with the requirements for asphalting works as per ERA 2013 Flexible Pavement Design Manual.

Table 4.5 Aggregate test results used for the asphalt mixes

Property	Test Executed	Acceptance Criteria	Results		
			Source #1	Source #2	Source #3
Strength	Flakiness Index	< 35	21.5	16.7	9.6
	Aggregate Crushing Value	< 25	18.2	16.52	15.1
	Los Angeles Abrasion (LAA)	< 30	16.2	12.63	15.3
	10% FACT (dry) KN	> 160	251.8	366	248.6
	10 % FACT wet/dry ratio	Min. 75 %	105.3	92.9	89.4
Water Absorption	Water Absorption	< 2	1.64	1.02	1.57
Stripping	Stripping	>95	>95	>95	>95
Soundness	Sodium Sulphate Test				
	Coarse	< 10	2.02	1.88	1.79
	Fine	< 16	3.82	2.28	2.0

All aggregates were crushed and from the igneous rock type. Source aggregate properties including the soundness, toughness of the aggregate, and the deleterious materials contained are determined using the Sodium Soundness test (AASHTO T104), Los Angeles Abrasion test (AASHTO T96, and the Clay Lumps and Friable Particles test (AASHTO T112) respectively. Source aggregate properties closely related to the quality of the parent rock.

As shown in the tables above, the selected aggregates used in the experiment were cohesion less and sound, hard, strong, durable pieces, free of coherent coating and conforms to the required specification.

4.2.1 Aggregate Gradation Analysis

Accordingly, the design aggregate structure was determined using the Marshall mix design system which includes developing various blends of aggregate that approach the maximum density line of the specified criteria. As stated in section-3 of this study, one aggregate blend was used to prepare two asphalt mixes by exchanging the bitumen type. The nomination of the asphalt mixes in the table and figure below represents the same. The grading analyses of combined aggregates of the mixes with NMAS of 19 mm are shown in Table 4.6 below and Figure 4.1. Table 4.7 and figure 4.2 show the grain size distributions for NMAS of 12.5 mm.

Table 4.6 Grading of Combined aggregates as per ERA specification

Design specification		Nominal Aggregate Size = 19mm					
		Specification Limit		Mix-1 and Mix-2	Mix-11 and Mix-22	Mix-11 and Mix-222	Maximum Density Line
Sieve size mm	Sieve size raise to 0.45 power	Min.	Max.	Percent Passing	Percent passing	Percent Passing	Percent Passing
25	4.3	100	100	100	100	100	100
19	3.8	90	100	99.5	98.9	94.6	
12.5	3.1						
9.5	2.8	56	80	71.9	75.7	73.7	
4.75	2.0	35	65	52.4	56.6	54.4	
2.36	1.5	23	49	38.3	36.8	35.5	
1.18	1.1						
0.6	0.8						
0.3	0.6	5	19	16.4	9.4	12.2	
0.15	0.4						
0.075	0.3	2	8	9.8	5.3	6.3	
0	0.0						0

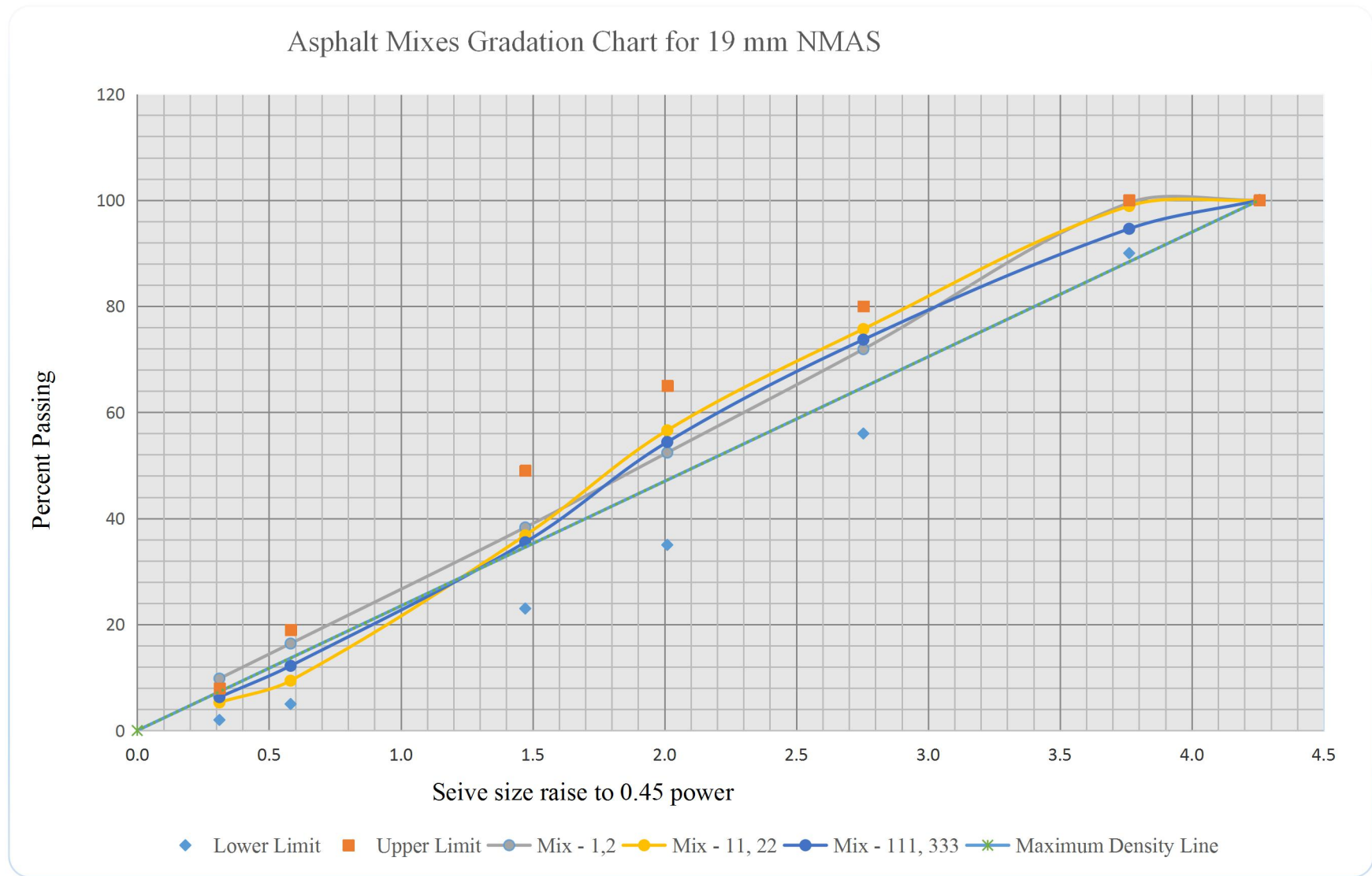


Figure 4.1 Combined grading for 19mm NMAAS

Table 4.7 Grading of Combined aggregates 12.5mm NMAS as per ERA specification

Design specification		Nominal Aggregate Size = 12.5mm					
		Specification Limit		Mix-3 and Mix-4	Mix-333 and Mix-444	Mix-33 and Mix-44	Maximum Density Line
Sieve size mm	Sieve size raise to 0.45 power	Min.	Max.	Percent Passing	Percent passing	Percent Passing	Percent Passing
19	3.8	100	100	100	100	100	100
12.5	3.1	90	100	99.5	90.5	95	
4.75	2.0	44	74	64.8	61.3	65	
2.36	1.5	28	58	39.4	44.5	39	
1.18	1.1						
0.6	0.8						
0.3	0.6	5	21	10.1	15.2	10	
0.15	0.4						
0.075	0.3	2	10	6.1	7.6	6.0	
0	0.0						0

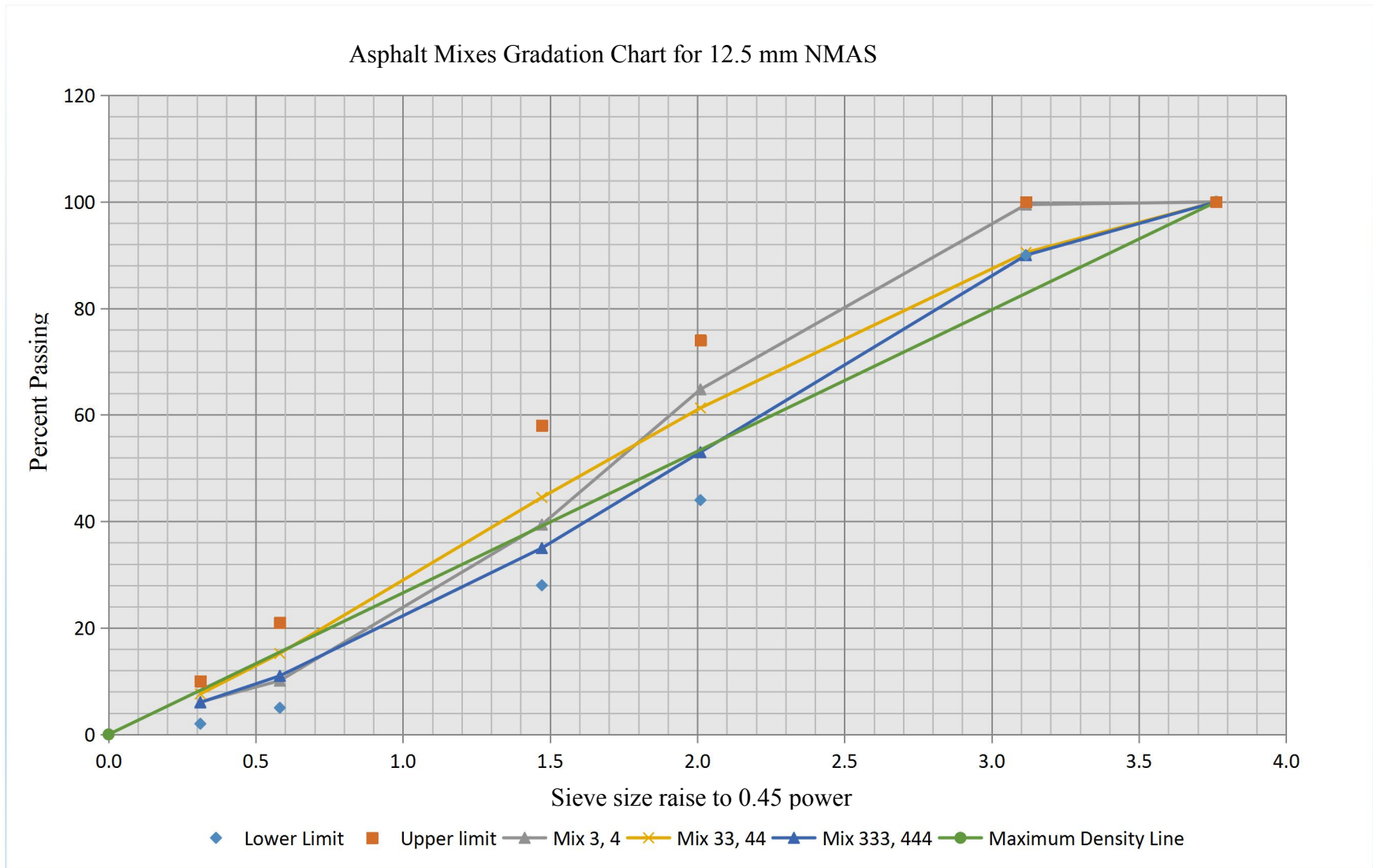


Figure 4.2 Combined grading for 12.5mm NMA5

4.3 Asphalt mix design

The basics in asphalt mix design are to determine an adequate proportion of aggregate and asphalt binder in a way that the desired bituminous mixture is achieved (i.e. a mix that resists deformation and cracking).

In this study, the asphalt mixes were designed by considering the road subjected to heavy traffic. In MS-2, heavy traffic is defined as greater than 1 million ESAL, and 75 - blow Marshall Compaction is recommended for the design of AC's which are expected to carry this amount of traffic. The level of Marshall compaction used in the design process should produce a density in the design mix which is equal to that which will be produced in the road after secondary compaction under traffic [27]. The Marshall requirements for mixes designed for heavy traffic design were summarized in Table 4.8 below.

Table 4.8 Marshall Requirements for Mixes designed for Heavy Traffic

Category and design Traffic (million ESAL)	No. Of blows of Marshall Compaction Hammer	Minimum Stability (N)	Flow (mm)	VFB (%)	VIM at optimum binder content (%)
Very heavy (> 5)	75	9000	2 - 3.5	65 - 73	5

4.3.1 Optimum Asphalt Binder Estimation

As described under Table 3.7 of this research paper, the initial asphalt binder contents are considered for volumetric analyses of the asphalt mixes under study.

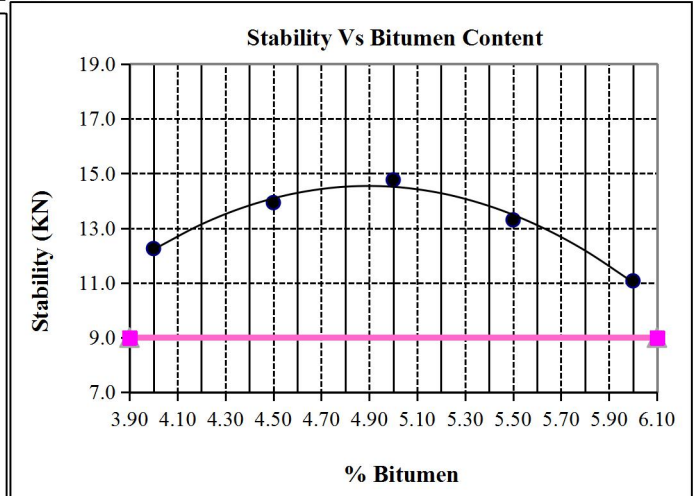
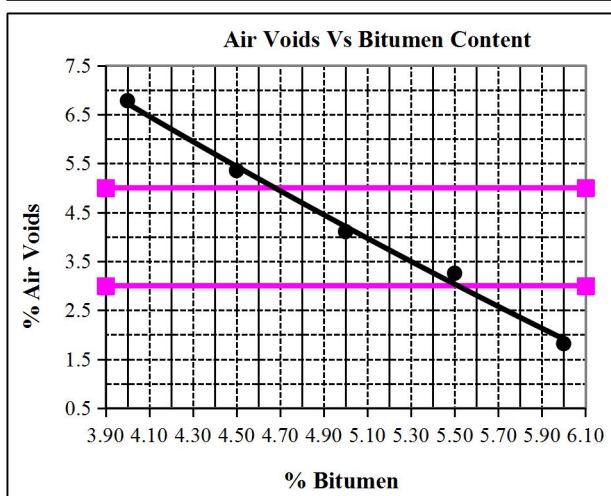
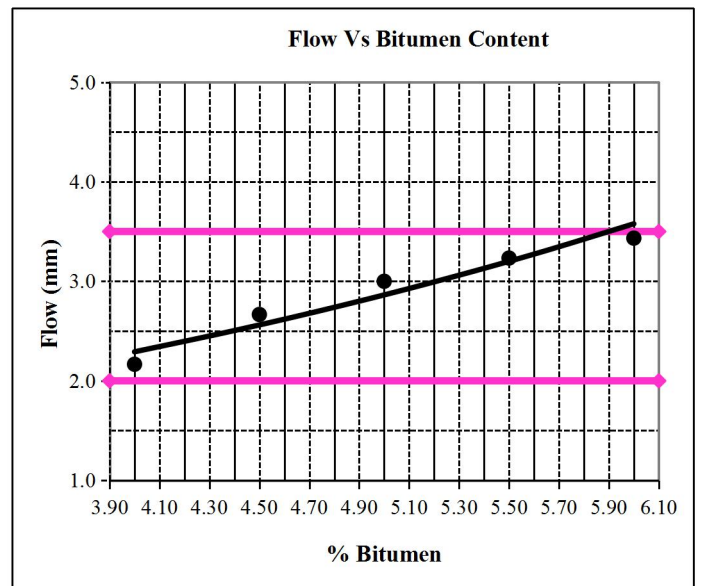
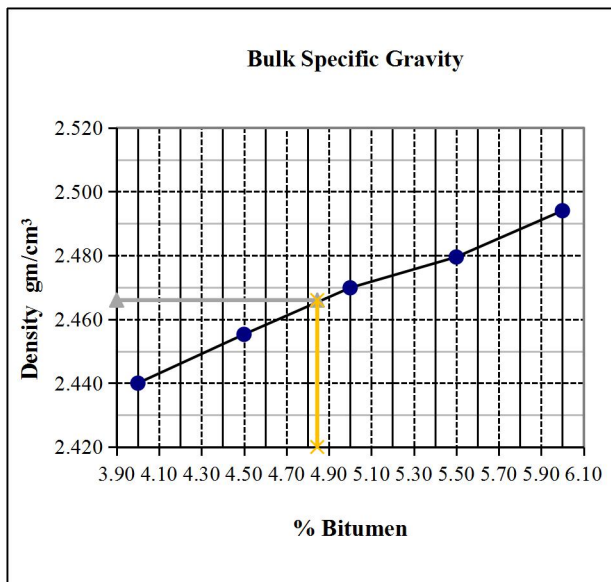
4.3.2.1 Mixture Volumetric Results

The design bitumen content of the mix was selected by considering VIM, VFA, VMA, stability, and flow of the mixes. The volumetric properties were calculated based on the procedure and / formula described in section three of this research.

Table 4.9 shows the volumetric ratios of M11 after the test specimens are subjected to the Marshall compaction for different binder content.

Table 4.9 Summary of Volumetric data for M11 asphalt mix type

Asphalt Content (%)	Void (%)	Flow (mm)	Stability (KN)	VMA (%)	Bulk S.G. (g/cm ³)	Gmm (g/cm ³)	VFA (%)
4	6.8	2.2	12.3	14.9	2.44	2.617	54.5
4.5	5.4	2.7	13.9	14.8	2.455	2.594	63.9
5	4.1	3	14.8	14.8	2.47	2.576	72.2
5.5	3.3	3.2	13.3	14.9	2.48	2.563	78.1
6	1.8	3.4	11.1	14.8	2.494	2.54	87.7
Average					2.466	2.58	
Acceptance Criteria	3 ~ 5	2 ~ 3.5	≥ 9	≥ 13	---	---	65~73



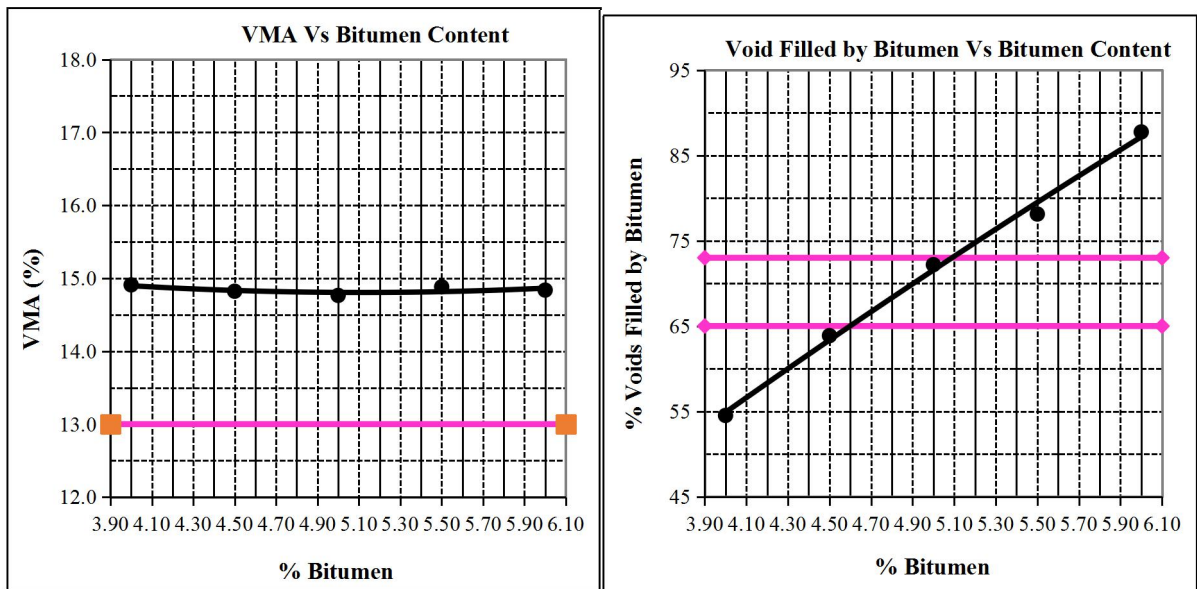


Figure 4.3 Graphical presentation of volumetric properties of asphalt mixes

Table 4.10 shows the optimum asphalt content of M11 mix type

Table 4.10 Determination of optimum bitumen content

Asphalt parameter	Unit	Suited Asphalt Content (%)		Acceptance criteria	
				Minimum	Maximum
VMA	%	4.00	6.00	13	—
Flow	mm	4.00	5.91	2	3.5
Stability	KN	4.00	6.00	9	—
VFA	%	4.55	5.06	65	73
Air Void	%	4.63	5.53	3	5
Common Range:	%	4.63	5.06		
Optimum Asphalt Content (OBC):	%	4.85			

From the above table and figure, the optimum asphalt bitumen content for this mix was 4.85 %. In the same way the remaining 11 (Eleven) different mixes were prepared with NMAS of 19mm and 12.5mm, and with 60/70 and 80/100 penetration grade. The results of those mixes were attached in appendix B of this paper. Table 4.11 shows the OBC along with the VIM after the refusal density test.

Table 4.11 Summary of the OBC and VIM of the different mixes used in this study.

Mix type	OBC	VIM after refusal density test
M1	4.9	2.1
M11	4.9	3.0
M111	4.85	3.12
M2	4.9	2.47
M22	4.9	2.8
M222	4.85	2.9
M3	5.1	2.91
M33	5.1	2.88
M333	4.8	4.01
M4	5.1	3.1
M44	5.1	2.92
M444	4.8	3.76

4.3.2 Refusal Density

After computation and determination of the optimum binder content based on the specification and procedure on the MS-2 manual of the asphalt mixes, refusal density was executed to determine the air voids of each mix. To conduct the refusal density, the number of blows of the Marshall compactor has been determined. Compaction of refusal could be achieved in the laboratory by applying several hundred blows of the Marshall hammer to each face of the test briquettes. In this study, 400 and 450 blows of Marshall hammer compaction is considered to evaluate the air voids of the mixes for 12.5 mm and 19 mm NMAS respectively. Marshall mix design procedures have always required the VIM (Void in Mix) or air voids to be above 3 %. A minimum of two and three specimens have been prepared for each mix and the results are also taken as the average of those specimens.

Computation of the air voids after secondary compaction for the M11 mix type above (19 mm NMAS with 80/100 penetration grade) is illustrated below in Table 4.12.

Table 4.12 Computation of Air Voids in the Asphalt Mix after 450 blows of Marshall Hammer

Specimen no.	Asphalt Content %	Weight of specimen			Volume of Sample D=B-C	Specific gravity of the mix		VIM (1-E/F)*100
		In air (gm) =A	SSD wt (gm)=B	In water (gm)=C		Bulk E= A/D	Gmm F	
A		1259.7	1261.0	757.4	503.6	2.501	2.582	3.1

B	4.9	1257.3	1259.2	757.2	502.0	2.505	2.582	3.0
C		1258.0	1259.8	757.7	502.1	2.505	2.582	3.0
Average								3.0

From the above table, we have noted that the refusal density after 450 blows of Marshall hammer is 3.0 %. Figure 4.4 shows maximum VIM along with VIM of the mixes after refusal density test.

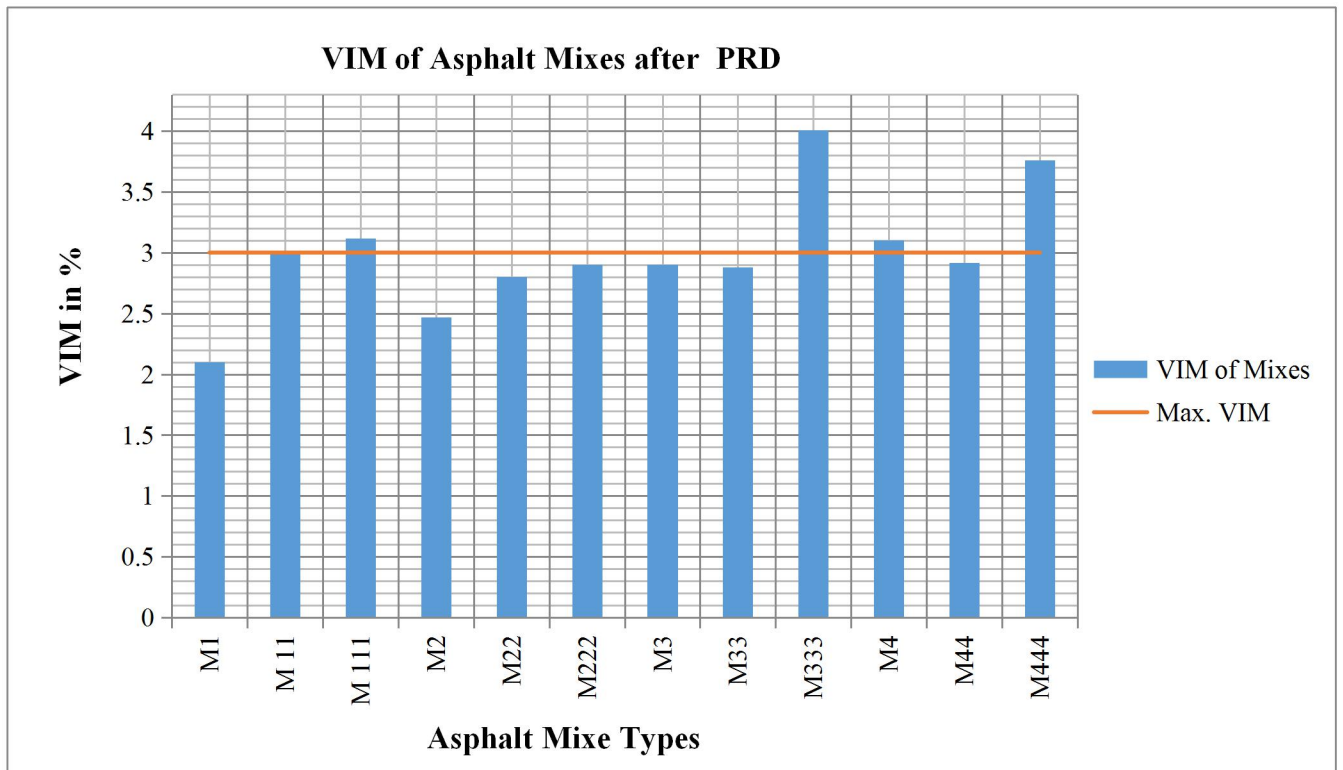


Figure 4.4 VIM of asphalt mixes after Refusal Density Test

4.3.3 Wheel tracking test

The wheel track machine used in this study was called Dyna – Track wheel tracker. Based on the proportion of the designed mixes, specimens were prepared in the form of the slab with 300 x 300 mm dimension and 50mm thickness. The specimens then subjected to compaction using a slab compactor (i.e. with 25 number of the pass which simulates the actual site condition), and the compacted samples/moulds were detained for 24hrs. Consequently, the test samples were subjected to wheel tracking test at a frequency of 53 passes per minute with a total of 20,000 passes with loading condition 700 ±10 N (i.e. the number of pass simulates heavy traffic condition which exceeds 30 million ESAL) at test temperatures of 46 °C and 50 °C depend on the bitumen type. Finally, the rut depths were recorded with 250 load cycles intervals. A minimum of two specimens were tested for each mix.

Specification limit for Wheel Tracking test

The rut depth limit of the wheel tracking test is different in different countries. The ERA 2013 Pavement Design manual uses the current UK Specifications as indicated in table 4.13. In this specification, the sample is subjected to repeated passes of a load wheel, specified at 520 N, for 45 minutes at a test temperature of 45°C and 60 °C.

Table 4.13 UK Wheel-Tracking specification

Traffic classification	Test temperature (°C)	Maximum Tracking Rate (mm/hr)	Maximum Rut Depth (mm)
Moderate to heavily stressed sites	45	2.0	4.0
Very heavily stressed sites	60	5.0	7.0

Because this test is not as widely used as some others of this type, agencies wishing to use the HWTD test as a performance test should consider performing an engineering study to develop appropriate requirements for their local conditions and materials. Following this, the Texas Department of Transportation provides the requirement for HWTD test with binder grade and minimum passes to 12.5mm rut depth as indicated in Table 4.14.

Table 4.14 Texas Hamburg Wheel Test Requirement (as per the NCHRP Report 673)

High-Temperature Binder Grade	Minimum Passes to 12.5mm Rut depth
PG 64 or lower	10,000
PG 70	15,000
PG 76 or higher	20,000

Given the above requirements and consideration of the test temperature site condition, the wheel tracking test requirement was considered as 20,000 passes. Figure 4.5, 4.6, 4.7 and 4.8 shows the wheel tracking test report for mixes with 19 mm NMA and 80/100 pen. grade bitumen, 19 mm NMA and 60/70 pen. grade bitumen, 12.5 mm NMA and 80/100 pen. grade bitumen, 12.5 mm NMA and 60/70 pen. grade bitumen respectively.

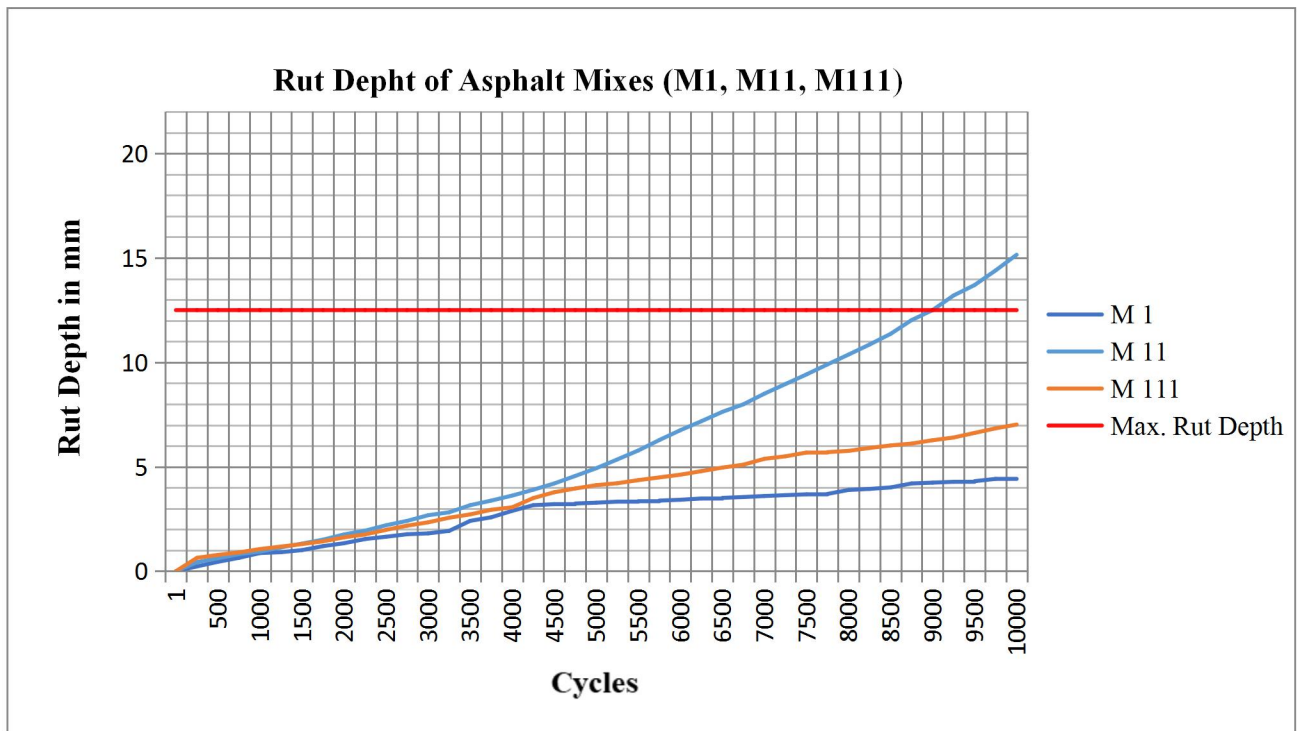


Figure 4.5 Rut depth of asphalt mixes (M1, M11, and M111)

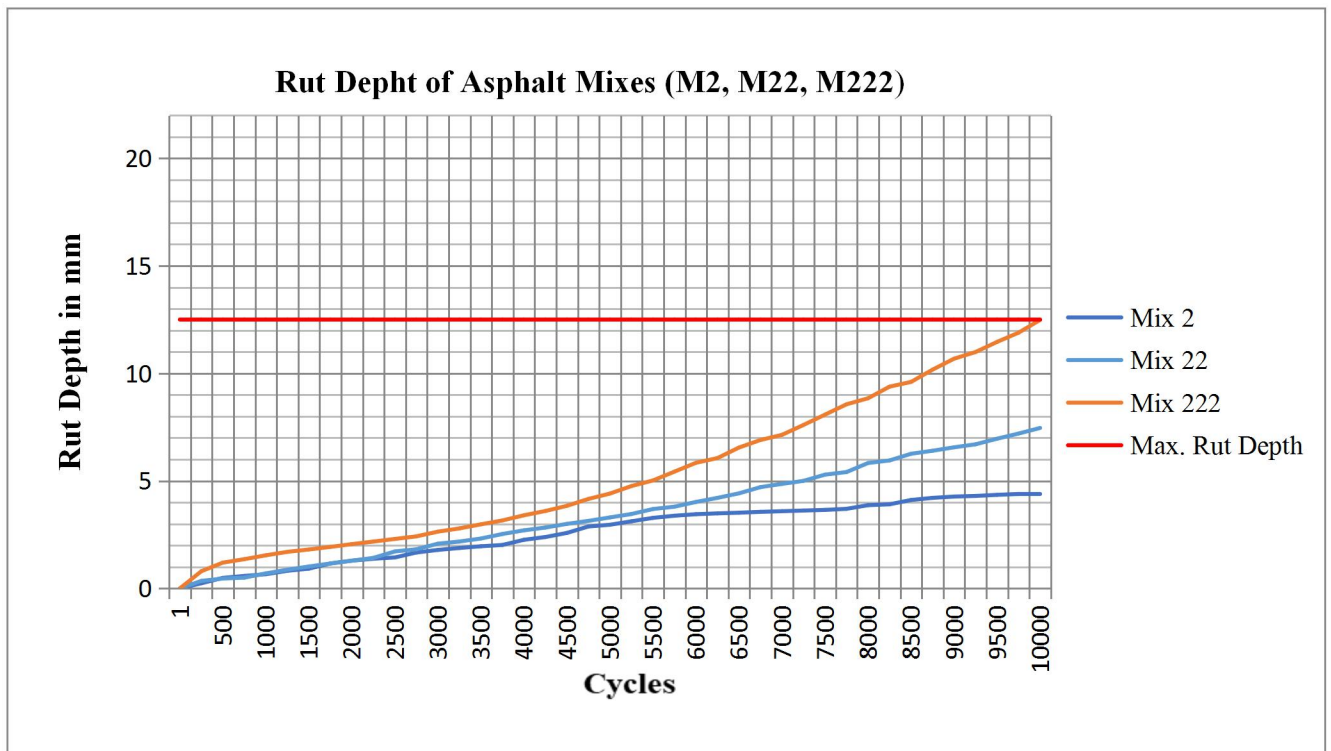


Figure 4.6 Rut depth of asphalt mixes (M2, M22, and M222)

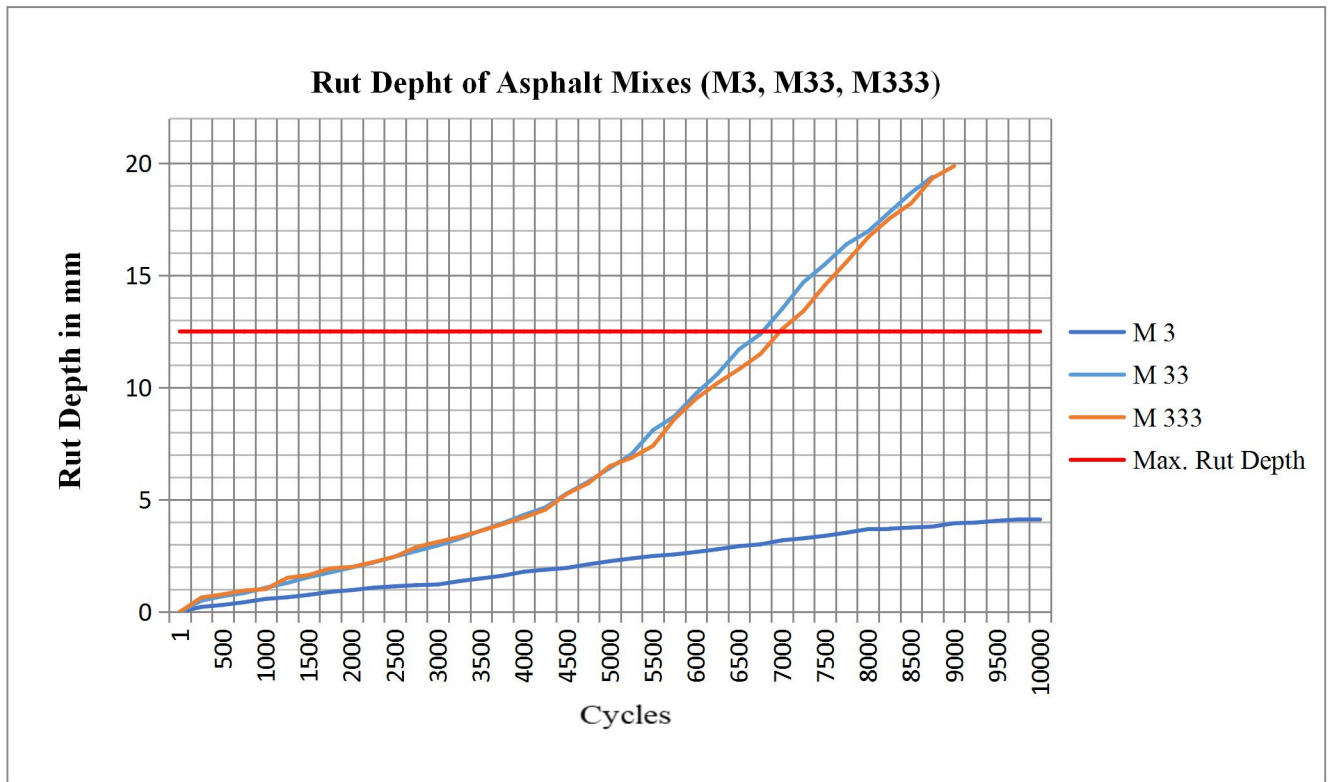


Figure 4.7 Rut depth of asphalt mixes (M3, M33, and M333)

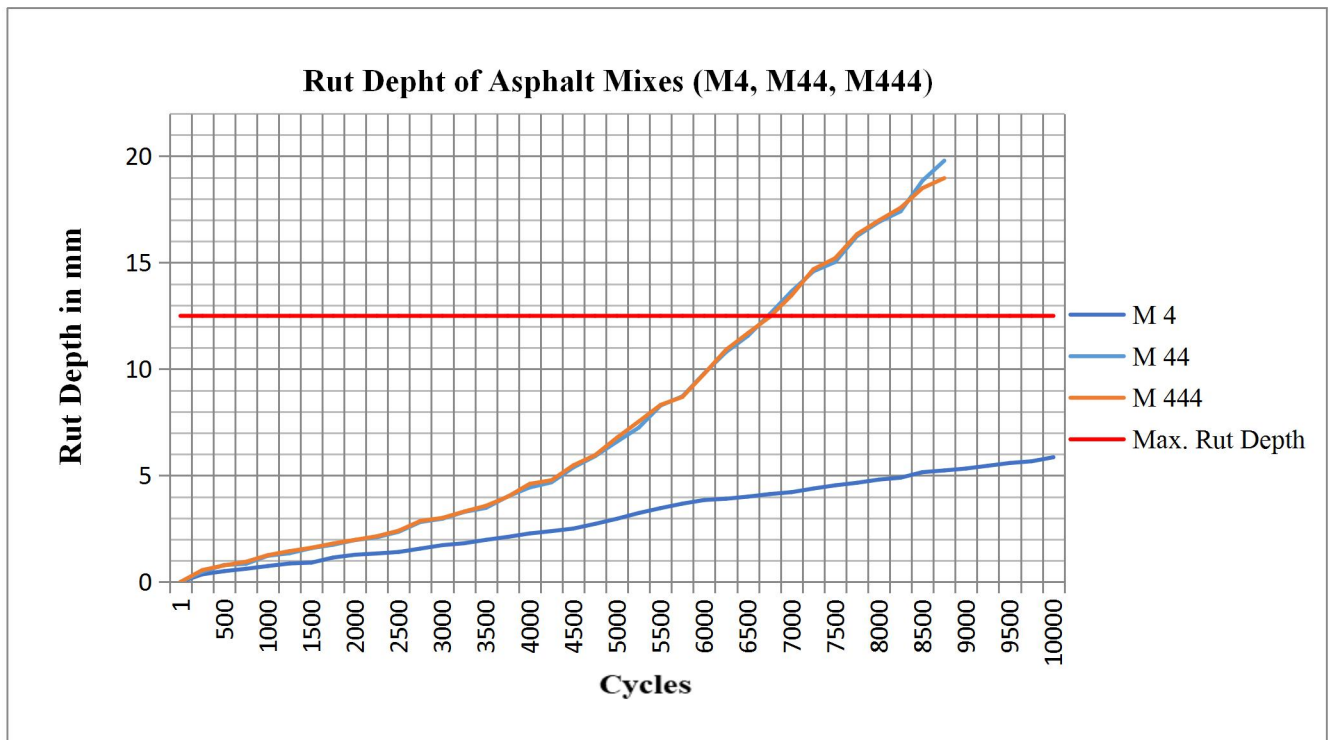


Figure 4.8 Rut depth of asphalt mixes (M4, M44, and M444)

The test method used in the study complies with the HWTD test procedure which includes the number of passes, samples of air voids, loading condition and also test frequency. The only difference from the HWTD test procedure are samples are soaked in air instead of water and also specimens are compacted in rectangular shape instead of cylindrical shape. The effect of water in the HWTD test procedure used to predict the moisture susceptibility of the asphalt mixes. The difference of the test machine from the HWTD has no significant effect on the evaluation of the rut resistance of the asphalt mixes. Accordingly, the evaluation of the mixes proceeds with the Texas Hamburg Wheel test requirement (THWTR) which has a maximum limit of 12.5 mm.

4.4 Analysis and Discussion

Analysis

The analysis was conducted based on the result of the refusal density test which is the VIM after a number of compaction efforts and the rut depth from the wheel tracking test.

The VIM and the rut depths of the mixes in the study were described in Table 4.15.

Mix type	Description	Average VIM after Refusal Density Test (%)	Average Rut depth after Wheel Track Test (mm)
Mix-1	19 mm NMAS and 80/100 Bitumen grade	2.1	4.44
Mix-11	19 mm NMAS and 80/100 Bitumen grade	3.0	15.15
Mix-111	19 mm NMAS and 80/100 Bitumen grade	3.12	7.02
Mix-2	19 mm NMAS and 60/70 Bitumen grade	2.47	4.41
Mix-22	19 mm NMAS and 60/70 Bitumen grade	2.8	7.46
Mix-222	19 mm NMAS and 60/70 Bitumen grade	2.9	12.48
Mix-3	12.5 mm NMAS and 80/100 Bitumen grade	2.9	4.14

Mix type	Description	Average VIM after Refusal Density Test (%)	Average Rut depth after Wheel Track Test (mm)
Mix-33	12.5 mm NMAS and 80/100 Bitumen grade	2.88	>20
Mix-333	12.5 mm NMAS and 80/100 Bitumen grade	4.01	>20
Mix-4	12.5 mm NMAS and 60/70 Bitumen grade	3.1	5.86
Mix-44	12.5 mm NMAS and 60/70 Bitumen grade	2.92	>20
Mix-444	12.5 mm NMAS and 60/70 Bitumen grade	3.76	>20

Table 4.15 Summary results of refusal and wheel tracking test

The rut depths and VIM after PRD were evaluated against the maximum limit of its values which were described in figure 4.9 below.

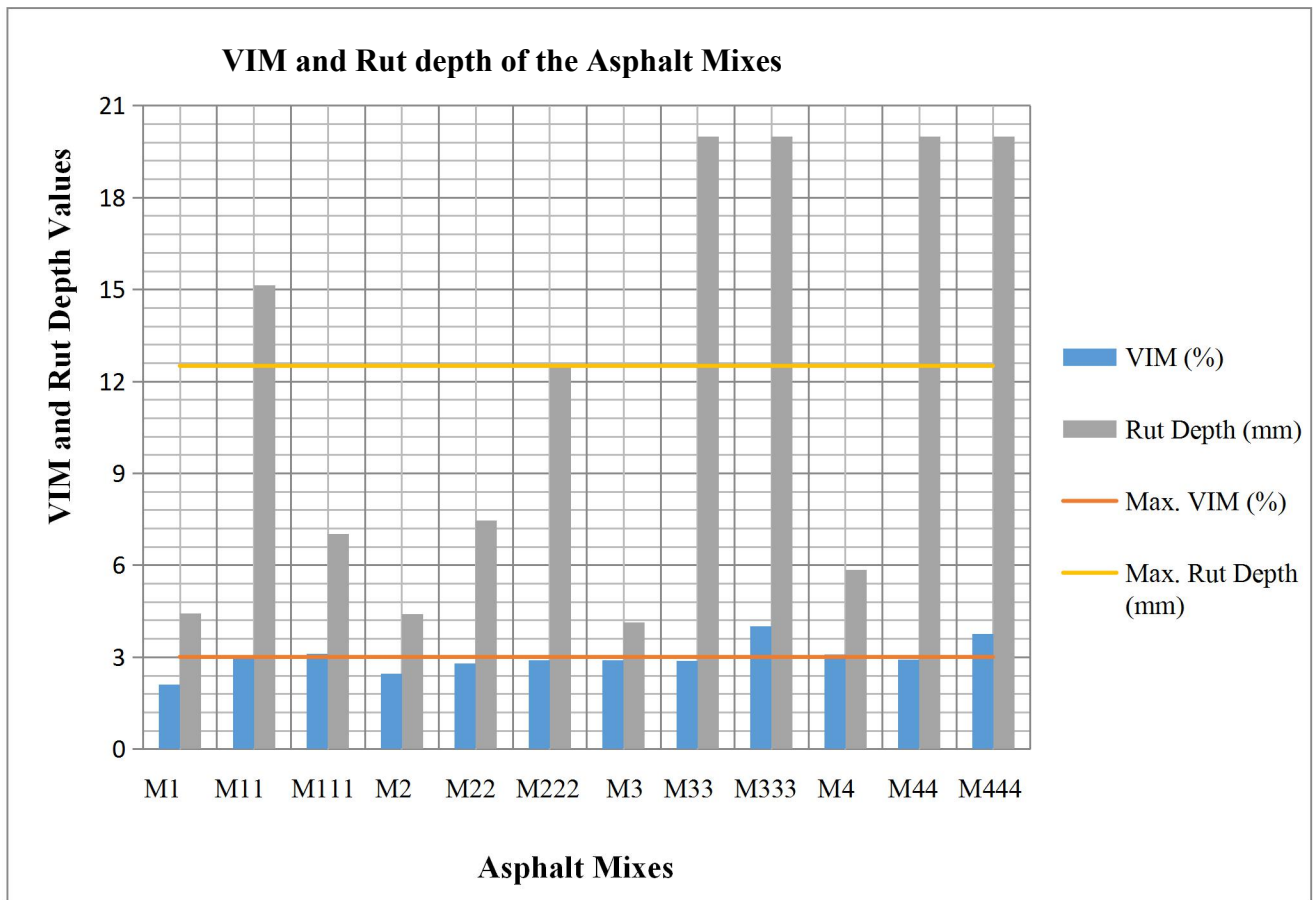


Figure 4.9 Graphical representation of Air void and Rut depth of the asphalt mixes under this study.

Discussion

Nowadays, most of our road corridors are experiencing big shortfalls in long-term and adequate service provision due to the presence of different failures on the road surface among which rutting is one type of failure. Air void is used as criteria for the asphalt mixes for severe site conditions (high traffic volume) after the refusal density test in which the mixes shall fulfil a minimum of 3% air void as a requirement for rutting criteria of asphalt mixes. Performance test (i.e. wheel tracking test) has considerable potential for identifying mixes that would be unsuitable for use. Rutting performance can be affected by different parameters of the asphalt mixes.

Bitumen grade

It is known that when the bitumen is going to stiffer the performance of the mix also increases proportionally. Mixes prepared using 60/70 pen grade bitumen showed better performance compared to mixes made of 80/100 for the same temperature. Even if the wheel passes in wheel tracking test was the

same for all mixes (20,000 passes), the test temperatures was different for 60/70 and 80/100 pen grade mixes. Due to that, the effect of the bitumen penetration grade on the performance of the asphalt mixes was not visible.

Nominal Maximum Aggregate Size

The aggregates are the major parts of the asphalt mixes which affects the performance of the mixes. When the nominal maximum aggregate size of the mixes increases the performance of the asphalt mixes also increases [36]. From the result in table 4.14, most of the mixes with NMAS 19 mm have less rut depth than mixes with NMAS 12.5 mm. But, mixes with 12.5 mm NMAS have also better performance than mixes with 19 mm NMAS (for example, M3 and M4 have better performance than M11, M111, M22, M222). Besides, mixes with the same NMAS have different rut performances. Therefore, NMAS by itself is not the only factor that affects the rut resistance of the asphalt mixes, instead, aggregate interlock (aggregate structures) are also the influencing factors.

Air Void (VIM) after Refusal Density

All mixes prepared using the Marshall method with 75 blows have VIM from 3% to 5%. The same mixes were subjected to secondary compaction (400 and 450 blows) and the VIM value falls below the maximum 3% limit. From Table 4.14, seven asphalt mixes (M1, M2, M22, M222, M3, M33, and M44) have a VIM value of less than 3%. Therefore, the study indicates that all the asphalt mixes designed with 75 blows do not always fulfil the secondary compaction criteria.

Rut depth with VIM

Table 4.16 indicates that some asphalt mixes fulfil VIM criteria but failed with rut depth criteria, some fulfil both VIM and rut depth. On the other hand, some did not fulfil VIM but rut depth and some did not fulfil both VIM and rut depth. Table 4.16 shows types of asphalt mix types along with pass/ fail criteria.

Table 4.16 summary of type of asphalt mixes with fail /pass criteria

Asphalt Mixes Pass / Fail Criteria			
<i>Pass both VIM and Rut depth</i>	<i>Pass VIM but fail Rut depth</i>	<i>Pass Rut depth but fail VIM</i>	<i>Fail both Rut depth and VIM</i>
M4, M111	M11, M333 and M444	M1, M2, M22, M3, M222	M44, M33
16.5%	25%	42%	16.5%

From the table 4.15 analysis, refusal density criteria (VIM) of the asphalt mixes does not indicate the rut resistance of the asphalt mixes, and also mixes which have good rut resistance doesn't mean fulfil refusal density criteria.

Possibilities of failure to fulfil VIM of refusal density test:

- The VIM interval (3-5%) of the mixes with 75 blows:- when the OBC of the mixes are designed with a near lower margin of the VIM (3%), then it will fail when subjected to the compaction of 400/450 blows.
- The compaction procedure for refusal density test:- Marshall hammer was used instead of the vibratory compactor in which the Marshall compactor may crush the aggregates in the mixtures while compaction.

Possibilities of failure to fulfil both rut depth and VIM:

- M33 and M44 have the same aggregate blend and are also prepared from the same sources. Table 4.16 also shows both of the mixes failed to fulfil the rut depth and VIM criteria. Thus, the problem may be an improper aggregate blend (aggregate proportion) in the mixes.

Possibilities of failure to rut depth criteria:

- Table 4.16 shows that mix types M11, M33, M44, M333, and M444 failed to perform rut depth criteria. Most of these mixes were prepared with 12 mm NMAS and have similar aggregate proportions. Thus, the failure may be due to the NMAS of the asphalt mixes.

Data Quality

- The test results from the research are expected to be consistent. Here, there are some inconsistencies on the results of the wheel track test data. For example, mix types M11, M111 and M22, M222 have significant difference on the rut depths with the same source and aggregate blends. The only difference between those mixes is the bitumen type in which 80/100 bitumen for M11 and M111, whereas 60/70 bitumen for M22 and M222. This may be due to the workmanship problems at a time of conducting the tests. There are also some differences on the refusal density of the asphalt mixes with the same aggregate blends and aggregate sources (i.e., M1 and M2). This indicates that several tests are required for each mix both for the refusal and wheel tracking tests.

5 Conclusion and Recommendation

5.1 Conclusion

Twelve types of asphalt mixes were prepared in this study to investigate the rutting criteria of the asphalt mixes with 60/70 and 80/100 pen. grade along with the 12.5 mm and 19 mm NMAS. Crushed aggregates were sampled from different locations with relatively similar rock types. The mixes were subjected to the refusal density and wheel tracking test. From the results obtained, the following conclusions can be derived:

Effects of aggregate structures (blends) in the mixes

Grain size distribution (aggregate structures) is critical in the preparation of asphalt mixes. It directly affects the VIM of the asphalt mixes. The study considers two types of NMAS (19 mm and 12.5 mm) in preparation for different asphalt mixes. The result of the study indicates that mixes that have 19mm NMAS have better resistance to rutting than mixes with 12.5 mm NMAS. Besides, mixes with the same NMAS had also different rut performances. Thus, different aggregate structures (blends) of the asphalt mixes have a greater influence on the rutting performance of asphalt mixes.

Bitumen type in the mix

Two types of bitumen type 60/70 and 80/100 Pent. Grade was used in the asphalt mixes in the study. The performances of the mixes related to the bitumen type are not visible that the testing temperature of the same is different. Thus, the performance of the asphalt mixes relating to the bitumen type used in the mix cannot be compared with the different temperature.

VIM at design and refusal stage of the asphalt mix

The optimum bitumen content (OBC) of the asphalt mixes was determined with 75 blows considering that VIM falls in the range of 3% to 5%. However, more than half of the mixes in the study fail to fulfil the secondary compaction criterion (3%) after the refusal density test. Therefore, all asphalt mixes designed using the Marshall method with 75 blows may not fulfil secondary compaction criteria (min. 3% VIM after refusal density).

Rut depth and VIM

The result indicates that among the twelve mixes tested, two mixes fulfilled both the VIM and rut depth criteria and two other mixes failed to fulfil both. Three mixes passed the VIM criterion and failed in rut depth criterion. Moreover, five mixes failed the VIM criterion and passed the rutting criterion. The results indicated that the parameters in refusal density and wheel tracking have no clear relation. In light of the above, it can be concluded that the VIM criterion is not reliable parameter to determine the asphalt mixes resistance to rutting. Therefore, this study indicate that the refusal density test may not be a reliable indicator for rutting resistance of asphalt mixes especially for the asphalt mixes used in heavy traffic conditions.

Limitation

- The study was limited to twelve types of the asphalt mixes.
- In this study, a minimum of two and maximum three test specimens were tested for each mixes for refusal density test. Additionally, only two specimens were tested for wheel tracking tests according to the recommendation for wheel tracking test. This may introduce inconsistency of test results due to the variability of specimens.

5.2 Recommendation

- The results from this research indicate that mixes that fulfil the air void requirement after secondary compaction may not fulfil the rut depth requirements. Due to the limited number of laboratory tests in this study, further study is recommended to validate the results of this study based on extensive laboratory tests and field performances. Furthermore, implementations of performance tests as a requirement for rutting criteria instead of refusal density test for the asphalt mixes should be considered for roads subjected to high traffic volume.
- Besides, as the wheel tracking test is not widely used procedure in Ethiopia. A separate study should be conducted to determine the rut depth requirement of the asphalt mixes in Ethiopia.

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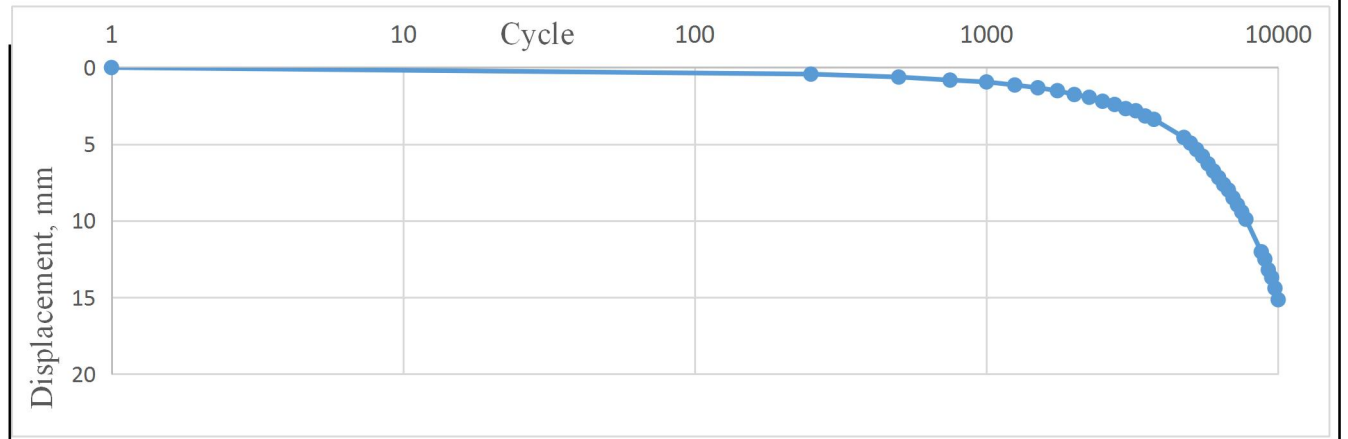
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Appendixes

**Appendix A,
Wheel Tracking Test Results**

Table A - 1

WHEEL TRACKING TESTING REPORT FOR MIX 11					
PROCEDURE B					
<i>Specimen information:</i>					
Slab		Weight, Kg	18.25	Test number:	M-11
Dimensions:		Volume: M3	0.0081	Test name:	Wheel Track
Length, mm	300	Height: mm	50	Machine	Wheel Tracker
Width, mm	300	Compaction Cycle	25	Station	Procedure B
		Air Void	7%	Bitumen Type	80/100
				Wheel tracking Cycle:	10,000
				Test temperature:	46°C
Results					
				Final deformation:	RD(mm) 15.15 mm.



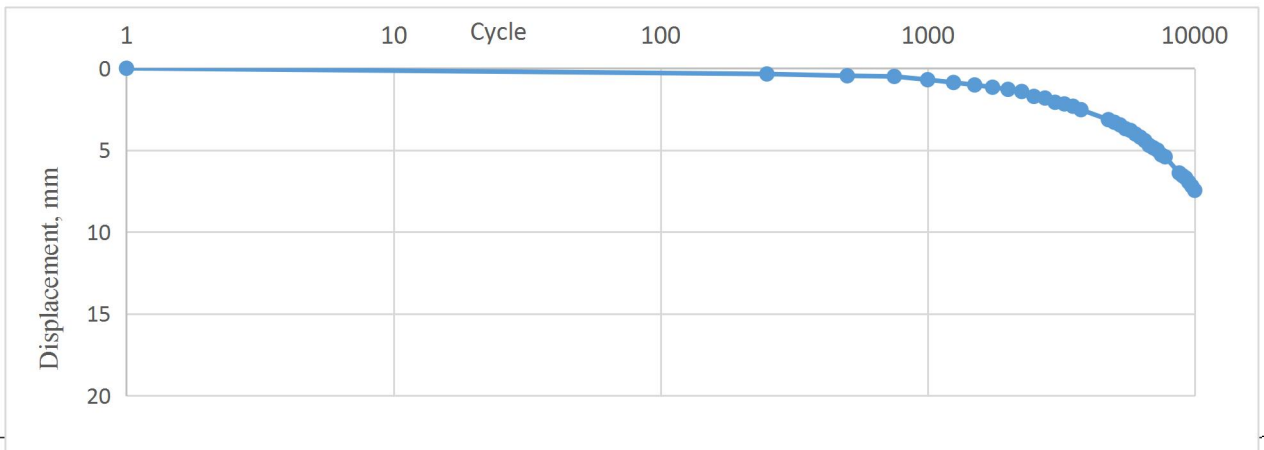
Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	3.62		
250	0.43	4250	3.9	8000	10.37
500	0.62	4500	4.2	8250	10.85
750	0.82	4750	4.56	8500	11.36
1000	0.94	5000	4.93	8750	12.02
1250	1.14	5250	5.35	9000	12.50
1500	1.32	5500	5.78	9250	13.20
1750	1.51	5750	6.28	9500	13.70
2000	1.76	6000	6.75	9750	14.40
2250	1.94	6250	7.18	10000	15.15
2500	2.20	6500	7.63		
2750	2.41	6750	7.99		
3000	2.68	7000	8.50		
3250	2.82	7250	8.96		
3500	3.16	7500	9.42		
3750	3.38	7750	9.90		

Table A -2

WHEEL TRACKING TESTING REPORT FOR THE MIX 22

PROCEDURE B

Specimen information:					
Slab		Weight, Kg	18.25	Test number:	M-22
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track
Length, mm	300	Height: mm	50	Machine	Wheel Tracker Procedure B
Width, mm	300	Compaction Cycle	25	Station	Asphalt Plant
			Air Void	7%	Bitumen Type
				Wheel tracking Cycle:	10,000
				Test temperature:	50°C
Result					
Final deformation:				RD (mm) = 7.46mm.	



Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	2.70	8000	5.83
250	0.35	4250	2.83	8250	5.95
500	0.46	4500	3	8500	6.26
750	0.5	4750	3.14	8750	6.4
1000	0.7	5000	3.3	9000	6.56
1250	0.87	5250	3.46	9250	6.70
1500	1.02	5500	3.69	9500	6.96
1750	1.16	5750	3.8	9750	7.20
2000	1.29	6000	4.02	10000	7.46
2250	1.42	6250	4.21		
2500	1.72	6500	4.42		
2750	1.82	6750	4.71		
3000	2.08	7000	4.86		
3250	2.18	7250	5.00		
3500	2.32	7500	5.29		
3750	2.53	7750	5.41		

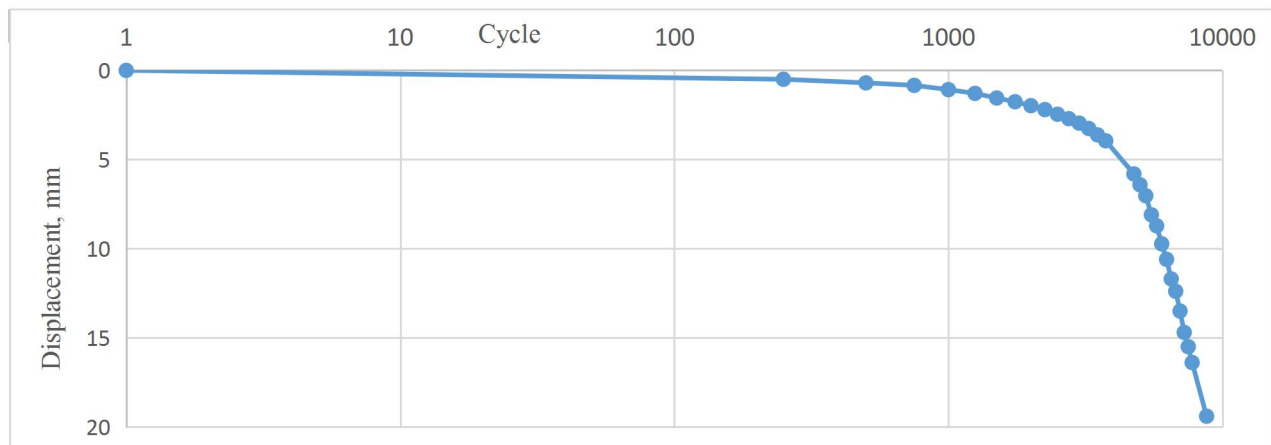
Table A -3

WHEEL TRACKING TESTING REPORT FOR THE MIX 222							
PROCEDURE B							
<i>Specimen information:</i>							
Slab		Weight, Kg	18.25	Test number:	M222		
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track		
Length, mm	300	Height: mm	50	Machine	Tracker		
Width, mm	300	Compaction Cycle	25	Station	Asphalt Plant		
		Air Void	7%	Bitumen Type	60/70		
				Wheel tracking Cycle:		10,000	
				Test temperature:	50°C		
Result							
Final deformation:				RD(mm) =12.48 mm.			

The graph plots Displacement (mm) against Cycle. The x-axis is logarithmic, ranging from 1 to 10,000 cycles. The y-axis is linear, ranging from 0 to 20 mm. The data points show a very low rate of displacement until about 1000 cycles, after which the displacement increases rapidly, reaching 12.48 mm at 10,000 cycles.

Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	3.40		
250	0.8	4250	3.6	8000	8.84
500	1.2	4500	3.84	8250	9.38
750	1.36	4750	4.16	8500	9.6
1000	1.54	5000	4.41	8750	10.17
1250	1.7	5250	4.76	9000	10.68
1500	1.81	5500	5.02	9250	10.99
1750	1.93	5750	5.43	9500	11.46
2000	2.06	6000	5.84	9750	11.89
2250	2.18	6250	6.06	10000	12.48
2500	2.30	6500	6.55		
2750	2.42	6750	6.90		
3000	2.64	7000	7.14		
3250	2.79	7250	7.60		
3500	2.98	7500	8.08		
3750	3.16	7750	8.56		

Table A -4					
WHEEL TRACKING TESTING REPORT FOR THE MIX 33					
PROCEDURE B					
<i>Specimen information:</i>					
Slab		Weight, Kg	18.25	Test number:	M33
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track
Length, mm	300	Height: mm	50	Machine	Wheel Tracker Procedure B
Width, mm	300	Compaction Cycle	20	Station	Asphalt Plant
			Air Void	7%	Bitumen Type
				Wheel tracking Cycle:	10,000
				Test temperature:	46°C
Results					
Final deformation:				RD(mm) >20 mm.	



Cycle	Displacement	Cycle	Displacement	Cycle	Displacement
1	0	4000	4.32		
250	0.5	4250	4.66	8000	16.96
500	0.7	4500	5.28	8250	17.82
750	0.84	4750	5.81	8500	18.68
1000	1.08	5000	6.42	8750	19.4
1250	1.29	5250	7.03	9000	
1500	1.55	5500	8.10	9250	
1750	1.76	5750	8.72	9500	
2000	1.98	6000	9.73	9750	
2250	2.20	6250	10.60	10000	
2500	2.46	6500	11.70		
2750	2.71	6750	12.39		
3000	2.96	7000	13.50		
3250	3.26	7250	14.70		
3500	3.62	7500	15.50		
3750	3.95	7750	16.39		

Table A -5

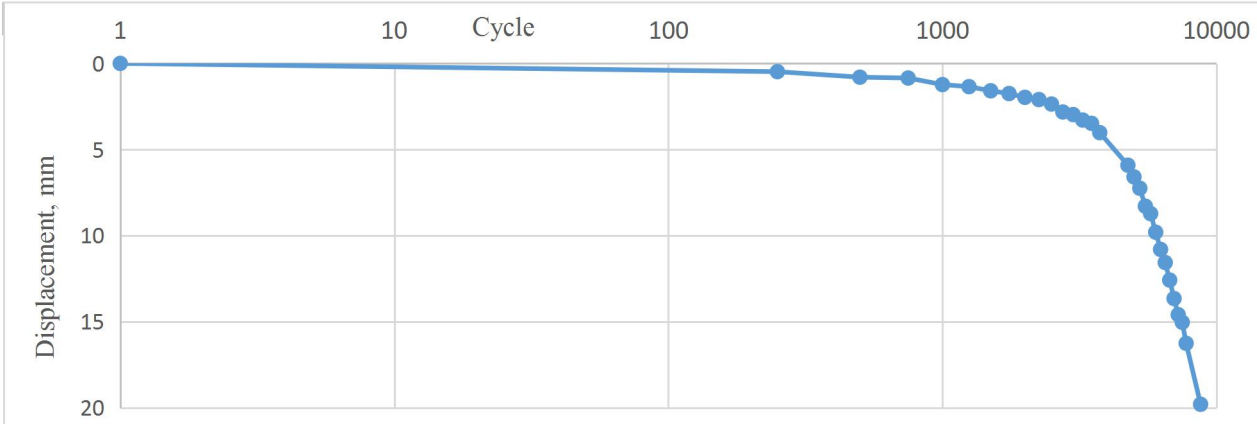
WHEEL TRACKING TESTING REPORT FOR THE MIX 111						
PROCEDURE B						
<i>Specimen information:</i>						
Slab		Weight, Kg	18.25	Test number:	M111	
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track	
Length, mm	300	Height: mm	50	Machine	Wheel Tracker _Procedure B	
Width, mm	300	Compaction Cycle	25	Station	Asphalt Plant	
		Air Void	7%	Bitumen Type	80/100	
				Wheel tracking Cycle:		10,000
				Test temperature:	46°C	
Result						
				Final deformation:	RD(mm) 7.02 mm.	

The graph plots Displacement (mm) against Cycle. The x-axis is logarithmic, ranging from 1 to 10,000 cycles. The y-axis is linear, ranging from 0 to 20 mm. The data points show a steady increase in displacement over time, with a noticeable upward curve starting around 8,000 cycles, reaching a final displacement of 7.02 mm at 10,000 cycles.

Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	3.06		
250	0.64	4250	3.5	8000	5.76
500	0.78	4500	3.78	8250	5.9
750	0.9	4750	3.96	8500	6.02
1000	1.06	5000	4.12	8750	6.11
1250	1.18	5250	4.21	9000	6.27
1500	1.3	5500	4.36	9250	6.40
1750	1.43	5750	4.49	9500	6.62
2000	1.62	6000	4.62	9750	6.84
2250	1.76	6250	4.79	10000	7.02
2500	1.98	6500	4.96		
2750	2.18	6750	5.10		
3000	2.34	7000	5.38		
3250	2.56	7250	5.50		
3500	2.72	7500	5.68		
3750	2.94	7750	5.70		

Table A-6

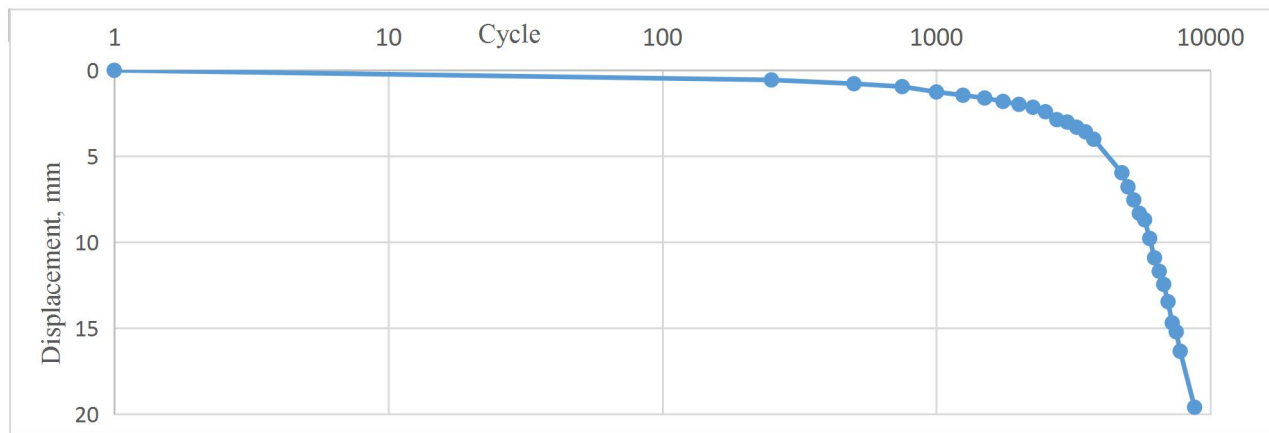
WHEEL TRACKING TESTING REPORT FOR THE MIX 44					
PROCEDURE B					
<i>Specimen information:</i>					
Slab		Weight, Kg	18.25	Test number:	M44
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track
Length, mm	300	Height: mm	50	Machine	Wheel Tracker Procedure B
Width, mm	300	Compaction Cycle	20	Station	Asphalt Plant
		Air Void	7%	Bitumen Type	60/70
				Wheel tracking Cycle:	10,000
				Test temperature:	50°C
Result					
				Final deformation:	RD(mm) >20 mm.



Cycle	Displacement	Cycle	Displacement	Cycle	Displacement
1	0	4000	4.44		
250	0.48	4250	4.68	8000	16.91
500	0.8	4500	5.38	8250	17.41
750	0.85	4750	5.91	8500	18.85
1000	1.23	5000	6.59	8750	19.79
1250	1.35	5250	7.25	9000	
1500	1.59	5500	8.29	9250	
1750	1.75	5750	8.72	9500	
2000	1.97	6000	9.8	9750	
2250	2.10	6250	10.80	10000	
2500	2.36	6500	11.56		
2750	2.82	6750	12.58		
3000	2.97	7000	13.65		
3250	3.29	7250	14.59		
3500	3.48	7500	15.03		
3750	4.02	7750	16.25		

Table A -7

WHEEL TRACKING TESTING REPORT FOR THE MIX 444					
PROCEDURE					
E		B			
<i>Specimen information:</i>					
Slab		Weight, Kg	18.25	Test number:	M444
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track
Length, mm	300	Height: mm	50	Machine	Wheel Tracker
Width, mm	300	Compaction Cycle	20	Station	Asphalt Plant
		Air Void	7%	Bitumen Type	60/70
				Wheel tracking Cycle:	10,000
				Test temperature:	50°C
Result					
Final deformation:		RD(mm) >20 mm.			



Cycle	Displacement	Cycle	Displacement	Cycle	Displacement
1	0	4000	4.61		
250	0.56	4250	4.78	8000	16.98
500	0.78	4500	5.48	8250	17.58
750	0.95	4750	5.96	8500	18.50
1000	1.26	5000	6.78	8750	18.97
1250	1.45	5250	7.54	9000	19.54
1500	1.61	5500	8.32	9250	
1750	1.81	5750	8.69	9500	
2000	1.98	6000	9.78	9750	
2250	2.15	6250	10.91	10000	
2500	2.41	6500	11.69		
2750	2.87	6750	12.45		
3000	3.01	7000	13.46		
3250	3.31	7250	14.69		
3500	3.58	7500	15.21		
3750	4.01	7750	16.34		

Table A -8

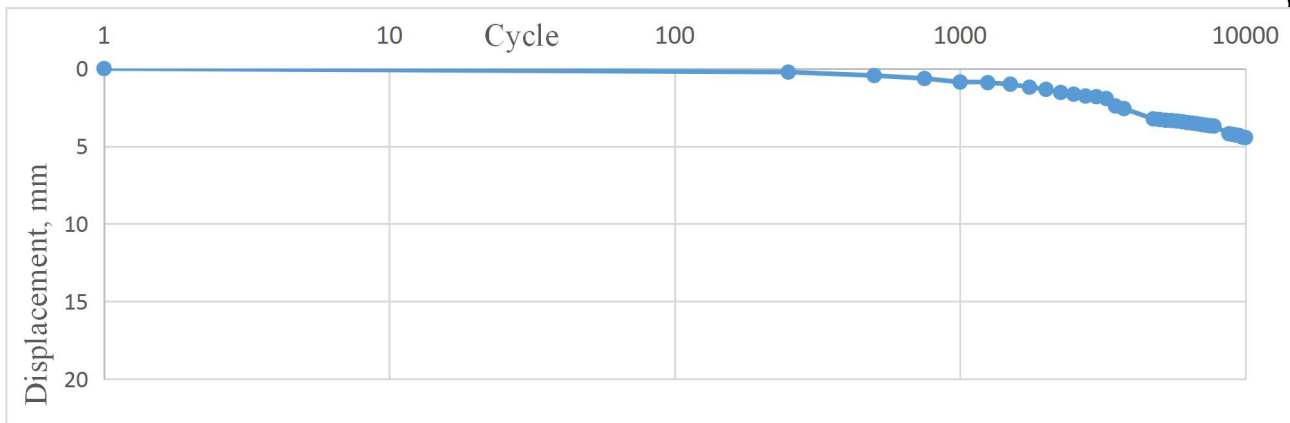
WHEEL TRACKING TEST REPORT FOR MIX-333						
PROCEDURE						
E			B			
<i>Specimen information:</i>						
Slab		Weight, Kg	18.25	Test number:	M333	
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track	
Length, mm	300	Height: mm	50	Machine	Wheel Tracker Procedure B	
Width, mm	300	Compaction Cycle	20	Station	Asphalt Plant	
			Air Void	7%	Bitumen Type	800/100
				Wheel tracking Cycle:		10,000
				Test temperature:	46°C	
Result						
Final deformation:				RD(mm) >20 mm.		

The graph plots Displacement (mm) against Cycle. The x-axis is logarithmic, ranging from 1 to 10,000 cycles. The y-axis is linear, ranging from 0 to 20 mm. The data points show a sharp increase in displacement starting around 1000 cycles, reaching approximately 20 mm at 10,000 cycles.

Cycle	Displacement	Cycle	Displacement	Cycle	Displacement
1	0	4000	4.21		
250	0.64	4250	4.56	8000	16.7
500	0.78	4500	5.26	8250	17.54
750	0.95	4750	5.74	8500	18.21
1000	1.02	5000	6.5	8750	19.34
1250	1.52	5250	6.87	9000	19.87
1500	1.64	5500	7.40	9250	
1750	1.94	5750	8.6	9500	
2000	2	6000	9.5	9750	
2250	2.22	6250	10.20	10000	
2500	2.46	6500	10.82		
2750	2.89	6750	11.50		
3000	3.12	7000	12.60		
3250	3.34	7250	13.41		
3500	3.61	7500	14.57		
3750	3.91	7750	15.60		

Table A -9

WHEEL TRACK TESTING REPORT FOR THE MIX 1					
PROCEDURE B					
<i>Specimen information:</i>					
Slab		Weight, Kg	18.25	Test number:	M1
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track
Length, mm	300	Height: mm	50	Machine	Wheel Tracker Procedure B
Width, mm	300	Compaction Cycle	25	Station	Asphalt Plant
		Air Void	7%	Bitumen Type	80/100
				Wheel tracking Cycle:	10,000
				Test temperature:	46°C
Results					
				Final deformation:	RD(mm) 15.15 mm.



Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	2.89		
250	0.23	4250	3.16	8000	3.89
500	0.45	4500	3.21	8250	3.94
750	0.64	4750	3.24	8500	4.01
1000	0.87	5000	3.28	8750	4.2
1250	0.91	5250	3.33	9000	4.24
1500	1.01	5500	3.35	9250	4.28
1750	1.2	5750	3.38	9500	4.31
2000	1.34	6000	3.42	9750	4.42
2250	1.54	6250	3.48	10000	4.44
2500	1.65	6500	3.51		
2750	1.77	6750	3.55		
3000	1.81	7000	3.60		
3250	1.93	7250	3.64		
3500	2.41	7500	3.68		
3750	2.58	7750	3.70		

Table A-10

WHEEL TRACK TESTING REPORT FOR THE MIX 2						
PROCEDURE B						
<i>Specimen information:</i>						
Slab		Weight, Kg	18.25	Test number:	M2	
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track	
Length, mm	300	Height: mm	50	Machine	Wheel Tracker Procedure B	
Width, mm	300	Compaction Cycle	25	Station	Asphalt Plant	
			Air Void	7%	Bitumen Type	60/70
				Wheel tracking Cycle:	10,000	
				Test temperature:	50°C	
Results						
				Final		

Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	2.26		
250	0.24	4250	2.39	8000	3.87
500	0.49	4500	2.58	8250	3.91
750	0.58	4750	2.88	8500	4.11
1000	0.66	5000	2.96	8750	4.21
1250	0.82	5250	3.12	9000	4.27
1500	0.92	5500	3.28	9250	4.30
1750	1.16	5750	3.38	9500	4.35
2000	1.29	6000	3.45	9750	4.39
2250	1.38	6250	3.49	10000	4.41
2500	1.44	6500	3.52		
2750	1.67	6750	3.56		
3000	1.79	7000	3.59		
3250	1.88	7250	3.62		
3500	1.96	7500	3.65		
3750	2.02	7750	3.70		

Table A-11

WHEEL TRACKING TESTING REPORT FOR THE MIX 4						
PROCEDURE B						
<i>Specimen information:</i>						
Slab		Weight, Kg	18.25	Test number:	M4	
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track	
Length, mm	300	Height: mm	50	Machine	Wheel Tracker	
Width, mm	300	Compaction Cycle	20	Station	Asphalt Plant	
			Air Void	7%	Bitumen Type	60/70
				Wheel tracking Cycle:	10,000	
				Test temperature:	50°C	
Results						
Final deformation:				RD(mm) 5.86 mm.		

Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	2.28		
250	0.36	4250	2.39	8000	4.81
500	0.51	4500	2.51	8250	4.9
750	0.62	4750	2.73	8500	5.16
1000	0.75	5000	2.97	8750	5.24
1250	0.87	5250	3.24	9000	5.33
1500	0.91	5500	3.47	9250	5.46
1750	1.15	5750	3.68	9500	5.59
2000	1.28	6000	3.85	9750	5.67
2250	1.34	6250	3.91	10000	5.86
2500	1.41	6500	4.01		
2750	1.57	6750	4.13		
3000	1.73	7000	4.22		
3250	1.82	7250	4.39		
3500	1.98	7500	4.54		
3750	2.12	7750	4.66		

Table A -12

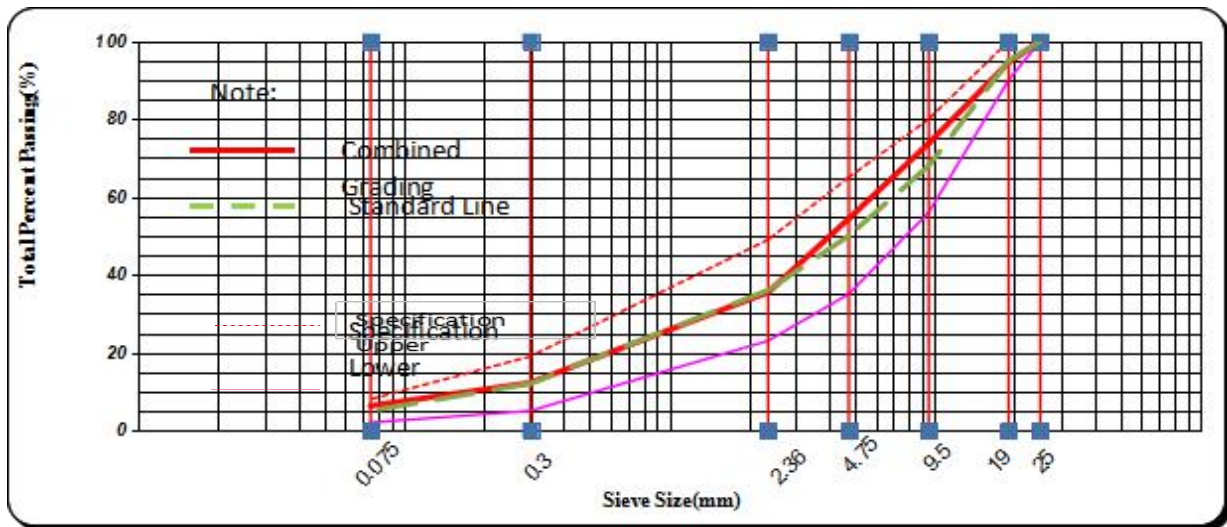
WHEEL TRACK TESTING REPORT FOR THE MIX 3						
PROCEDURE B						
<i>Specimen information:</i>						
Slab		Weight, Kg	18.25	Test number:	M3	
Dimensions:		Volume: M3	0.0045	Test name:	Wheel Track	
Length, mm	300	Height: mm	50	Machine	Wheel Tracker	
Width, mm	300	Compaction Cycle	20	Station	Asphalt Plant	
		Air Void	7%	Bitumen Type	80/100	
				Wheel tracking Cycle:	10,000	
				Test temperature:	46°C	
Results						
				Final deformation:	RD(mm) 4.14 mm.	

Cycle	Average Displacement	Cycle	Average Displacement	Cycle	Average Displacement
1	0	4000	1.79		
250	0.22	4250	1.88	8000	3.69
500	0.31	4500	1.96	8250	3.71
750	0.43	4750	2.12	8500	3.76
1000	0.58	5000	2.26	8750	3.8
1250	0.65	5250	2.38	9000	3.95
1500	0.76	5500	2.49	9250	3.98
1750	0.89	5750	2.56	9500	4.06
2000	0.97	6000	2.67	9750	4.12
2250	1.08	6250	2.79	10000	4.14
2500	1.14	6500	2.93		
2750	1.19	6750	3.01		
3000	1.22	7000	3.19		
3250	1.37	7250	3.28		
3500	1.49	7500	3.39		
3750	1.61	7750	3.53		

Appendix B,
Asphalt Mixes and Refusal Density Results

Table B -1
Mix 111 and Mix 222 Combined grading

Sieve Size(mm)	Nominal Aggregate Size (mm)				Filler	Combined Grading	Specification	
	10~20	5~10	3~5	0~3				
25	100.0	100.0	100.0	100.0	100.0	100.0	100	100
19	80.6	100.0	100.0	100.0	100.0	94.6	90	100
9.5	7.6	98.0	100.0	100.0	100.0	73.7	56	80
4.75	1.1	13.2	94.1	100.0	100.0	54.4	35	65
2.36	0.9	5.3	27.3	94.8	100.0	35.5	23	49
0.3	0.9	2.1	3.4	30.0	97.9	12.2	5	19
0.075	0.7	1.3	2.2	12.2	70.3	6.3	2	8
% by Agg. Wt	28.0%	19.0%	24.0%	26.0%	3.0%	100.0%		



Asphalt Type	80/100			Date of Testing :				
Asphalt Content (%)	Void (%)	Flow (mm)	Stability (KN)	VMA (%)	Bulk S.G. (g/cm ³)	Gmm (g/cm ³)	VFA (%)	
4.00	6.8	2.4	16.7	14.0	2.479	2.660	51.5	
4.50	5.3	2.5	15.3	13.7	2.501	2.641	61.4	
5.00	3.8	2.8	14.0	13.4	2.523	2.622	72.0	
5.50	2.0	3.2	13.8	13.7	2.529	2.581	85.2	
6.00	0.5	4.0	13.2	13.8	2.540	2.553	96.2	
					2.518	2.628		
OBC=4.85								
Acceptance Criteria	3 ~ 5	2 ~ 3.5	≥ 9	≥ 13	---	---	65~73	

Refusal Density Test Result M111

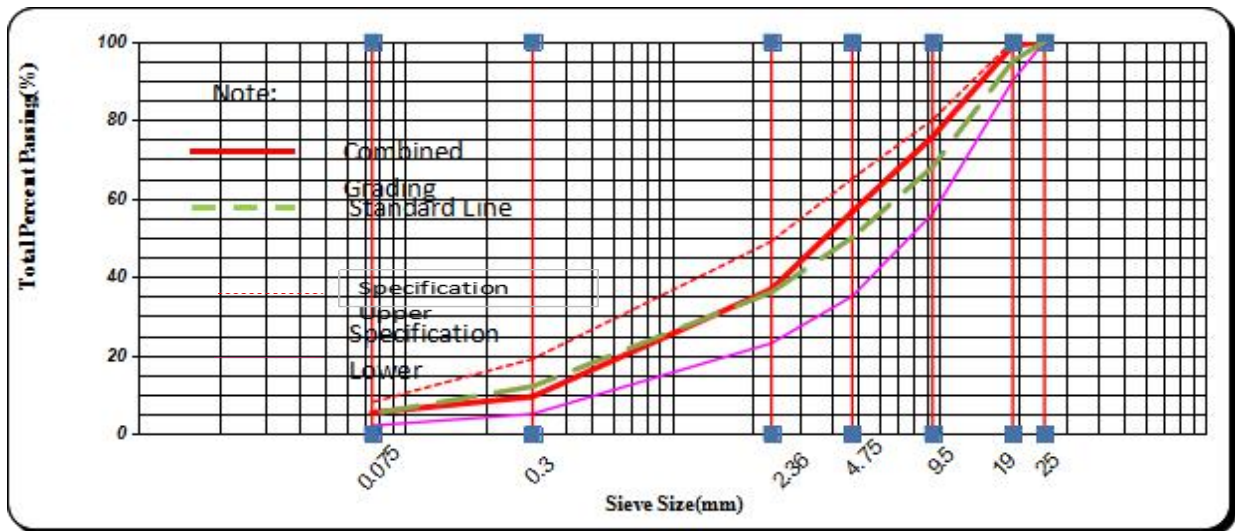
Specimen No	Asphalt Content by total mix (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	4.90	1229.3	1231.0	748.0	483.0	2.545	2.628	3.15
B		1228.0	1229.2	746.8	482.4	2.546	2.628	3.14
C		1228.7	1230.0	747.6	482.4	2.547	2.628	3.08
Average						482.6	2.546	2.628

Refusal Density Test Result M222

Specimen No	Asphalt Content by total mix (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	4.90	1241.7	1243.6	742.6	501.0	2.478	2.548	2.7
B		1237.3	1239.0	738.3	500.7	2.471	2.548	3.0
Average						500.9	2.475	2.548

Table B -2
M11and M22 Combined grading

Sieve Size(mm)	Nominal Aggregate Size (mm)				Filler	Combined Grading	Specification	
	10~20	5~10	3~5	0~3				
25	100.0	100.0	100.0	100.0	100.0	100.0	100	100
19	95.8	100.0	100.0	100.0	100.0	98.9	90	100
9.5	8.2	97.7	100.0	100.0	100.0	75.7	56	80
4.75	1.6	14.3	96.6	100.0	100.0	56.6	35	65
2.36	1.3	1.6	19.6	93.9	100.0	36.8	23	49
0.3	1.3	0.8	0.8	15.8	99.7	9.4	5	19
0.075	1.0	0.6	0.8	3.8	89.6	5.3	2	8
% by Agg. Wt	26.0%	20.0%	20.0%	30.0%	4.0%	100.0%		



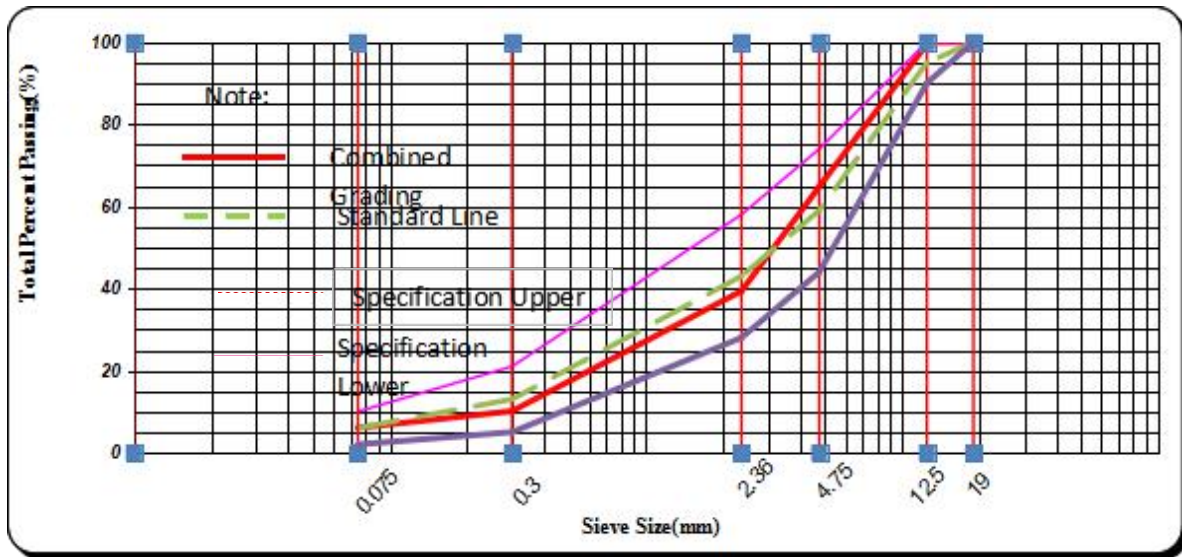
Asphalt Type		80/100		Date of Testing :			
Asphalt Content (%)	Void (%)	Flow (mm)	Stability (KN)	VMA (%)	Bulk S.G. (g/cm ³)	Gmm (g/cm ³)	VFA (%)
4.00	6.8	2.2	12.3	14.9	2.440	2.617	54.5
4.50	5.4	2.7	13.9	14.8	2.455	2.594	63.9
5.00	4.1	3.0	14.8	14.8	2.470	2.576	72.2
5.50	3.3	3.2	13.3	14.9	2.480	2.563	78.1
6.00	1.8	3.4	11.1	14.8	2.494	2.540	87.7
Average					2.466	2.580	
OBC=	4.9						
Acceptance Criteria	3 ~ 5	2 ~ 3.5	≥ 9	≥ 13	---	---	65~73

Refusal Density Test Result M11								
Specimen No	Asphalt Aggregate Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F = D - E	G = C / F		J = (1 - G/H) * 100
A	4.85	1259.7	1261.0	757.4	503.6	2.501	2.582	3.1
B		1257.3	1259.2	757.2	502.0	2.505	2.582	3.0
C		1258.0	1259.8	757.7	502.1	2.505	2.582	3.0
Average						502.6	2.504	2.582

Refusal Density Test Result M22								
Specimen No	Asphalt Aggregate Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F = D - E	G = C / F		J = (1 - G/H) * 100
A	4.9	1242.6	1243.6	744.3	499.3	2.489	2.555	2.6
B		1241.1	1242.5	742.0	500.5	2.480	2.555	2.9
Average						499.9	2.484	2.555

Table B -3
Combine Grading for M3 and M4

Sieve Size(mm)	Nominal Aggregate Size (mm)			Filler	Combined Grading	Specification	
	5~15	3~5	0~3				
19	100.0	100.0	100.0	100.0	100.0	100	100
12.5	98.9	100.0	100.0	100.0	99.5	90	100
4.75	18.0	97.6	99.3	100.0	64.8	44	74
2.36	2.5	26.4	92.0	99.7	39.4	28	58
0.3	0.3	4.2	15.2	98.4	10.1	5	21
0.075	0.2	2.8	4.4	89.6	6.1	2	10
% by Agg. Wt	42.0%	23.5%	30.0%	4.5%	100.0%		



Asphalt Type		80/100		Date of Testing :			
Asphalt Content (%)	Void (%)	Flow (mm)	Stability (KN)	VMA (%)	Bulk S.G. (g/cm ³)	Gmm (g/cm ³)	VFA (%)
4.00	6.5	2.4	9.9	17.6	2.394	2.560	63.1
4.50	5.7	2.8	10.2	17.9	2.398	2.542	68.3
5.00	4.9	3.1	10.7	18.2	2.402	2.525	73.3
5.50	4.1	3.3	10.6	19.0	2.391	2.493	78.5
6.00	3.4	3.6	8.3	19.1	2.387	2.470	82.5
Average					2.402	2.522	
OBC=	5.1						
Acceptance Criteria	3 ~ 5	2 ~ 3.5	≥ 9	≥ 13	---	---	65~75

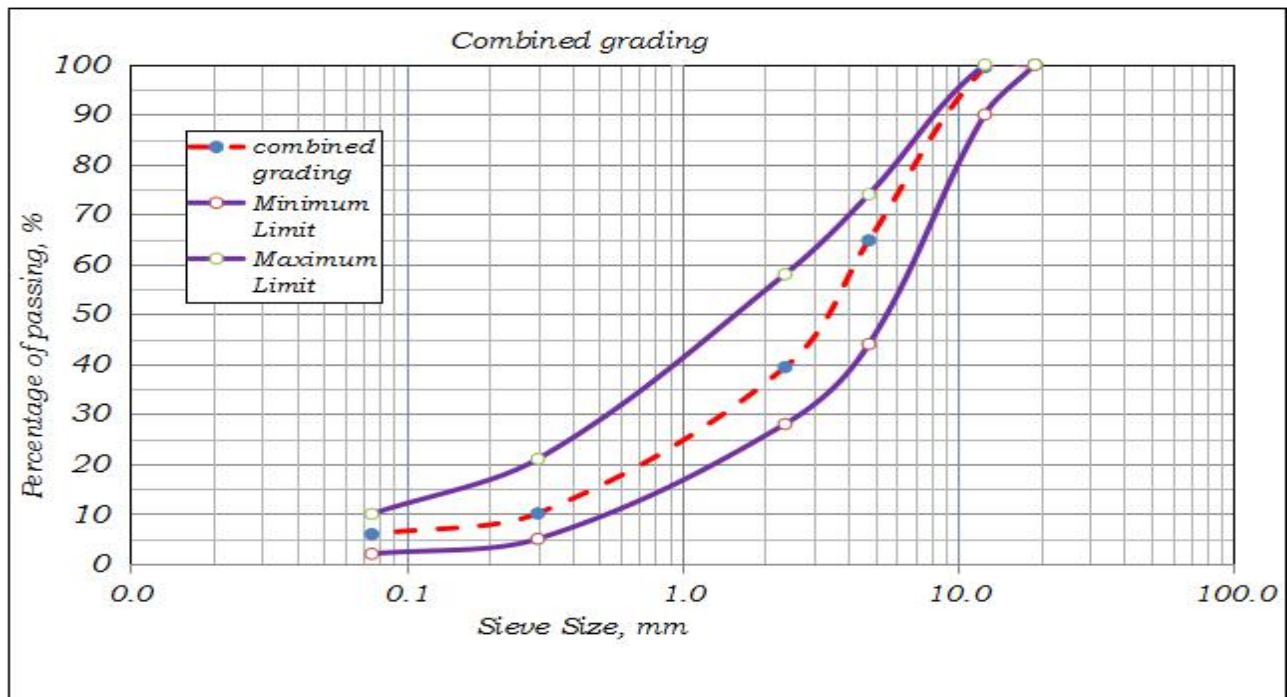
Refusal Density Test Result M-4								
Specimen No	Asphalt Aggregat Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	5.1	1197.2	1198	707.5	490.5	2.441	2.516	3.1
B		1189	1190.4	702.2	488.2	2.435	2.516	3.0
Average						489.4	2.438	2.516

Refusal Density Test Result M-3								
Specimen No	Asphalt Aggregat Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	5.1	1185.1	1186.3	700	486.3	2.437	2.518	3.21
B		1186.4	1187.6	700.7	486.9	2.452	2.518	2.62
Average						486.6	2.444	2.518

Table B -4

Combined Grading for M-33 and M-44

Sieve Size, mm.	Filler		0 - 4.75mm		4.75 - 12.5mm		12.5 - 19mm		19 - 25mm		JMF	100.0%	
	% Passing	6.0%	% Passing	37.0%	% Passing	28.0%	% Passing	26.0%	% Passing	3.00%	% Total Pass	Grading Specification Limit from ERA Manual	
19.0	100.0	6.0	100.0	37.0	100.0	28.0	100.0	26.0	58.9	1.8	100	100	100
12.5	100.0	6.0	100.0	37.0	100.0	28.0	50.9	13.2	13.1	0.4	100	90	100
9.50	100.0	6.0	100.0	37.0	95.6	26.8	6.4	1.7	5.9	0.2			
4.75	100.0	6.0	98.9	36.6	34.5	9.7	1.0	0.3	3.0	0.1	65	44	74
2.36	100.0	6.0	74.5	27.5	5.4	1.5	0.6	0.2	1.9	0.1	39	28	58
1.18	99.9	6.0	44.4	16.4	1.4	0.4	0.4	0.1	1.3	0.0			
0.6	99.8	6.0	25.1	9.3	0.7	0.2	0.4	0.1	0.9	0.0			
0.3	98.3	5.9	13.2	4.9	0.5	0.1	0.3	0.1	0.6	0.0	10	5	21
0.15	89.6	5.4	7.1	2.6	0.3	0.1	0.3	0.1	0.4	0.0			
0.075	70.9	4.3	4.2	1.6	0.2	0.1	0.2	0.1	0.2	0.0	6	2	10



Experimental Investigation on Rutting Criteria of Asphalt Mix

Bitumen Content %	Bulk Specific Gravity of Compacted Mix (g/cm ³)	Air voids %	VMA %	VFA%	Stability KN	Flow mm
4.6	2.428	6.2	16.0	61.0	12.19	2.85
4.9	2.439	5.4	15.9	65.8	13.78	2.95
5.0	2.443	4.7	16.0	70.8	13.20	3.33
5.1	2.451	3.7	16.0	76.8	12.26	3.45
5.2	0.000	0.0	0.0	0.0	0.00	0.00
5.5	0.000	0.0	0.0	0.0	0.00	0.00
OBC	5.1					
Specification		3 - 5%	min 14%	65-73%	min 9KN	2 - 3.5mm

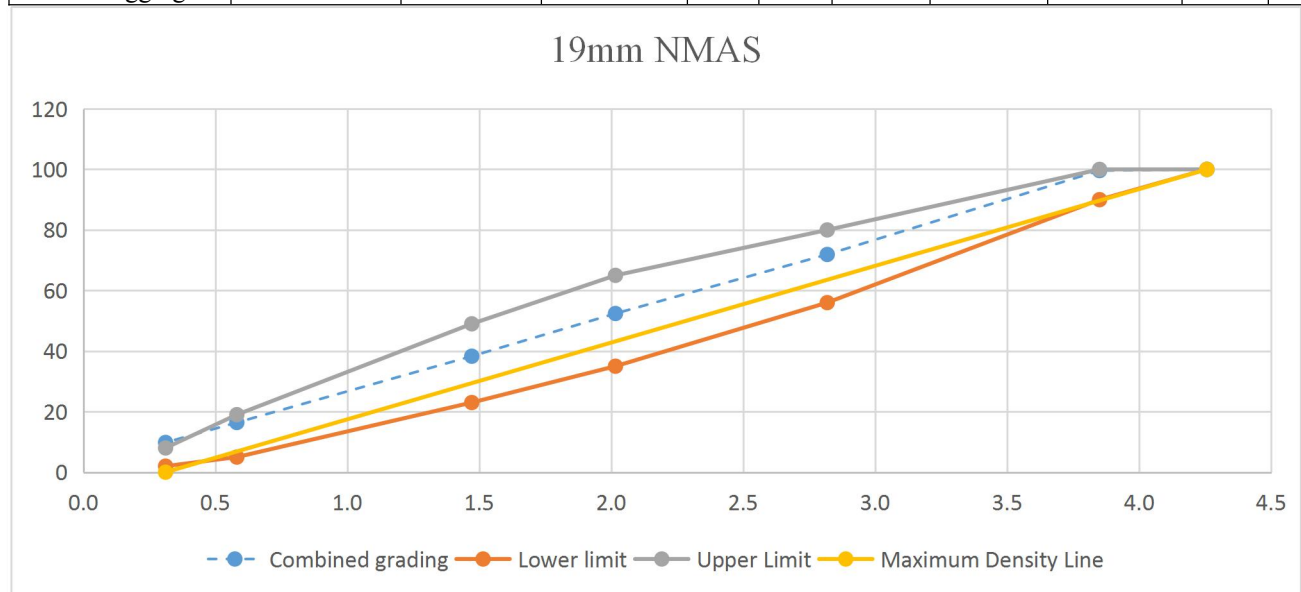
Refusal Density Test Result M-33								
Specimen No	Asphalt Aggregate Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F = D - E	G = C / F		$J = (1 - G/H) * 100$
A	5.1	1238.5	1239.0	731.4	507.6	2.440	2.513	2.9
B		1239.8	1240.2	734.0	506.2	2.449	2.513	2.55
C		1238.6	1239.1	729.9	509.2	2.432	2.513	3.22
Average						486.6	2.699	2.518

Refusal Density Test Result M-44								
Specimen No	Asphalt Aggregate Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F = D - E	G = C / F		$J = (1 - G/H) * 100$
A	5.1	1223.32	1239.0	731.4	507.6	2.440	2.515	2.98
B		1239.68	1240.2	734.0	506.2	2.449	2.515	2.62
C		1240.41	1239.1	729.9	509.2	2.436	2.515	3.14
Average						486.6	2.442	2.515

Table B -5

Combined grading for M1 and M2

Sieve Size (mm)	Sieve size raise to 0.45 power	Nominal Aggregate Size (19mm)				Dust	limestone	Combined Grading	Specification	
		13.5~ 20	6~13.5	6~ 3.5	0-3.5					
25	4.3	100	100	100	100	100	100	100	100	
20	3.9	98.2	100	100	100	100	99.586	90	100	
10	2.8	0.9	78.1	100	100	100	71.951	56	80	
4.75	2.0	0.4	3	94.2	100	100	52.42	35	65	
2.36	1.5	0.3	0.7	41.5	95.8	100	38.315	23	49	
0.3	0.6	0.3	0.4	1.6	37.7	98.5	16.391	5	19	
0.075	0.3	0.3	0.4	0.5	15	67.7	9.82	2	8	
% wt of aggregate		23%	24%	24%	21%	5%	3%	100%		



Asphalt Content	Void	VMA	Bulk S.G.	Gmm	VFA
(%)	(%)	(%)	(g/cm ³)	(g/cm ³)	(%)
4.00	5.2	13.6	2.329	2.456	61.8
4.50	4.8	14.9	2.306	2.422	67.8
5.00	3.7	14.5	2.329	2.418	74.5
Average			2.321	2.432	
OBC	4.9				
Acceptance Criteria	3 ~ 5	≥ 13	---	---	65~73

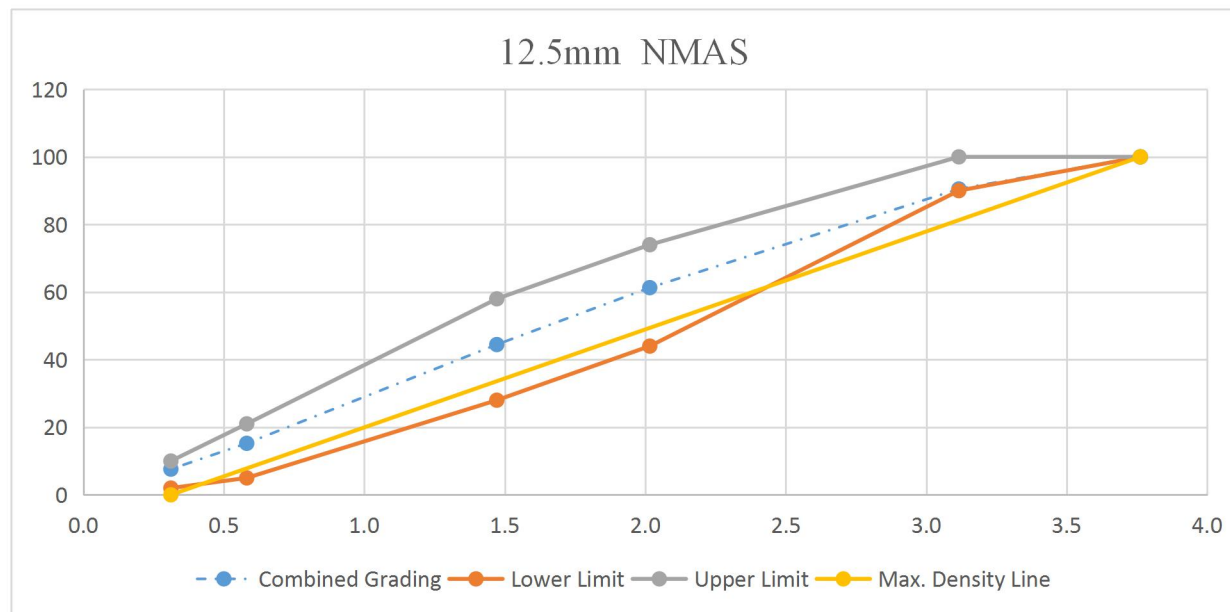
Refusal Density Test Result M-1								
Specimen No	Asphalt Aggregate Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	4.9	1209.1	1210.0	697.8	512.2	2.36	2.418	2.39
B		1197.0	1198.0	694.1	503.9	2.375	2.418	1.78
Average						486.6	2.442	2.515

Refusal Density Test Result M-2								
Specimen No	Asphalt Aggregate Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	4.9	1197.3	1201.2	681.0	520.2	2.421	2.427	2.47
B		12748.	1252.2	712.0	513.2	2.433	2.427	2.47
Average						516.7	2.367	2.427

Table B -6

Combined Grading for M333 &444

Sieve Size(mm)	Sieve size raise to 0.45 power	Nominal Aggregate Size (12.5 mm) M333 and M444				Dust	Limestone	Combined Grading	Specification	
		13.5~ 20	6~13.5	6~ 3.5	0-3.5					
19	3.8	100	100	100	100	100	100	100	100	
12.5	3.1	37.9	99	100	100	100	90.46	90	100	
4.75	2.0	0.5	1.7	87.5	100	100	61.32	44	74	
2.36	1.5	0.2	0.2	4.1	93.4	100	44.46	28	58	
0.3	0.6	0.2	0.1	0.2	12.4	98	15.24	5	21	
0.075	0.3	0.2	0.1	0.2	0.5	61.8	7.65	2	10	
% wt of aggregate		15%	22%	17%	35%	9%	100%			



Experimental Investigation on Rutting Criteria of Asphalt Mix

Asphalt Content (%)	Void (%)	VMA (%)	Bulk S.G. (g/cm ³)	Gmm (g/cm ³)	VFA (%)
4.40	5.8	14.7	2.306	2.448	60.5
4.60	4.7	14.4	2.320	2.434	67.4
4.80	4.0	14.0	2.334	2.430	71.4
Average			2.320	2.437	
OBC	4.8				
Acceptance Criteria	3 ~ 5	≥ 13	---	---	65~73

Refusal Density Test Result M-333								
Specimen No	Asphalt Aggregat Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	4.8	1214.3	1217.8	695.7	522.1	2.325	2.426	4.16
B		1207.6	1208.2	700.6	507.1	2.329	2.426	3.99
Average						514.6	2.327	2.426

Refusal Density Test Result M-444								
Specimen No	Asphalt Aggregat Ratio (%) (P _b)	Weight of Specimen			Volume of Sample	Specific gravity of mix (gm/cm ³)		Voids Percent
		In air (gm)	SSD wt. (gm)	In water (gm)		Bulk	Gmm	Air in Mix Volume (VIM)
	A	C	D	E	F	G	H	J
					F= D - E	G = C / F		J=(1-G/H) *100
A	4.8	1219.1	1217.8	695.7	522.1	2.335	2.418	3.43
B		1175.96	1208.2	700.6	507.1	2.319	2.418	4.09
Average						514.6	2.327	2.418