



**EFFECT OF AGGREGATE SURFACE AREA ON
PERFORMANCE OF ASPHALT CONCRETE BY USING
MARSHALL TESTS**

By

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MASTERS OF SCIENCE

**ADDIS ABABA SCIENCE AND TECHNOLOGY
UNIVERSITY**

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By

YIBELTAL AYCHEW BEYENE

A Thesis Submitted to

The Department of Civil Engineering for the Partial Fulfillment to the Requirements for Degree
of Master of Science in Road and Transport Engineering


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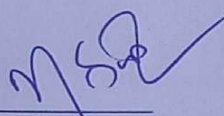
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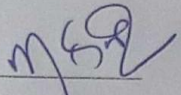
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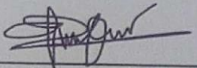
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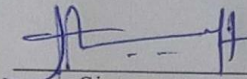
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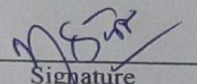
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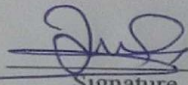
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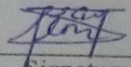
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DEDICATION

To my beloved family

ABSTRACT

Hot Asphalt Mixtures (HMA) is composite of mineral aggregates, asphalt binder, and air voids. Mineral aggregate is covered about 95 percent of the total mixture. In asphalt pavement production, aggregate gradation is specified in a large percent passing range to use locally available material and to be economical. This large gap of the aggregate gradation specification range alters the performance of the asphalt concrete by change the aggregate surface area. The aggregate surface area has a critical role in the hot mix asphalt performance by altering the coated asphalt film thickness on the aggregate surface and this controls overall mixture properties. Various studies have shown that the variation aggregate surface area has a significant effect on the performance of asphalt concrete pavements by using Marshall Test methods. This study was mainly evaluated the effect of aggregate surface area on the mixture volumetric properties and moisture damage. Different aggregate surface areas were determined in the blending aggregate gradation percent passing specification range by multiplying empirical surface area factor. Using $3.12\text{m}^2/\text{kg}$, $4.58\text{m}^2/\text{kg}$, $6.19\text{m}^2/\text{kg}$, $7.93\text{m}^2/\text{kg}$, and $9.64\text{m}^2/\text{kg}$ aggregate surface areas a number of trial mixes have been prepared using the Marshal Mix design method. The stability, flow, volumetric properties, and moisture resistance of the hot mix asphalt were discussed. The mixture produces in $4.58\text{ m}^2/\text{kg}$ and $6.19\text{m}^2/\text{kg}$ aggregate surface areas have better Marshall Stability, flow, volumetric, and stripping resistance. In general, $4.58\text{m}^2/\text{kg}$ and $6.19\text{ m}^2/\text{kg}$ of aggregate surface are, not only achieve the hot mix asphalt performance but also economically effective by saving 3.6 to 18% of the total bitumen to construct asphalt concrete. Based on the result of this study conclude that the better performance of the asphalt concrete is observed close to the middle gradation and recommends that, the preferable aggregate surface areas are $4.58\text{ m}^2/\text{kg}$ and $6.19\text{m}^2/\text{kg}$ to produce well performance and economical hot mix asphalt.

Key Words: Aggregate Surface Area (ASA), Hot Mix Asphalt Performance, Moisture Susceptibility, aggregate gradation and asphalt concrete.

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ABBREVIATIONS AND ACRONYMS

AASHTO – American Associates of State Highway and Transport Official

ASA- Aggregate surface area

AC – Asphalt Concrete

ERA – Ethiopian Roads Authority

Gmb- Bulk specific gravity a compacted mixture

Gmm- Theoretical maximum specific gravity a loose mixture

HMA – Hot Mix Asphalt

ITS- indirect tensile strength ratio

LL-Lower limit of gradation

ML- middle limit of gradation

MS-2 – Asphalt Institute’s Manual Series – 2

OBC – Optimum Binder Content

TSR-tensile strength ratio

UL- Upper limit of gradation

VFA – Voids Filled with Asphalt

VMA – Voids in Mineral Aggregate

VTM – Voids in Total Mix synonymous with air voids

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1. INTRODUCTION

1.1. Background

Road transport is the major mode of transport in Ethiopia. It is the backbone of Ethiopian economic development. The road network is the main issue in Ethiopia and other countries. The authority has recently reported that the country's main-road coverage has increased from less than 19,000 km to 113,000 km during the last 27 years (Xinhua, 2018).

Ethiopia's main-road coverage was less than 19,000 km in 1991, of which the share of rural areas was less than 6,000 km while urban areas with around 12,000 km. The country's road access has now also reached 1.23 km per 1,000 Ethiopians and the total road network at the end of 2020 planned to reach 200 thousand kilometers. This report shows that the Ethiopian road network increased at a fast rate and takes a huge country's budget (Xinhua, 2018).

There are three types of asphalt surfaces in the world characterized by a mixture of bitumen and aggregate. These are dense graded asphalt (asphalt concrete); stone mastic asphalt and open-graded asphalt (Gazia khurshid shid Khan, AR Sukhmanijt, 2017). The reason of this study was need to construct the Wearing surface with satisfying performance and economic aspects by considering effect of ASA on asphalt concrete mixture properties.

Almost all of the main roads in Ethiopia are flexible pavements. The surface course consists of a mixture of mineral aggregates cemented by a bituminous material. HMA wearing courses are the most critical layer in a pavement structure and must be of high quality and have predictable moisture damage resistance performance. Hot Mix Asphalt wearing courses (AC) was a heterogeneous material that consists of bitumen, natural or artificial aggregate, mineral filler, additives and air voids. Aggregate comprise the vast bulk of paving mixture and therefore, exerted significant influence on the resulting engineering properties of the structure. The content of aggregates in hot -mix asphalt concrete, covers about 95% of the total mass of the mix but the aggregate used to AC expressed with a large gap of percent of passing and this should be studied. The quality of the aggregate type and ASA significantly influences pavement performance and economy (Getu, 2019).

Wearing surface on flexible pavement is more expensive due to bitumen cost. Two-third of the total road project cost is taken by asphalt concrete and 50% of this is covered by the bitumen cost. Therefore, the AC design to be economical and well performance must consider the ASA effect on the bitumen content consumption and selection of the appropriate aggregate surface area to save bitumen during Hot-Mix asphalt design.

Dense graded asphalt (AC) is one of the HMA that contains all aggregate size and transfers stress through both coarse and fine aggregate. Asphalt concrete by far is the most common type of HMA used in tropical countries and it is usually designed by using the Marshall Method (Asphalt Institute, 1994) (Volume, 2013). Ethiopia is one of the tropical countries which mostly uses AC pavement. Asphalt concrete material has a continuous distribution of aggregate particle sizes which is often designed to follow closely the Fuller curve to give the maximum density of AC after compaction but adjusted slightly to make room for sufficient bitumen and for secondary compaction. A dense structure makes AC and it is sensitive to error in composition and the effect of this becomes more critical as traffic load increases (ERA, 2013).

One important property that can be computed from the aggregate gradation is the surface area the aggregate surface area interferes on asphalt pavement performance by disturbing asphalt film thickness. This research is important to solve the contradict ideas about performance and gradation, reduce the large aggregate gradation gap specified in the ERA,2013 specification and to recommenced appropriate aggregate surface area based on economy and performance. Thus, the research used to study effect of the aggregate surface area on asphalt concrete pavement performance with Marshall Tests.

1.2. Statement of the Problem

Several studies have been undertaken so far throughout the world to investigate and identify the best gradation in hot-mix-asphalt (HMA). However Sangsefidi et al (2016) states that "The results of that study show that mixture performance is not related to the gradation specification limits, so the author suggested using 'free design' of gradation to achieve the required performance of HMA" and on the contrary the Banerji et al. (2014) explained that "the results indicate that the performance of mixes made with mid-point value of gradation range shows

higher Marshall Stability value than other mixes while the optimum binder content (OBC) increases from coarser gradation to finer gradation for both grading specifications".

The flexible pavements have no longer service life. In different parts of our country the surface course of the pavements are damaged and the maintenance costs are increased year to year due to Ethiopia mostly uses AC pavement and which is sensitive to aggregate gradation and OBC and the effect of this becomes more critical as traffic load increases. Although the aggregate surface area is an important property to determine optimum binder content, ERA specification 2013 specifies the gradation of aggregates with a large range percent passing. This high range of percent passing allows to variation of OBC in the HMA mix design. This cause to flexible pavement premature failure such as moisture damage resistance, and mixture volumetric properties and this in turn affect AC performance. Specially, moisture damage is well known to be an aggregate-asphalt problem affected by aggregate surface area and other physical properties of aggregate (Getu, 2019).

Aggregate quality is different from source to source and at different institutions that provide locally available aggregates. Gradation is the critical issue to assure the quality of aggregate; even if this is expressed based on a percent passing ranges in a series of the sieve size. The specification has been achieved with trial and error by blending different materials to consider local materials. However, asphalt pavement is popular in the world; it takes two-third of the total cost of the road project due to expansiveness of binder content. The amount of bitumen varies with the variation of ASA in the mix design and bitumen requirement in hot mix asphalt (HMA) is directly dependent on the surface area of the aggregates in the mix, which in turn affects the asphalt film thickness and the flow characteristics. Thus; aggregate structure and proportion of particle size play a great role in HMA.

There is a custom for researchers to choose a gradation lower limit, upper limit, and the middle of the band is preferable. Further investigated the effect of gradation by consider mean value of lower and middle limit and mean value of middle and upper limit to fill the gap and can create appropriate aggregate gradation range for understanding this contradicts ideas and the effect of ASA on bitumen consumption and hot-mix asphalt mixture properties.

1.3. Research Questions

The study is attempted to answer the following questions concerning effect of aggregate surface area on asphalt concrete performance by using Marshall Test method.

1. What is the effect of an aggregate surface area on optimum binder content?
2. What is the effect of an aggregate surface area on hot mix asphalt property?
3. What is the relation between an aggregate surface area with moisture damage resistance?
4. Is there any economic advantage (bitumen consumption) when considering the aggregate surface area in HMA mix design?

1.4. Research Objective

1.4.1. Main Objective

The main objective of the study is effect of aggregate surface area on performance of asphalt concrete by using Marshall Test.

1.4.2. Specific Objective

The specific objectives of this study are the following:

- ❖ To find out the effect of aggregate surface area on optimum binder content in hot-mix asphalt.
- ❖ To determine the effect of aggregate surface area on stability, flow, and volumetric properties in hot-mix asphalt.
- ❖ To identify the effect of the ASA on moisture damage.
- ❖ To investigate the possible cost-effective hot mix asphalt design by using different aggregate surface area that satisfies the basic properties of hot-mix asphalt.

1.5. Significance of the Research

Aggregate surface area variation has significant influence on durability, moisture damage, asphalt film thickness and economic aspect of asphalt concrete. These effects on the mixtures are controlled by select the best ASA during hot mix asphalt mix design. This paper is mainly used

to show sensitivity of hot mix asphalt mixture properties and performance due to aggregate surface area variation. The study is used to try to improve the mixtures durable, moisture resistance and volumetric properties by using appropriate ASA in HMA design.

The study help to explain the relationship between aggregate surface area with optimum binder content, mixture volumetric properties and performance of hot mix asphalt. This used to understand where the best ASA is selected in the gradation specification limit to produce well durability and performance of asphalt concrete and also used to solve the contrary ideas that "mixture performance not related on gradation specification limit ('free design') " and on the other hand "at the midpoint value of aggregate gradation range shows higher Marshall Stability value than other mixes". In addition to this, the study used to evaluate aggregate particle size distribution provided in the ERA specification, 2013 to obtain durable & economical HMA mix design.

1.6. Scope of the Research

There are different types of asphalt surfacing from which dense graded asphalt in HMA is called AC involved in the research. The performance of AC such as permanent deformation, fatigue cracking, moisture damage resistance, low temperature cracking and durability depends on an aggregate surface area. But from this study volumetric properties and moisture damage resistance were mainly evaluated using Marshall Mix design method alone.

Aggregate surface area one of the aggregate qualitative property which is estimated from aggregate gradation percent passing. There are different techniques used to estimate the aggregate surface area. These are 3D Laser image model, mathematical model, and empirical surface area factor method. But in this study ASA estimation was done using the empirical ASF method which mainly used aggregate gradation percent passing and simplified factor. The main target of the research finds the effect of ASA on AC performance within gradation percent passing range specified in ERA specification 2013 by taking five different ASA as samples.

1.7. Limitation of the Research

During the study, many limitations and constraints were expected. During experimental tests, there are usually human, instrument calibration, and measurement errors. The surface area of aggregate blend in HMA is calculated using the specific surface area factors assigned to percent passing through some specific standard sieve. Estimation of the surface area of aggregates in HMA is difficult due to their irregular shapes and the roughness of surface texture. Whoever, the surface area which is one of the vital inputs in the design of HMA, the surface area of the aggregate size greater than 4.75mm specify for all is $0.41\text{m}^2/\text{kg}$ constant even different percent of passing. The empirical aggregate surface area factor constant in every type of aggregate but the reality is different from this. That not considers the aggregate shape and other structures of the aggregate. The surface area factor considers spherical shape of aggregates. Institutes Manual Series MS-2 standardized the surface area factor (SAF) for a specified set of sieve sizes. However, these techniques have a limited accuracy and human error.

1.8. Organization of the Thesis

This thesis is organized into five chapters. It includes an introduction, literature review, methodology, analysis and discussion, and conclusion and recommendations. Under the introduction chapter general introduction, statement of the problem, research question, objective of the study, the significance of the study, and the scope and limitations of the study are explained. Chapter two presents the literature review about the performance of hot mix asphalt, factors affecting hot mix asphalt performance, moisture damage cause of moisture damage, mechanism of moisture damage and moisture susceptibility tests.

In the third chapter materials and methodological approach of the study is presented. In this chapter deals materials quality test, the mix design selection, specimen preparation and experimental investigation of the specimen. Chapter four states about the results, discussions, and analysis of the laboratory test results. The last chapter deals with conclusions and recommendations obtained from the thesis work and study areas for future researchers.

2. LITERATURE REVIEW

2.1. Introduction

Asphalt Concrete is the dense graded bituminous mixture consists of a carefully proportioned mixture of coarse aggregate, fine aggregate, mineral filler and bitumen. Coarse and Fine aggregates act as a structural skeleton for the pavements while bitumen uses as a binder for the mixture (Maharjan, Bir, and Tamrakar, 2017). Aggregates make up approximately 80% of an asphalt mixture by volume or 95% by weight. The suitably designed bituminous mix will resist heavy traffic loads under adverse climatic conditions and also fulfill the requirements of structural and pavement surface characteristics. The most important elements of designing an asphalt mixture are identifying and selecting component materials for the specific application, selecting an appropriate aggregate gradation, and determining optimal bitumen content for selected aggregate gradation. When these are applied in a specific pavement structure, the result will have an acceptable performance (Little, Allen, and Bhasin, 2018).

The performance of the HMA mixture depends on temperature, moisture, aggregate property, asphalt film thickness, binder content, and volumetric property. It is obvious that the use of poor-quality raw materials will not result in a high-quality or durable asphalt mixture. Thus, aggregates in HMA are generally required to be hard, tough, strong, durable, properly graded to consist of cubical particles with low porosity; to have a clean, tough, and hydrophobic surface (Brown et al., 2009).

Although designing a bituminous mix to meet the desired requirements of a particular paving project requires careful selection of the compatible aggregate source, aggregate gradation, and bitumen grade to sustain till its design life, the choice of gradation has a direct influence on the ultimate performance of the asphalt mixture. Variation in gradation limit tends to affect almost all the vital properties of HMA including stiffness, stability, durability, permeability, workability, fatigue resistance, and resistance to moisture damage (Banerji et al., 2014).

The objective of the design for a bituminous mix is to determine an economical proportion of materials through several trial mixes with the desired performance of the asphalt mixture. Even though the large volume or mass proportion, aggregates typically cover up to 50% or less of the total cost of the materials used to produce an asphalt mixture (Little et al., 2018). For economic

reasons, aggregates are mostly used from the nearest available location. This may cause to alter the normal performance of the asphalt concrete mixture. Because of the AC wearing courses tend to be sensitive to variations in composition. To compensate for the locally available aggregates used in HMA many institutions provided the specification limit about the structural arrangement of the aggregate to achieve both economic and performance of HMA mixtures. A high level of quality control is essential during laboratory design, manufacturing, testing, and construction (ERA, 2013).

One important property that can be computed from the aggregate gradation is the surface area. The aggregate surface area is important since it affects the amount of asphalt needed to coat the aggregate and in turn, this affects the performance of the HMA, such as strength, durability, resistance to stripping, shoving, and bleeding of bitumen on asphalt pavement. The surface area of the aggregates blended in HMA can directly affect the asphalt film thickness and flow characteristics (Panda, Das, and Sahoo, 2016).

2.2. HMA Mixture Performances

When AASHTO road test was being designed in the 1960s, the statisticians recognized that some objective measurement of performance was required if the pavement design equations were to be developed. Due to this, researchers try to develop the concept of asphalt pavement performance definitions and measurement mechanisms. These are: i) highways are designed and built for the comfort and convenience of the traveling public. Therefore, a good highway is one that is smooth and safe, ii) one user's option about how well a highway is serving its function is subjective, and iii) Performance is defined as the area under the serviceability-time curve from the time of construction to the time performance is being evaluated.

The serviceability/performance/ concept was first applied at the AASHTO road test. The study showed that about 95% of the information about the serviceability of pavement is contributed by the roughness of the surface profile. This means that only 5% of the information is explained by all the objective measurements. The original performance regression equation relates to the percent serviceability index to make measurements on the pavement.

$$PSI = 5.03 - 1.91 \log(1 + SV) - 1.38 RD^2 - 0.01 \sqrt{(C + P)} \quad (2.1)$$

Where,

PSI = Percent serviceability index;

SV =Slope variance, the variance of the slope measured over 6-inch wheelbase the profilometer

RD = Average rutting depth, in inch;

C = Pavement cracking in feet/1000 square feet of pavement surface; and

D =Patching in square feet/1000 square feet of pavement.

Generally, the new pavement performance has a PSI value between 4 and 5, and to decide the pavement required to repair, the PSI will be usually laid between 1.5 and 2.5. This type of relationship has been useful in presenting the performance concepts as shown in Fig 2.1. The serviceability begins at the high level, typically between 4 and 4.5, remains fairly constant for some time, and then begins to drop off quickly until it reaches a selected terminal level where some rehabilitation action is required, typically overlay. With the overlay, the serviceability level is restored to some higher value shown by the dashed line in Fig2.1.and the second performance period begins. The performance for the first period is represented by the area under the PSI versus the cumulative traffic curve. Comparisons between competing thickness design combinations can be made using the estimated or observed historical performance (Brown et al., 2009; Dave and Koktan, 2011).

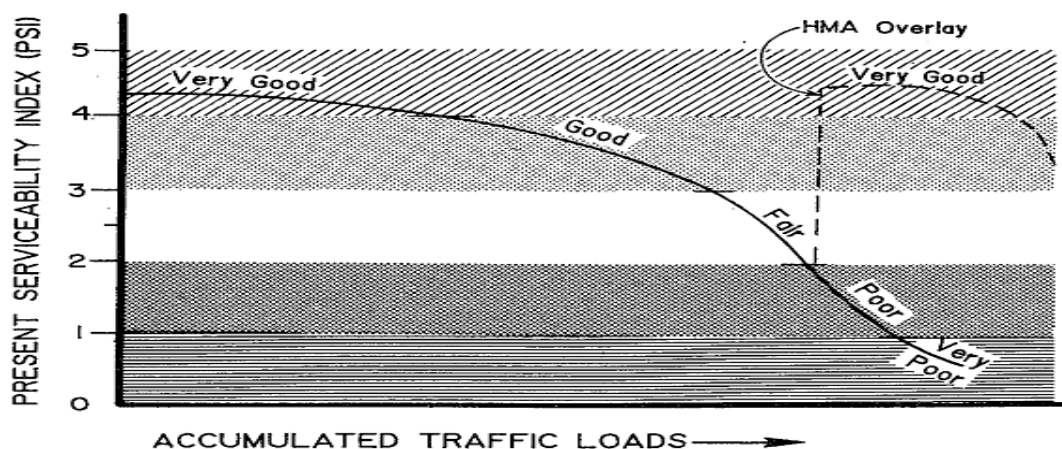


Figure 2: 1 typical relationship between PSI and cumulative traffic

Therefore, the performance (initial PSI) of the asphalt pavement is affected by mixture composition, weather condition, construction (laying and appropriate compaction), structural and mix design. To design a better performing Hot Mix Asphalt (HMA) mixture's aggregate and asphalt binder should also be combined optimally such as the proportion of individual constituents and volumetric result in HMA mixture. These volumetric properties control resistance against rutting, fatigue as well as permeability (Singh and Swamy, 2017).

Failure in a pavement performance can occur at the end of a pavement's planned service life or it could be premature (occurred before the design period) because of improper design or construction. In general, failure of pavement can be attributed to the failure of component materials selection, mixture design (proportion of aggregate gradation and binder content), pavement structure design (thickness design of different layers), and construction (laying and compaction). This means, does not mean asphalt mixture performance properties achieved well by selecting the best quality of mineral aggregates, asphalt binder, and mineral fillers alone (Little et al., 2018; Zhao, 2011).

The HMA industry needs a simple performance test to ensure the quality of mixture. There are five distresses which used to guide and evaluate the level of performance in the pavement. These are fatigue cracking, rutting, thermal cracking, friction (skid), and moisture susceptibility. All of these distresses can result in a loss of performance, but rutting is the one distress that is most likely to be a sudden failure as a result of unsatisfactory HMA. Other distresses are typically long-term failures that show up after a few years of traffic load applied (asphalt institute, 2007).

The cumulative performance of the asphalt pavement is determined by measuring the individual performance elements such that deformation resistance, fatigue resistance, low temperature cracking resistance, durability, moisture damage resistance, and skid resistance. These used to evaluate the total performance of the pavement are detail discussed below.

2.2.1. Deformation Resistance

Deformation resistance is the resistance of HMA pavement from distorting (rutting) or deform (shove) under traffic loading within design service life. The accumulation of permanent deformation may lead to pavement deterioration and eventual failure of the structure at the moment of its service life. Improving the design and enhancing the long-term performance of a

pavement structure requires an accurate and reliable prediction of cumulative permanent strain. (N. Zhalehjoo, 2017). HMA pavement deformation is related to one or more of the following; Aggregate surface and abrasion characteristics, Rounded particles tend to slip by one another causing HMA distortion under load while angular particles interlock with one another providing a good deformation-resistant structure. Brittle particles cause a mix distortion because they tend to break apart under load. Tests for particle shape and texture as well as durability and soundness can identify problem aggregate sources. These sources can be avoided or minimized. Blending aggregates with good surface and abrasion characteristics can provide better overall characteristics.

2.2.2. Fatigue Resistance

Fatigue resistance is the resistance of HMA pavement from cracking when subjected to repeated loads over time. Alligator, edge, longitudinal, random/block, and transverse cracking are various types of cracks. Fatigue cracking often is called alligator cracking. The name is given because of its closely spaced crack pattern is similar to the pattern on an alligator's back. This type of failure generally occurs when the pavement has been stressed above the limit of its fatigue life by repetitive axle load applications. Fatigue cracking is often associated with loads that are too heavy for the pavement structure or more repetitions of a given load than provided for in the design.

In the past mind that, fatigue cracking is initiated from the bottom and migrate towards the surface. These cracks began at the bottom because of the high tensile strain is at the bottom of the HMA. Recently, fatigue cracks have been observed starting at the surface and migrating downward. The surface cracking starts at the surface because tensile strains occur in the surface of the HMA. Generally speaking, it is believed that, for thin pavements, the fatigue cracking typically starts at the bottom of the HMA, and for thick pavements, the fatigue cracking typically starts at the HMA surface (Asphalt Institute, 2007).

The possible causes of cracking are traffic load, environment, improper construction practices, and mixture composition. The cracking failures depend on the tensile performance of HMA. HMA fatigue cracking is related to asphalt binder content and stiffness. Higher asphalt binder contents will result in a mix has a greater tendency to deform elastically rather than fracture under repeated load. Cracking is a major distress in asphalt pavement. Once the micro-cracks

associate into macro cracks and reach the surface, the rate of deterioration of the pavement tends to accelerate because water can infiltrate into the pavement. The optimum asphalt binder content as determined by mix design should be high enough to prevent excessive fatigue cracking. The use of an asphalt binder with a lower stiffness will increase a mixture's fatigue life by providing greater flexibility. However, the potential for rutting must also be considered in the selection of an asphalt binder. Note that fatigue resistance is also highly dependent upon the relationship between structural layer thicknesses and loading. However, this section only addresses mix design issues (Brown et al., 2009) and (Little et al., 2018).

2.2.3. Durability

Durability is the ability of HMA not to suffer excessive aging during production and service life. HMA durability is related to one or more of the following; the asphalt binder film thickness around each aggregate particle, if the film thickness surrounding the aggregate particles is insufficient, it is possible that the aggregate may become accessible to water through holes in the film. If the aggregate is hydrophilic, water will displace the asphalt film and asphalt-aggregate adhesion will be lost. This process is typically referred to as stripping. Thus, optimum asphalt binder content determined by mix design should provide adequate film thickness.

Excessive air voids cause to increase HMA permeability and allow oxygen easier access to contact more asphalt binder and this accelerates oxidation reaction and volatilization. In other words, when the air void increases, aging of bitumen facilitate and the bitumen cohesion characteristic is lost. This is cause to adhesion failure between aggregate and binder. To address this, HMA mix design seeks to adjust items such as asphalt content and aggregate gradation to produce design air voids of about 4 percent. Excessive air voids can be either a mix design or a construction problem and this section only addresses the mix design problem (pavement Interactive, 2007) and (Little et al., 2018).

2.2.4. Skid Resistance

HMA placed as a surface course should provide sufficient friction when the vehicle's wheel in contact with the asphalt surface. Friction is defined as the relationship between the vertical force and the horizontal force developed as the tire slides along the pavement surface. To the vehicle operator, friction is a measure of how quickly a vehicle can be stopped.

The friction of a pavement surface is a function of the surface texture. Surface texture is divided into two components: micro-texture and macro texture. The micro-texture provides a good frictional resistance between the tire and the roadway by covering the loose particles on the hot mix asphalt. The macro texture provides drainage channels for water expulsion between the tire and the roadway. Thus, allowing better tire contact with the pavement to improve frictional resistance and to prevent fast speed (Asphalt Institute, 2007).

Low skid resistance is generally related to aggregate characteristics such as, aggregate surface area, shape, size, and resistance to polish. Smooth, rounded, or polish-susceptible aggregates are less skid resistant. Tests for particle shape and texture can identify the quality of aggregate sources. These sources can be rejected or modified, by blending aggregate with good surface and abrasion characteristics to provide better overall characteristics (Interactive, 2007).

2.2.5. Low-Temperature Cracking

Low-temperature cracking of asphalt pavements is attributed to the tensile strain induced in HMA as the temperature drops to some critically low level. Low-temperature cracking is a distress caused by low pavement temperatures rather than by applied traffic loads. Low-temperature cracks form when an asphalt pavement layer shrinks in cold weather. As the pavement shrinks, tensile strains build within the layer. At some point along the pavement, the tensile stress exceeds the tensile strength, and the asphalt layer cracks. Thus, low-temperature cracks often occur from a single event of low temperature.

Low-temperature cracking also can be a fatigue phenomenon that results from the cumulative effect of many cycles of cold weather. The magnitude and frequency of low temperatures and stiffness of the asphalt mixture on the surface are major factors in the occurrence and intensity of low-temperature transverse cracking. The crack starts at the surface and goes downward. The mixture stiffness, which is primarily related to the properties of the asphalt binder, is probably the greatest contributor to low-temperature cracking (Asphalt Institute, 2007).

2.3. Factors Affecting HMA Mixture Performance

Several factors affect the performance of an asphalt mixture in flexible pavement. Surface texture, penetration of pores and cracks with asphalt, aggregate angularity, aging of the aggregate

surface through environmental effects, and adsorbed coatings on the surface of the aggregate influences the asphalt– aggregate bond (Little et al., 2018). The performance effectiveness is also related to mixture ingredient properties, mixture design, structure design, and construction. The flexible pavement roads in Ethiopia often deteriorate in different ways, because of the harsh climatic conditions, lack of proper design and quality control, sudden increase of traffic high loads, and inadequate assessment for identifying causes of deterioration before carrying out construction. (Shiferaw G.W. & Dessalegn G. A, 2019)).

2.3.1. Mixture Compositions

Asphalt mixture is a multiphase composite material which consists of aggregates with appropriate gradation as load-bearing, asphalt as the binder, and air void as filler of the void in the mineral aggregate with a proportion of about 95%, 5 %, and 0% by weight. To ensure reliable mixture performance over a wide range of materials, traffic, and climatic conditions should be quantified based on the required specification. Gradation of asphalt mixture means the percentage of coarse aggregate, fine aggregate and mineral filler. Aggregate characteristics and gradation affect the performance of asphalt pavement (Wu, Wang, & Zhang, 2011). The mechanical properties of asphalt mixtures are influenced by the fractions and properties of each phase. Since aggregate occupies the majority part of the asphalt mixture. The physical and mechanical performances of asphalt mixture are greatly influenced by the geometric of aggregate particles and the mutual interaction among them (Wang, Bu, Wang, Yang, & You, 2016).

The purpose of the Mix design is normally to select the most economical and durable asphalt mixture that meets all of the established criteria for high-performance asphalt. The mixtures with high values of Marshall Stability but low flow values are often less desirable; because the pavement of such mixes tends to be more rigid or brittle and may break under heavy volumes of traffic. This may occur due to the composite materials' properties such as aggregate particle; asphalt binder and air void are not well.

2.3.1.1. Aggregates Properties

HMA pavement deformation is related to one or more of the following: Aggregate surface, abrasion characteristics, and shape of aggregate particles. Rounded particles tend to slid by one another and this is cause to HMA distortion under load while angular particles interlock with one

another and providing a good deformation-resistant structure. Brittle particles cause mix distortion because they tend to break apart under load.

Gradations with excessive fines cause distortion because the large quantity of fine particles tends to push the larger aggregate particles apart and act as lubricating between these larger particles. A gradation resulting in low VMA or excessive asphalt binder content can have the same effect. Gradation specifications are used to ensure acceptable aggregate gradation.

Asphalt binder content; Excess asphalt binder content tends to lubricate and push aggregate particles apart making their rearrangement under load easier. The optimum asphalt binder content as determined by mix design can prevent this problem. Asphalt binder viscosity at high temperatures; in the hot session, asphalt binder viscosity is the lowest and the pavement will deform more easily under load. To avoid the premature failure of pavement, it needs to be designed in such a way that no, or only small, permanent deformations accumulate in the pavement layers (Little et al., 2018) and (N. Zhalehjoo, 2017)

Porous aggregate used in the hot mix asphalt mixture has a critical factor in pavement failures. If pores in the aggregate are large enough to allow asphalt binder entry, they may be a contributor to moisture susceptibility. High porosity results in high bitumen absorption, which means asphalt binder content must be added more to achieve the desired effective asphalt binder content to protect the adhesion failure and provide adequate asphalt film thickness. Conversely, if high porosity is not considered, for a given amount of asphalt binder, more will be absorbed and less will be available to create the asphalt binder film around aggregate particles causing faster aging, fatigue cracking, less durability, and possibly stripping (Pavement Interactive, 2015).

Aggregates are affected by moisture depending on the aggregate type, aggregate source properties, and aggregate chemical properties. The surface texture of the aggregate affects its ability to coat and a good coating is necessary to prevent stripping. The effects of the crushing of the aggregate are very interesting. The more likely process, water, oil, or other contaminants in the air are attracted to the fresh surface to satisfy broken bonds. Since water is normally available in the atmosphere, the driving force for the absorption of water on the freshly crushed aggregate faces is that it reduces the free energy of the system. Although asphalt and other organics may also spread over the crushed faces of the aggregate, the rate at which they spread depends largely

on their viscosity. Water is more predominant and spreads much more quickly and causes stripping unless freshly crushed aggregate is coated with different agents.

The asphalt–aggregate bond is enhanced by three processes: (a) preheating the aggregate, (b) weathering the aggregate, and (c) removing aggregate coatings. When the aggregate surface is heated, the outermost adsorbed water layer is released, improving the state of interfacial tension between the asphalt and aggregate. This is improving the bond between asphalt and aggregate. The weathering process results in a replacement of the adsorbed water layer with organic fatty acids from the air. This results in an improved asphalt–aggregate bond. A dust coating on the aggregate surface promotes stripping by preventing intimate contact between the asphalt and aggregate and by creating channels through which water can penetrate (Brown et al., 2009; Little et al., 2018; Pan & Tutumluer, 2005).

2.3.1.2. Asphalt Binder

Asphalt grade and characteristics are critical to the performance of the asphalt pavement. The asphalt grading expresses by three methods, i) based on penetration, ii) based on viscosity, and iii) based on performance. Another property of the mixture that must be evaluated is asphalt content. The asphalt content of HMA is very important to ensure satisfactory performance. An HMA mixture with low asphalt content is not durable, and one with high asphalt content is susceptible to bleeding and becomes unstable. The actual asphalt content directly affects mixture properties, such as asphalt film thickness, voids, Marshall Stability, and Flow. Therefore, it is important to monitor asphalt content, but it is really these mixture properties that need to be controlled. The design procedure also includes a density-voids analysis of the compacted specimens to determine the percent air voids and percent voids filled with asphalt (VFA). After determinations, the specimens are tested at 60⁰C, and the Marshall Stability (maximum load observed in the test) and flow (deformation corresponding to the maximum load) are obtained (Huang, Shu, Dong, & Shen, 2010), (Nigatu, 2015) and (RAHA, 2016).

2.3.1.3. Air voids

Pores in aggregates absorb asphalt binder and affect the percentage volume of air voids in the HMA mixture. When HMA air voids exceed about 8 percent by volume, they may become interconnected and allow water to easily penetrate the HMA and cause moisture damage through pore pressure or ice expansion. To address this, the HMA mix design adjusts asphalt binder

content and aggregate gradation to produce design air voids of about 4 percent. Excessive air voids can be either a mix design or a construction problem (ERA, 2013) and (Pavement Interactive, 2015).

2.3.2. Structural Design

The functional performance of a pavement structure greatly relies on the selection of materials and thicknesses of the different layers. Structural design of pavements involves the selection of materials and thicknesses of the different layers based on load carrying requirements, topography, climatic conditions, bearing capacity of the existing subgrade, availability of the materials, and economic considerations. The base and sub base layers of pavements are the most commonly constructed Unbound Granular Materials (UGMs) of well-graded rock aggregates with dense configuration to provide the desired stiffness and resistance against permanent deformation (M.S. Rahman, 2017).

The design of flexible pavements presented in ERA, 2013, based on the catalog of pavement structures of TRL Road Note 31. To achieve the required performance; a flexible pavement must satisfy many structural design criteria. These are:

- i) The subgrade should be able to sustain traffic load and provide uniform support to the pavement layer without excessive deformation, and this is controlled by the vertical compressive stress or strain at this level,
- ii) Bituminous materials and cement-bound materials used in road base design should not crack under the influence of traffic; and this is controlled by the horizontal tensile stress or strain at the bottom of the road base,
- iii) The road base is often considered the main structural layer of the pavement, required to distribute the applied traffic load so that the underlying materials are not overstressed. It must be able to sustain the stress and strain generated within itself without excessive or rapid deterioration of any kind,
- iv) In pavements containing a considerable thickness of bituminous materials, the internal deformation of these materials must be limited; and their deformation is a function of their creep characteristics,
- v) The load spreading ability of granular sub-base and capping layers must be adequate to provide a satisfactory construction platform (ARA, 2002).

Asphalt mixes are used as surfacing layers of road and airfield pavements. Structural design of the flexible pavement considers traffic class, subgrade class, and assessment of material quality on the economic aspect which provide equal strength on the pavement structure. Pavement structure constitutes of capping layer, sub-base, base, and surface layer. The sub-grade or sometimes improved subgrade is the natural soil on which the road is constructed. (The subgrade ultimately carries all the traffic loads). Therefore, the structural function of a pavement is to support a wheel load on the pavement surface and transfer and spread that load to the subgrade without exceeding either the strength of the subgrade or the internal strength of the pavement itself. Thus, the design of the subgrade should have sufficient total thickness and internal strength to carry the applied load on it (Huang et al., 2010) and (Michael, 2017).

When the asphalt pavement was introduced, determining the proper thickness was a matter of option based on experience. The thickness design for flexible pavements is an effort to economize the amount and the type of material used to support the predicted traffic, on a given subgrade under the specific climate conditions at the site. The objective of achieving thickness is to balance the structural capacity and life cycle cost. The thickness of the pavement depends on the traffic load applied over it, the material quality that the pavement is constructed, the environment that the pavement is served, and the design period of the pavement (Huang et al., 2010).

When the thickness of the pavement is not properly designed, the flexible pavement may expose to both surface and structural failures and makes the pavement incapable to sustain the load imposed upon its surface. The distress due to structural failure such as cracking, patching, and potholes occurred at the surface of the wearing course. In turn, these failures cause moisture damage and other serious defects happened as a result of water introduced into the asphalt pavement through the crack opening. So, the total collapse of the pavement occurred. Thus, pavement performance does not mean safe if the mix design and material quality achieved the criteria.

2.3.3. Construction/ Compaction

Compaction is the process used to reduce the volume of a mass of material. For hot mix asphalt (HMA), compaction locks aggregate particles together to provide stability and resistance to deformation while simultaneously reducing the permeability of the mixture and enhancing its

durability (Scherocman & Walker, 2008). A typical requirement at the time of construction is that AC mixes should be compacted to at least 96 percent of the design density. This means that a mix that has been designed to 4 percent void in the mix can have up to 8 percent void in the mix immediately after construction. In the past, some authorities have encouraged a target void in a mix from 3 to 5 percent immediately after compaction and this has resulted in the contractors to increase the bitumen content to achieve the required densities, a practice which dramatically increases the risk of plastic deformation, especially for heavily trafficked roads.

There will be a considerable improvement in durability; if the HMA layer can be compacted to higher densities at the design bitumen content. However, the possibility is dependent on both the availability of effective modern compaction rollers and on the characteristics of the mix. Well compaction during construction is vital because traffic is likely to give very little additional compaction outside of the wheel paths. When the design traffic loads grow on the HMA surface, the mixes should have a higher resistance to rutting.

The well-compacted HMA density indicates the best mechanical performance of the mixture. The major portion of asphalt concrete mixture is occupied by aggregate and consequently, aggregate properties affect the performance of mixture significantly. To achieve the optimum mechanical performance of asphalt mixture, the specimen should have well distributed and representative aggregate structure as exists in field samples. Such a representative aggregate structure can be guaranteed through the proper selection of gradation and compaction procedures.

The compaction is affected by several parameters such as binder grade, binder content, aggregate source, aggregate, texture, aggregate type, aggregate shape, and aggregate gradation, etc. During the compaction, aggregate particles may disintegrate and change aggregate surface area due to the impact of the hammer. Among all the compaction methods used, the Marshall Compaction approach is more susceptible to aggregate degradation.

The aggregate gradation affects HMA performance more than other factors. In general coarser aggregates gradation degraded more as compared to the finer aggregates gradation. The size of the specimen affects the degradation of aggregates. The 6-inch specimens were less affected by

degradation as compared to 4-inch specimens because of the availability of more space for aggregate reorientation.

The type of binder also affects aggregate degradation mainly through OBC. Availability of more lubrication through higher binder content ensures particles are allowed to reorient themselves during compaction. This in turn decreases the aggregate deterioration mechanism. The degradation of aggregates significantly affects the VMA of HMA mixes due to variation of aggregate surface area from the design value (Singh & Swamy, 2017).

During the compaction of HMA, asphalt coated aggregates are connected together, air voids are reduced, and mix density is increased and affects pavement performance takes place. These aggregate squeezing together causes an increase in the surface-to-surface contact and inter particle friction resulting in higher mix stability and pavement strength. The reduction of air voids to the optimum level in the mix produces a pavement that nearly impermeable. In under compacted mix, the voids tend to be interconnected, thereby permitting the intrusion of air and water into the pavement structure and premature pavement distress can then occur.

Water permitting into and through the pavement can lead to the stripping of asphalt binder from the aggregate, the weakening of the base and subgrade soils, or freeze-thaw damage in colder climates. Finally, if an optimal level of compaction is not achieved during construction, subsequent traffic will further densify the mix. This will occur principally in the wheel paths, and the resulting may be a safety hazard for traffic, especially during wet weather. The goal of HMA is to achieve optimum air void content. Behind the paver, the HMA typically has 15 to 20 percent in-place air voids. It is the task of the rollers to reduce the void content to 8 percent or less for dense-graded HMA mixes(Huang et al., 2010).

2.3.4. HMA Mixture Volumetric Properties

HMA is made up of 3 materials; aggregate, asphalt binder, and air. Typically, HMA is described by volume. So, it is important to know how these materials are related to one another with Volume. Even though the volume of each mix component is the controlling factor in the design of asphalt concrete mixes for all the performance, hot mix asphalt mixture components are proportioned by weight for convenience of the workability. The proportions of the different aggregates and filler, the specific gravity of the materials, the amount of bitumen absorbed by

aggregate, and the amount of non-absorbed bitumen are the factors that affect the volume of the mix (School of Engineering, 2018).

When the volume of the ingredients of the mixture is not well quantified, the result will disturb the performance of paving pavement due to improper arrangement of aggregate particles. Thus, the amount of binder content is either too excessive or too low. Pavement Interactive, 2014 Said that basic HMA weight-volume relationships are important to understand for both mix design and construction purposes. Therefore, analysis of the mixture's volumetric properties include Bulk Specific Gravity of the Compacted Asphalt Mixture (G_{mb}), Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures (G_{mm}), air void (V_a), voids filled with asphalt (VFA), voids in mineral aggregate (VMA), absorbed asphalt content (P_{ab}) and effective asphalt pavement (P_{be}) in detail is very important (Tarrer and Wagh, 1991).

A. Bulk Specific Gravity of the Compacted Asphalt Mixture (G_{mb})

The bulk specific gravity of a mixture means the specific gravity of a specimen of compacted mixture, including the air voids within the mixture. It is defined as the ratio of the mass in air of a unit volume to the mass in air of an equal volume of gas-free distilled water at room temperature. It is equivalent to the mass of a given specimen in grams divided by its total volume include air void in cubic centimeters. This value is used to determine the weight per unit volume of the compacted mixture. It is very important to measure G_{mb} as accurately as possible. During determining the G_{mb} value care should be taken not to make any small errors because it is sensitive and the resulted value is affected by a small error significantly.

Bulk specific gravity is highly affected by gradation, fillers, binder, and voids. When the bulk specific gravity increases as the amount of proportional mineral filler increases in the mixture up to some point and then decreases. This is due to an increased amount of mineral fillers will decrease the void in the mix and the greater amount of filler tends to push the larger particles apart and act as lubricating ball-bearings between these larger particles which in turn lower the bulk density, while more binder is required to cover extra filler to fulfill the requirement of asphalt film thickness the amounts added to the mix which is not economical, thus, density must be closely controlled to ensure that the voids keep within an acceptable range. The bulk specific

gravity is determined for each specimen at 25°C following the test procedure described in ASTM D2726 (ERA PDM ,2013 and Nigatu, 2015).

B. Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures (G_{mm})

The theoretical maximum specific gravity is referred to as the maximum theoretical density of HMA excluding air voids. It is also defined as the ratio of the mass of a given volume of void less ($V_a = 0$) HMA at 25°C temperature to a mass of an equal volume of gas-free distilled water at the same temperature (pavement interactive, 2014). Theoretically, if all the air voids were eliminated from the HMA sample, the remaining is aggregate and asphalt binder; these would produce the G_{mm} . G_{mm} is a critical HMA characteristic because it is used to calculate percent air voids in compacted HMA and provide target values for HMA compaction (Nigatu, 2015 and Pavement Interactive, 2015).

C. Air Voids (V_a);

The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture is expressed as a percent of the bulk volume of the compacted paving mixture. Air void content does not include pockets of air within individual aggregate particles, or air contained in microscopic surface voids or capillaries on the surface of the aggregate.

The stability and durability of asphalt concrete highly depend on air voids in a mixture is extremely important to regulate the mixture performance such as rutting and low-temperature cracking. For dense-graded mixes with 12.5 mm nominal maximum aggregate sizes air voids below 3 percent result in an unstable mixture; while air voids above about 8 percent result in a water-permeable mixture. Asphalt content and aggregate gradation should be adjusted to produce design air voids of HMA mix design. Bulk and theoretical maximum specific gravity of mixture are used to calculate air void content (Nigatu, 2015) and (pavement interactive, 2014).

D. Voids in the Mineral Aggregate (VMA)

VMA is the volume of intergranular void space between the aggregate particles of a compacted paving mixture. VMA is the void in aggregate particles occupied by air voids and the effective

asphalt content and expressed as a percent of the total volume of the specimen. In the hot mix asphalt mix design the aggregate gradation should be optimized to provide appropriate VMA.

The Minimum VMA is necessary to achieve an adequate asphalt film thickness, which results in durable asphalt pavement; while aggregate gradation density increases at a point where below minimum VMA values are obtained and that leads to a thin film thickness of the asphalt and a low durability mix. Asphalt content, VMA, and VFA are very important parameters for durability and performance that are closely related to the gradation of aggregates. Aggregate gradation and asphalt mixture performance relation recognized in the development of mix design methods. Gradation is the main factor to limit the VMA in the mix; in turn, VMA and air void in the mix are the main factors on permanent deformation (Banerji et al., 2014) and (Webeshet, 2015).

When the VMA is not well quantified, this will disturb the normal proportion and function of the asphalt concrete. i.e., too low, there is not enough room in the mixture to add sufficient asphalt binder to adequately coat the individual aggregate particles and mixes are more sensitive to small changes in asphalt binder content due to low VMA in the mixture. On the other hand, excessive VMA will cause low stability, low-temperature crack, and an uneconomical mix. Generally, a minimum VMA is specified and a maximum VMA may or may not be specified due to the presence of different asphalt mix types such as stone mastic asphalt, open-graded asphalt, and gap graded asphalt which is required excess VMA (Little et al., 2018) and (Michael, 2017) and (pavement interactive, 2014).

E. Voids Filled with Asphalt (VFA)

Voids filled with asphalt (VFA) are the void spaces that exist between the aggregate particles in the compacted asphalt mixture that are filled with a binder. VFA is expressed as a percentage of the VMA that contains the binder. Maximum levels of VMA and maximum levels of binder content limited by VFA (Little et al., 2018), (Nigatu, 2015) and (School of Engineering, 2018)

F. Effective Asphalt Content (P_{be})

Effective asphalt content is the amount of binder used in HMA to coat the aggregate particles excluding the binder content absorbed by aggregate pores. In other words, it is the portion of

bitumen that coats the outside of the aggregate particles. This governs the performance of the mix. On the other hand, the absorbed bitumen has the effect of changing the specific gravity of the mix (School of Engineering, 2018).

G. The volume of Absorbed Asphalt (P_{ab})

The volume of asphalt binder in the HMA that has been absorbed into the pore structure of the aggregate is called absorbed asphalt. It is the volume of the asphalt binder in the HMA that is not accounted for the effective asphalt content. Any bitumen that is absorbed into the aggregate particles does not play a role in the performance characteristics of the mix. The amount of the absorbed asphalt binder depends on the properties of aggregates such as type and quality. That means the aggregate particles used in hot mix asphalt mix design have a large quantity of pores and this is a cause to absorb excess binder content. Thus, the absorbed bitumen content in turn affects the performance of the mixture by reducing the bitumen content, asphalt film thickness, and produces uneconomical mixes (AASHTO, 2013), (University of Arkansas, 2020) and (pavement interactive, 2014).

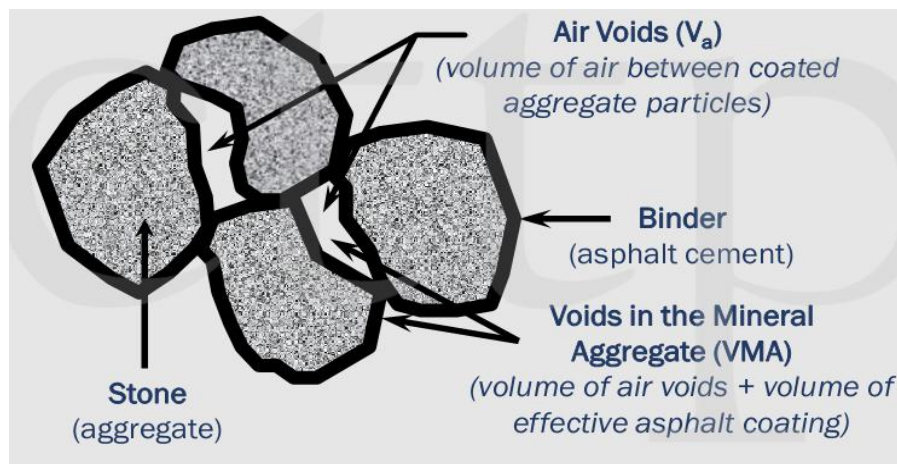


Figure 2: 2 Mixture component materials arrangement

2.4. Aggregate Properties and Performance

Physical, mechanical, and chemical properties of aggregates characterize assist the material engineer to evaluate the different aggregates used in road construction. Aggregate particles have certain physical and chemical properties that make the aggregate acceptable or unacceptable for specific uses and conditions.

The properties of the aggregates used in asphalt concrete are generally associated with asphalt mixture performances. Proper aggregate selection is necessary to attain the desired performance of the asphalt mixture. Most of the pavement distress is directly related to improper aggregate selection based on quality and gradation for the proposed project.

Aggregate properties can affect asphalt mix properties in different ways. The aggregate should be strong, sound, and durable. For asphalt mixture to be durable, the aggregates must be resistant to degradation during production and under traffic loading. In other ways, the aggregates used for hot mix asphalt mixtures are weak, and they may disintegrate easily under the action of different loads during construction, compaction, and over the service life. As a result, fines and filler content in the mix may increase and disturb the design gradation. This effect exposes to the pavement defects such as resistance to permanent deformation, raveling, stripping, and cracking due to the deficiency of bitumen content. Due to this, the broken aggregates produce the additional surface area and the additional surface area requires additional binder content to keep the hot mix asphalt pavement to have good bondage (Tessema & Ponnurangam). Clay particles are also undesirable in asphalt concrete mixtures because clay particles decrease the bond between the asphalt binder and the aggregate resulting in the potential for moisture damage.

The aggregate tests were developed to characterize an aggregate empirically that may have strong relationships with the pavement performance of the final product (Kandhal & Parker, 1998). Aggregates are characterized by tests such as gradation test, flakiness index, durability, soundness; percent crushed particles of aggregates, unit weight, absorption, and voids. As to many ASTM and AASHTO index tests, ERA, 2013 also characterizes the qualities of aggregates needed for HMA mixtures; they measure size and gradation, aggregate cleanliness, toughness/hardness, durability soundness, surface texture, particle shape, absorption, and affinity for asphalt (Kandhal & Parker, 1998; Tessema & Ponnurangam).

2.4.1. Physical/Mechanical Properties of Aggregate

The physical properties of aggregates refer to the physical structure of aggregate; while mechanical properties of aggregate refer to the ability and mechanism of aggregate give repose to loads applied on it. Aggregates can be classified into coarse, fine, and filler based on their size. They can be defined as i) coarse aggregates are those retained on the sieve No. 4 (4.75 mm) (ASTM D692); ii) Fine aggregates are those passing through the sieve No. 4 (4.75 mm) (ASTM

1073) and retained on .075mm sieve size and iii) Fillers are those materials of which pass through the sieve No. 200 (0.075 mm) (ASTM D242) (Aragão, 2007).

Aggregate suitability to asphalt mixtures is dependent on its mechanical and physical properties. In Ethiopia, the aggregates for asphalt mixture production are selected to satisfy the requirements of ERA specification (Bulevičius, Petkevičius, Žilionienė, & Drozdova, 2010). The required aggregate qualities are described in terms of shape, hardness, durability, cleanliness, bitumen affinity, and porosity. In addition to these properties, the micro-texture of the aggregate particles will also strongly influence the performance of the compacted HMA layer. Smooth-surfaced river gravel, even partly crushed, may not generate as much internal friction as a crushed aggregate. However, Tarrer and Wagh (1991) states that laboratory tests indicate that stripping is more severe when angular aggregates are used. This phenomenon is believed to be related to the increased potential for film rupture provided by angular aggregates.

The physical properties of aggregates used for wearing courses have a direct correlation to the performance of the asphalt mixture. The aggregate should be angular and not excessively flaky, to provide good mechanical interlock. Hot Mix Asphalt (HMA) stiffness, fatigue response, shear resistance, and permanent deformation are some forms of distresses that are influenced by aggregate property. Several methods have been used to identify physical properties either achieved or not (Ofori-Abebresse & Martin, 2006) and (ERA,2013).

A. Cleanness

It is important to have clean aggregates used in the production of asphalt mixtures. When clean aggregates are contaminated with organic or inorganic materials which cause to most deleterious impact on the overall quality of the mixture it negatively affects the mixture produced. Aggregates should be clean from excess dust to prevent asphalt coats with dust. When the dust is increased in the mixture, it may tend to be slightly stiffer and low-temperature cracking compared to the design. Washing contaminated aggregate by dust with water is an effective remedial action to remove the dust and make the aggregate clean. Thus, the aggregate produced from basaltic stone free from this problem.

B. Toughness,

Toughness refers to the ability of the aggregate particles to resist fracture under the action of loads during construction and service life; while Hardness refers to the ability of the aggregate to retain its surface texture for a long time when subjected to wear. Aggregate particles shift and pack themselves by interlocking with each other under the action of the compaction. During this moment, the binder is in a fluid state and unable to resist any deformation. Soft aggregates that do not possess adequate toughness will fracture during placement and compaction. This affects the overall aggregate gradation and mixture properties.

There are several different empirical tests by which the toughness of aggregate particles can be measured. Some of the more common tests are the LA abrasion test and the aggregate crushing value tests.

C. Hardness

The hardness of aggregates refers to the ability of the aggregates to resist abrasion and retain their surface texture. This property is particularly important for aggregates that are used in surface mixes. The surface of the aggregate plays an important role in providing frictional resistance between the tire and the pavement surface when the aggregates are hard enough. However, over time the surface of the aggregate may be susceptible to abrasion cause to lose its surface texture. Aggregates with higher hardness are more resistant to this abrasive action and tend to retain their surface texture longer and consequently provide a safe and skid-resistant driving surface for a longer period of time. The test that is used to measure aggregate hardness is very similar to the LA impact test with two exceptions. First, the size of the drum used is much smaller. Second, the steel spheres were used as a charge is also lighter in weight and smaller.

D. Durability

Durability refers to the ability of the aggregate to resist breakage due to freeze-thaw action. The dark-colored aggregate particles are igneous in origin, whereas the light-colored aggregate particles are a soft porous limestone with low durability. The use of a porous aggregate with low durability and the freeze-thaw action may result in fracture or disintegration of the aggregate particles into several smaller pieces on the surface of the pavement. This may further lead to aggregate loss and also gradually progress into further deterioration and degradation of the pavement structure. The durability of aggregates can be measured using a few different test

methods such as the sodium sulfate or magnesium sulfate soundness test or a simple freeze-thaw test. The sodium or magnesium sulfate soundness tests simulate the freeze-thaw process that the aggregate may experience in an accelerated manner.

E. Shape, angularity, and texture

Shape, angularity, and texture of aggregates, refer to three geometrical characteristics of the aggregate particles. These aggregate characteristics control different aspects of the overall performance of asphalt mixtures. The aggregate particles that have a flat and elongated form tend to orient themselves so that the smaller dimension is along the direction of compaction. This is called the preferred orientation of aggregates with a flat or elongated form. As a result of this preferred orientation, flat and elongated particles are exposing to fracture during compaction that induces very high stresses in the aggregate particles. This in turn reduces the integrity and mechanical stability of the asphalt mixture. The aggregate structure consisting of roughly textured and more angular particles results in systems that more efficiently distribute traffic loads and are less prone to rutting during service. The importance of using angular aggregates is to ensure adequate mixture resistance to shear deformation (Aragão, 2007; Brown et al., 2009; Little et al., 2018; Maharjan et al., 2017).

Table 2. 1 Specifications of aggregates for the surface course for different sources

Property	Test	ERA	UK (1994)	South Africa Manual
Cleanliness (%)	Sedimentation	<5	>40(se)	>35(se)
Particle shape (%)	Flakiness index	<45	<35	<40
ACV (%)	Ten percent fine value	<25	<25	<25
AIV (%)	Aggregate impact test	<25	<25	<25
Abrasion (%)	Los Angeles Abrasion	<30	<30	<30
Polishing (%)	Polishing stone value	50-70	>45	>50
Water absorption (%)	Water absorption	<2	<2	<1
Durability (%)	Soundness test	12-18	13-17.5	<12
Bitumen affinity (%)	Coating and stripping	>95	>95	>95

2.4.2. Aggregate Gradation

Engineers have control over the appropriate aggregate properties to select for the mix design of the HMA mixture. One of these properties is the selection of aggregate gradation. The aggregate gradation in turn indicates the aggregate structure and the ability of the aggregate structure to distribute stresses and transfer loads.

Super pave introduced the restricted zone to the aggregate gradation. The aggregate gradation is classified as above and below the restricted zone. Now, the classification for aggregate gradation is coarse-graded and fine-graded. A gradation below the restricted zone was encouraged to have better shear resistance provided by the coarse aggregate skeleton (Institute, 1996). The coarse gradation also produced the lowest tensile strength, whereas, the fine gradation generally exhibited the highest value. Air void content had a more sensitive influence on the tensile strength than that of gradation variation (Zhao, 2011).

For the construction of asphalt pavement layers, the maximum aggregate size selected is typically one-third the thickness of the pavement layer. The term "maximum aggregate size" is somewhat ambiguous. Some states in the USA define maximum aggregate size as the smallest sieve size through which 100% of the aggregates pass and nominal maximum aggregate size as the next smaller sieve size. The Superpave mix design method refers to the nominal maximum aggregate size is one sieve size larger than the first sieve to retain more than 10% of the aggregates (Little et al., 2018).

Depending on the mixture's nominal maximum aggregate size (NMAS), a primary control sieve (PCS) is determined for the aggregate mixture. A combined aggregate gradation passing below the PCS is comprised primarily of coarse aggregate and is classified as coarse-graded; if the gradation curve passes above the PCS, it is classified as fine-graded (Bonaquist, 2016).

Table 2. 2 Classification of dense-graded mix-based percent passing in control sieve

Sieve size	Control sieve (mm)	Coarser dense-graded	Finer dense-graded
NMAS (mm)		Percent passing	Percent passing
37.5	4.75	<35	>35
25	4.75	<40	>40
19	2.36	<35	>35
12.5	2.36	<40	>40
9.5	2.36	<45	>45

The gradation defines as the internal aggregate structure of the asphalt mixture. On the other hand, Aragao (2007) mentioned that gradation is defined as the distribution of particle sizes expressed as a percent of the total weight. The gradation of aggregates can be also classified as dense-graded or continuous graded, Open-graded, and Gap-graded (Little et al., 2018).

This study involves a dense-graded design of wearing course. To say the aggregate gradation is best for the mix, the mix should give the highest density. When fine particles are properly packed between coarser particles, the voids space between the particles reduces and the gradation becomes best. OBC is minimum for coarser gradation and maximum for finer grade i.e., OBC is increasing from lower to upper grade within the gradation range. Thus, a lower gradation limit is more economical in terms of bitumen content. Since OBC increases from lower to upper grade, it can be concluded that finer grading aggregates require more bitumen than that of the coarse grading aggregates (Maharjan et al., 2017).

The effect of gradation of aggregates has many ambiguous and contradictory ideas on hot mix asphalt performance. The result of (Sangsefidi et al., 2016) research indicates that the lower, middle and upper limit of mixture gradations demonstrate better performance in decreasing order, so it is predicted that a gradation coarser than a lower gradation limit (outside the considered band) may produce a better result. It is also believed that the conventional method to select aggregate gradation (using pre-specified bands) is not meaningful, in other words, the

gradation specification requirement is redundant for mixes. So the authors suggest a "free design" to select the aggregate skeleton (Sangsefidi et al., 2016). The study Nigatu, 2015 also indicates that a larger proportion of coarse aggregate with the same nominal maximum aggregate size compared to medium gradation did not show a significant effect on permanent deformation of asphalt mixture.

Analysis conducted by the Strategic Highway Research Program (SHRP) showed that aggregate gradation and properties are among the main factors that influence the stability of hot mix asphalt (HMA). According to the SHRP study outputs, the properties that contribute to rutting to some extent for asphalt concrete (AC) are coarse aggregate size and shape properties (Nigatu, 2015). Also, researchers (Vivar & Haddock, 2006) concluded that gradations that pass below the maximum density line (MDL) are more permeable than gradations that pass above the MDL.

2.4.3. Aggregate Surface Area

The ASA is one of the most important factors of gradation which has a significant impact on the amount of bitumen required to coat aggregates and VMA. Aggregate gradations that shift above the maximum density line are defined as "fine" while those that shift below the maximum density line are "coarse". An analysis for surface area indicates that particle diameter decreases the surface area per unit mass increases.

The aggregate gradation and "surface area factor" are the key factors to determine the surface area and compute the asphalt film thickness. Asphalt film thickness is an important factor in expressing the behavior of the HMA mixture. The outcomes of surface area and asphalt film thickness were determined using gradation and surface area factors presented in the table (Sangsefidi et al., 2016).

Table 2. 3 Surface area factor

Sieve size(mm)	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
SAF(m ² /kg)	0.4	0.4	0.4	0.4	0.82	1.64	2.87	6.14	12.29	32.77

The blend of aggregates employed in the mix is used to calculate the surface area of aggregate. This calculation consists of multiplying the total percent passing each sieve size by a “surface-area factor”. The Sum of these products will represent the surface area of the sample in terms of square meters per kilogram (m^2/kg). It is important to note that all the surface-area factors must be used in the calculation.

$$SA = \sum_{n=1}^n (Saf, n. PNo.) \quad 2.2$$

Where SA =is the surface area in m^2/kg

Saf, n. =is the surface area factor for sieve number n. and

PNo.=is the percentage passing by weight that sieve

The aggregate gradation is directly related to the optimum asphalt content. For finer mix gradation, the total aggregate surface area is higher and consequently increases the amount of bitumen content required to satisfy the asphalt film thickness coated on the surface of the aggregate particles. On the other hand, coarser mixes have less total aggregate surface area and require less amount of bitumen. Minimum VMA is necessary to achieve an adequate asphalt film thickness, which results in durable asphalt pavement, as increasing the density of the aggregate gradation to a point where below minimum VMA values are obtained leads to the thin-film thickness of the asphalt and a low durability mix (Banerji et al., 2014; Sangsefidi, Ziari, & Sangsefidi, 2015)and (Nigatu, 2015).

These surface-areas are used to calculate an average film thickness using the volume of asphalt binder in the mix. This determination of asphalt film thickness can provide an indicator of mix durability. The Asphalt Institute strongly recommends comparing this calculated value with specific mix design criteria (Mark Buncher, Mike Anderson, 2014).

HMA durability is related to Air voids and the asphalt binder film thickness around each aggregate particle. If the film thickness surrounding the aggregate particles is insufficient and the aggregate is hydrophilic, the aggregate may become accessible to water through holes in the film and this water will displace the asphalt film and asphalt-aggregate adhesion will be damaged.

This process is typically referred to as stripping. The optimum asphalt binder content as determined by mix design should provide adequate film thickness.

Mix durability is also affected by excessive air void increase in HMA that allows more asphalt binder to oxidation and volatilization. To address this, HMA mix design needs to adjust asphalt content and aggregate gradation to produce design air voids of about 4 percent. Excessive air voids can be either a mix design or a construction problem (Banerji et al., 2014; Maharjan et al., 2017; Sangsefidi et al., 2015), (ERA, 2013) and (pavement Interactive, 2007).

2.5. Moisture Damage

Moisture damage can be defined as the progressive deterioration of asphalt mixes by loss of adhesion and cohesion bondage between aggregate and asphalt binder and alone in asphalt binder respectively due to the action of water. Moisture damage often disturbs the normal integrity of the hot mix asphalt mix orientations. As a result, it can reduce pavement performance by accelerating all distress modes including fatigue cracking, permanent deformation (rutting), and thermal cracking occurring in the asphalt concrete. This also causes rutting in the unbound material layers due to the reduced load-carrying capacity of asphalt concrete layers (Dave & Koktan, 2011; Hefer, 2005; Little et al., 2018; Lu, 2005) and (Pavement Interactive, 2015).

Sometimes, moisture may only simply weaken the asphalt mix by softening or partially emulsifying the asphalt film without removing it from aggregate surfaces while the pavement not under the effect of loading. At this condition, the effects like loss of stiffness or strength are reversible when water is removed from the mix. But moisture damage occurred when the pavement is under the effect of load during the weakened condition; damage is accelerated and may become irreversible (Lu, 2005). On the other said, (Dave & Koktan, 2011) states that, in asphalt mixtures, moisture damage is defined as the loss of stiffness and strength due to moisture exposure under mechanical loading and the phenomenon referred to as stripping.

Moisture damage is a widespread problem in the world and it generally starts at the bottom of an asphalt layer or the position where water content is the highest. Moisture damage is the major cause of premature pavement failure which causes loss of the performance and service life of the asphalt pavement (Sangsefidi et al., 2016).

But moisture damage resistance does not degrade essentially due to moisture penetration into the mix alone. Moisture damage resistance is related to aggregate mineral and chemical properties, air voids, asphalt binder content, and aggregate gradation. Some aggregates (hydrophilic aggregates) attract moisture into their surfaces, which can cause stripping. To address this, either stripping-susceptible aggregates can be avoided or an anti-stripping asphalt binder modifier can be used. When in HMA air voids exceed about 8 percent that allows water to easily penetrate the HMA and cause moisture damage through pore pressure or ice expansion. To overcome this problem, HMA mix design properly quantifies asphalt binder content and aggregate gradation to produce design air voids of about 4 percent. The cause of excessive air voids is either a mix design or a construction problem (Vivar & Haddock, 2006) and (pavement Interactive, 2007).

2.5.1. Causes of Moisture Damage

Moisture susceptibility is a complex phenomenon due to different mechanisms of failure. Moisture can degrade the integrity of the HMA bond by three mechanisms. These are; Loss of cohesion within the asphalt binder, an adhesive failure between aggregate and asphalt, and degradation of the aggregates (Moraes, Velasquez, & Bahia, 2017) and (Asphalt Institute, 2007).

There are different ideas and theories about the adhesion bond between the asphalt binder and aggregate particles. The mechanical theory states that the bonding of asphalt aggregate is affected by the physical properties of the aggregate such as porosity, texture, and surface area. The chemical theory suggests that adhesion depends on the PH and the functional groups of both the asphalt binder and aggregate. On the other hand, the weak boundary theory suggests that rupture always occurs at the weakest region of the asphalt aggregate interface. Finally, the thermodynamic theory evaluates the compatibility between asphalt-aggregate-water is due to differences in their surface energies. These theories and associated mechanisms are not exclusively independent and many researchers agree that a combination of mechanisms takes place in asphalt mixes. Thus, moisture damage is a very complex problem (Moraes et al., 2017).

The resistance of asphalt mixtures to moisture attack depends on aggregate mineralogy, the tension between the asphalt binder and the aggregate, chemical composition of the asphalt binder, binder viscosity, surface texture of the aggregate, aggregate porosity, aggregate cleanliness, and the compatibility between bitumen and aggregate. In addition to this the permeability of the asphalt mixtures, rate and amount of water absorption of the aggregates, and

volumetric properties of the binder are all important when considering the susceptibility of asphalt mixture. These factors summarized under poor construction practice, poor drainage and composite materials quality include a binder and aggregate properties (Abo-Qudais & Al-Shweily, 2007; Zhang, Apeagyei, Airey, & Grenfell, 2015).

2.5.1.1. Effect of Binder Property on Moisture Damage

Bitumen constituents are classified into saturates aromatics, resins, and asphaltenes. Saturates are non-polar viscous oils with the fraction forms 5–20% of bitumen. Aromatics are viscous liquids and non-polar carbon chains constitute 40-65% of the total bitumen. Resins are solid or semi-solid and strongly adhesive. Asphaltenes are insoluble amorphous solids that have a significant effect on the rheology property of the bitumen. In addition to carbon and hydrogen, some nitrogen, sulfur, and oxygen atoms are present. In the bitumen the asphaltene increase in the bitumen largely hardness and more viscous property occurred in the binder. Asphaltenes constitute 5 – 25% of the bitumen (Michael, 2017).

Viscosity is important because it may indicate higher concentrations of asphaltenes (large polar molecules). Polar molecules can create greater adhesion tension and molecular orientation adhesion. Asphalt's viscosity increases when the asphaltenes concentration is higher, while lower viscosities represent lower concentrations of asphaltenes is generally more susceptible to stripping. Individual components in asphalt binder such as sulfoxides, carboxylic acids, phenols, and nitrogen bases can also affect stripping potential in increasing order (Pavement Interactive, 2015).

Asphalt chemistry, asphalt rheology, aggregate surface chemistry, and physical properties play important roles in moisture damage of aggregate-asphalt adhesion problem. In the presence of water; the adhesion property is degraded and displaced by water. Most of the aggregates used in road construction have an acidic property and possess a weak negative charge on the surface that causes to form weak adhesion bond between asphalt binder and aggregate surface. On the other hand, it forms a strong bond with water better than the asphalt binder. This means water is highly polar and hence it gets strongly attached to the aggregate displacing the bituminous coating (Behiry, 2013; Kanitpong & Bahia, 2003; Vishal, Goli, & Chowdary) and (Michael, 2017).

2.5.1.2. Effect of Aggregate Property on Moisture Damage

The nature of asphalt coatings on a given aggregate is related to its mineralogical and chemical composition. The substances that have been retained on the surface of aggregates include clay, silt, calcium carbonate, iron oxides, gypsum, manganic ferrous substances, soluble phosphates, dusts from crushing, ferruginous coatings, oil, fatty acids, oxygen, and water. These substances make the aggregates either hydrophilic or hydrophobic. The aggregate used for road construction should be hydrophobic or use an anti-stripping asphalt binder modifier. The acidic (hydrophilic) aggregate surfaces are more susceptible to stripping.

Moisture damage resistance is related to aggregate mineral and chemical properties. Siliceous aggregate sources are exposing to stripping due to a high silica dioxide component. The asphalt binder does not make a good bond with this type of aggregate. Some aggregates such as granite, gravel, and other siliceous type materials are sensitive to moisture and are exposing to stripping in asphalt concrete, while limestone is less susceptible to moisture damage. The weakening of the asphalt cohesion occurs in the presence of moisture; because asphalts are hydrophilic. Asphalt has an affinity for water greater than that of the aggregates. Thus, water will replace the asphalt binder and weakens the structure of the asphalt concrete (Abo-Qudais & Al-Shweily, 2007; Bausano & Williams, 2009; Huang et al., 2010; Vishal et al.).

The aggregate contains the property of iron, magnesium, and calcium is considered as beneficial to resist the moisture damage while sodium and potassium are considered as cause for the stripping. Also, the aggregate surface consists of clay, silt, dust from crushing, and water are detrimental factors with regard to the susceptibility of an aggregate to stripping; whereas ferruginous coatings, oil, and fatty acids have been found to beneficial (Tarrer & Wagh, 1991) and (Pavement Interactive, 2015).

The magnitude of the work of deboning in the presence of water was found to be aggregate type dependent. Sometimes a newly crushed aggregate exhibits a poor stripping resistance as compared to the same stockpiled aggregate for some period of time. When aggregate stoke the surface adsorbed water molecules may become partially replaced or covered by organic compounds present in the air, such as fatty acids and oils. This is used to reduce the stripping potential by reduces the free radicals, and reactive sites on the aggregate surface (Liu, Apeagyei, Ahmad, Grenfell, & Airey, 2014; Moraes et al., 2017) and (Asphalt Institute, 2007).

2.5.2. Mechanism of Moisture Damage

A bituminous mixture derives its strength from the cohesion strength of the binder and grain interlock and frictional resistance of the aggregate. When the bond between aggregate and binder is strong, the hot mix asphalt mixture failure occurs within the binder or in cohesion failure. However, if the bond between asphalt binders is poor, the failure may occur at the binder-aggregate interface and may result in premature failure of the mix (Tarrer & Wagh, 1991). To understand the failure mechanism of adhesion and cohesion bonds, it is necessary having awareness about the principles of asphalt binder and aggregate adhesion bond formation mechanism.

Mechanical, asphalt binder contacts into the aggregate irregular surfaces and pores of the aggregate and hardens due to a mechanical lock. The asphalt binder penetration into the aggregate and the mechanical lock existing between the aggregate surface and asphalt binder decreases due to the moisture contact in the aggregate surface.

Chemical, chemical adhesion formed due to chemical reaction between the asphalt binder and aggregate surface. Aggregates that have acidic surfaces do not react as strongly with asphalt binders. This weaker reaction develops a weak bond and the developed bond is not strong enough to resist moisture damage. This weak reaction occurred when the aggregate is acidic on the surface weak van der Waals force may be formed between the aggregate acidic functional group and a carboxylic acid functional group founded in the binder. The strong bonds such as a covalent bond, ionic bond, and hydrogen bond developed between acidic and basic materials (Hefer, 2005).

Adhesion tension: - is the tension between the asphalt binder and aggregate at the wetting line is less than the tension between water and aggregate. Therefore, if all three are in contact, water will tend to displace the asphalt binder. This can result in a poor coating of the aggregate surface by the asphalt binder and lead to stripping. This interfacial tension between asphalt binder and aggregate depend on asphalt binder, aggregate type, and aggregate surface roughness.

Molecular orientation: -When bitumen mixes with aggregate, asphalt molecules tend to orient themselves by basically consider the ions on the aggregate surface. Water molecules are more polar than asphalt binder molecules. So, water may satisfy the energy demands of the aggregate

surface while binder has low polar and it allows weak asphalt binder-aggregate bond can result in stripping (Asphalt Institute, 2007).

The objective of asphalt concrete mixes is to coat all aggregate surfaces with a film of asphalt to form a cemented composite material. Loss of cohesion within the asphalt binder, an adhesive failure between aggregate and asphalt, and degradation of the aggregates are three mechanisms of moisture that can degrade an asphalt mixture performance (Dave & Koktan, 2011). The attraction bond between asphalt films and aggregate surfaces is defined as an adhesion bond and Water can destroy this bond by five different mechanisms of stripping. These are detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scouring. These mechanisms are explained below in detail.

Detachment; Detachment is the separation of an asphalt film from an aggregate surface by a thin layer of water. Stripping occurred by detachment and the asphalt can be peeled from the aggregate. This shows a complete loss of adhesion. The surface tension of water is much lower than that of asphalt. Most aggregates have electrically charged surfaces. Asphalt is composed of a high molecular weight of hydrocarbons and has low polarity than water. Water molecules are highly polar and attracted to aggregates by strong forces.

Displacement; Stripping by displacement occurred by penetration of water into the aggregate surface through a break in the asphalt film. The break can appear due to incomplete coating of the aggregate or by asphalt film break suddenly. Because the asphalt film is generally thinner and under tension, the asphalt film breaks suddenly by the sharp edges and corners of angular aggregate. When asphalt coats a dusty aggregate, a thin hole appears in the asphalt film. Thus, stripping by displacement is occurred between asphalt binder and aggregate surface

The chemical composition of asphalt and aggregate may form chemical bonding, such as covalent bonds. When water comes into contact with aggregate surfaces, a series of hydrolysis reaction and slow decomposition processes begin. Those reactions affect the type of polar groups hold by aggregates by altering the pH of the microscopic water accumulations at the aggregate surface can alter the type of polar groups on the aggregate surface and that leads to the build-up of negatively-charged on the aggregate and asphalt interface. Thus, materials attract more water and lead to the physical separation of the asphalt from the aggregate.

Spontaneous Emulsification; Spontaneous emulsification is the reverse emulsion of water droplets in asphalt cement. Emulsions are aggravated by the presence of emulsifiers such as clays and asphalt additives. Spontaneous emulsification occurs when asphalt films are immersed in water and that the rate of emulsification depends on the nature of the asphalt and the presence of additives. Organic amines, which are basic nitrogen compounds, binds strongly to aggregates in the presence of water, and the rate of emulsification is dependent on the nature and viscosity of asphalt

Hydraulic Scouring; Hydraulic scouring is one of the mechanisms of stripping that commonly occurs only on surface courses. The stripping due to hydraulic scouring results from the action of vehicle load on a saturated pavement surface. When the load has pressed the water down into the pavement in front of the vehicle and sucked after the load leaves the pavement that causes to strip of the asphalt film from the aggregate due to compression tension cycle.

Pore Pressure; Pore pressure developed in water can lead to distress. Stresses induced in water occurred due to repeated traffic load applications will increase the pore pressure on the asphalt film from the aggregate surface and also can cause micro-cracks in the asphalt mastic (Little et al., 2018; Lu, 2005; Moraes et al., 2017; Tarrer & Wagh, 1991).

2.5.3. Effect of Moisture Damage on HMA Performance

Moisture-induced damage gradually reduces the overall functionality of asphalt mixtures due to the loss of the adhesive bond between the aggregate surface and the asphalt binder. Characterization of moisture-induced damage is a challenging task. Because it represents the combined effect of various chemical, physical, and mechanical processes that occur simultaneously at different intensities and rates (Caro, Masad, Bhasin, & Little, 2010; Liu et al., 2014).

A general definition of stripping is "the breaking of the adhesive bond between the aggregate surface and the asphalt binder" in asphalt pavement. Stripping depends on many variables, such as asphalt characteristics, aggregate characteristics, environment, traffic, construction practice, and the use of anti-strip additives. However, the presence of moisture at the aggregate/asphalt interface is a common factor to all stripping related problem (Tarrer & Wagh, 1991). The other researcher Zhao (2011) states that stripping that occurred on the pavement surface includes

various premature problems such as fatigue cracking, rutting, raveling, shoving, and potholes. It is one of the most serious problems concerning pavement performance. When aggregates are acidic and have an affinity for water over asphalt, the mix suffers from stripping.

The direct result of the moisture effect is weakening or loss of bond strength within asphalt mixes. It has been recognized that moisture can influence the physical and mechanical properties of bituminous paving mixtures. According to Liu et al (2014), asphalt pavement defects such as fatigue cracking, rutting, raveling, and bleeding are due to moisture damage. When the shear stress due to wheel loading is high and the mix is moisture sensitive, rutting on the asphalt concrete mainly occurs in the surface layer. Loss of cohesion in the binder due to water reduces the shear strength of asphalt concrete and accelerates the development of rutting and may also promote top to down cracking. The lower portion of the asphalt layer often accumulates moisture for a long period because of the slow rate of evaporation through the surface layers. This portion is in tension under the traffic loading. This stress state accelerates the degradation of the adhesion and cohesion within the asphalt-aggregate composition and contributes to the development of bottom-up fatigue cracks.

Raveling occurs at the pavement surface. When the traffic is applied on the surface layer, it produces the non-uniform vertical stresses and the horizontal forces, and that causes to generate horizontal tensile stresses. The pavement must resist the tension force which developed at the bottom of the wearing course, to protect from the failures and to increase the performance of the pavement. However, the pavement resistance from the tensile stress, water progressively reduces the tensile strength of the surface mixture so that cracks and disintegration will occur under repeated traffic loading. Moisture damage typically first occurs at the bottom of asphalt concrete layers or at the interface of two surface layers, gradually developed upward (Lu, 2005).

Damage caused by moisture such as stripping, rutting, raveling, and fatigue cracking contributes to failure in bituminous pavements. When the degree of saturation increases, the modulus of resilience, indirect tensile strength, and fatigue life is decreased (Behiry, 2013). The fatigue life of an HMA mixture appears to be more sensitive to moisture than to air voids content (Vivar & Haddock, 2006). Fatigue cracking is often associated with loads. But the problem is often made worse by moisture drainage. Fatigue cracking can lead to the development of potholes (Asphalt Institute, 2007). Moisture sensitivity in asphalt mixture depends on the individual asphalt

components, loose asphalt mixtures, and asphalt mixtures pavement performance (Liu et al., 2014).

2.5.4. Preventive Measure of Moisture Damage

The moisture damage is a serious problem for asphalt pavement. So, different measures should be taken to prevent or minimize the pavement distress that helps to save the country's economy which needs to reconstruct and maintain damaged road pavement. Various measures of material selection, proper construction practice, pavement design, and HMA anti-strapping additives are taken to improve the moisture resistance of the asphalt pavement.

Aggregate selection means choose low porosity, rough and clean aggregate. Moisture penetration into the HMA pavement and permeability of the pavement structure can prevent by regulating air void content, lift thickness, and gradation. Aggregate surface properties treat with a chemical and lime to replace ions that are likely to contribute to poor asphalt binder-aggregate adhesion.

Chemicals used for this technique used to reduce surface tension in the asphalt binder to promote better coating and impart an electrical charge to the asphalt binder that is opposite that of the aggregate surface charge. Most chemicals used for this purpose contain amines with amount about 0.1 to 1.0 percent by weight of asphalt binder. Chemical additives are added to the asphalt binder or to the aggregate before mixing is done. Adding Chemical additives into the aggregate surface is better than adding into asphalt binder to prevent waste chemicals to reach the critical asphalt binder-aggregate interface and that used to make entire additive is on the aggregate surface.

Lime is mostly added at about 1.0 to 1.5 percent by total aggregate weight to the aggregate to improve the HMA moisture resistance. The purpose of the addition of Lime into the hot mix asphalt is used to replace negative ions on an aggregate surface with positive calcium ions. This is used to prevent the hydrophilic property of aggregate and improve the bondage between asphalt binder and aggregate adhesion. Lime also reacts with molecules include in asphalt binder (carboxylic acid) and in aggregate (acidic OH groups) that results in the molecules are absorbed on the aggregate surface or molecules that are low to dissociate and associate with water molecules (Kanitpong & Bahia, 2003) and (Pavement Interactive, 2015).

A number of treatments were carried out on asphalt mixes, including filler replacement by Portland cement, aggregate coating by Portland cement, use of limestone aggregates, proper mix design of gradation, asphalt film thickness, and air voids (Behiry, 2013) and (Nigatu, 2015). Limestone aggregates also have better bonding properties compared with granite aggregates. Limestone aggregates are generally hydrophobic and have higher affinity for bitumen than water, while granite is hydrophilic and contains high silica and alumina content. Consequently, asphalt mixtures containing granite aggregates are more likely to strip than limestone aggregates (Liu et al., 2014).

2.5.5. Moisture Susceptibility Test

Moisture susceptibility tests quantify an HMA mixture's ability to resist moisture damage rather than measure individual factors. They are typically capable of providing gross results or comparative results and are not able to predict the degree of moisture damage. These tests can be generally divided into two tests: tests for loose bitumen-coated aggregate mixtures and tests for compacted asphalt mixtures (Liu et al., 2014). The tests for moisture susceptibility are Boiling test (ASTM D 3625), Static-immersion test (AASHTOT 182), Lottman test, Tunnicià, and Root conditioning, Modified Lottman (AASHTO T 283), Immersion-compression (AASHTO T 165), and Hamburg wheel-tracking device. Among these tests Boiling Test (ASTM D 3625) for loose mix and Modified Lottman (AASHTO T 283) for compacted mix are used to measure the resistance of moisture damage (Hefer, 2005; Liu et al., 2014) and (Pavement Interactive, 2015).

2.5.5.1. Boiling Water Test

This test performed at least 100g of loose HMA is added to boiling water to measure the percentage of the total visible area of the aggregate surface that retains its asphalt binder coating after conditioning. The test is simple and subjective, but does not involve any strength determination and is used to compare the two sets of specimens to see the effect of the experimental group from the control group. The mixture was boiled for 10 min. The percentage of the total visible area of the aggregate that retained its original coating of bitumen was used as an estimate of moisture damage (Liu et al., 2014).

In the loose mix test, the results are mostly qualitative, and the interpretation of results becomes a subjective matter depending on the evaluator's experience and judgment. Loose mixture tests

are used for comparison between different aggregate asphalt mixtures in terms of compatibility, the strength of adhesion, and stripping. Tests in the second category are conducted on laboratory compacted specimens. The results can be measured quantitatively, which minimizes the subjective evaluation of test results. But these test results show the mechanism of moisture damage in HMA (Sangsefidi et al., 2016).

2.5.5.2. Modified Lottman (AASHTO T 283)

This test method is done by the combination of the Lottman and Tunnicliffe and Root tests. It compares the indirect tensile strength of unconditioned specimens to samples partially saturated using water. The test conditioned group with partial vacuum saturation and an optional freeze-thaw cycle. Although it is expected that the water conditioned samples will have a lower tensile strength, excessively low values indicate the potential for moisture damage.

ITS test required a minimum of six test specimens are compacted to a 7 ± 0.5 percentage of air voids to simulate the expected in-place air void percentage. The compacted specimens are then separated into the control subset and condition subset. It is particularly important to assure that the two sets have equivalent average air void contents. And the specimen was compacted with 50 blows to achieve 7 ± 0.5 % (Mark Buncher, Mike Anderson, 2014).

Marshall specimens are prepared by using the standard Marshall hummer with 50 blows on either side. The specimens are soaking in the vacuum saturation apparatus. When the samples are conditioned, the air voids are filled with water, and saturation level is different on many factors such as conditioning time, type of material, and bitumen content. The stripping resistance reduces by about 19–40% with increasing the degree of saturation from 50% to 80% respectively. The AASHTO T-283 was used in this test where the tensile strength ratio (TSR) value less than 70% was considered moisture susceptible. The TSR values of mixtures were greater than 85% regardless of moisture resistance (Behiry, 2013).

2.6. Summary

As aggregates comprise 95% by weight of the HMA, ASA is taken as the main reason behind performance problems. Different factors that are supposed to change with varying ASA are

discussed in this section. Such factors include OBC, volumetric mixture properties, Marshall Stability and flow, moisture damage resistance.

There are different types of ASA determination methods are present in the world. But in this section empirical SAF methods only discussed estimate ASA. The AI gradation specification effect on ASA is clearly visualized in this section and this in turn affects the moisture resistance performance of asphalt concrete. Different mechanisms and modes of moisture damage are clearly discussed in this section. Even though gradation of aggregates is the main factor that affects performance of HMA, moisture damage is complex phenomenon in which a single factor is not fully in determine the stripping action such as aggregate quality and type, bitumen type and quality and fillers also involved.

The researcher Sangsefidi et al (2016) states that "The results of that study show that mixture performance is not related to the gradation specification limits, so the author suggested using 'free design' of gradation to achieve the required performance of HMA" and on the contrary the Banerji eta al. (2014) explained that "the results indicate that the performance of mixes made with mid-point value of gradation range shows higher Marshall Stability value than other mixes while the optimum binder content (OBC) increases from coarser gradation to finer gradation for both grading specifications". This study was done by using lower, middle, and upper limit of the gradation specified in AI. But this study consider the mean of lower and middle limit and mean value of middle and upper limit to evaluate the performance and economical effect.

3. MATERIAL AND METHODOLOGY

3.1. Introduction for Study Area and General Laboratory Techniques

The methodology discusses the methods used to achieve the objectives of the study. This gives a clear understanding of general activity and performed work techniques from starting to ending of the research. The selection of required materials, material quality test techniques and standards used during the study were clearly explained. The research focuses on the relationship between Marshall Stability and flows, optimum binder content, mix volumetric properties, and resistance of moisture damage of hot mix asphalt by using the Marshall Mix design method for different aggregate surface areas.

The mixes were prepared using one type of Asphalt binder and five aggregate gradations with different aggregate surface areas in one type of aggregate. The aggregates used for hot mix asphalt mixtures were selected from IFH Company currently producing in Bahir Dar, Ethiopia. The bitumen type of 80/100 penetration grade was selected for this study and obtained from the site of Muketuri to Alem Ketema Lot 1: Muketuri to Kokeb Mask road project around Addis Ababa. This penetration grade of bitumen was selected to compatible with the local weather condition to achieve the pavement required performance and counterbalance the cracking and rutting pavement failure.

The selections of ingredient materials are not enough to achieve the good performance of the hot mix asphalt mix. The material quality tests should be conducted to check whether the materials fulfill the minimum requirement of the specification or not. Thus, the laboratory tests were done in order to determine their physical properties whether they meet the recommended specification limits. The quality tests were conducted on the aggregates include specific gravity, aggregate flakiness index, Los Angeles abrasion, aggregate crushing value tests, and gradation sieve analysis. The tests were conducted on the asphalt binder including penetration test, ductility test, durability, softening point test, and specific gravity test. The main goal of a mixture design procedure is to determine; appropriate type of binder, aggregate gradation structure and optimum binder content for that final mix demonstrates acceptable performance over its service life. Using these materials, the different specimens were prepared with various aggregate surface areas for

the same type of bitumen by the Marshall Mix design method in order to find the optimum bitumen content.

After obtained optimum bitumen content, the Marshall Stability and flow, consumption of bitumen content in the economic aspect, the resistance of moisture damage, and mechanism of moisture failure for variation aggregate surface area were tested and analyzed. During the mix design, all other ingredients were controlled and made constant in the mix. Modified Lottman Test (AASHTO T283) and Boiling Water Test (ASTM D3625) were used to evaluate the effect of ASA on moisture damage of the mixture.

3.2. Materials

Bitumen, crushed aggregate and fillers were used for this experimental study. The Selection, proportion and characterization of individual material are very important to obtain the desired performance and properties of asphalt pavement mix. It is recommended that the physical properties of component materials of the hot mix asphalt meet all the requirements to ensure the material has a good performance.

These ingredient materials were tested in the laboratory in order to determine their physical properties and cross check whether they meet the specifications limit or not. The tests were conducted for mineral aggregates include: Los Angeles abrasion, soundness, aggregate flakiness index, aggregate crushing value and specific gravity while for bitumen conducted tests were: penetration, ductility, durability, softening point and specific gravity. In the design and construction of HMA mixtures, the sources of these materials are: The 80/100 penetration grade bitumen taken from Muketuri to Alem Ketema road project; asphalt mix plant Asphalt Laboratory, around Addis Ababa, Ethiopia and Crushed Aggregate materials was also collected from aggregate crusher site on– IFH Company in Bahir Dar, Ethiopia.

3.2.1. Aggregate

Mineral aggregates make up approximately 80% of an asphalt mixture by volume and 95% by weight. Despite the large volume or mass proportion, mineral aggregates typically make up 50% or less of the total cost of the materials used to produce an asphalt mixture. For economic

reasons, aggregates are almost always used from the nearest available location. Even if all aggregate available in a local location is not used for AC design purposes.

It also required different necessary tests, to cross-check with the specification whether accept or reject the aggregate produce on the local area to use for asphalt surface course.

The 12.5mm nominal aggregate size bulk samples were collected from the IFH aggregate crusher in Bihar Dar, Ethiopia. The aggregate was taken into the laboratory and quartering to appropriate sampling and give enough material to complete aggregate quality tests the in hot mix asphalt mix design. In order to define the properties of these aggregates, Sieve Analysis, Specific gravity (AASHTO T 85), Los Angles abrasion (ASTM C131, 1996), Flakiness Index (%) (BS 812 Part 105), soundness tests (AASHTO T 104) and Aggregate Crushing Value (BS 812 Part 110) laboratory tests were conducted.

The coarse and fine aggregate particles were separated into different sieve sizes and proportioned to obtain the desired gradation for bituminous mixtures which is given in the ERA technical specifications. The proportion was done first by drying aggregates to constant weight at 105°C to 110°C and separated by dry sieving to desire size fractions to meet the needed gradation for bituminous mixtures. The samples were grouped into five different aggregate gradation structures. For each aggregate gradation surface area was calculated using the surface area factor (SAF) in one specification band with 12.5 mm nominal maximum aggregate size for surface course design.

Typically, the qualities required for aggregates are described in terms of shape, durability, cleanliness, and bitumen affinity. As a general guideline, the coarse aggregates used for making HMA should be produced by crushing sound un weathered rock or natural gravel. To investigate the physical properties of the aggregates and their suitability for road construction, various tests were conducted using the appropriate standards indicated in the table below.

Table 3: 1 HMA required aggregate physical properties tests and standards

No	Test description	Test method	Specification	Test aggregate property
1	Elongation index	BS812, 1989	<35	

2	Flakiness index	BS812, part 104		Shape
3	Los Angles Abrasion (LAA)%	ASTM C131,1996	<30	Strength
4	Aggregate crashing value (ACV)%	BS812, Part 110,1985	<35	
5	10%Fines Aggregate Crushing Test (KN)	BS812,1990	>140	
6	Aggregate Impact Value (AIV)	BS812, 1990	≤26	
7	Aggregate Abrasion Value (AAV)	BS812, 1985	<12	Durability
8	Water Absorption (coarse)	ASTM C127	<2	
S9	Sand Equivalent Value	AASHTO 1990		Cleanness
10	immersion strength tests (index of retained Marshall stability)	D. Whiteoak 1990	>75	Bitumen affinity
11	Specific gravity	AASHTO T85		Density

Sieve analysis was done to use for HMA mix design to control the gradation of aggregate and aggregate surface area for appropriate coating of aggregate particles surface. This is used to manage the performance of asphalt concrete such as stripping resistance, raveling resistance, and durability. As explain above, the aggregates are taken from the source dried with the temperature range of 105⁰C to 110⁰C to prevent the dust cover of the aggregate surface. The dried aggregate was separated with the series of required sieve size which specified in ASTM. Then using percent of retained, the mass of the aggregate which needed to blend was calculated and achieved the gradation within the specification that specified in ERA flexible pavement design manual, 2013 for surface course asphalt concrete design that is called design six (D-6).

Table 3: 2 Particle size distributions for AC wearing courses (ERA, 2013)

Sieve size	Nominal maximum aggregate size (mm)		
	Percentage passing		
	19	12.5	9.5
25	100		
19	90-100	100	
12.5	-	90-100	100
9.5	56-80	-	90-100
4.75	35-65	44-74	55-85
2.36	23-49	28-58	32-67
1.18	-	-	-
0.6	-	-	-
0.3	5-19	5-21	7-23
0.15	-	-	-
0.075	2-8	2-10	2-10
Bitumen weight % of the total mixture	4-10	4-11	5-12

For this study the 12.5mm of Nominal maximum aggregate size was selected for surface course and within this gradation specification limit, five aggregate surface areas were calculated using empirical surface area factor (SAF) methods as shown in table:

Table 3: 3 Surface area factors for standard sieve

Total percent passing sieve size	Maximum size	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Surface area factor(m ² /kg)	0.41	0.41	0.82	1.64	2.87	6.14	12.29	32.77

3.2.1.1. Sampling Techniques and Calculation of Aggregate Surface Area

The aggregate used in this study was taken from IFH in Bahir Dar, Ethiopia. This aggregate restructured based on ERA specification, 2013 requirement with 12.5mm NMA. The five aggregate surface areas were prepared by dividing the aggregate gradation percent passing range into five equal parts. Each aggregate surface area was obtained by multiplying percent passing with empirical surface area factor (SAF). The empirical surface area factor (SAF) method is applicable only all the series of the sieve is present. So, to achieve this requirement the following steps were used and then determined the aggregate surface area for the purpose of aggregate proportion design and asphalt film thickness. These steps were:

1. The aggregates were heated at the temperature of 105 °C to 110°C;
2. The heated aggregate was separated by the series of sieves specified in the specification (12.5, 4.75, 2.36, 0.3 and 0.075mm);
3. The new aggregate gradations were prepared by blending the separated aggregate fractions in step two based on mix design requirement;
4. The new prepared aggregate gradations were done the sieve analysis again with the series of sieves listed in parallel to empirical surface area factor (SAF) (12.5, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15- and 0.075-mm sieve size) to find the percent passing;

The aggregate surface areas were calculated the by the formula of:

$$SA = \sum_{i=1}^n \text{percent passing} \times SAF + z$$

Where:

SA= surface area in m²/kg

SAF =surface area factor

N= number of sieves involved in the sieve analysis less than or equal to 4.75mm (n=1to7)

Z =surface area for aggregate size greater than 4.75mm =0.41m²/kg

The aggregate surface area used for one mix is the surface area multiplied by the amount of aggregate weight required per mix in kg (1.2kg).

$$ASA = 1.2 \text{ kg} \times SA \quad 3.1$$

Where: ASA= aggregate surface area per mix

Table 3: 4 ASA calculations at lower gradation limit

No	Sieve size in mm	Specification gradation for 12.5mm NMA %passing	Blending gradation % passing	SAF in m ² /kg
1	19	100	100	0.41
2	12.5	90	90	
3	9.5	-	80	
4	4.75	44	44	0.41
5	2.36	28	28	0.82
6	1.18	-	17	1.64
7	0.6	-	9	2.87
8	0.3	5	5	6.14
9	0.15	-	4	12.29
10	0.075	2	2	32.77

Table 3: 5 ASA calculations between lower and middle gradation limit

No	Sieve size in mm	Specification gradation for 12.5mm NMA %passing	Blending gradation % passing	SAF in m ² /kg
1	19	100	100	0.41
2	12.5	92.5	92.5	
3	9.5	---	83	
4	4.75	51.5	51.5	0.41
5	2.36	35.5	35.5	0.82
6	1.18	---	24	1.64
7	0.6	---	15	2.87

8	0.3	9	9	6.14
9	0.15	...	8	12.29
10	0.075	4	4	32.77

Table 3: 6 ASA calculations at middle gradation limit

No	Sieve size in mm	Specification gradation for 12.5mm NMA S %passing	Blending gradation % passing	SAF in m ² /kg
1	19	100	100	0.41
2	12.5	95	95	
3	9.5	.....	86	
4	4.75	59	59	0.41
5	2.36	43	43	0.82
6	1.18	.....	30	1.64
7	0.6	.....	20	2.87
8	0.3	13	13	6.14
9	0.15	.....	11	12.29
10	0.075	6	6	32.77

Table 3: 7 ASA calculations between middle and upper gradation limit

No	Sieve size in mm	Specification gradation for 12.5mm NMA S %passing	Blending gradation % passing	SAF in m ² /kg
1	19	100	100	0.41
2	12.5	97.5	97.5	
3	9.5	...	90	
4	4.75	66.5	66.5	0.41
5	2.36	50.5	50.5	0.82
6	1.18	...	37	1.64
7	0.6	...	25	2.87

8	0.3	17	17	6.14
9	0.15	...	15	12.29
10	0.075	8	8.0	32.77

Table 3: 8 ASA at upper gradation limit

No	Sieve size in mm	Specification gradation for 12.5mm NMA %passing	Blending gradation % passing	SAF in m ² /kg
1	19	100	100	0.41
2	12.5	100	100	
3	9.5	...	93	
4	4.75	74	74	0.41
5	2.36	58	58	0.82
6	1.18	...	42	1.64
7	0.6	...	30	2.87
8	0.3	21	21	6.14
9	0.15	...	19	12.29
10	0.075	10	10	32.77

3.2.2. Asphalt

The bitumen sample was taken from Muketuri to the Alem Ketema road project's asphalt mix plant Asphalt Laboratory around Addis Ababa the storage tank. Asphalt grade selection depends on pavement temperature and air temperature or climate condition at which the pavement serve. Bitumen with 80/100 standard penetration grade was selected as paving grade bitumen to prepare trial mixes because it is widely used and acceptable for temperature condition of colder regions of Ethiopia like Addis Ababa. For bitumen 80/100 penetration grade was evaluated under conventional bitumen tests to ensure the physical properties include Penetration test, Ductility test, Softening point test, and Specific gravity test. The tests were done based on ASTM standards as seen below in the Table3.9.

Table 3: 9 the tests and standards for 80/100 penetration bitumen grade

Test	80/100 bitumen grade specification	Test methods
Penetration at 25 °C	80-100	ASTMD5
Softening point at °C	42-51	ASTMD36
Ductility at 25°C	≥75cm	ASTMD113
Specific gravity	1.00-1.05	ASTM D70

3.3. Marshall Mix Design

There are three principal bituminous mix design methods. They are the Hveem Method, Marshall Method, and Supersaver Method. Marshall Mix design is a widely used method in Ethiopia. This research was worked with the standard specification of the Marshall Mix design method. Designed bituminous mix should be suitable to withstand heavy traffic loads under worst climatic conditions and also fulfill the structural and pavement surface characteristics requirements. The objective of the design of the bituminous mix is to determine an economical proportion of the asphalt mix ingredient materials through several trial mixes.

After the materials were collected and quality tests worked, the specimens were prepared to achieve the objective of the mixture using the Marshall Design method. The procedure for the Marshall Asphalt mix design method starts with the preparation of test specimens. The materials which fulfill the quality requirements were blended to meet the graduation requirement. The bulk specific gravity of all aggregate used in the blend and asphalt cement was determined to analyze the volumetric property of the mixture. The experimental works were started by determining the optimum asphalt content with the compaction effort of 75 blows on either side. The 75 blows compaction effort is taken from the Marshall criteria for heavy traffic load which is suggested for asphalt concrete Mix design.

3.3.1. Mix Design and Sample Size

This experimental work has five samples. The five samples (ASA1, ASA2, ASA3, ASA4, and ASA5) were prepared based on the aggregate surface area variation. For each sample 15 specimens for optimum bitumen content determination, 3 specimens for the trial mix to get $7 \pm 0.5\%$ air void for indirect strength tests, 3 specimens at OBC used to check Marshall test result based on ERA specification criteria and 6 specimens for AASTHO T283 test to evaluate moisture damage for dry and water conditioning were prepared. Totally 135 compacted specimens were prepared. For the water boiling test, the loss mix specimens were used to test the mechanism of moisture damage.

The aggregate samples were dried for sieve analysis work and separate with a required sieve size to a constant weight at 105^0 C to 110^0 C. The proposed samples of aggregates gradation were obtained by blending the per-determined aggregate fractions to meet the specification. The laboratory mixing and compaction temperatures shall be considered equal to the mix design. The mix and compaction temperature were determined from specification sets or use viscosity versus temperature relation to prepare the hot mix asphalt mixture.

In the specification, in an asphalt mix, the mixing temperature can be defined as the temperature at which the aggregate can be sufficiently dried and uniformly coated and lay in the range of 135-165°C (ERA, 2013) but not to exceed 177°C . On the other hand, the compaction temperature for an asphalt mix is usually in the range of $135\text{--}155^{\circ}\text{C}$ (MS-2). Based on viscosity-temperature relation, mixing temperatures were determined where the viscosity-temperature line crosses the mixing viscosity range of 0.17 ± 0.02 Pa-s (170 ± 20 centistokes) and compaction temperatures were determined where the viscosity-temperature line crosses the compaction viscosity range of 0.28 ± 0.03 Pa-s (280 ± 30 centistokes).

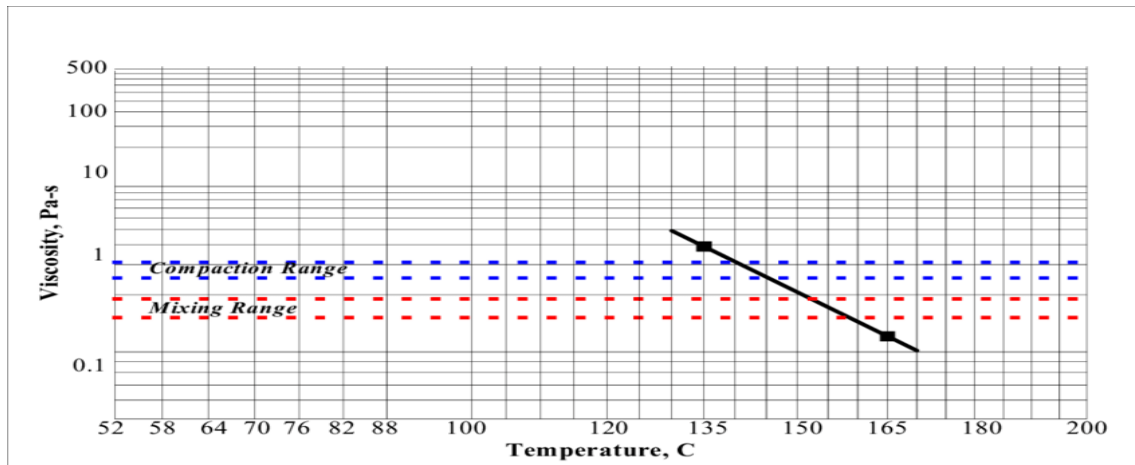


Figure 3: 1 Determination of mixing and compaction temperatures (ASTM D 2493)

This method is used to control the effect of asphalt binder stiffness on the mixture. Researcher Ithnin, 2008 stated that bitumen grade of 80-100 penetration, the typical mixing and compacting temperature has been normally set as 160°C and 140°C based on experience. By following this fact, 160°C and 140°C were selected for mixing and compacting temperature respectively.

Measure the weight of aggregate from the blended aggregate was measured to produce a cylindrical compacted 102mm diameter and 63.5±1.27mm height specimen. About 1.2kg of heated aggregate and 80/100 penetration grade of heated bitumen was mixed in a bowl at a temperature previously determined. The mixture was placed in a clean heated mold and compacted with the compacted temperature. The mix was compacted using 75 blows of either side with the compaction hammer with a free fall of 457mm. the compacted test specimens of unit weight, void analysis, and stability and flow were determined by varying the bitumen content by 0.5% until obtained optimum binder content.

3.3.2. Optimum Bitumen Content (OBC) Determination

The optimum binder content is the binder content that balances the rutting and fatigue cracking characteristics of the mixture. This was achieved by multiple mixture performance tests for each trial binder's contents. The main steps followed to determine optimum binder content of the asphalt concrete mixture were including:

i) The appropriate bitumen grade was selected for this study. Viscosity, ductility, softening, and specific gravity tests were conducted for the quality of binder; ii) The type of aggregate structure was selected for this design application; iii) Aggregate was blended with varying mass fractions of the binder and expressed as percent binder by weight of the mix. Initially, the mineral aggregate was mixed with the estimated binder value and then varied by 0.5% from the expected design bitumen content.

The “expected design bitumen content” was estimated by the empirical formula (Asphalt Institute, 1994).

$$\text{DBC} = 0.035a + 0.04b + Kc + F \quad 3.2$$

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

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

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

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

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

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

The blend aggregates were weighted with a mass of 1.2kg and five bitumen contents were prepared by increasing 0.5% interval from DBC that determined in the formula above. For one trial bitumen content, three-bath aggregate samples were weighted. Dried aggregate and heated bitumen were mixed at mix temperature (160°C). Types of equipment used in the preparation of the specimens were kept clean and maintained at a temperature of 93°C to 149°C.

iv) The mixes were compacted using Marshall Hammer compaction device at 140°C; (v) the fabricated test specimens were evaluated to determine the optimum asphalt content. The optimum binder content was determined at 4% air voids. The volumetric property, stability, flow, and density of the mix were evaluated and calculated for checking whether the mix result

achieves the specification or not by comparing the result to mix property result evaluation for Marshall Mix expressed in the table (MS-2).

Table 3: 10 Marshall Mix design criteria

	Light traffic		Medium traffic		Heave traffic	
Traffic condition	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
NO. of blows by Marshall compaction hammer	35		50		75	
Stability in (N)	3336	--	5338	--	8006	--
Flow in (0.25mm)	8	18	8	16	8	14
Air void in (%)	3	5	3	5	3	5
Voids filled in asphalt in (%)	70	80	65	78	65	75
VMA (%) for 4%AV & 12.5mm NMAS	14	---	14	--	14	--

After selecting the optimum bitumen content using Marshall Mix design procedure, the mix was prepared for each five aggregate surface areas sample to prepare the specimen for moisture susceptibility tests (Modified Lottman Test (AASHTO T283), Boiling Water Test (ASTM D3625))

3.3.3. Marshall Stability and flow test

Marshall Method of the test procedure was used in designing and evaluating bituminous paving mixes. Specimen was cool at room temperature until no deformation will result when removing it from the mold and then placed on a smooth, level surface until ready for testing. The specimens were heated in a constant temperature in water bath for 35 minutes at 60°C.

The specimen was then placed in a Marshall testing machine, where reading of stability and flow are simultaneously taken. In this method load was applied to a cylindrical specimen of bituminous mix and the specimen was monitored until its failure observed as specified in the ASTM standard (ASTM D1559). In this test compressive loading was applied on the specimen at the rate of 50.0 mm/min until it was broken. The temperature 60°C represents the weakest condition for a bituminous pavement, while flexibility was measured in terms of the 'flow value' which was measured by the change in diameter of the sample in the direction of load applied between the start of loading and at the time of maximum load.

3.4. Specimen Preparation for Moisture Damage Test

This section describes the specimen preparation methods for laboratory specimens to conduct Modified Lottman (AASHTO T 283) test, Boiling Water Test (ASTM D3625). In the laboratory, conditions with tape water were used to evaluate the effect on the level of saturation, air voids (Air), and indirect tensile strength (ITS). This was done to predict moisture damage. The specimens were prepared and divided into two sets. One set was used as the control set, whereas the other set was used for moisture conditioning with water. The specimens were prepared based on the standards AASHTO T-283 and ASTM D-3625. After the conditioning and control specimen prepared the tests were done to compare the value of ITS and aggregate coating with asphalt with control specimens at the different aggregate surface areas.

3.4.1. Modified Lottman test (AASHTO T283)

Modified Lottman (AASHTO T 283) is the method of combination of the Lottman and Tunnicliff and Root tests to evaluate the moisture susceptibility of compacted HMA mixture in the laboratory. It compares the indirect tensile strength of unconditioned and partially saturated with water conditioning specimens. The sample was conditioned to represent real conditions on the service life of the pavement with partially vacuum saturation.

The modified Lottman test AASHTO T283 is mostly used to evaluate the extent of moisture damage of asphalt concrete mixtures. This test determines the indirect tensile strength when the pavement is exposed to moisture. The procedure adopted in this study the mixture compacted having air voids in the range of 6–8% or 7 ± 0.5 . The specimens were then divided into two

groups. One group is used as the control, whereas the other group was the moisture conditioning group.

A. Moisture conditioning

For the conditioned group, three compacted specimens were partially saturated by submerging in water and applying a vacuum for 5 to 10 minutes with 25.4 kilo Pascale pressure. The ultimate purpose of saturation is to achieve a targeted final saturation level. The Asphalt Institute recommends the AASHTO T 283 specimen saturation level range of 70 to 80 percent while ASTM uses the range of 55 to 80 percent to test the moisture damage effect. For saturation specimens, the volumetric properties were calculated.

For this study, the Moisture conditioning was adjusted between 55 and 80% saturation level to represent duration and real weather condition occurred in the service life of the pavement. The samples were then immersed in the water bath at 60 ± 0.5 ° C for 24 ± 0.5 h. The moisture-conditioned specimens were ready for testing after they were removed from the water bath and cool at the temperature of 25 ± 0.5 ° C water bath for 40 ± 5 min to attend to the environmental condition.

B. Unconditioned group

The unconditioned specimens were placed at room temperature until the indirect tensile strength test start. The ITS strength of both the control group and conditioned group of specimens was determined at 25°C and the TSR was calculated to evaluate the moisture susceptibility of the asphalt concrete. The indirect tensile strength test was performed on the conditioned and unconditioned specimens by loading at the rate of 50 mm per minute.

Indirect tensile strength; Indirect tensile strength of the asphalt concrete used to evaluate stripping resistance of the hot mix asphalt mixture due to the presence of moisture on the pavement. The specimen preparation and test procedure were done based on AASHTO T283. For the indirect tensile strength test, the compressive loads, parallel to the vertical diameter using the Marshall loading equipment was applied on the cylindrical specimens, the sample produces tensile stress perpendicular to the applied load. Using the load recorded on the specimen failure, ITS was calculated by using the equation:

$$ITS = \frac{2000 \times P}{\pi \times h \times D} \quad 3.3$$

Where: ITS is the indirect tensile strength (kPa); P the maximum load (N); h the specimen thickness (mm); and D is the specimen diameter (mm).

Moisture susceptibility depends on environmental, construction, and pavement design factors such as internal structure distribution, quality and type of materials used in the asphalt mixture. Moisture susceptibility of the compacted specimens was evaluated by tensile strength ratio (TSR) using the formula;

$$TSR\% = \frac{S_1}{S_2} 100 \quad 3.4$$

Where: TSR= is the tensile strength ratio, S2= the average indirect tensile strength of conditioned specimens, S1= is the average indirect tensile strength of dry (unconditioned) specimens.

When an asphalt mixture's TSR greater than or equal to 80 percent, the mixture not sensitive to moisture damage. Some agencies have chosen to accept TSR values when the TSR greater than or equal to 70 percent based on their experience. The results of the TSR% observed in the equation were compared to specifications.

3.4.2. Boiling Water Test (ASTM D3625)

Boiling Water test is used to determine the relative compatibility of aggregates with asphalt in the existence of water. The boiling test was done in a loss mix to evaluate the bond between the asphalt and aggregate (adhesion). The extent of retained asphalt coating on the aggregate was evaluated relative to a non-conditioned specimen. Tests performed on compacted samples such as TSR were used to characterize both adhesion properties and cohesion properties but the boiling water test evaluated only the bond that exists between aggregate and the asphalt cement (adhesion).

The asphalt cement was heated at a temperature of $160 \pm 5^\circ\text{C}$ for 24 to 26 hours to harden the asphalt that was used to closely simulate asphalts characteristics that occurred in the mixing plant. For the evaluation of stripping by boiling water test required amount of aggregate per mix

is 100 g. The dry aggregate was heated at $160 \pm 5^{\circ}\text{C}$ for 1 to 1.5 hours. The asphalt cement was poured into the aggregate and mixed manually in a hot container. The mixture was allowed to cool at room temperature (25°C) for 2 hours before testing.

A beaker was filled half with water and heated to boiling. The prepared mixture stayed at room temperature was added to the boiling water. Control the boiling water temperature to not decrease below the boiling temperature. For the evaluation of the loose mix of asphalt concrete, two sets of the loose mix were prepared. Set one is the control group and the other set is the immersed group in boiling water to compare the percentage of asphalt film retained on aggregates.

The loose mix was staying at boiling water for 10 minutes with stirring every 3-minute intervals for 10 seconds to expose the mix for boiling water and to provide greater surface area exposure of the mixture during boiling. During and after boiling, the floated asphalt should be removed away from the surface of the water to prevent recoating of aggregate. The mixture is then allowed to cool at room temperature (25°C) while still in the beaker.

After cooling, the water is drained from the beaker and allowed to dry. Then the amount of stripping was determined by observation and expressed in terms of the percent of asphalt retained on the aggregate.

The mixture should be evaluated at the air-dried condition to visualize the stripping of the fine aggregate in the mixture. The observation was compared with the Texas Boiling Test Rating Board standard shown in Fig 3.2. The result was reported that percent asphalt retained after boiling should be based on a comparison with the standard scale, not a photograph. Select the specimen nearest in appearance to the test specimen and report that as the test result.

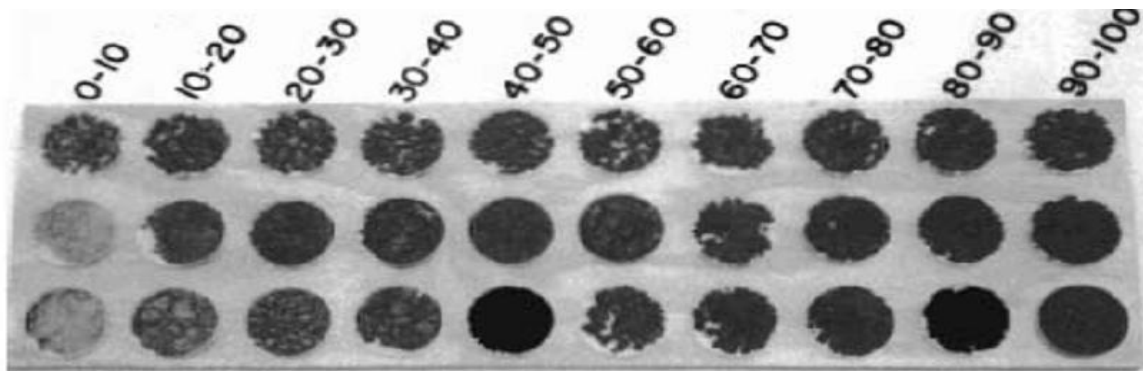


Figure 3: 2 Texas Boiling Test Rating Board

3.5. Method of the Tests Result Analysis

The test result of the mixture and individual materials were analyzed by using Microsoft Excel and Minitab to arrange, organize, analyses and to present. The Microsoft Excel was used to organize the raw test data and then to construct graphs, table and formulas of the analysis data. While the MINITAB was used to develop fitted line equations and that equations were explained the relationship between ASA and optimum binder content, mixture volumetric properties, Marshall Stability, flow, or moisture resistance performance of the mixture by using the coefficient of determination (r^2). The coefficient of determination is a measure of the variation of the dependent variable that is explained by the regression line and the independent variable.

4. RESULT AND DISCUSSION

4.1. Introduction

This topic discusses the test result of the hot mix asphalt with a variation of aggregate surface area. From this chapter, the result shows the effect of the ASA on the mix volumetric properties, moisture damage resistance, and status of stripping, stripping mechanism of hot mix asphalt, the asphalt consumption, and economic aspect.

This study was done by varying ASA on one bitumen type. These aggregate surface areas were selected to understand the effect of percent passing is expressed in large gape range and these were designed from 12.5mm NMAS aggregate gradation percent passing specification limitation rage by dividing into five equal parts. Five different ASAs were involved in the hot mix asphalt preparation to determine mixtures properties and performance.

The five ASAs were obtained from within the gradation specification limit recommended by ERA, 2013 for wearing course design. These surface areas were nominated as ASA1, ASA2, ASA3, and ASA4 ASA5. ASA1, ASA2, ASA3, ASA4, and ASA5 were calculated from the lower limit, the mean value of the lower and middle limit, the middle limit, the mean value of middle & upper limit, and upper limit in the gradation specification limit percent passing respectively by multiplying empirical surface area factor.

4.2. Materials Quality Test

This section shows the result of the quality test result of asphalt binder and mineral aggregate. All the quality tests of aggregate and bitumen were satisfied to use for mix design which specified in different specifications. The results of the materials were explained as seen below in Table 4:1 and 4:2

4.2.1. Bitumen Quality Tests

This section shows the result of the quality test result of asphalt binder and mineral aggregate. All the quality tests of aggregate and bitumen were satisfied to use for mix design which specified in different specifications. The results of the materials were explained as seen below in Table 4:1 and 4:2

Table 4: 1 Bitumen quality test results

Test	80/100 bitumen Grade specification	Test methods	Result
Penetration at 25 ⁰ C	80-100	ASTMD5	91.5
Softening point at ⁰ C	42-51	ASTMD36	44
Loss mass%	≤0.8	ASTMD2042	-
Ductility at 25 ⁰ C	≥75cm	ASTMD113	86
Specific gravity	1.00-1.05	ASTM D70	1.025
Purity in%	99	AASHTOT44	-

4.2.2. Aggregate

The aggregate quality tests were conducted to determine the quality of the aggregate before the asphalt concrete mix design was done and the result was compared to the specifications set in ERA flexible pavement design manual, 2013, BS812 ASTM and AASHTO. The results of the quality tests are presented in the tables below.

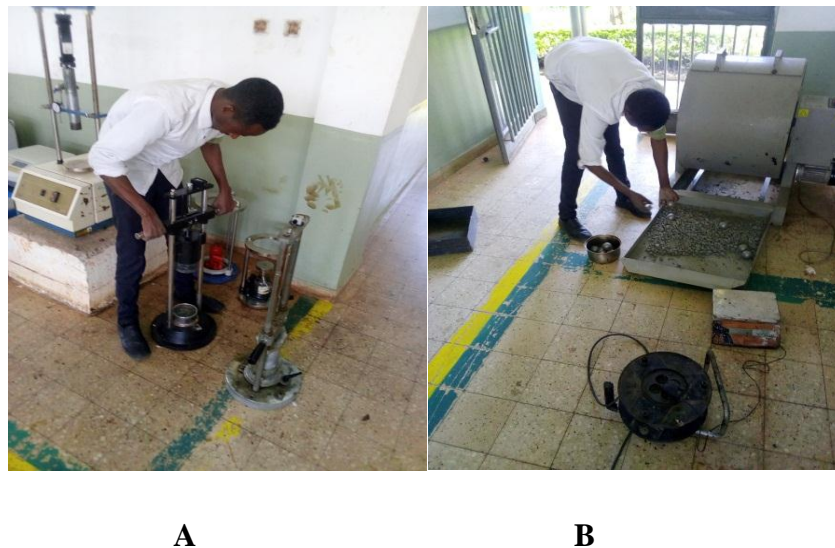


Figure 4: 1 aggregate crushing value (A) and Los Angeles Abrasion test (B)

Table 4: 2 HMA required aggregate physical properties test results

No	Test description	Test method	Result	specification	Test aggregate
----	------------------	-------------	--------	---------------	----------------

					property
1	Elongation index	BS812, 1989	25%	<35	Shape
2	Flakiness index	BS812, part 104			
3	Los Angles Abrasion (LAA)%	ASTM C131,1996	21%	<30	Strength
4	Aggregate crashing value (ACV)%	BS812, Part 110,1985	6%	<35	
5	10%Fines Aggregate Crushing Test (KN)	BS812,1990		>140	
6	Aggregate Impact Value (AIV)	BS812, 1990		≤26	
7	Aggregate Abrasion Value (AAV)	BS812, 1985	6%	<12	Durability
8	Water Absorption (coarse)	ASTM C127		<2	
S9	Sand Equivalent Value	AASHTO 1990			Cleanness
10	immersion strength tests (index of retained Marshall stability)	D. White oak 1990			Bitumen affinity
11	Specific gravity (Gsb)	AASHTO T85			Density

The specific gravity of aggregate for different gradations were done as seen in the table below.

Table 4: 3 Calculation of bulk specific gravity of aggregates for five different ASAs

Sample	ASA1	ASA2	ASA3	ASA4	ASA5
Weight aggregate in mix for (12.5-4.75mm sieve) (g)	672	582	492	402	312.0
Weight aggregate in mix for (2.36-.075mm sieve) (g)	504	570	312	702	768.0
Weight of filler in mix (passing 0	24	48	72	96	120.0

.075) (g)					
Specific gravity coarse aggregate	2.789	2.789	2.788	2.786	2.786
Specific gravity fine aggregate	2.695	2.695	2.655	2.651	2.651
Specific gravity dust filler	2.680	2.680	2.680	2.680	2.680
Bulk specific gravity of aggregate	2.747	2.739	2.730	2.697	2.688

The bulk specific gravity of the aggregate varies at different ASA as seen in Table 4.3. As the test result indicates that the bulk specific gravity is incensed when the ASA is decreased. This relates to the fact that, the specific gravity of course aggregate greater than the fine aggregate for the same source and type of parent rocks.

The aggregates were collected in aggregate sources and dry sieve analysis was done. But the dry sieve analysis results were not satisfied with the gradation design criteria. So, to obtain the required aggregate gradation the aggregates were blended after separated the aggregate with a standard series of sieve size. $3.12\text{m}^2/\text{kg}$, $4.58\text{ m}^2/\text{kg}$, $6.19\text{ m}^2/\text{kg}$, $7.93\text{ m}^2/\text{kg}$, and $9.64\text{ m}^2/\text{kg}$ ASA were calculated by using blending aggregates gradations. The blended aggregates gradation and calculated ASAs were presented in the appendix. The result of five blending aggregates gradation curves are shown in Figure4.3 below and these were within the specification of gradation curve boundary sets in ERA, 2013 as seen in Figure 4.2.

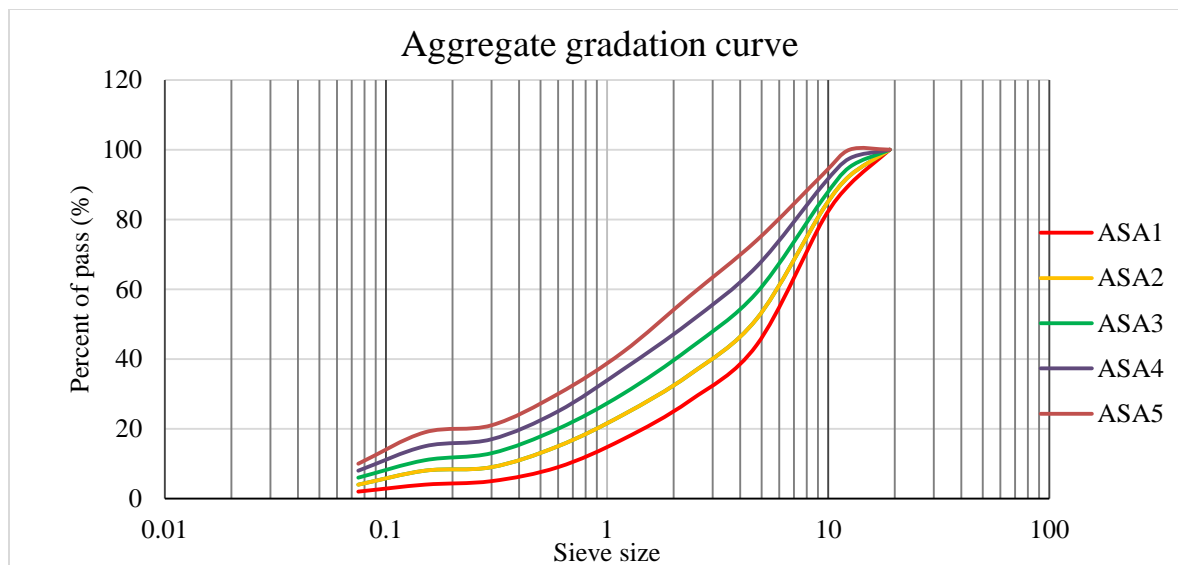


Figure 4: 2. Blending aggregate gradation curve

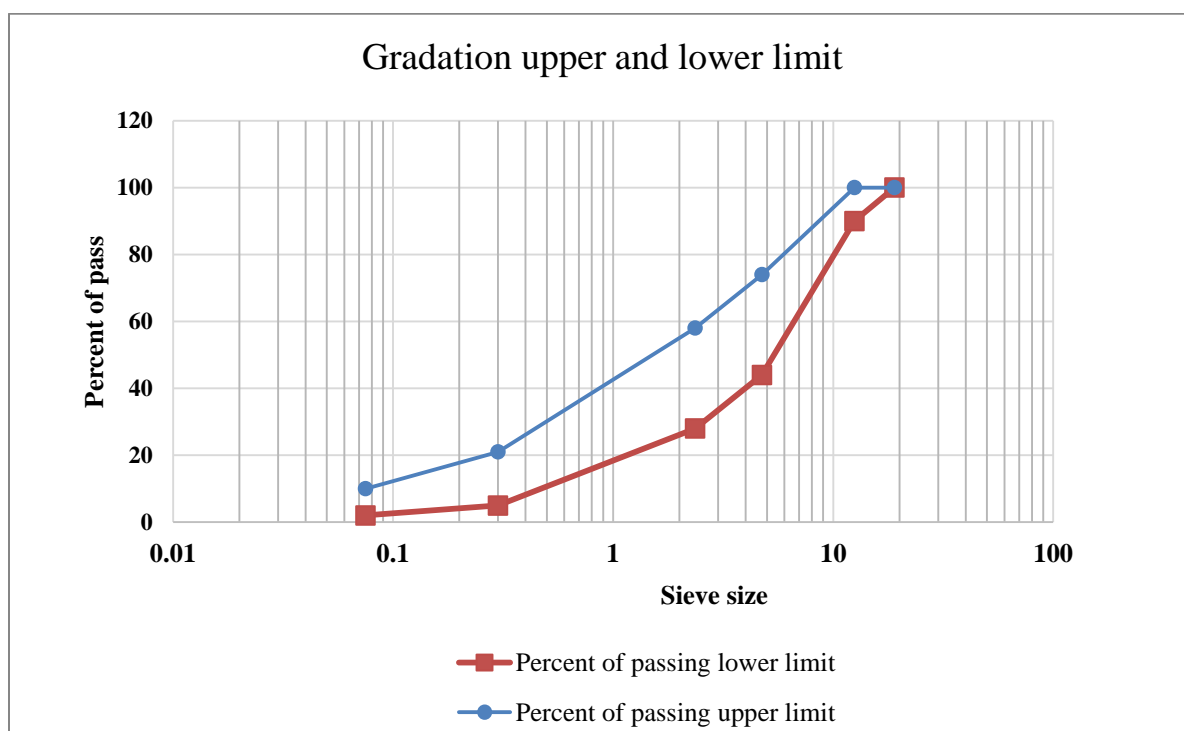


Figure 4: 3 Aggregate gradation curves for lower and upper limit

4.3. The effect of ASA on Optimum Binder Content (OBC)

The study indicates the bitumen content required to coat the aggregate well in the mixture was increased as the surface area of the aggregate increased. At $3.12\text{m}^2/\text{kg}$ of ASA required 5% of

the total mix, while at $9.64\text{m}^2/\text{kg}$ of ASA, the amount of bitumen require to achieve the mix design properties is 5.9% of the total mix. The asphalt mixture produced with the high ASA consumes a large amount of asphalt binder to coat the surface of the aggregate particles with appropriate asphalt film thickness.

However, the optimum binder content determined in high aggregate particles surface area used to asphalt mixture production, the bitumen per-determined not enough to produce required asphalt film thickness like mixtures produced using low ASA. Because when the binder is added into the mixture to achieve the required asphalt film thickness, other properties of the mixture may disturb such as rutting and bleeding property of the pavement. So, the pavement constructed using fine gradation, not only uneconomic based on bitumen coast but also cause to low durability.

Asphalt film thickness refers to the average of binder coating aggregate particles in the mixture. The asphalt film thickness depends on the effective asphalt binder, ASA, and density of bitumen. The computed value that is shown in the table4.4, defines the thickness of the effective asphalt binder coating on each particle in the mixture and which is used to check the HMA has adequate asphalt binder to achieve the desired level of mix durability or not (Michael, 2017).

Table 4: 4 Asphalt film thicknesses at different ASA

OBC %	ASA m^2/kg	AFT micro m
5	3.12	13.17
5	4.58	8.97
5.5	6.19	7.67
5.7	7.93	6.65
5.9	9.64	5.70

4.4. The Effect of ASA on HMA Volumetric Property

Volumetric properties in the compacted hot mix asphalt used to evaluate the overall performance during the service life of the pavement. As the test results indicate that almost all volumetric properties were influenced when the surface areas of the aggregate vary in the mix design. Thus, the performance of asphalt pavement was disturbed due to mixture volumetric properties change as a result of aggregate surface area variation.

4.4.1. The effect of ASA on bulk specific gravity of the HMA (Gmb)

The laboratory test results indicate that the bulk specific gravity of the compacted asphalt concrete increases with bitumen content increases and then starts to decrease. The bulk specific gravity decreases as a result of asphalt binder further increased for a constant aggregate surface area. This is occurred due to the fact that the amount of bitumen beyond the required limit cause voids filled with asphalt to increase, lubricate the mixture rather than bind the aggregate particles. Thus, the compacted mixture unit weight decreases as bitumen content increase above the limit.

For different aggregate gradation, the bulk specific gravity was varied for the same aggregate type. When the surface areas of aggregate were increased, the bulk specific gravity of the compacted mixture was increased until specific points and then was decreased. This shows that the bulk specific gravity of compacted mixtures was decreased as a result of more fine aggregate occupied the volume of the mixture and that causes to flow and deform rather than compact during load applied. This reflects the fact that the aggregate used for the hot mix asphalt mixture is about 95% of the mixture by weight was covered and the structural strength was obtained from the aggregate particles.

The aggregate particles become finer, the finer aggregate used to fill the voids occurred between the coarse aggregate, and this finer increased beyond the required limit, the coarse aggregates particles become very small and inadequate to resist the load applied. Due to this fine aggregate starts to slide and decrease the specific gravity of compacted mixture, rather than resist the applied load. This is a mechanism of finer aggregate particles mechanical response for traffic loads that unlike of the coarse aggregate.

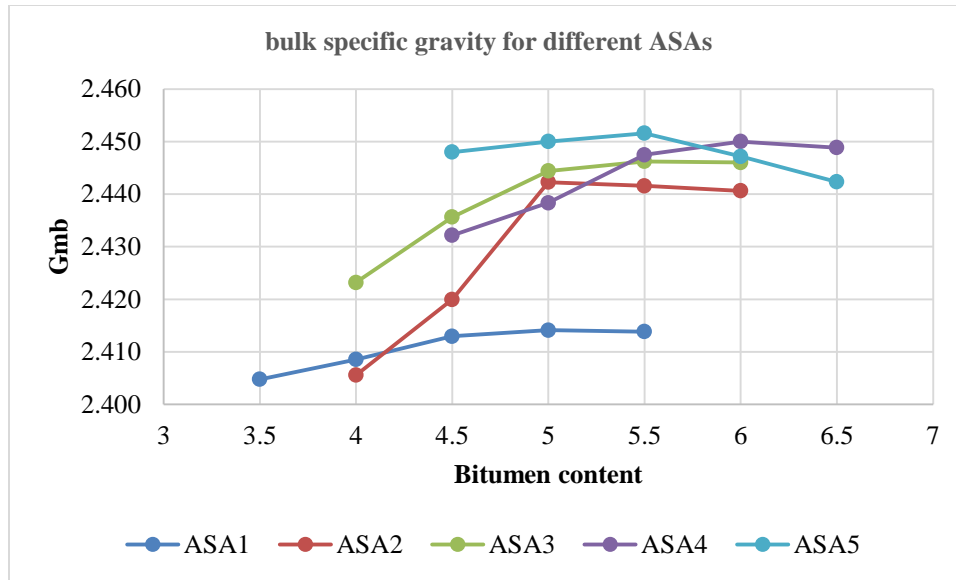


Figure 4: 4 the effect of ASA on bulk specific gravity of compacted mix

4.4.2. The effect of ASA on Void in minimal aggregate (VMA)

The voids in the mineral aggregate are the void found between aggregate particles in a compacted mixture that is occupied by air void and effective bitumen content. As the laboratory result at 3.12m²/kg of ASA show that the voids in mineral aggregate were decreased as the binder content increased up to a certain point. At this point, the amount of bitumen is around the optimum binder content. When the bitumen was increased beyond that limit, the voids in mineral aggregates (VMA) were increased due to the binder content further added in the mix and that cause the bitumen has missed the function. This means the purpose of the asphalt binder to bind the aggregate together to form strong adhesion boned by different mechanisms, but binder beyond the limit the binder tray to push the aggregate particles and cause to increase the voids in mineral aggregate.

As seen from the figure, the ASA was increased, the voids in mineral aggregate were decreased up to some point and then start to increase. In other words, the aggregate particles used to hot mix asphalt become finer the voids in mineral aggregate increase due to the coarse aggregate fractions float in the fine aggregate matrix which leads particles to slide one another instead of increasing the compaction level and this allows the VMA was increased. As seen from the test

result, the voids in mineral aggregate were decreased from aggregate surface area $3.12\text{m}^2/\text{kg}$ to $9.64\text{m}^2/\text{kg}$ and start to increase at the surface area of $9.82\text{m}^2/\text{kg}$.

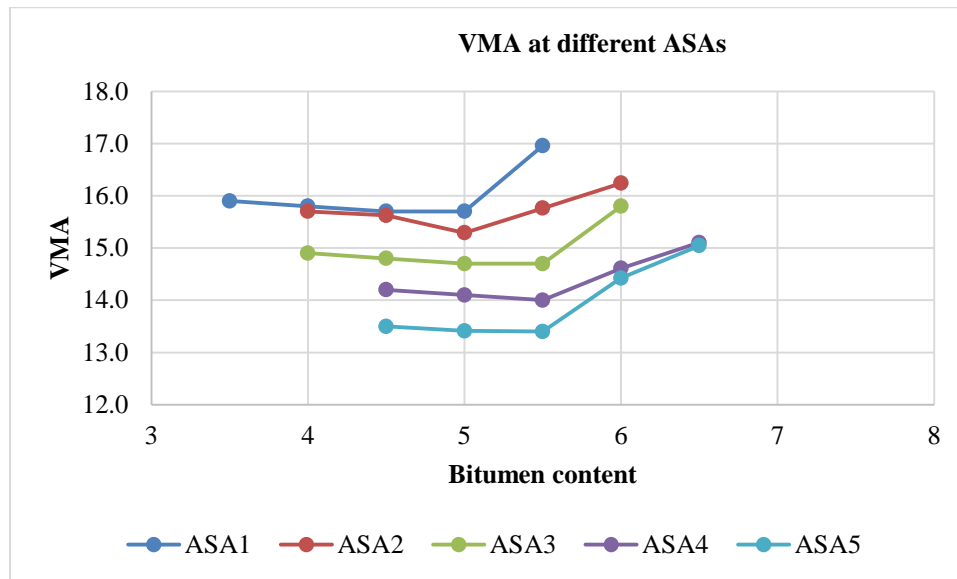


Figure 4: 5 the effect of ASA on VMA

4.4.3. The effect of ASA on Void in total mix (VTM)

Voids in the total mix are the total volume of small pockets of air between the coated aggregate particles throughout a compacted paving mixture. The test result indicates that the air voids in the compacted asphalt paving mixture decreased as the bitumen content increased. The void exists in aggregate particles filled by either air void or bitumen. This means that when the binder content covers more portion of the void in mineral aggregate, the remaining voids are filled by air void. This shows that, asphalt binder and air void inverse relationship.

The total air void in the compacted hot mix asphalt was decreased due to an increase in the surface area of the aggregate as seen in the test result. ERA flexible pavement design manual, 2013 specified that total air void is about 3% to 5% of the total mix at the optimum binder content. The air void of a mixture for $3.12\text{m}^2/\text{kg}$ of ASA aggregate gradation was about 6%. The result was out of the specified limit. This could occur due to the coarser aggregate gradation was used in the mix design and that had a deficiency of fine aggregate to fill the void present in the

mineral aggregate. Based on this result, the mix at the lower limit of gradation the bitumen exposes to oxidation reaction and this cause to bitumen aging and the binding property damaged.

For aggregate surface areas greater than $3.12\text{m}^2/\text{kg}$ the air voids approach to the specification limit. The aggregate gradation at $4.58\text{m}^2/\text{kg}$, $6.19\text{m}^2/\text{kg}$, $7.93\text{m}^2/\text{kg}$, and $9.64\text{m}^2/\text{kg}$ ASA the air void becomes decrease continuously. At the $9.64\text{m}^2/\text{kg}$ of ASA the total air void below the recommended value. This indicates that the lower limit gradation has finer aggregate particles and lower coarse aggregate. So, the void in the compacted mix very low and that filled by asphalt binder. This type of mix is suffering by rutting and bleeding when the load is applied and the temperature increased.

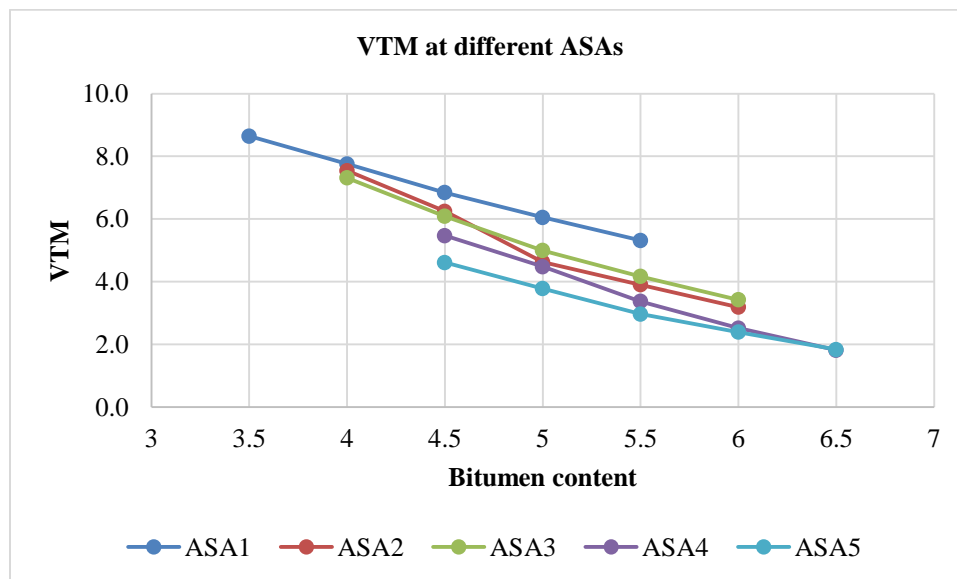


Figure 4: 6 the effect of ASA on VTM

4.4.4. The Effect of ASA on Void Filled with Asphalt

The void filled with asphalt, (VFA) is the void spaces that exist between the aggregate particles in the compacted asphalt mixture that is filled with the binder. The result shows that the VFA has a direct relation to the bitumen content and inverse relation to the total air voids in the compacted HMA. As the asphalt content increases the amount of voids filled with asphalt increases and the voids in the total mix, VTM, decreases.

Based on the ERA specification the voids filled with asphalt lay between in range of 65-75%. The voids filled with asphalt VFA in the mixture, at the aggregate gradation with $3.12\text{m}^2/\text{kg}$ ASA is 63.5% and this is not found within the specified limit. This is occurred related to the large void present in the mineral aggregate due to courser gradation and voids in the total mix is beyond the limit as discussed in the previous section. While the mix produced using aggregate gradation with $9.64\text{m}^2/\text{kg}$ of SA the voids filed asphalt beyond the limit.

As seen from the graph the surface area of the aggregate particles increases voids filled with asphalt also increase. While the total air voids decrease as mention above and voids in mineral aggregate also decrease. VFA, VTM, and VMA have a relation; VTM covered a small portion of the VMA, the reaming voids filled by effective bitumen content. In other words, the voids in mineral aggregate occupied by air void and asphalt binder with the different amounts with inverse relation. The air voids in a mixture minimized due to fine particles filled the VMA as a result of ASA increased in the mixture. Thus, most of the voids are filled by effective asphalt binder, and this increases VFA in the compacted hot mix asphalt.

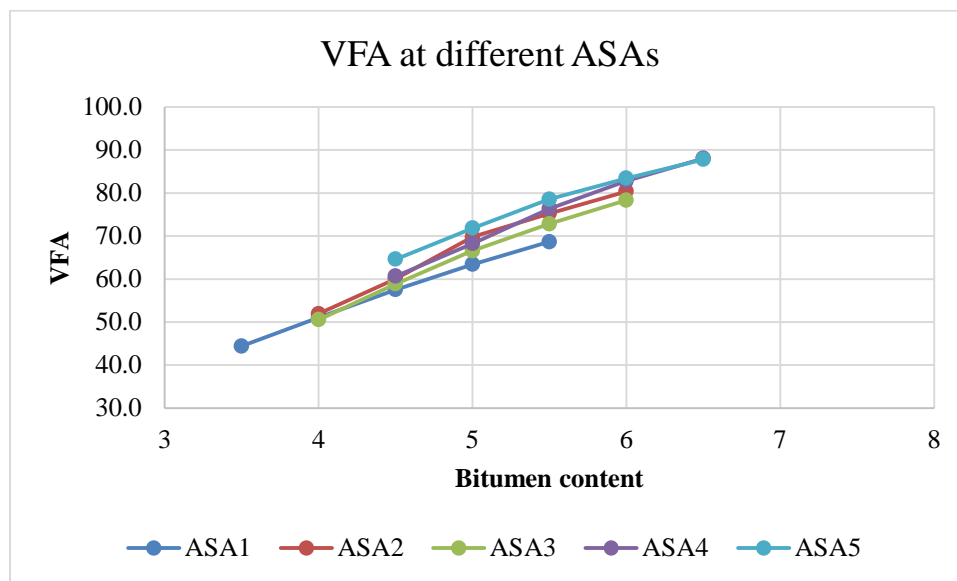


Figure 4: 7 the effect of ASA on VFA

4.5. Effect of ASA on Marshall Stability and flow

The effect of the ASA on the HMA mix stability and flow were evaluated by using the Marshall Mix design. Marshall Stability and flow values are independent each other and the test result is taken at the same time. The Marshall tests were prepared at various ASA. As shown the properties of the mix different with ASA variation. The effect of the ASA on stability and flow was discussed in the next section.

4.5.1. The effect of ASA on Marshall Stability

The effect of ASA on stability is shown in the Figure below. The stability at all ASAs approximately satisfied the minimum requirements specified by ERA flexible pavement design manual, 2013. The stability of the hot mix asphalt at all ASA is not shown much difference even the gradation allows a high ASA difference. This means do not mean, ASA does not affect the stability.

As the test result is shown in the figure, the Marshall Stability increase as the ASA increase up to some points and then started to decrease. The maximum Marshall stability is observed at the 6.19m²/kg ASA. When the SA used for asphalt pavement further increase, the Marshall stability became low. This result supports the ideas (Banerji, Das, Mondal, Biswas, & Obaidullah, 2014) that stats, the best stability found at the middle point of the aggregate gradation and oppose the ideas of Sangsefidi et al (2016) that the optimum performance achieved at the gradation of free design. The Marshall stability for 4.58m²/kg ASA is greater than 7.93m²/kg ASA.

Based on this, it better uses a lower ASA for wearing course asphalt pavement design than a larger ASA. When the aggregate particles used for hot mix asphalt mix design is coarser, the mixture may resist the load due to the arrangement of the aggregate particle, and that gives a response for applied load rather than shear and deform because this gradation required minimum asphalt cement to bind the aggregate together. The coarser aggregate has a better internal fraction and resists the shear effect and permanent deformation.

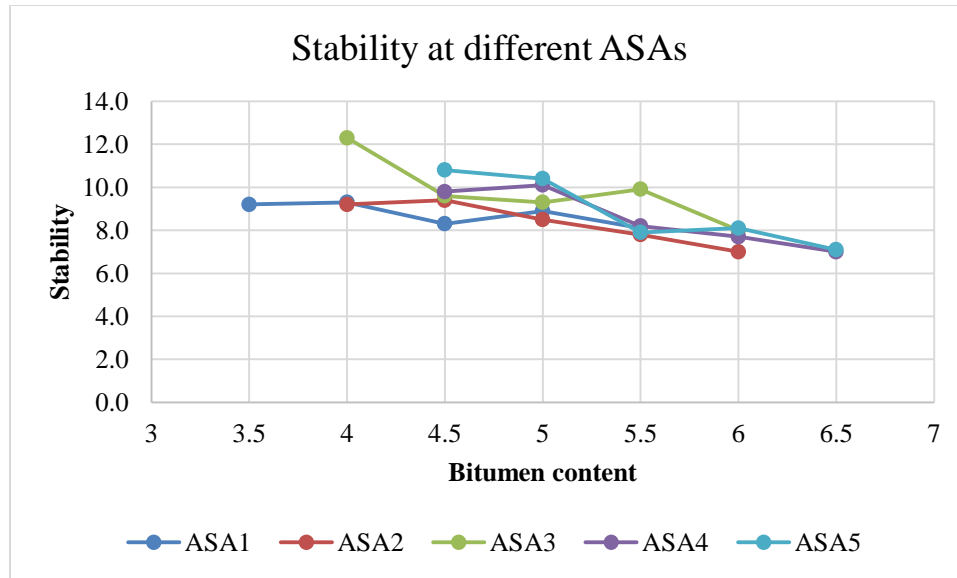


Figure 4: 8 the effect of ASA on Marshall Stability

4.5.2. The effect of ASA on Marshall Flow

The flow is the vertical deformation of the compacted specimen at the maximum load to measure Marshall Stability. From this test, the flow value is low when the bitumen content is less than the optimum bitumen content. The bitumen content has a direct relation with Marshall Flow. This is due to the fact that the mixture at low bitumen content hard enough to resist load and the failure line has a high fraction between aggregate particles. But when the bitumen content increase, the mixture was started to lubricate and the fraction between aggregates decrease.

As seen from the test result, ASA influences the value of Marshall Flow. The Flow value for almost all ASAs lay under ERA flexible pavement design manual, 2013 limitation except at 9.64 m²/kg ASA. The ERA flexible pavement design manual suggests that the flow value for a heavy traffic load, the allowable flow range is 2 to 3.5mm. The flow values for 3.12m²/kg, 4.58 m²/kg, 6.19 m²/kg, and 7.93 m²/kg ASAs are within the range of the specification set in ERA flexible pavement design manual, 2013. The flow at 9.64m²/kg is out of the limit value. This indicates that the Flow value in hot mix asphalt mixture increases due to the ASA increased.

When the aggregate particles used for the production of asphalt pavement for heavy traffic load have a large surface area, the mixture required a large amount of bitumen content to well coat the large ASA and to produce thick asphalt film for hot mix asphalt durable. This causes to decrease

in the contact areas between aggregate particles as a result of bitumen lubricate the internal friction that exists between the aggregate particles. Thus, the asphalt pavement suffers to rutting due to fine aggregate gradation use for the design of hot mix asphalt.

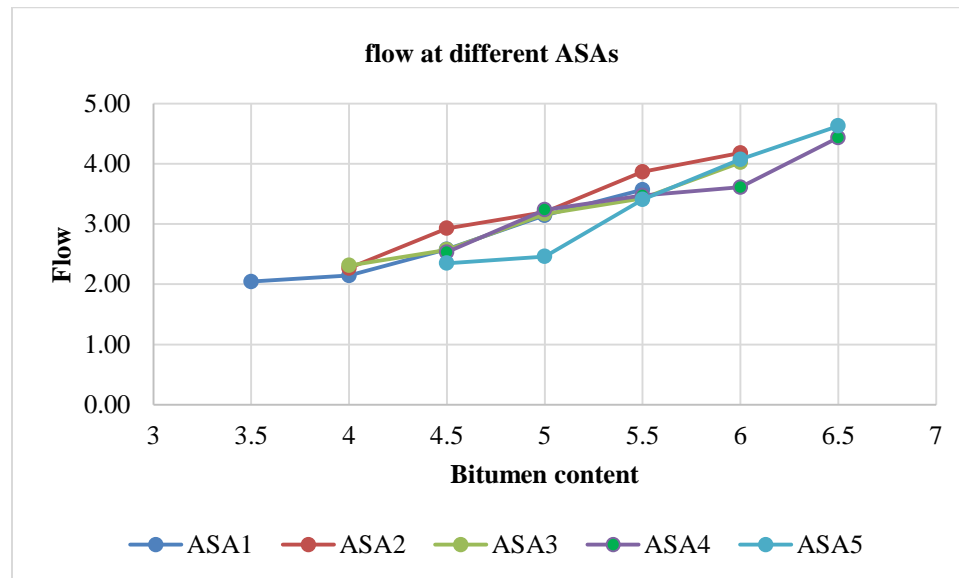


Figure 4: 9 the effect of ASA on Marshall Flow

4.6. The Effect of ASA on Moisture Susceptibility

This topic involved on the test result of prepared samples for moisture susceptibility of hot mix asphalt. The study was showed that the effects of ASA on the moisture damage of hot mix asphalt mixtures. The results of the tests were analyzed and compared the conditioning samples with control samples for different ASAs. The next sections describe the effect of ASA on moisture damage resistance and means of failure mechanisms.

4.6.1. Indirect Tensile Strength (AASHTO T283)

The 30 samples were prepared for different five ASAs as mention in the methodology to see the effect of ASA on the moisture susceptibility of hot mix asphalt mixture. The test results indicated that the aggregates used to hot mix asphalt mixture for high surface area produce high tensile stress resistance mixture. This is true when the mixture is free from moisture attack.

The result shows that aggregate surface area direct relation to tensile strength at the dry condition and inverse relation at the wet condition. At $3.12\text{m}^2/\text{kg}$ of ASA the mixture can resist up to

474.9kpa indirect tensile stress and at 9.64m²/kg of ASA the mixture resisted about 524.9kpa indirect tensile stress. This demonstrates that when the ASA used for HMA increases, the resistance of the indirect tensile strength also increases, for moisture not introduce into the mixture.

In another way, the surface area of the aggregate has an inverse relation to the indirect tensile strength of the hot mix asphalt after water conditioning. As seen from Table 1 below, the asphalt concrete indirect tensile resistance is the highest when the aggregate surface area is the lowest in the aggregate gradation specification limit band. At 3.12m²/kpa of ASA, the mixture after conditioning with water the indirect tensile stress resistance was reduced to 444.1m²/kpa. The reduction rate of the indirect tensile strength is increased at high SA of aggregate due to the moisture effect on the mixture. At 9.64m²/kg of ASA was highly reduced from 524.9kpa to 415.9kpa.

This indicates that the gradation of the aggregate used to wearing course is more susceptible to moisture damage due to the surface area increased. The gradations used to produce mixtures become fine and that required a greater amount of bitumen to coat the aggregate well and to improve durability, but this bitumen amount is controlled by the rutting property of the mixture. This means that added the amount of asphalt binder to achieve durability, the asphalt concrete exposed to rutting failure. The greatest reduction of ITS due to conditioning; eventually demonstrate the fine gradation of aggregate is poor performance in moisture damage. This reflects the thin asphalt film thickness in mixtures manufactured using such greatest ASA in wet conditions.

$$ITS = \frac{2 \times P}{\pi \times h \times D}$$

Where: ITS is the indirect tensile strength (kPa); P the maximum load (N); h the specimen thickness (mm); and D is the specimen diameter (mm).

Table 4: 5 the effect of ASA on ITS and TSR due to the presence of moisture

AASHTO T-283 Test result for five types of ASAs							
No	ASA	bitumen %	Dry sample		Conditioning sample		TSR
			tensile strength KN	ITS Kpa	tensile strength KN	ITS Kpa	
1	3.12	5	4.990	474.9	4.602	444.1	93.5
2	4.58	5	5.110	495.8	4.570	441.9	89.1
3	6.19	5.5	5.240	514.0	4.450	431.6	84.0
4	7.93	5.7	5.290	517.5	4.300	420.8	81.3
5	9.64	5.9	5.300	524.9	4.183	415.9	79.2

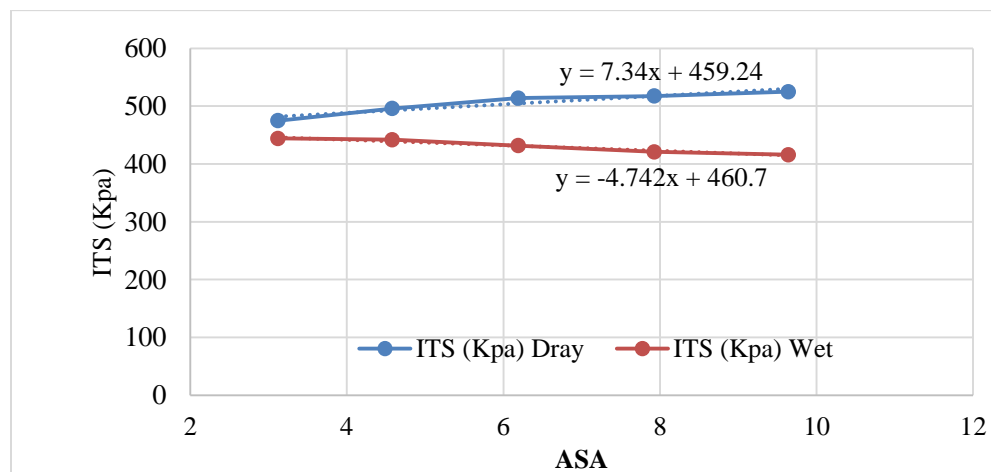


Figure 4: 10 AASHTO T283 test result of TSR and ITS in dry and wet condition

4.6.2. Tensile Strength Ratio (TSR)

The tensile strength ratio is one of the methods used to evaluate the moisture susceptibility of hot mix asphalt mixture. The mixtures were produced by using 3.12, 4.58, 6.19, 7.93, and 9.64 m²/kg of ASA. The mixtures have different moisture damage resistance due to variation of ASA as seen in the result. HMA prepared using higher ASA shows, the highest result for dry ITS and the greatest reduction due to water conditioning and eventually demonstrate the lowest TSR value. The performance of the mixture due to moisture was decreased caused by increment of ASA because this cause to produce thin asphalt film thinness that not resists stripping.

Even though the mixture moisture damage was affected by ASA, the mixture performance due to this variation was within the acceptable limit. When an asphalt mixture's TSR greater than or equal to 80 percent, the mixture not much sensitive to moisture damage. Almost all TSR calculated values were greater than or equal to 80%. So, all the mixture were produced at different ASA can use in wearing coarse construction, even performance variation appear due to water introduced into the asphalt pavement.

The researcher Sangsefidi et al (2016) result shows that the TSR at the lower, middle, and upper limit of the gradation band were 90%, 85%, and 74% respectively. This results difference may occur due to material variation. When the aggregate is limestone, the resistance of the moisture damage is higher than the granite. Because aggregate produced in limestone is hydrophilic, while granite is hydrophobic. Limestone not only forms strong adhesion boned but also used to modify the bitumen property. In general, the AASHTO T283 test was used to identify the sensitivity of the mixture and to measure the degree of damage induced in samples rather than giving any vision of the moisture susceptibility mechanism.

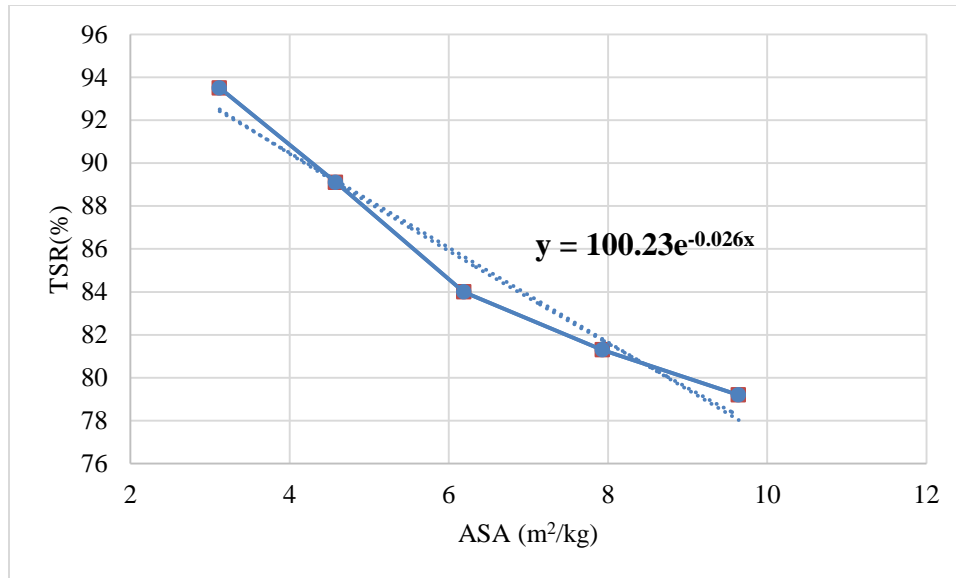


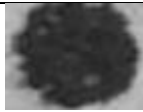

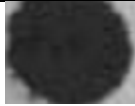


Figure 4: 11 AASHTO T 283 test Tensile strength ratio (TSR) result

4.6.3. Water Boiling Test

The percent reduction retains its original coating in the surface area of aggregate after water conditioning in the boiling water. This is used to estimate and used as an indication of the potential of HMA to fail by stripping. This test result is obtained based on observation of bitumen color.

The table1 indicates the Texas Boiling Test result, the color observed after boiling water condition as compared with sandaled rating board. The image observed in the test results was compared with the Texas Boiling Test Rating Board standard. The results lay between 80-90% and 90- 100% asphalt coated percent of retained in the aggregate surface. This observation is used to check moisture-related adhesion failure. Based on this result, ASA has an inverse relation to moisture resistance. When the ASA increases, the percent bitumen retained on the aggregate surface decrees, and this causes to stripe off the asphalt concert. The result of the AASHTOT-283 test relates to the water boiling test. Thus, the failure mechanism of the pavement is adhesion failure.

Table 4: 6 Texas Boiling water test result based on Texas Boiling Test Rating Board

ASA(m ² /kg)	Image after condition by comparing rating board	% coated bitumen retained
3.12		90-100
4.58		90-100
6.19		90-100
7.93		80-90
9.64		80-90

4.7. Select Optimum Aggregate Surface Area (OASA)

The materials used for the mixture production should be making the asphalt mixture well performance, economical, and balance all other properties. The material has the best result for one or more of the asphalt concrete performances not mean the material is good and select for asphalt pavement production purposes. Because the asphalt pavement may expose to premature failures due to one or more of the mix properties which are not satisfied with the limitation.

The aggregate particles used in this study have a different amount of ASA and that causes to alter the asphalt mixture properties either to best or to worst condition. As seen in the previous topic the indirect tensile strength at the dry condition better at higher ASA than lower ASA. On contrary, the indirect tensile strength at the wet condition the reverse is true. So, the aggregate gradation with 9.64m²/kg SA does not mean the best, even the tensile stress resistance of the mixture is the highest value at the dry condition. Thus, based on Marshall Stability and flow volumetric properties, moisture damage resistance, and economic aspect the preferable ASAs were 4.58 m²/kg and 6.19m²/kg for almost all mixture properties.

4.8. The Effect of ASA on Economic Analysis of HMA Mixture

In general, objective of the bituminous mix design is to determine an economical blend through several trial mixes. OBC is minimum for the lower ASA and maximum for the higher ASA i.e. OBC is increasing from lower to upper ASA within the gradation specification range. So, lower ASA with in limit is more economical in terms of bitumen content.

In general, the road type used in Ethiopia is mostly flexible pavement, especially dense graded asphalt pavement. From the road construction one third of AC cost taken by cost of bitumen. To save this economy use low aggregate surface area without loss the required performance of the hot mix asphalt.

The economic analysis of the mixture was done based on OBC by selecting 4.58m²/kg or 6.19m²/kg aggregate surface area from the others aggregate surface areas. When mixtures produced using 4.58m²/kg, 0.5%, 0.7% and 0.9% of bitumen saved from mixtures produced by using 6.19m²/kg, 7.93m²/kg and 9.64m²/kg respectively. On the other hand, the mixture produced using 6.19m²/kg ASA, save 0.2% and 0.4% of bitumen from 7.93m²/kg and 9.64m²/kg. This bitumen saved due to ASA variation is large when consider in a huge road project. This bitumen amount of bitumen saved shown in the Table 4.7. Therefore, by using appropriate ASA could save about 18% of bitumen from the total bitumen consumption to construct asphalt concrete.

Table 4: 7 The effect of ASA economic aspect

ASA(m ² /kg)	%OBC	Use ASA to produce mixture	If use other preferable ASA to be economical (m ² /kg)	%Bitumen saved in the total mix	% bitumen saved in the total consumption
3.12	5	6.19	4.58	0.5	10
4.58	5	7.93		0.7	14
6.19	5.5	9.64		0.9	18
7.93	5.7	7.93	6.19	0.2	3.6
9.64	5.9	9.64		0.4	7.3

4.9. The MINITAB Analysis Result of the Marshall Test

Table 4:8 The MINITAB result relation of ASA with Marshall Test results

No.	Response variable due to ASA variation	Fitted formula	Coefficient of determination (R^2)
1	OBC%	$Y_1 = 4.427 + 0.1642 x - 0.00089 x^2$	$R^2=94\%$
2	Gmb%	$Y^2=2.329+0.0345x-.002388x^2$	$R^2=84.1\%$
3	VMA%	$y_3 = 19.31 - 1.104 x + 0.06446 x^2$	$R^2=85.6\%$
4	VTM%	$Y_4 = 9.302 - 1.214 x + 0.05478 x^2$	$R^2=94.9\%$
5	VFA%	$y_5 = 57.27 + 2.807 x - 0.0242 x^2$	$R^2=98.4\%$
6	Stability (KN)	$y_6 = 8.896 + 0.1520 x - 0.02410 x^2$	$R^2=70.5\%$
7	Flow (mm)	$y_7 = 3.401 - 0.1880 x + 0.02844 x^2$	$R^2=96.1\%$
8	ITS in dry condition (kpa)	$y_8 = 415.1 + 23.26 x - 1.247 x^2$	$R^2=98.6\%$
9	ITS in wet condition (kpa)	$y_9 = 458.7 - 4.026 x - 0.0561 x^2$	$R^2=97.2\%$
10	TSR%	$y_{10} = 107.4 - 5.141 x + 0.2298 x^2$	$R^2=99.9\%$

As seen from the MINITAB analysis results the OBC has a relation to ASA with a correlation coefficient ($R^2=0.94$). This result showed that OBC has a high relationship with ASA. The volumetric properties of the mixtures have a significant relation with ASA variation as seen in the fitted equation. The volumetric properties of the mixtures have 84.1% to 98.4% correlation coefficient. This indicates that volumetric properties of the hot mix asphalt mixture depend on ASA.

The relationship between ASA and Marshall Stability and flow are 70.5% and 96.1% R^2 value respectively. Based on this analysis result, the effect of ASA on stability was not as much as flow. The flow value relates to rutting performance while stability related to the stiffness of asphalt mixture. Thus, rutting performance may greatly be affected by ASA than low-temperature cracking. The moisture resistance of hot mix asphalt mixture related to ASA significantly ($R^2=99.7\%$). Based on this relation the moisture resistance greatly depends on ASA. So, to keep the moisture damage of the asphalt pavement need to deserve the appropriate ASA in the mix design.

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study aims to determine the effect of ASA on the performance of HMA using the Marshall Mix design method and to analyze the effect of ASA variation on different hot mix asphalt properties. As a result of this study, the selection of ASA in the process of mixture design influences the performance of the mixture. By using the test results of this research, the following conclusions are drawn.

- 1) From the test result as the ASA increases, the optimum bitumen content increases. This is because higher ASA requires a high amount of bitumen to coat the aggregate. Hence the ASA has a direct relation with optimum binder content.
- 2) The volumetric properties of the hot mix asphalt mixture highly affected due to a small change of the aggregate surface area. The effect of aggregate surface area on the volumetric properties was concluded as the following individually.
 - The Gmb (bulk specific gravity in a compacted mixture) increases as ASA increases; because the voids in mineral aggregate are low for high ASA.
 - The voids in mineral aggregate (VMA) are decrease as ASA increases. This is due to the fact that the fillers (fine particles) fill the voids between coarse aggregate.
 - The air voids in the total mix (VTM) increases as the ASA decreases; since voids between coarse aggregates filled by fillers were lower than finer aggregate.
 - The voids filled with asphalt (VFA) increases as the ASA increases. This is due to the fact that some of the voids in the mineral aggregate are filled by asphalt.Therefore, ASA significantly alter the volumetric property of the mixture.
- 3) Marshall Stability and flow depending on the aggregate surface area. The Marshal stability of the HMA increases from ASA 3.12 m²/kg to ASA 6.19m²/Kg and decreases from 6.19m²/kg to 9.64m²/kg. Hence, maximum stability is obtained at ASA of 6.19m²/kg. While the flow of HMA increases as ASA increases. This is because fine

aggregates have less shear resistance due to low aggregate interlock (low internal aggregate friction).

- 4) Based on the results of Marshal Tests, $9.64\text{m}^2/\text{kg}$ of ASA is the most susceptible to moisture damage. The change in ASA not only affects the moisture performance but also can influence on moisture susceptibility mechanism. As a result, the selected aggregate surface area gets smaller; the "adhesion failure" becomes the dominant mechanism.
- 5) Based on this study, the preferable aggregate surface areas for asphalt concrete production are $4.58\text{m}^2/\text{kg}$ and $6.19\text{m}^2/\text{kg}$ in both hot mix asphalt performance and economic aspects. Therefore, a contractor can save up to a maximum of 18% bitumen content for the production of HMA at $9.64\text{m}^2/\text{kg}$ ASA as compared to $4.58\text{m}^2/\text{kg}$.

Generally, Overall results indicate that the aggregate surface area closer to the mid-value of the gradation has to be selected in the specification limit for the designing of bituminous mixes.

5.2. Recommendation

From the test results of this research the following recommendations are suggested.

1. The moisture resistance ability of the mixture in the aggregate gradation limit was different. The mixtures were produced in coarser gradation is better than fine gradation. Hence, it recommends that in gradation specification limit use coarser gradation than finer gradation to prevent moisture damage problems of the asphalt pavement roads. Especially, a road constructed in rainy and in near groundwater table region. But for dry environments and roads exposed to high stresses, asphalt pavements have to construct with higher aggregate surface area to improve the indirect tensile strength of the asphalt pavement by considering the rutting performance of the pavement.
2. The gradation within the gradation limit in the AI gradation envelope does not relate to the performance of asphalt concrete in the wearing course. The gradation found within the AI gradation limit does not give a guarantee for performance. It is also difficult to select the approver aggregate gradation set in the specification without conduct the tests. Hence, aggregate surface area should be included in addition to AI aggregate gradation limit to consider the performance of asphalt pavement such as durability and moisture resistance and

try to eliminate moisture sensitivity in the mix design process by reducing ASA in the mixture.

3. The large gape of the aggregate gradation specification limit allows the huge difference of mixture properties and moisture resistance. So, it is better minimizes the gap between the upper and lower limit by reducing percent passing of the upper limit gradation specification to be economical and HMA has high moisture resistance ability. Thus, contractors should use coarser gradation than finer aggregates gradation for the production of HMA.
4. The gradation used for mix design affects not only moisture resistance, but also can influence on moisture failure mechanism. It was observed that as selected gradation gets finer the "adhesion failure" becomes the dominant mechanism. It was observed that the resistance to moisture damage is largely affected by the aggregate surface area. Hence, it is recommended that use a lower aggregate surface area to prevent adhesion failure due to the presence of the water in the asphalt pavement. The mixture should be achieving the minimum requirement of the mix which is set in the ERA specification criteria and economic aspect. Thus, almost all criteria were satisfied in the middle limit of the gradation specification. This means to be economical and to produce a good performance of mixture use aggregate gradation with $6.19\text{m}^2/\text{kg}$ of aggregate surface area. The mixture at this aggregate surface area was durable and high moisture resistance.

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LIST OF APPENDICES

APPENDIX A: AGGREGATE MIX DESIGN (AGGREGATE SURFACE AREA)

Table1: Different aggregate gradation used in this study.

Five gradation limits in the specification band							
N o	Sieve size	% Passing rang	LL %PASS	UL %PASS	Middle % pass	b/n middle &LL % pass	b/n middle &UL %pass
1	19	100	100	100	100.0	100	100
2	12.5	90-100	90	100	95.0	92.5	97.5
3	9.5	...	...	...	...	...	...
4	4.75	44-74	44	74	59.0	51.5	66.5
5	2.36	28-58	28	58	43.0	35.5	50.5
6	1.18	...	...	...	...	...	...
7	0.6	....	....	....	....	....	....
8	0.3	5 to 21	5	21	13.0	9	17
9	0.15	...	.....	.....	....	....	....
10	0.075	2 to 10	2	10	6.0	4	8

Table 2: ASA1 aggregate gradation blending design

Sample 1 blending design						
No	Sieve size	LL % PASS	% Retained	Cumulative % retained	Amount of blending (Kg)	Blending amount in gram
1	19	100	....	...	...	...
2	12.5	90	10	10	0.12	120.0
3	9.5	...	....	....	...	...
4	4.75	44	46	56	0.552	552.0
5	2.36	28	16	72	0.192	192.0
6	1.18	...	...	...	...	...
7	0.6	...	...	...	...	...
8	0.3	5	23	95	0.276	276.0
9	0.15	...	...	...	....	...
10	0.075	2	3	98	0.036	36.0
Fillers					0.024	24.0
Sum					1.176	1200.0

Table 3: ASA2 aggregate gradation blending design

Sample 2 blending design						
No	Sieve size	LL % PASS	% Retained	Cumulative % retained	Amount of blending (Kg)	Blending amount in gram
1	19	100	0	0	0	0.0
2	12.5	92.5	7.5	7.5	0.09	90.0
3	9.5	0	0	0	0	0.0
4	4.75	51.5	41	48.5	0.492	492.0
5	2.36	35.5	16	64.5	0.192	192.0
6	1.18	0	0	0	0	0.0
7	0.6	0	0	0	0	0.0
8	0.3	9	26.5	91	0.318	318.0
9	0.15	0	0	0	0	0.0
10	0.075	4	5	96	0.06	60.0
Fillers					0.048	48.0
Sum					1.152	1200.0

Table 3: ASA3 aggregate gradation blending design

Sample 3 blending design						
No	Sieve size	LL % PASS	% Retained	Cumulative % retained	Amount of blending (Kg)	Blending amount in gram
1	19	100	...	...	...	...
2	12.5	95	5	5	0.06	60.0
3	9.5	...	...	...	...	...
4	4.75	59	36	41	0.432	432.0
5	2.36	43	16	57	0.192	192.0
6	1.18	...	....	....	...	...
7	0.6	....	....	....	....	....
8	0.3	13	30	87	0.36	360.0
9	0.15	....	....	....	....	....

10	0.075	6	7	94	0.084	84.0
Fillers					0.072	72.0
Sum					1.128	1200.0

Table 5: ASA4 aggregate gradation blending design

Sample 4 blending design						
No	Sieve size	LL % PASS	% Retained	Cumulative % retained	Amount of blending (Kg)	Blending amount in gram
1	19	100	....	.....	....	.....
2	12.5	97.5	2.5	2.5	0.03	30.0
3	9.5	....	...	...	...	...
4	4.75	66.5	31	33.5	0.372	372.0
5	2.36	50.5	16	49.5	0.192	192.0
6	1.18	...	...	...	...	...
7	0.6	...	...	...	...	...
8	0.3	17	33.5	83	0.402	402.0
9	0.15	...	...	...	...	...
10	0.075	8	9	92	0.108	108.0
Fillers					0.096	96.0
Sum					1.104	1200.0

Table 6: ASA5 aggregate gradation blending design

Sample 5 blending design						
No	Sieve size	LL % PASS	% Retained	Cumulative % retained	Amount of blending (Kg)	Blending amount in gram
1	19	100	0	0	0	0.0
2	12.5	100	0	0	0	0.0
3	9.5	...	...	...	...	...
4	4.75	74	26	26	0.312	312.0
5	2.36	58	16	42	0.192	192.0

6	1.18	...	...	...	...	...
7	0.6	...	...	...	...	...
8	0.3	21	37	79	0.444	444.0
9	0.15	...	...	...	...	...
10	0.075	10	11	90	0.132	132.0
Fillers					0.12	120.0
Sum					1.08	1200.0

Table 7: Aggregate gradation sieve analysis and ASA1 calculation

Sample 1 (ASA1)								
Sieve size (mm)	Sieve weight	Mass aggregate +Sieve Wt.	Mass of retained	% Retained	Cumulative % retained	% Pass	SAFm2/hg	ASAm2/kg
12.5	659.3	899.7	240.4	10.02	10.02	90.0		
9.5	683	938.6	255.6	10.65	20.67	80.0	0.41	0.41
4.75	748.4	1597.2	848.8	35.37	56.03	44.0	0.41	0.18
2.36	746.7	1130.9	384.2	16.01	72.04	28.0	0.82	0.23
1.18	618	873.9	255.9	10.66	82.70	17.0	1.64	0.28
0.6	605.2	786.3	181.1	7.55	90.25	9.0	2.87	0.26
0.3	574	686.4	112.4	4.68	94.93	5.0	6.14	0.31
0.15	570.7	574.1	3.4	0.14	95.08	4.0	12.29	0.49
0.075	541.2	608.8	67.6	2.82	97.89	2.0	32.77	0.66
Filler	288.3	338.9	50.6	2.11	100.00	0.0		
Sum			2400	ASA in m2/kg				3.12

Table 8: Aggregate gradation sieve analysis and ASA2 calculation

Sample 2 (ASA2)								
Sieve size (mm)	Sieve weight	Mass aggregate +Sieve Wt.	Mass of retained	% Retained	Cumulative % retained	% Pass	SAFm2/hg	ASAm2/kg
12.50	659.90	838.70	178.80	7.47	7.47	92.5		
9.50	684.00	922.40	238.40	9.95	17.42	83.0	0.41	0.41

4.75	750.30	1440.80	690.50	28.83	46.25	51.5	0.41	0.21
2.36	745.70	1177.00	431.30	18.01	64.26	35.5	0.82	0.29
1.18	616.60	885.90	269.30	11.24	75.50	24.0	1.64	0.39
0.60	599.20	822.80	223.60	9.34	84.84	15.0	2.87	0.43
0.30	573.90	725.00	151.10	6.31	91.15	9.0	6.14	0.55
0.15	570.90	583.80	12.90	0.54	91.69	8.0	12.29	0.98
\$0.075	541.20	652.40	111.20	4.64	96.33	4.0	32.77	1.31
Filler	288.30	386.20	97.90	4.09	100.42			
Sum			2405.00	ASA in m2/kg				4.58

Table 9: Aggregate gradation sieve analysis and ASA3 calculation

Sample 3 (ASA3)								
Sieve size (mm)	Sieve weight	Mass aggregate +Sieve Wt.	Mass of retained	% Retained	Cumulative % retained	% Pass	SAFm2/hg	ASAm2/kg
12.50	660.00	768.50	108.50	4.54	4.54	95.0		
9.50	683.80	891.40	207.60	8.69	13.22	86.0	0.41	0.41
4.75	753.10	1381.70	628.60	26.30	39.52	59.0	0.41	0.24
2.36	746.10	1161.60	415.50	17.38	56.90	43.0	0.82	0.35
1.18	617.90	920.00	302.10	12.64	69.54	30.0	1.64	0.49
0.60	604.80	852.40	247.60	10.36	79.90	20.0	2.87	0.57
0.30	574.00	738.30	164.30	6.87	86.78	13.0	6.14	0.80
0.15	570.90	602.80	31.90	1.33	88.11	11.0	12.29	1.35
\$0.075	541.40	681.70	140.30	5.87	93.98	6.0	32.77	1.97
Filler	288.40	432.30	143.90	6.02	100.00	0.0		
Sum			2390.30	ASA in m2/kg				6.19

Table 10: Aggregate gradation sieve analysis and ASA4 calculation

Sample 4 (ASA4)								
Sieve size (mm)	Sieve weight	Mass aggregate +Sieve Wt.	Mass of retained	% Retained	Cumulative % retained	% Pass	SAFm2/hg	ASAm2/kg
12.50	658.30	744.90	86.60	3.58	3.58	97.5		
9.50	684.50	821.10	136.60	5.64	9.22	90.0	0.41	0.41
4.75	753.80	1327.30	573.50	23.68	32.90	66.5	0.41	0.27
2.36	754.00	1160.90	406.90	16.80	49.70	50.5	0.82	0.41
1.18	617.90	932.90	315.00	13.01	62.71	37.0	1.64	0.61
0.60	604.80	887.50	282.70	11.67	74.38	25.0	2.87	0.72
0.30	573.70	776.60	202.90	8.38	82.76	17.0	6.14	1.04
0.15	570.90	603.10	32.20	1.33	84.09	15.0	12.29	1.84
\$0.075	541.30	731.30	190.00	7.85	91.94	8.0	32.77	2.62
Filler	288.40	483.60	195.20	8.06	100.00	0.0		
Sum			2421.60	ASA in m2/kg				7.93

Table 11: Aggregate gradation sieve analysis and ASA5 calculation

Sample 5 (ASA5)								
Sieve size (mm)	Sieve weight	Mass aggregate +Sieve Wt.	Mass of retained	% Retained	Cumulative % retained	% Pass	SAFm2/hg	ASAm2/kg
12.50	659.90	659.90	0.00	0.00	0.00	100.0		
9.50	681.10	842.20	161.10	6.72	6.72	93.0	0.41	0.41
4.75	753.70	1182.40	428.70	17.89	24.61	74.0	0.41	0.30
2.36	743.00	1154.50	411.50	17.17	41.79	58.0	0.82	0.48
1.18	618.00	983.40	365.40	15.25	57.04	42.0	1.64	0.69

0.60	604.10	903.40	299.30	12.49	69.53	30.0	2.87	0.86
0.30	573.70	791.40	217.70	9.09	78.61	21.0	6.14	1.29
0.15	569.70	616.00	46.30	1.93	80.54	19.0	12.29	2.34
\$0.075	541.30	763.30	222.00	9.26	89.81	10.0	32.77	3.28
Filler	288.40	532.60	244.20	10.19	100.00	0.0		
Sum			2396.20	ASA in m2/kg				9.64

Table 12: Summarized aggregate gradation percent passing and ASA calculation

Summarized Percent Passing and ASA											
Sieve Size (mm)	SAF	% Passing	ASA1	% passing	ASA2	% Passing	ASA3	% Passing	ASA4	% passing	ASA5
19	0	100		100		100		100		100	
12.5	0	90		92.50		95.00		97.50		100.00	
9.5	0.41	80	0.41	83.00	0.41	86.00	0.4	90.00	0.41	93.00	0.41
4.75	0.41	44	0.18	51.50	0.21	59.00	0.2	66.50	0.27	74.00	0.30
2.36	0.82	28	0.23	35.50	0.29	43.00	0.4	50.50	0.41	58.00	0.48
1.18	1.64	17	0.28	24.00	0.39	30.00	0.5	37.00	0.61	42.00	0.69
0.6	2.87	9	0.26	15.00	0.43	20.00	0.6	25.00	0.72	30.00	0.86
0.3	6.14	5	0.31	9.00	0.55	13.00	0.8	17.00	1.04	21.00	1.29
0.15	12.29	4	0.49	8.00	0.98	11.00	1.4	15.00	1.84	19.00	2.34
0.075	32.77	2	0.66	4.00	1.31	6.00	2.0	8.00	2.62	10.00	3.28
ASA in m2/kg			3.12		4.58		6.2		7.93		9.64

APPENDIX B: MARSHAL MIX TEST RESULT

Table 13: marshal mix test result for 3.12m²/Kg ASA

Test Results Obtained at ASA1 (3.12m ² /Kg)													
No.	Bitumen content	Dry wt	SSD wt	Suspension wt	Gmb	Gsb	Gse	Gmm	VMA	VIM	VFA	Stability	Flow
1	3.5	1235.0	1245.4	734.6	2.418	2.747	2.791	2.632	15.1	8.1	45.9	9.2	2.04
2	3.5	1183.3	1192.3	702.4	2.415	2.747	2.791	2.632	15.2	8.2	45.6	10.3	1.90
3	3.5	1219.2	1229.9	717.9	2.381	2.747	2.791	2.632	16.3	9.5	41.7	8.2	2.19
Average					2.405			2.632	15.5	8.6	44.4	9.2	2.04
1	4	1199.3	1209.7	709.3	2.397	2.747	2.791	2.611	16.2	8.2	49.4	9.5	1.90
2	4	1192.5	1201.7	707.4	2.412	2.747	2.791	2.611	15.7	7.6	51.5	10.2	2.31
3	4	1237.4	1246.0	734.0	2.417	2.747	2.791	2.611	15.5	7.4	52.1	8.3	2.22
Average					2.409			2.611	15.8	7.8	51.0	9.3	2.14
1	4.5	1228.1	1233.8	724.6	2.412	2.747	2.791	2.590	16.2	6.9	57.4	8.0	2.56
2	4.5	1246.9	1253.0	736.6	2.415	2.747	2.791	2.590	16.0	6.8	57.8	8.9	2.71
3	4.5	1243.9	1249.0	733.3	2.412	2.747	2.791	2.590	16.1	6.9	57.4	8.0	2.47
Average					2.413			2.590	16.1	6.8	57.5	8.3	2.58
1	5	1225.6	1233.5	721.8	2.395	2.747	2.791	2.570	17.2	6.8	60.5	9.6	3.12
2	5	1223.6	1230.7	727.5	2.432	2.747	2.791	2.570	15.9	5.4	66.3	9.4	3.08
3	5	1215.9	1223.9	720.5	2.415	2.747	2.791	2.570	16.5	6.0	63.5	7.7	3.23
Average					2.414			2.570	16.5	6.1	63.4	8.9	3.14

1	5.5	1241.9	1245.1	730.5	2.413	2.747	2.791	2.549	17.0	5.3	68.6	7.9	3.67
2	5.5	1243.2	1247.0	731.2	2.410	2.747	2.791	2.549	17.1	5.5	68.0	8.4	3.61
3	5.5	1244.1	1248.1	733.6	2.418	2.747	2.791	2.549	16.8	5.2	69.3	8.1	3.42
Average					2.414	2.747	2.791	2.549	17.0	5.3	68.6	8.1	3.6

Table 14: Marshall Test result Obtained at 4.58m²/Kg ASA

No.	Bitumen content	A	SSD B	C	Gmb	Gsb	Gse	Gmm	VMA	VIM	VFA	Stability	Flow
1	4	1232.0	1241.0	728.9	2.406	2.739	2.780	2.602	15.7	7.5	51.9	9.0	2.15
2	4	1234.0	1243.1	729.1	2.401	2.739	2.780	2.602	15.9	7.7	51.3	9.6	2.19
3	4	1227.9	1235.7	726.2	2.410	2.739	2.780	2.602	15.5	7.4	52.5	9.1	2.47
Average					2.406	2.739	2.780	2.602	15.7	7.5	51.9	9.24	2.27
1	4.5	1217.9	1227.0	723.2	2.417	2.739	2.780	2.581	15.7	6.4	59.6	9.1	2.98
2	4.5	1213.8	1222.3	718.3	2.408	2.739	2.780	2.581	16.0	6.7	58.2	9.4	2.85
3	4.5	1236.0	1243.9	736.2	2.435	2.739	2.780	2.581	15.1	5.7	62.4	9.6	2.95
Average					2.420	2.739	2.780	2.581	15.6	6.2	60.1	9.37	2.93
1	5	1238.3	1243.9	735.2	2.434	2.739	2.780	2.561	15.6	4.9	68.3	8.3	3.33
2	5	1231.4	1238.0	734.4	2.445	2.739	2.780	2.561	15.2	4.5	70.3	8.6	2.95
3	5	1234.7	1239.9	735.4	2.447	2.739	2.780	2.561	15.1	4.4	70.7	8.7	3.33
Average					2.442	2.739	2.780	2.561	15.3	4.6	69.8	8.53	3.20
1	5.5	1222.5	1229.4	729.2	2.444	2.739	2.780	2.541	15.7	3.8	75.7	8.3	3.99
2	5.5	1243.2	1252.1	742.2	2.438	2.739	2.780	2.541	15.9	4.0	74.6	7.2	3.71

3	5.5	1255.3	1263.5	749.6	2.443	2.739	2.780	2.541	15.7	3.9	75.5	7.8	3.90
Average					2.442	2.739	2.780	2.541	15.8	3.9	75.2	7.75	3.87
1	6	1214.5	1221.9	724.0	2.439	2.739	2.780	2.521	16.3	3.2	80.1	5.8	4.28
2	6	1221.5	1228.9	728.7	2.442	2.739	2.780	2.521	16.2	3.1	80.6	7.3	4.18
3	6	1256.4	1263.3	748.5	2.441	2.739	2.780	2.521	16.2	3.2	80.4	8.0	4.09
Average					2.441	2.739	2.780	2.521	16.2	3.2	80.4	7.02	4.18

Table 15: Marshall Test result Obtained at 6.19m²/Kg ASA

No.	Bitumen content	A	SSD B	C	Gmb	Gsb	Gse	Gmm	VMA	VIM	VFA	Stability	Flow
1	4	1211.9	1222.8	722.4	2.422	2.730	2.795	2.614	14.8	7.4	50.3	12.2	2.00
2	4	1226.3	1237.3	730.7	2.421	2.730	2.795	2.614	14.9	7.4	50.2	12.8	2.22
3	4	1223.6	1233.7	729.6	2.427	2.730	2.795	2.614	14.6	7.2	51.1	11.9	2.72
Average					2.423			2.614	14.8	7.3	50.5	12.3	2.31
1	4.5	1248.9	1258.5	744.2	2.429	2.730	2.795	2.593	15.0	6.4	57.7	8.9	2.59
2	4.5	1231.3	1239.8	734.4	2.436	2.730	2.795	2.593	14.8	6.1	59.0	10.0	2.47
3	4.5	1235.9	1243.2	737.1	2.442	2.730	2.795	2.593	14.6	5.8	59.9	9.8	2.65
Average					2.436			2.593	14.8	6.1	58.9	9.6	2.57
1	5	1255.5	1262.7	749.6	2.447	2.730	2.795	2.573	14.9	4.9	67.0	9.2	3.04
2	5	1247.5	1255.8	744.7	2.441	2.730	2.795	2.573	15.1	5.1	65.9	9.0	3.33
3	5	1239.2	1246.3	739.6	2.446	2.730	2.795	2.573	14.9	4.9	66.8	9.8	3.14

Average					2.444			2.573	14.9	5.0	66.6	9.3	3.17
1	5.5	1245.4	1251.5	742.6	2.447	2.730	2.795	2.553	15.3	4.1	73.0	9.4	3.42
2	5.5	1236.7	1243.2	737.3	2.445	2.730	2.795	2.553	15.4	4.2	72.5	9.9	3.32
3	5.5	1245.9	1252.8	743.7	2.447	2.730	2.795	2.553	15.3	4.1	73.0	10.4	3.54
Average					2.446			2.553	15.3	4.2	72.8	9.9	3.43
1	6	1248.4	1254.3	744.6	2.450	2.730	2.795	2.533	15.7	3.3	79.0	7.8	4.18
2	6	1239.9	1245.9	739.5	2.448	2.730	2.795	2.533	15.7	3.3	78.8	8.6	3.99
3	6	1258.6	1265.6	749.8	2.440	2.730	2.795	2.533	16.0	3.7	77.1	7.5	3.90
Average					2.446			2.533	15.8	3.4	78.3	8.0	4.02

Table 16: Marshall Test result Obtained at 7.93m²/Kg ASA

No.	Bitumen content	A	SSD B	C	Gmb	Gsb	Gse	Gmm	VMA	VIM	VFA	Stablity	Flow
1	4.5	1223.7	1229.9	723.7	2.417	2.697	2.770	2.573	14.4	6.0	58.0	10.1	2.66
2	4.5	1238.7	1244.5	736.1	2.437	2.697	2.770	2.573	13.7	5.3	61.4	9.6	2.38
3	4.5	1232.9	1238.2	733.4	2.442	2.697	2.770	2.573	13.5	5.1	62.5	9.7	2.57
Average					2.432		2.770	2.573	13.9	5.5	60.6	9.79	2.53
1	5	1251.9	1257.2	743.0	2.434	2.697	2.770	2.553	14.3	4.6	67.4	10.4	3.51
2	5	1248.3	1251.3	740.2	2.442	2.697	2.770	2.553	14.0	4.3	69.1	9.7	3.04
3	5	1243.4	1248.7	738.8	2.438	2.697	2.770	2.553	14.1	4.5	68.3	10.3	3.16
Average					2.438		2.770	2.553	14.1	4.5	68.3	10.11	3.24

1	5.5	1232.9	1236.5	732.3	2.445	2.697	2.770	2.533	14.3	3.5	75.8	7.7	3.48
2	5.5	1251.6	1254.2	743.7	2.452	2.697	2.770	2.533	14.1	3.2	77.3	7.9	3.51
3	5.5	1245.4	1250.0	740.8	2.446	2.697	2.770	2.533	14.3	3.4	75.9	9.0	3.43
Average					2.447		2.770	2.533	14.2	3.4	76.3	8.22	3.47
1	6	1238.1	1241.0	736.5	2.454	2.697	2.770	2.513	14.5	2.4	83.6	8.1	3.71
2	6	1235.5	1239.2	733.4	2.443	2.697	2.770	2.513	14.9	2.8	81.1	7.3	3.23
3	6	1247.7	1251.2	742.7	2.454	2.697	2.770	2.513	14.5	2.4	83.6	7.6	3.90
Average					2.450		2.770	2.513	14.6	2.5	82.8	7.66	3.61
1	6.5	1258.7	1263.6	747.9	2.441	2.697	2.770	2.494	15.4	2.1	86.2	6.8	4.09
2	6.5	1232.2	1236.2	734.4	2.456	2.697	2.770	2.494	14.9	1.5	89.6	6.7	4.94
3	6.5	1235.2	1239.7	735.5	2.450	2.697	2.770	2.494	15.1	1.8	88.3	7.5	4.28
Average					2.449		2.770	2.494	15.1	1.8	88.0	7.01	4.43

Table 17: Marshall Test result Obtained at 9.64m²/Kg ASA

No.	Bitumen content	A	SSD B	C	Gmb	Gsb	Gse	Gmm	VMA	VIM	VFA	Stablity	Flow
1	4.5	1225.5	1231.3	730.7	2.448	2.688	2.762	2.566	13.0	4.6	64.6	11.8	2.57
2	4.5	1230.3	1236.6	733.6	2.446	2.688	2.762	2.566	13.1	4.7	64.2	11.3	2.09
3	4.5	1201.5	1206.9	716.5	2.450	2.688	2.762	2.566	13.0	4.5	65.0	9.4	2.39
Average					2.448			2.566	13.0	4.6	64.6	10.81	2.35
1	5	1208.1	1214.3	720.6	2.447	2.688	2.762	2.546	13.5	3.9	71.2	10.6	2.10

2	5	1240.2	1244.1	738.9	2.455	2.688	2.762	2.546	13.2	3.6	72.9	9.3	1.81
3	5	1237.0	1242.9	737.6	2.448	2.688	2.762	2.546	13.5	3.9	71.4	11.2	3.48
Average					2.450			2.546	13.4	3.8	71.8	10.35	2.46
1	5.5	1222.3	1227.3	728.2	2.449	2.688	2.762	2.527	13.9	3.1	77.9	8.2	3.52
2	5.5	1229.5	1234.5	732.3	2.448	2.688	2.762	2.527	13.9	3.1	77.8	7.6	3.42
3	5.5	1216.7	1220.7	725.6	2.457	2.688	2.762	2.527	13.6	2.7	79.9	7.9	3.29
Average					2.452			2.527	13.8	3.0	78.5	7.89	3.41
1	6	1213.3	1219.5	722.7	2.442	2.688	2.762	2.507	14.6	2.6	82.3	8.6	4.15
2	6	1221.6	1227.3	728.5	2.449	2.688	2.762	2.507	14.4	2.3	83.9	7.8	4.09
3	6	1219.7	1225.2	727.4	2.450	2.688	2.762	2.507	14.3	2.3	84.1	8.7	3.99
Average					2.447			2.507	14.4	2.4	83.4	8.09	4.07
1	6.5	1222.7	1230.3	728.4	2.436	2.688	2.762	2.488	15.3	2.1	86.4	6.6	4.59
2	6.5	1220.9	1227.2	727.3	2.442	2.688	2.762	2.488	15.0	1.8	87.8	7.1	4.37
3	6.5	1226.2	1231.7	730.9	2.449	2.688	2.762	2.488	14.8	1.6	89.3	7.6	4.93
Average					2.442	2.688	2.762	2.488	15.0	1.8	87.8	7.1	4.6

Table 18: Marshall Test result at optimum binder content (OBC)

ASA	No.	OBC (%)	dry wt	SSD B	wt in water	Gsb	Gse	Gmm	Gmb	VMA	VIM	VFA	Stability	flow
for 3.2 m ² /kg	1	5.0	1226.3	1234.0	722.1	2.747	2.791	2.570	2.396	17.2	6.8	64.0	9.12	3.02
	2	5.0	1224.1	1231.1	727.8	2.747	2.791	2.570	2.432	15.9	5.4	66.3	10.22	2.94
	3	5.0	1237.3	1246.1	729.9	2.747	2.791	2.570	2.397	17.1	6.7	65.2	8.24	3.22
	Average								2.408	16.7	6.3	65.2	9.19	3.06
for 4.58 m ² /kg	1	5.0	1243.0	1247.3	740.0	2.739	2.780	2.561	2.450	15.0	4.3	71.3	9.02	3.22
	2	5.0	1241.3	1248.2	739.1	2.739	2.780	2.561	2.438	15.4	4.8	69.0	8.31	2.95
	3	5.0	1235.1	1240.3	737.5	2.739	2.780	2.561	2.456	14.8	4.1	72.5	9.20	3.31
	Average								2.447	15.1	4.4	70.9	8.84	3.16
for 6.93 m ² /kg	1	5.5	1241.3	1247.2	739.9	2.730	2.795	2.553	2.447	15.3	4.1	72.9	9.42	3.42
	2	5.5	1240.2	1246.6	738.8	2.730	2.795	2.553	2.442	15.5	4.3	72.1	9.90	3.32
	3	5.5	1239.2	1243.1	738.8	2.730	2.795	2.553	2.457	14.9	3.7	75.0	10.41	3.54
	Average								2.449	15.2	4.1	73.3	9.91	3.43
for 7.19 m ² /kg	1	5.7	1227.0	1229.8	728.5	2.697	2.770	2.524	2.448	14.4	3.0	79.0	9.67	3.61
	2	5.7	1247.4	1250.3	739.3	2.697	2.770	2.524	2.441	14.7	3.3	77.6	7.50	3.37
	3	5.7	1238.1	1241.8	732.6	2.697	2.770	2.524	2.431	15.0	3.7	75.5	7.75	3.67
	Average								2.446	14.7	3.3	77.4	8.31	3.55
for 9.64 m ² /kg	1	5.9	1224.9	1227.3	725.8	2.688	2.762	2.507	2.442	14.6	2.6	82.3	8.00	4.15
	2	5.9	1230.6	1235.8	732.3	2.688	2.762	2.507	2.444	14.5	2.5	82.7	8.70	4.09
	3	5.9	1225.9	1229.3	727.4	2.688	2.762	2.507	2.443	14.6	2.6	82.3	7.90	3.99
	Average								2.443	14.6	2.6	82.5	8.20	4.29

APPENDIX C: MOISTURE SENSITIVITY TEST RESULT

	N o.	Bitumen content	A	B	C	Gmb	Gsb	Gse	Gmm	Pba	Pbe	VMA	VIM	VFA
Dry sample for ASA1	1	5	1237.3	1246.1	729.9	2.397	2.747	2.791	2.570	0.6	4.4	17.1	6.7	60.7
	2	5	1229.7	1242.3	722.1	2.364	2.747	2.791	2.570	0.6	4.4	18.2	8.0	56.1
	3	5	1211.7	1224.4	712	2.365	2.747	2.791	2.570	0.6	4.4	18.2	8.0	56.2
	Average					2.375	2.747	2.791	2.570	0.6	4.4	17.9	7.6	57.7
Water conditioning for ASA1	1	5	1238.3	1249.1	728.4	2.378	2.747	2.791	2.570	0.6	4.4	17.8	7.5	58.0
	2	5	1243.6	1255.2	731.2	2.373	2.747	2.791	2.570	0.6	4.4	17.9	7.6	57.4
	3	5	1219.7	1230.4	717.3	2.377	2.747	2.791	2.570	0.6	4.4	17.8	7.5	57.9
	Average					2.376	2.747	2.791	2.570	0.6	4.4	17.8	7.5	57.8
Dry sample for ASA4	1	5	1238	1248.4	726.7	2.373	2.739	2.780	2.561	0.6	4.5	17.7	7.3	58.6
	2	5	1243	1253	730.8	2.380	2.739	2.780	2.561	0.6	4.5	17.4	7.0	59.6
	3	5	1217	1226.6	715.1	2.379	2.739	2.780	2.561	0.6	4.5	17.5	7.1	59.4
	Average					2.378	2.739	2.780	2.561	0.6	4.5	17.5	7.2	59.2
Water conditioning for ASA2	1	5	1228.7	1237.8	721.5	2.380	2.739	2.780	2.561	0.6	4.5	17.5	7.1	59.5
	2	5	1222.5	1232.8	717.4	2.372	2.739	2.780	2.561	0.6	4.5	17.7	7.4	58.4
	3	5	1227.3	1236.8	720.8	2.378	2.739	2.780	2.561	0.6	4.5	17.5	7.1	59.3
	Average					2.377	2.739	2.780	2.561	0.6	4.5	17.6	7.2	59.1
Dry sample for ASA3	1	5.5	1240.2	1251	730.8	2.384	2.730	2.795	2.553	0.9	4.7	17.5	6.6	62.2
	2	5.5	1240.8	1251.2	730.7	2.384	2.676	2.795	2.553	1.6	4.0	15.8	6.6	58.2
	3	5.5	1224.9	1234.4	720.5	2.384	2.676	2.795	2.553	1.6	4.0	15.8	6.6	58.2

	Average					2.384	2.694	2.795	2.553	1.4	4.2	16.4	6.6	59.5
Water conditioning for ASA3	1	5.5	1252.4	1262.4	737.8	2.387	2.730	2.795	2.553	0.9	4.7	17.4	6.5	62.7
	2	5.5	1243	1253.2	731	2.380	2.730	2.795	2.553	0.9	4.7	17.6	6.7	61.7
	3	5.5	1239.1	1249.5	730.2	2.386	2.730	2.795	2.553	0.9	4.7	17.4	6.5	62.5
	Average					2.385	2.730	2.795	2.553	0.9	4.7	17.5	6.6	62.3
Dry sample for ASA4	1	5.7	1229.5	1239.6	719.3	2.363	2.697	2.770	2.525	1.0	4.8	17.4	6.4	63.1
	2	5.7	1246.6	1257.6	729.7	2.361	2.676	2.770	2.525	1.3	4.5	16.8	6.5	61.4
	3	5.7	1227	1237	717.8	2.363	2.676	2.770	2.525	1.3	4.5	16.7	6.4	61.7
	Average					2.363	2.683	2.770	2.525	1.2	4.6	17.0	6.4	62.1
Water conditioning for ASA4	1	5.7	1210.9	1221.8	708.7	2.360	2.697	2.770	2.525	1.0	4.8	17.5	6.5	62.6
	2	5.7	1246.5	1256.2	729.1	2.365	2.697	2.770	2.525	1.0	4.8	17.3	6.3	63.4
	3	5.7	1230.4	1241.8	720.4	2.360	2.697	2.770	2.525	1.0	4.8	17.5	6.5	62.6
	Average					2.362	2.697	2.770	2.525	1.0	4.8	17.4	6.5	62.9
Dry sample for ASA5	1	5.9	1232	1243	720.9	2.360	2.688	2.762	2.511	1.0	4.9	17.4	6.0	65.4
	2	5.9	1251.4	1262	731.5	2.359	2.688	2.762	2.511	1.0	4.9	17.4	6.1	65.2
	3	5.9	1230.6	1241	720	2.362	2.688	2.762	2.511	1.0	4.9	17.3	5.9	65.7
	Average					2.360	2.688	2.762	2.511	1.022	4.939	17.375	6.0	65.449
Water conditioning for ASA5	1	5.9	1248	1257.3	729.8	2.366	2.688	2.762	2.511	1.0	4.9	17.2	5.8	66.4
	2	5.9	1241	1252	725.9	2.359	2.688	2.762	2.511	1.0	4.9	17.4	6.1	65.2
	3	5.9	1220.1	1229	713.6	2.367	2.688	2.762	2.511	1.0	4.9	17.1	5.7	66.6
	Average					2.364	2.688	2.762	2.511	1.022	4.939	17.242	5.9	66.065

Table20. Prepared samples' properties for moisture test

	N o.	Bitum en Conte nt	A	B	C	abs o	Gm b	Gsb	Gse	Gm m	Pba	Pbe	VM A	VI M	VFA	Volum e of specim en E (Cm3)	Va cm3	Absorb ed J (Cm3)	Saturati on (%)
Water condition ing sample for ASA1	1	5	1238 .3	1285 .8	743 .1	8.8	2.2 82	2.7 47	2.7 91	2.57 0	0.6	4.4	21.1	11. 2	46.9	542.7	60.8	47.5	78.1
	2	5	1243 .6	1289 .3	746	8.4	2.2 89	2.7 47	2.7 91	2.57 0	0.6	4.4	20.8	10. 9	47.6	543.3	59.3	45.7	77.0
	3	5	1219 .7	1271 .2	732	9.6	2.2 62	2.7 47	2.7 91	2.57 0	0.6	4.4	21.8	12. 0	45.0	539.2	64.5	51.5	79.8
	Average					8.9	2.2 78	2.7 47	2.7 91	2.57 0	0.6	4.4	21.2	11. 4	46.5	541.7	61.6	48.2	78.3
Water condition ing sample for ASA2	1	5	1228 .7	1269 .3	731 .7	7.6	2.2 86	2.7 39	2.7 80	2.56 1	0.6	4.5	20.7	10. 7	48.1	537.6	57.8	40.6	70.3
	2	5	1222 .5	1261 .5	728 .2	7.3	2.2 92	2.7 39	2.7 80	2.56 1	0.6	4.5	20.5	10. 5	48.8	533.3	55.9	39.0	69.8
	3	5	1227 .3	1270 .8	730 .4	8.0	2.2 71	2.7 39	2.7 80	2.56 1	0.6	4.5	21.2	11. 3	46.7	540.4	61.1	43.5	71.2
	Average					7.6	2.2 83	2.7 39	2.7 80	2.56 1	0.6	4.5	20.8	10. 8	47.9	537.1	58.3	41.0	70.4
Water condition ing sample for ASA3	1	5.5	1252 .4	1282 .6	741 .3	5.6	2.3 14	2.7 30	2.7 95	2.55 3	0.9	4.7	19.9	9.4	53.0	541.3	50.7	30.2	59.6
	2	5.5	1243	1275 .2	737 .2	6.0	2.3 10	2.7 30	2.7 95	2.55 3	0.9	4.7	20.0	9.5	52.6	538.0	51.0	32.2	63.1
	3	5.5	1239 .1	1270 .1	734 .9	5.8	2.3 15	2.7 30	2.7 95	2.55 3	0.9	4.7	19.9	9.3	53.2	535.2	49.8	31.0	62.3
	Average					5.8	2.3 13	2.7 30	2.7 95	2.55 3	0.9	4.7	19.9	9.4	52.9	538.2	50.5	31.1	61.7

Water condition ing sample for ASA4	1	5.7	1210 .9	1233 .3	715 .7	4.3	2.3 39	2.6 97	2.7 70	2.52 5	1.0	4.8	18.2	7.3	59.6	517.6	38.0	22.4	58.9
	2	5.7	1246 .5	1268 .4	737 .5	4.1	2.3 48	2.6 97	2.7 70	2.52 5	1.0	4.8	17.9	7.0	60.8	530.9	37.2	21.9	58.8
	3	5.7	1230 .4	1254 .8	726 .6	4.6	2.3 29	2.6 97	2.7 70	2.52 5	1.0	4.8	18.6	7.7	58.3	528.2	40.9	24.4	59.6
	Average					4.4	2.3 39	2.6 97	2.7 70	2.52 5	1.0	4.8	18.2	7.4	59.6	525.6	38.7	22.9	59.1
Water condition ing sample for ASA5	1	5.9	1248	1270 .8	732 .9	4.2	2.3 20	2.6 88	2.7 62	2.51 1	1.0	4.9	18.8	7.6	59.5	537.9	40.9	22.8	55.8
	2	5.9	1241	1263 .4	730 .4	4.2	2.3 28	2.6 88	2.7 62	2.51 1	1.0	4.9	18.5	7.3	60.7	533.0	38.8	22.4	57.8
	3	5.9	1220 .1	1241 .6	716 .2	4.1	2.3 22	2.6 88	2.7 62	2.51 1	1.0	4.9	18.7	7.5	59.8	525.4	39.5	21.5	54.4
	Average					4.1 78	2.3 24	2.6 88	2.7 62	2.51 1	1.0 22	4.9 39	18.6 58	7.5	60.0 06	532.10 0	39.7 09	22.233	56.004

	No.	Bitumen Content	A	B	C	abso	Gmb	Gsb	Gse	Gmm	Pba	Pbe	VMA	VIM	VFA	Volume of specimen E (Cm3)	Va cm3	Absorbed J (Cm3)	Satura tion (%)
Water conditioning sample for ASA1	1	5	1238.3	1285.8	743.1	8.8	2.282	2.747	2.791	2.570	0.6	4.4	21.1	11.2	46.9	542.7	60.8	47.5	78.1
	2	5	1243.6	1289.3	746	8.4	2.289	2.747	2.791	2.570	0.6	4.4	20.8	10.9	47.6	543.3	59.3	45.7	77.0
	3	5	1219.7	1271.2	732	9.6	2.262	2.747	2.791	2.570	0.6	4.4	21.8	12.0	45.0	539.2	64.5	51.5	79.8
	Average					8.9	2.278	2.747	2.791	2.570	0.6	4.4	21.2	11.4	46.5	541.7	61.6	48.2	78.3
Water conditioning sample for ASA2	1	5	1228.7	1269.3	731.7	7.6	2.286	2.739	2.780	2.561	0.6	4.5	20.7	10.7	48.1	537.6	57.8	40.6	70.3
	2	5	1222.5	1261.5	728.2	7.3	2.292	2.739	2.780	2.561	0.6	4.5	20.5	10.5	48.8	533.3	55.9	39.0	69.8
	3	5	1227.3	1270.8	730.4	8.0	2.271	2.739	2.780	2.561	0.6	4.5	21.2	11.3	46.7	540.4	61.1	43.5	71.2
	Average					7.6	2.283	2.739	2.780	2.561	0.6	4.5	20.8	10.8	47.9	537.1	58.3	41.0	70.4
Water conditioning sample for ASA3	1	5.5	1252.4	1282.6	741.3	5.6	2.314	2.730	2.795	2.553	0.9	4.7	19.9	9.4	53.0	541.3	50.7	30.2	59.6
	2	5.5	1243	1275.2	737.2	6.0	2.310	2.730	2.795	2.553	0.9	4.7	20.0	9.5	52.6	538.0	51.0	32.2	63.1
	3	5.5	1239.1	1270.1	734.9	5.8	2.315	2.730	2.795	2.553	0.9	4.7	19.9	9.3	53.2	535.2	49.8	31.0	62.3
	Average					5.8	2.313	2.730	2.795	2.553	0.9	4.7	19.9	9.4	52.9	538.2	50.5	31.1	61.7
Water conditioning sample for ASA4	1	5.7	1210.9	1233.3	715.7	4.3	2.339	2.697	2.770	2.525	1.0	4.8	18.2	7.3	59.6	517.6	38.0	22.4	58.9
	2	5.7	1246.5	1268.4	737.5	4.1	2.348	2.697	2.770	2.525	1.0	4.8	17.9	7.0	60.8	530.9	37.2	21.9	58.8
	3	5.7	1230.4	1254.8	726.6	4.6	2.329	2.697	2.770	2.525	1.0	4.8	18.6	7.7	58.3	528.2	40.9	24.4	59.6
	Average					4.4	2.339	2.697	2.770	2.525	1.0	4.8	18.2	7.4	59.6	525.6	38.7	22.9	59.1
Water conditioning sample for ASA5	1	5.9	1248	1270.8	732.9	4.2	2.320	2.688	2.762	2.511	1.0	4.9	18.8	7.6	59.5	537.9	40.9	22.8	55.8
	2	5.9	1241	1263.4	730.4	4.2	2.328	2.688	2.762	2.511	1.0	4.9	18.5	7.3	60.7	533.0	38.8	22.4	57.8
	3	5.9	1220.1	1241.6	716.2	4.1	2.322	2.688	2.762	2.511	1.0	4.9	18.7	7.5	59.8	525.4	39.5	21.5	54.4
	Average					4.178	2.324	2.688	2.762	2.511	1.022	4.939	18.658	7.5	60.006	532.100	39.709	22.233	56.004

Table21. Modified Lottman Test Result

TSR Determination															
Dry sample								Saturated sample							TSR
	No.	Bitumen Content	A	t (mm)	D (mm)	Tensile strength (KN)	ITS (Kpa)	No.	Bitumen Content	A	t (mm)	D (mm)	Tensile strength (KN)	ITS (KPa)	
ASA1	1	5	1237.3	65.0	102.0	4.80	461.5	1	5	1237.3	65.0	102.0	4.57	438.6	95.0
	2	5	1229.7	66.0	102.0	5.19	491.0	2	5	1243.6	66.0	102.0	4.89	462.7	94.2
	3	5	1211.7	66.0	102.0	4.99	472.0	3	5	1102.7	63.0	102.0	4.35	431.2	91.3
	Average					4.99	474.9						4.60	444.1	93.5
ASA2	1	5	1238	65.0	102.0	5.01	481.3	1	5	1228.7	65.0	102.0	4.50	432.7	89.9
	2	5	1243	64.0	102.0	5.23	510.3	2	5	1222.5	64.0	102.0	4.87	475.2	93.1
	3	5	1217	64.0	102.0	5.08	495.7	3	5	1227.3	65.0	102.0	4.35	417.9	84.3
	Average					5.11	495.8						4.57	441.9	89.1
ASA3	1	5.5	1240.2	64.0	102.0	5.29	516.1	1	5.5	1252.4	65.0	102.0	4.55	436.8	84.6
	2	5.5	1240.8	64.0	102.0	5.19	506.4	2	5.5	1243	64.0	102.0	4.48	437.1	86.3
	3	5.5	1224.9	63.0	102.0	5.24	518.9	3	5.5	1239.1	64.0	102.0	4.31	420.9	81.1
	Average					5.24	513.8						4.45	431.6	84.0
ASA4	1	5.7	1229.5	64.0	102.0	5.34	521.0	1	5.7	1210.9	63.0	102.0	4.26	422.0	81.0
	2	5.7	1246.6	64.5	102.0	5.38	520.9	2	5.7	1246.5	64.5	102.0	4.84	468.6	90.0

	3	5.7	1227	63.0	102.0	5.15	510.5	3	5.7	1230.4	64.0	102.0	3.81	371.7	72.8
	Average					5.29	517.5						4.30	420.8	81.3
ASA5	1	5.9	1232	62.0	102.0	5.18	521.5	1	5.9	1248	64.0	102.0	4.31	420.5	80.6
	2	5.9	1251.4	64.0	102.0	5.41	528.0	2	5.9	1240	63.0	102.0	3.95	391.5	74.2
	3	5.9	1230.6	63.0	102.0	5.30	525.3	3	5.9	1220.1	61.5	102.0	4.29	435.6	82.9
	Average					5.30	524.9						4.18	415.9	79.2