ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

GRADUATE STUDIES

VOLUMETRIC AND PERFORMANCE COMPARISON OF FIELD PRODUCED LAB COMPACTED AND LABORATORY PRODUCED LAB COMPACTED HOT MIX ASPHALT MIXTURES: A CASE STUDY ON THREE ROAD PROJECTS IN ADDIS ABABA

BY

YONAS DESSIYE ZEWDE

A Thesis Submitted to the School of Graduate Studies in partial fulfillment of the Requirements for Degree of Master of Science in Civil Engineering

(Road and Transport Engineering)

Advisor

DR. ROBEAM SOLOMON

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DECLARATION

I the undersigned certify that this research work entitled "Volumetric and Performance Comparison of Field Produced Lab Compacted and Laboratory Produced Lab Compacted Hot Mix Asphalt Mixtures: A Case Study On Three Road Projects In Addis Ababa" is my own work. The work has not been presented to any University or Institute for assessment. Materials that have been used from other sources has been properly acknowledge or referred.

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List of Abbreviations

AASHTO	American Association State Highway and Transportation officials
AC	Asphalt Concrete
ASTM	American Society for Testing and Materials
DOT	Department of Transportation
ERA	Ethiopian Road Authority
FHWA	Federal Highway Administration
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel-Tracking Test
OBC	Optimum Binder Content
SSD	Saturated Surface Dry
SHRP	Strategic Highway Research Program
Superpave	Superior Performing Pavement
SGC	Superpave Gyratory Compactor
TxDoT	Texas Department of Transport

ABSTRACT

The aim of this study was to compare the mixture volumetric and performance of lab produced lab compacted and field produced lab compacted asphalt mixtures in terms of Marshal flow and stability (for Marshal samples), rutting and moisture sensitivity together with checking bitumen and aggregate qualities. In doing so, loose asphalt mixtures ready to be paved was collected from selected road sites in Addis Ababa and taken in to the laboratory. Raw materials like aggregate, filler and bitumen were also collected from their respective quarry sites and batching plants in order to produce laboratory control samples. In addition the batching plants of the study areas were assessed for age and capacity. The bitumen and aggregate were all found qualified with regard to design specifications on the case study areas. Those raw materials were then mixed in the laboratory by keeping the projects' aggregate gradation and optimum binder content.

Three road projects were involved in this study, namely Kality-Tuludimtu road project, Entoto-Kotebe Access road project and Imperial Kadisco Intersection project. The first two projects were designed using Marshal method and third project was designed using the Superpave method. The field and laboratory produced Marshal mixtures were compacted with Marshal compaction in accordance with design traffic level and the Superpave samples were compacted to Nin, Ndes and Nmax by a SGC machine according to field traffic level.

Understanding the performance and volumetric difference among field produced and lab produced Marshal and Superpave samples is used to mitigate the economic impact on the paving industry and take further implementations. Marshal samples were evaluated with indirect tensile strength, stability and flow. The Superpave samples were evaluated with indirect tensile strength and wheel-tracking test. On the way to these tests, the mix volumetric of both Superpave and Marshal samples were determined. The result of this assessment shows that, field produced Marshal samples show an average increment of 3.7% in bulk and theoretical maximum specific gravities while field Superpave samples found 0.2 times more than lab produced samples; which were manifested in the mix volumetric variation. The Marshal flow and stability test results also proven the difference between lab and field samples. Indirect tensile strength test results for Marshal laboratory mixtures were found 1.6 and 2.15 times more in accordance with field samples. The field Superpave samples, however show an improvement on indirect tensile strength test. The wheel-tracking test was also applied to Superpave samples to evaluate the rutting performance of the field and lab samples. The laboratory samples protected their structural integrity during the wheel loading duration and gave 24% lesser maximum rut depth than field samples. With the entire assessments of this study, laboratory samples of Marshal and Superpave samples proven better performance than field samples.

CHAPTER 1 INTRODUCTION

1.1 Background

The most used material for paving purposes globally, including Ethiopia, is hot mix asphalt (HMA). Mineral aggregates and asphalt cement binder make up the majority of its composition. The aggregate particles are joined together into a cohesive mass by the binder, which functions as a glue. Mineral aggregate functions as a stone structure that gives the system strength and durability when it is bound with asphalt binder. The characteristics of each component and how they interact with one another within the system determine how HMA behaves.

The job mix formula (JMF), which is the product of a successful mix design, will assign engineers the recommended asphalt binder type and aggregate gradation for the particular project site. Based on the JMF for HMA manufacture, goal values for gradation and asphalt binder content are established.

Over time, a number of mixture design techniques have been created with the aim of creating a combination that may meet a predetermined set of requirements and operate in an acceptable manner. Typically, this is accomplished by choosing the ideal design asphalt cement content to balance the required volumetric attributes. Durability, permeability, strength, stability, stiffness, fatigue resistance, and workability are a few possible desirable attributes. It is important to note, though, that no single asphalt cement composition will optimize each of these characteristics. Rather, the optimal qualities required for a given condition are taken into consideration while choosing the design asphalt cement content [1].

The volumetric design phase and the empirical or fundamental mechanical testing phase, which verifies the design, are often the two main components of the mixture design process. In order for the combination to fulfill the overall specification standard, the design approach may also incorporate additional requirements. Certain aggregate attributes, such as the minimum percentage of crushed aggregate, the maximum amount of rounded sand materials, and the required aggregate gradation, may be included in these standards [1].

The variations in laboratory mix design techniques stem from the compaction technique employed as well as the outcome of the assessment process. Combining aggregates and a binder in a way that can meet a certain performance level is the aim of the mix design process. Thus, it is crucial to use realistic methods when assessing the strength of bituminous mixes. There are some challenges with replicating a field mixture's composition in the lab, but they pale in comparison to creating a specimen of the combination that accurately captures the mixture's characteristics in the field [2].

To ensure that the mixes being tested are indicative of the mixtures that will be generated and used, they should ideally be prepared and compacted to a state that closely resembles field conditions. In order to assess the acceptability of the mixes and choose the best mix design to employ, the attributes of the mixtures to be measured should be reliable indications of how well the mixtures function in usage [3].

Failure of an asphalt pavement is a complex phenomenon. Conditions like air, water, and temperature may have a significant impact on how long asphalt concrete mixes last. The primary cause of degradation in moderate climates with access to high-quality materials and asphalt cement may be traffic load. Fatigue cracking, rutting (a permanent deformation), and ravelling are the symptoms that follow. But in a harsh environment, these pressures intensify due to subpar materials, improper management, traffic, and water, all of which are important factors in the deterioration of asphalt concrete pavements. Water causes a reduction of adhesion at the bitumen-aggregate contact. This early lack of adhesion is known as stripping in asphalt concrete pavements. The strength is reduced since the combination no longer functions as a cohesive structural unit. When adhesion fails, the interstitial bitumen body's cohesive resistance is rendered worthless. Water may penetrate the contact via diffusion over bitumen layers and gain direct access to partly coated aggregate. Water can produce stripping by five main mechanisms: detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scour [4].

So far, a variety of test methodologies have been used to assess the performance of JMFs created using a specific mix design process. Whatever mix design process is utilized, the goal is to create a combination that can withstand environmental and traffic pressures for the duration of its design life. This resistance is based on three forms of pavement distress: rutting, cracking, and moisture susceptibility. As a result, the mix design procedures must handle the pavement distresses. However, when predicting pavement performance, laboratory experiments may not always accurately reflect actual field conditions.

Several test methodologies have been utilized in the laboratory to evaluate the performance of HMA using mix design methods and varied testing temperatures. The Marshal Test, Hamburg Wheel Tracking (HWT) test, Semi Circular Bending (SCB) test, and Indirect Tensile Strength (ITS) test are the four most widely utilized test protocols.

The goal of this study is to asses and compares the performance of laboratory and field asphalt mixes. For this reason, sufficient asphalt concrete samples were obtained from three separate research regions, and their laboratory mixes were created. Both field and laboratory samples were compacted and tested for performance.

1.2 Statement of the problem

With the most dominant mode of transport in Ethiopia being the road transport, flexible pavements makes more than 90% of the road construction. This further proofed the reliance of flexible pavements over rigid pavements in terms of sustainability, initial cost and maintenance cost. The most common type of flexible pavements surfacing in Ethiopia is Hot Mix Asphalt (HMA). HMA is a combination of approximately 95% mineral aggregate and asphalt cement. The resulting HMA, after produced in mix plants is then loaded in to trucks for transport to the paving site. The trucks dump the HMA in to hoppers located at the front of paving machines. This asphalt is placed and compacted using a heavy roller as per the design requirement. Traffic is generally permitted to in the pavement as soon as the pavement has cooled.

When aggregate and asphalt binder are combined to produce a homogeneous substance, that substance, HMA, takes a new physical properties of its components. These physical properties are volumetric properties which are important properties in determining how the mixture behaves or perform in the field. Mechanical laboratory tests can be used to characterize the basic mixture or predict mixture properties. HMA mix design has evolved as a laboratory procedure that uses several critical tests to make key characterizations of each HMA blend. Although these characterizations are not comprehensive, they can give the mix designer a good understanding of how a particular mix will perform in the field during construction and under subsequent traffic loading.

There are numerous ways asphalt pavement can fail and it is necessary to understand how the components of HMA design work on each design methods. A full asphalt pavement design consists of three layers which include the asphalt pavement, sub-base aggregate layer, and a sub grade. Any of these three layers can fail, which could lead to pavement failure. Fatigue cracking, Rutting and Moisture damage are among the most common asphalt pavement failure modes. Fatigue cracking occurs because of repetitive traffic loading on a pavement at wide range of temperatures. Rutting is caused by in appropriate bitumen content and air void as well as poor compaction. Moisture damage is the result of mal-function of mixture components due to detachment of asphalt from aggregate.

Several variables influence the strength of bituminous mixes, one of which is the approach used in the laboratory to create a realistic test specimen that replicates the structure of the paving mixture when placed in the field. As a simulation, mix design has some limitations. There are significant changes between laboratory and field environments; thus, this procedure must be consistent in both the laboratory and on-site manufacturing and construction. However, if the mix design is done appropriately in relation to the real site circumstances, it can be indicative of the actual site loads. The issue here is whether those mix design criteria have been applied on the field or not. There is currently concern that inadequate control at any stage of combination manufacturing may result in field mixes that differ from laboratory mixtures. This problem intern leads to inadequate quality of pavement performance as well as economic inefficiency. As a result, it is necessary to identify the sources of differences between field and laboratory combinations.

Ensuring that a field mix can be reproduced in the laboratory is essential. Having the ability to compare the two can show whether or not mixing done in the field, which can be more difficult to control, can be replicated and check if the same properties can be achieved in a more controlled laboratory environment. Doing various performance tests on prepared asphalt pavement samples created from both the field and lab mixes can provide evidence to show the volumetric and performance variations. The secondary problem statement was to investigate the effect of Marshal and Superpave mix design methods on the performance of asphalt pavements with lab and field mixes.

1.3 Research questions

- What is the extent of performance variation between field produced lab compacted and laboratory produced lab compacted hot mix asphalt mixtures?
- What is the difference between Marshal and Superpave desugn systems?
- What factors contribute to performance variation of field and laboratory mixtures?

1.4 Objectives of the Research

1.4.1 General Objective

The General objective of this research is to compare and evaluate the volumetric properties performance of field produced lab compacted and laboratory produced Superpave and Marshal hot mix asphalt mixtures.

1.4.2 Specific Objective of the Study

The specific objective of the research is:

a. Compare mix volumetric between field produce lab compacted and lab produced lab compacted asphalt mixtures.

b. Compare the rutting performance of field and lab produced Marshal and Superpave samples

c. Compare moisture sensitivity of field and lab produced Marshal and Superpave samples

d. Investigate the variability among Marshal and Superpave mix designs

1.5 Significance of the study

- To point out the possible reasons behind early pavement failure.
- To encourage further implementation on mix design methods.
- To encourage further implementation of quality assurance program in the road construction sector.

1.6 Scope and Limitation of the study

This study mainly focuses on evaluation performance variation of laboratory and field asphalt concrete samples collected from three different road projects located in Addis Ababa. Based on the projects' design specification, a laboratory mixture were prepared and undergone performance tests. The raw materials were collected from the batching plants of the projects and brought in to Addis Ababa Science and Technology University Highway lab. Similarly uncompacted AC samples ready to be paved were collected from each road projects and brought to the laboratory.

The main limitation of this study is that it didn’t include fatigue cracking performance evaluation due to unavailability of crack tester machines like SCB. Also the study Scaped some bitumen and aggregate property tests since it is very tiresome and time taking to do so.

1.7 Research organization

This thesis is organized on to five chapters. The first chapter is the introduction part where the background, objectives and scope of the study discussed in detail. The second chapter presents the review of related literatures which gives deep understanding of mix design procedures and material tests. The third chapter consists the materials used alongside their tests and methods of the experimental work. The fourth chapter is the analysis and discussion of test results and the final chapter contains conclusions and recommendations.

CHAPTER 2 LITRATURE REVIEW

2.1 Introduction

This chapter encompasses all the literatures covered related to HMA mixture design and properties together with the ingredients. Performance tests performed on aggregates, bitumen and asphalt mixtures are also discussed in detail to help understand field and laboratory HMA mixtures performances. In this chapter, the significant mixture properties that relate to HMA concrete pavement performance/distresses and the associated laboratory test methods are discussed before the details of HMA design methods are presented. Several summary thoughts are provided at the end of this chapter.

2.2 HMA mixture design

The recent Asphalt Aggregate Materials and Mixture Study (AAMAS) focused on laboratory evaluation of asphaltic concrete mixtures for such distress to develop an improved mix design procedure [5]. Several studies have investigated the causes and remedies of distress such as early rutting, cracking, and stripping, all of which reduce pavement service life.

Asphalt mixes must be properly developed, specified, and manufactured in order to work successfully. However, the heterogeneity in performance of existing pavements suggests that present mixing and structural design techniques are insufficient [6]. To enhance the final result, namely the performance of asphalt concrete pavements, it is vital to understand the factors that govern this performance. This covers asphalt mixture specification, mix design, construction, and a qualitative performance assessment. The frequency and severity of pavement distress and failures can be used to assess performance. It is reflected in maintenance requirements and repair costs.

Pavement distress is the outcome of progressive degradation that can occur throughout the pavement's life. Rutting, cracking, stripping, and ravelling are among of the most common kinds of distress on roadways, and they occur on both new and ancient pavements. The most serious problem now impacting flexible pavements is rutting, which can occur even on recently constructed roadways [7]. Early, severe rutting is harmful and shortens the pavement's service life. Pavement distress is acceptable only if it happens gradually during the pavement's design life.

The existing mix design processes were designed using wheel loads and tire pressure magnitudes that have been considerably exceeded in recent years due to advancements in tire technology and vehicle size. Average truck tire pressures now vary between 80 and 120 psi [7], but they were significantly lower before the advancement of mix design procedures. The increase in tire pressure has coincided with a large increase in truck traffic volume.

The Strategic Highway Research Program (SHRP) [8] was a two-level study, with the first level incorporating findings from studies such as AAMAS to develop a performance-based mix design specification for a wide range of factors such as environment, construction variability, and loading conditions [9]. The second stage emphasized assessment and validation of these mixes in order to create a direct link between laboratory-measured fundamental engineering qualities and field-measured properties via short and long-term observation and testing. Such findings would be obtained utilizing both regular test equipment and accelerated test facilities. The SHRP Long Term Pavement Performance (LTPP) research would generate a much-needed database of field performance and material qualities that could be used to optimize the design process.

2.2.1 HMA MIXTURE DESIGN METHODS

HMA mixes were first designed in the late 1860s [9]. Since then, other HMA design methodologies have been created. However, the core notions and principles that were originally formed have remained unchanged [10]. As previously said, a combination must be stable to withstand traffic loads throughout the warmer seasons. This stability is strongly dependent on aggregate parameters such as size, gradation, form, and surface roughness. Asphalt binder also helps to maintain stability when used as a cementing material. However, excessive asphalt binder content affects stability. The primary role of asphalt binder is to give crack resistance and durability to the mixture.

In addition, the asphalt binder's consistency must be neither too brittle in winter nor too soft in summer. As a result, it is clear that the design of HMA mixes often involves three essential steps:

1. Select the type and gradation of aggregates.

2. Select the type and grade of asphalt binder, with or without modification.

3. Select the amount of asphalt binder to satisfy the project-specific requirements for HMA mixture properties.

The Marshall Method

The Marshall Mix Design approach is the most widely utilized mix design method in the United States, albeit criteria and practice differ in determining the optimal asphalt content [8]. The Marshall Method is popular because it is simple and portable. Mr. Bruce Marshall, a former bituminous engineer with the Mississippi State Highway Department, invented the Marshall technique of mix design. The Marshall approach was later enhanced by the United States Corps of Engineers, which incorporated new elements and created mix design criteria.

The Marshall mix design technique and criteria were first created for airport pavements, but were eventually used for highway pavements. Because of its simplicity, the Marshall technique of mix design was the most regularly used mix design approach in the United States prior to the advent of the Superpave design system, and it is now the most commonly used mix design method across the world. Despite the fact that it is an empirical approach, the Marshall method is a useful guide in determining initial plant mix parameters and monitoring mix production uniformity [11]. Variation sources in the mixture plant manufacturing process have been proven to exceed the intrinsic importance of mix design methodologies. According to Root (1989), many recent pavement problems are the result of inadequate specification control during manufacture and construction, rather than faulty mix design processes. Variable stockpile gradations and filler volumes are among the causes of variance. He also stated that a lack of quality control regularly resulted in field mixes with an optimal asphalt concentration that differed by up to 0.5 percent from the optimum design amount. This feature of manufacturing control has prompted state highway authorities to create quality assurance programs [12].

The Marshall stability is the maximum load that the specimen can sustain before failing when subjected to the Marshall stability test. The Marshall stability test is similar to the indirect tensile strength test, with the exception of the Marshall specimen being constrained by the Marshall testing head. Thus, Marshall stability is proportional to the tensile strength of the asphalt mixture. The Marshall flow is the total vertical deformation of the specimen, measured in 0.01 inches, when loaded to the maximum load in the Marshall stability test. The Marshall flow can give an indicator of an asphalt mixture's resistance to plastic deformation. Mixtures with low flow numbers are stiff and might be difficult to compress. However, these combinations are more rut-resistant than ones with high flow numbers. Mixtures with flow numbers that exceed the typical range may be "tender mixes," which are prone to irreversible deformation.

a. Compute volumetric characteristics of specimens. The percent air voids and VMA of the specimen are calculated using the specimen's bulk specific gravity, the mixture's maximum specific gravity, and the aggregate's bulk specific gravity. The percent air voids of the specimen may be calculated using the bulk specific gravity of the specimen and the maximum specific gravity of the mixture. VMA may be calculated using the bulk specific gravity of the mixture, the bulk specific gravity of the aggregate, and the aggregate percent by weight of the mix.
b. Marshall mix design criteria – The Asphalt Institute recommends five mix design criteria. They include (1) a minimum Marshall stability, (2) a range of permissible Marshall flow, (3) a range of acceptable air voids, (4) a percentage of voids filled with asphalt (VFA), and (5) a minimum quantity of VMA.

Table 1 provides the criteria for stability, flow, air voids, and VFA, whereas Table 2 lists the requirements for VMA. A mix design must meet all five of these characteristics.

c. Determination of design asphalt content — To facilitate the selection of optimum asphalt content, the following six plots are made:
i. Average unit weight versus asphalt content
ii. Average air voids versus asphalt content
iii. Average Marshall stability versus asphalt content
iv. Average Marshall flow versus asphalt content
v. Average VMA versus asphalt content
vi. Average VFA versus asphalt content

Table 1 Marshal Mix Design Requirement on Stability, Flow Air voids and VFA

Traffic Category Compaction, No. of blows/side	Light 35		Medium 50		Heavy 75	
	Min.	Max.	Min.	Max.	Min.	Max.
Stability, lb (N)	750 (3333)	—	1200 (5333)	—	1800 (8000)	—
Flow, 001 in. (0.25 mm)	8	18	8	16	8	14
Air Voids,%	3	5	3	5	3	5
VFA,%	65	75	65	78	70	80

Source: Asphalt Institute 1997. Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types, Manual Series No. 2, Sixth Edition, The Asphalt Institute, Lexington, KY

Table 2 Marshal Mix Design Criteria on VMA

Nominal Maximum Aggregate Size	Minimum Required VMA,%		
	Design Air Voids,%		
	3.0	4.0	5.0
#8 (2.36 mm)	19.0	20.0	21.0
#4 (4.75 mm)	16.0	17.0	18.0
3/8 in. (9.5 mm)	14.0	15.0	16.0
½ in. (12.5 mm)	13.0	14.0	15.0
¾ in. (19.0 mm)	12.0	13.0	14.0
1 in. (25.0 mm)	11.0	12.0	13.0
1.5 in. (37.5 mm)	10.0	11.0	12.0
2 in. (50 mm)	9.5	10.5	11.5
2.5 in. (63 mm)	9.0	10.0	11.0

Source: Asphalt Institute 1997. Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types, Manual Series No. 2, Sixth Edition, The Asphalt Institute, Lexington, KY

Determine the asphalt content at 4% air voids by plotting it against asphalt content. Using graphs (3) through (6), calculate the Marshall stability, Marshall flow, VMA, and VFA at this asphalt concentration and compare them to the Marshall mix design requirements in Tables 1 and 2. If all of the mix parameters are satisfied, this asphalt content represents the preliminary design asphalt content. The preliminary design asphalt content can then be changed within the range where all of the mix criteria are fulfilled based on the project's specific requirements to arrive at the final design asphalt content.

If one or more of the mix criteria are not fulfilled, modifications to aggregate type, aggregate gradation, and/or asphalt type must be made, and the mix design method must be repeated.

Superpave Volumetric Mix Design Method

The Superpave mix design approach is a novel mix design method that was developed as a consequence of the Strategic Highway Research Program (SHRP), which ran from 1988 to 1993. When SHRP researchers originally established the Superpave mix design approach, they aimed to have three degrees of sophistication and design effort. Level 1 design would only include material selection and volumetric proportioning, and it was designed for use on low-traffic roads with less than one million ESALs. Level 2 design would contain Level 1 design effort as well as performance prediction testing, and it was meant to be used on pavements with 1 to 10 million ESALs.

Level 3 design would contain Level 1 design effort as well as increased performance prediction testing, and it was designed for use on high-traffic pavements with more than 10 million ESALS. However, at the moment, only Level 1 design has been implemented, and it has been used for all levels of traffic. Superpave Level 1 mix design is now also known as Superpave Volumetric Mix Design. AASHTO MP2-99 [13] has full specifications for Superpave Volumetric Design.

AASHTO PP28-99[10] describes the Superpave volumetric mix design technique. However, because the Superpave design process is still in its early stages and updates are made on a regular basis, the most recent versions of these papers should be used when doing a Superpave volumetric mix design. The Superpave volumetric mix design technique includes the following major components:

1. Selection of asphalt — The asphalt binder should be PG grade asphalt that meets the AASHTO MP1 criteria and is suitable for the project site's climate and traffic conditions.

2. Selection of aggregate — The combined aggregate must meet the following requirements:

a. Nominal maximum size — Nominal maximum aggregate size should be 9.5 to 19.0 mm for surface course HMA and 19.0 to 37.5 mm for base course HMA.

b. Gradation control points — The gradation must pass through the control points as specified in Table 2.3

c. Gradation restricted zone — It is suggested that the gradation do not travel through the prohibited zones listed in Table 2.4. However, subsequent research investigations have found that mixes with aggregate gradations that breached the prohibited zone performed equally or better than those that did not [14].

Table 3 Superpave Mix Design Criteria on Aggregate Gradation Control Points

	Nominal Maximum Aggregate Size									
	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm	
Sieve Size	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
50 mm	100	—	—	—	—	—	—	—	—	—
37.5 mm	90	100	100	—	—	—	—	—	—	—
25.0 mm	—	90	90	100	100	—	—	—	—	—
19.0 mm	—	—	—	90	90	100	100	—	—	—
12.5 mm	—	—	—	—	—	90	90	100	100	—
9.5 mm	—	—	—	—	—	—	—	90	90	100
4.75 mm	—	—	—	—	—	—	—	—	—	90
2.36 mm	15	41	19	45	23	49	28	58	32	67
0.075 mm	0	6	1	7	2	8	2	10	2	10

Source: AASHTO 1999. AASHTO MP2–99 Standard Specification for Superpave Volumetric MixDesign, AASHTO Provisional Standards, Interim Edition, AASHTO, Washington, D.C.

Table 4 Boundaries of Aggregate Restricted Zone as recommended in Superpave Mix Design Method

	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm	
Sieve Size	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
0.30 mm	10.0	10.0	11.4	11.4	13.7	13.7	15.5	15.5	18.7	18.7
0.60 mm	11.7	15.7	13.6	17.6	16.7	20.7	19.1	23.1	23.5	27.5
1.18 mm	15.5	21.5	18.1	24.1	22.3	28.3	25.6	31.6	31.6	37.6
2.36 mm	23.3	27.3	26.8	30.8	34.6	34.6	39.1	39.1	47.2	47.2
4.75 mm	34.7	34.7	39.5	39.5	—	—	—	—	—	—

Source: *AASHTO 1999. AASHTO MP2–99 Standard Specification for Superpave Volumetric Mix Design, AASHTO Provisional Standards, Interim Edition, AASHTO, Washington, D.C.*

Table 5 Superpave Mix Design Criteria on Consensus Aggregate Properties

	Coarse Aggregate Angularity, Minimum (% with one fractured face/% with two factured faces)		Uncompacted Void Content of Fine Aggregate, Minimum (%)			
Design Traffic (million ESALs)	Thickness ≤100 mm	Thickness >100 mm	Thickness ≤100 mm	Thickness >100 mm	Sand Equivalent, Minimum (%)	Flat and Elongated, Maximum (%)
<0.3	55/–	–/–	–	–	40	–
0.3 to <3	75/–	50/–	40	40	40	10
3 to <10	85/80	60/–	45	40	45	
10 to <30	95/90	80/75	45	40	45	
≥30	100/100	100/100	45	45	50	

Source: AASHTO 1999. AASHTO MP2–99 Standard Specification for Superpave Volumetric Mix Design, AASHTO Provisional Standards, Interim Edition, AASHTO, Washington, D.C.

d. There are four consensus aggregate property criteria. The coarse aggregate must fulfill the ASTM D5821 angularity criteria, which are defined as the minimal percentages of particles having smashed faces. The fine aggregate must fulfill the fine aggregate angularity standards in terms of minimal uncompacted void contents as determined by AASHTO T304 Method A. The aggregate must fulfill the sand equivalent criteria in terms of minimum sand content as determined by AASHTO T176. The aggregate must fulfill ASTM D4791's maximum permitted proportion of flat and elongated particles. The Superpave mix design requirements for these four consensus features are listed in Table 5.

e. Aggregate source property standards – The aggregate must fulfill all of the source property criteria stated by the local highway agency, including L.A. abrasion loss, soundness, and toxic materials.

3. Asphalt mixes are prepared by mixing aggregate and asphalt at a temperature that achieves a kinematic viscosity of 170 ± 20 cSt. Prior to compaction, the loose asphalt mixture is cured

in a forced-draft oven at 135°C for 4 hours. AASHTO PP2-99 [13] provides a full explanation of the curing technique.

4. Compaction of asphalt mixtures — The asphalt mixture is compacted using the Superpave gyratory compactor, as detailed in AASHTO TP4-99. The Superpave gyratory compactor differs from the Corps of Engineers GTM in that its gyratory angle is fixed, whereas the GTM's gyratory angle varies depending on the stability of the tested combination. Superpave's gyratory compactor setups are as follows:

Table 6 Numbers of Gyrations for Superpave Gyratory Compaction

Design Traffic (million ESALs)	$N_{initial}$	N_{design}	N_{max}
<0.3	6	50	75
0.3 to <3	7	75	115
3 to 30	8	100	160
≥30	9	125	205

Source: AASHTO 1999. AASHTO PP28–99 Standard Practice for Superpave Volumetric Mix Design for Hot Mix Asphalt, AASHTO Provisional Standards, Interim Edition, AASHTO, Washington, D.C.

a. Vertical ram pressure: 600 kPa (87 psi)

b. Gyratory angle: 1.25° fixed angle

c. Speed: 30 gyrations per minute

d. Specimen diameter: 150 mm (5.9 in.)

e. Specimen height: 115 mm (4.5 in.)

Asphalt with a kinematic viscosity of 280 ± 30 cSt is compacted at this temperature. Table 6 shows that the number of gyrations to be applied depends on the intended traffic volume. For each amount of intended traffic, there are three degrees of compaction: Nini, Ndes, and Nmax gyrations. The specimen is compressed to Ndes gyrations, and its height is continually measured. After compaction, the specimen is taken from the mold and its bulk specific gravity and percentage Gmm are calculated. %Gmm equals 100% minus% air voids. The actual observed bulk density is compared to the predicted density based on specimen height, and a correction factor is determined.

This adjustment factor, along with the specimen height at Nini, is then used to compute the specimen's density and percentage Gmm. Following the measurement of the design asphalt content, duplicate samples with the same design asphalt content are compacted to Nmax gyrations to obtain the%Gmm of the mixture.

5. Determination of design asphalt content — The design asphalt content is the asphalt content at which the asphalt mixture contains 4% air voids (or a%Gmm of 96%) when compacted to Ndes gyrations while meeting all mix design parameters. The next section describes the mix design requirements.

Superpave mix design requirements

The asphalt mixture design must meet all the following requirements:

a. The asphalt mixture must have a target air void of 4% when compacted to Ndes gyrations.
b. The VMA of the compacted mixture at Ndes gyrations must meet the minimum VMA requirements as shown in Table 7.
c. The VFA (Voids Filled with Asphalt) of the compacted mixture at Ndes gyrations must fall within the range as shown in Table 7.
d. The dust-to-binder ratio, which is the ratio of the weight of the mineral filler to the weight of the binder, must be between 0.6 and 1.2.
e. The %Gmm of the asphalt mixture compacted to Nini must not exceed the limits as shown in Table 7. The %Gmm of the mixture compacted to Nmax must not exceed 98%.
f. The asphalt mixture, when compacted by the Superpave gyratory compactor to 7% air voids and tested in the AASHTO Designation T 283 Standard Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage, must have a retained tensile-strength ratio of at least 80%

Table 7 Superpave Mix Design Criteria on %Gmm, VMA, VFA and Dust-to-Binder Ratio

Design Traffic (million ESALs)	VFA (%)	Required $\%G_{mm}$			Required minimum VMA (%) Nominal Max.Agg. Size, mm					Dust-to-Binder Ratio
		$N_{initial}$	N_{design}	N_{max}	37.5	25.0	19.0	12.5	9.5	
<0.3	70–80	≤91.5	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	0.6 – 1.2
0.3 to <3	65–78	≤90.5								
3 to <10 10 to <30 ≥30	65–75	≤89.0								

Source: AASHTO 1999. AASHTO MP2–99 Standard Specification for Superpave Volumetric Mix Design, AASHTO Provisional Standards, Interim Edition, AASHTO, Washington, D.C.

2.3 Review of Mix Design in Relation to Pavement Performance

The primary goal of mix design is to create good-performing, long-lasting pavements. In fact, mix design has been recognized as one of the two most essential elements affecting asphalt pavement performance [15]. The other component is compaction. According to Goetz (1985), a mix design must meet two essential requirements: it must provide appropriate void content, and the design asphalt content must be sufficient to cover all of the aggregates with an ideal film thickness. Shell and colleagues [17] advocated the simple static creep test as a technique of detecting tender blends that the Marshall and Hveem procedures [18] do not identify.
Individual parts of the mix design process have been examined, including material qualities, handling procedures, mixture temperature, compaction, and testing. SHRP, 1986 devotes a significant percentage of its efforts on material characterization. Santucci [19] identified crucial parameters that determine pavement performance, demonstrating that mix design and materials are key aspects influencing performance.

2.4 Review of Asphalt Pavement Performance and related tests

Asphalt pavement performance has been classified as either structural or functional [20]. This review part will focus on functional pavement performance and mixture attributes associated to the most common distress kinds.

2.4.1 Major Distresses in Flexible Pavements

The major distresses that are of concern in flexible pavements are:

i. Rutting,
ii. Fatigue Cracking
iii. Thermal Cracking
iv. Moisture damage (moisture sensitivity)
v. Stripping

Other modes of distress in flexible pavements generally stem from these distresses or are not severe enough to affect the pavements functionally [5] [21] [22]. And we will discuss rutting and moisture damage as here under.

Rutting

HMA mixes must be able to withstand rutting (the buildup of permanent deformation) at high tire contact pressures and several load repetitions. Rutting is induced by a combination of densification (lower volume and AV) and shear deformation (equal volume movement and higher AV). Previous study [23] [24] has shown that the predominant rutting process for well-compacted HMA concrete pavements is shear deformation rather than densification. Resistance to permanent deformation or shear stress has been identified as a stability-related characteristic. Because HMA mixes must be constructed with appropriate stability in order to operate properly, stability is regarded as the most important feature of HMA mixture design in terms of rutting.

The kind or grade and amount of asphalt binder, aggregate qualities (such as absorption, texture, and particle shape), gradation and aggregate type, percent crushed aggregate, density, compaction level, and temperature all have an impact on stability.

Hard aggregates with rough surface textures, thick gradations, comparably low asphalt binder proportions, tougher (stiffer) asphalts, and well-compacted mixes all promote higher stability, as long as the air gaps do not fall below a particular threshold.

At least three laboratory procedures, the Hubbard-Field, Marshall, and Hveem tests, have been established to assess the stability of HMA mixtures. To provide acceptable pavement stability, minimum measured stability values have been determined in several HMA mixture design approaches [25] [26]. The minimal value established will, of course, be determined by the type of stability test, traffic weight and volume, as well as other criteria such as climate, underlying structure type, and surface thickness.

Moisture Sensitivity/Damage

Moisture sensitivity/damage refers to the loss of strength and durability in HMA mixes caused by moisture. Moisture damage has long been a serious issue among pavement engineers. Moisture-related issues are caused or exacerbated by either adhesive failure (the separation of the asphalt layer from the aggregate surface) or cohesion failure. These processes can be linked to either the aggregate or the binder, or the interaction between the two. Moisture-related distresses, such as stripping and raveling, are further exacerbated by HMA mixture design or construction difficulties, such as those described in Table 8.

Table 8 Factors That Can Contribute to Moisture-Related Distress.

MIX DESIGN	• Binder and aggregate chemistry • Binder content • Air voids • Additives
PRODUCTION	• Percent aggregate coating and quality of passing the No. 200 sieve • Temperature at plant • Excess aggregate moisture content • Presence of clay
CONSTRUCTION	• Compaction—high in-place air voids • Permeability—high values • Mix segregation • Changes from mix design to field production (field variability)
CLIMATE	• High-rainfall areas • Freeze–thaw cycles • Desert issues (steam stripping)
OTHER FACTORS	• Surface drainage • Subsurface drainage • Rehab strategies—chip seals over marginal HMA materials • High truck ADTs

Solaimanian et al. [30] evaluated available laboratory techniques and those under preparation for determining the moisture sensitivity of HMA mixes. The experiments are divided into two categories: loose HMA mixes and compacted HMA combinations. The static immersion and boil tests, both performed on loose HMA mixes, were among the earliest tests introduced into the paving business. These were followed by the immersion-compression test in the late 1940s. This test, performed on compacted HMA materials, was the first to be adopted as an ASTM standard in the mid-1950s. Research in the 1960s raised pavement engineers' knowledge of the important impacts of climate and traffic on moisture degradation.

Lottman's extensive study [31][32] culminated in the laboratory test (IDT strength ratio test), which is today the most widely accepted in the pavement industry. Tunnicliff and Root [33] made further changes to this test. Wheel tracking of HMA mixes submerged in water became popular for determining moisture damage in the 1990s. The HWTT is one of these wheel-track tests. The Colorado DOT conducted considerable study on HMA mixes using the HWTT. Aschenbrener et al. [34] examined the elements that impact the HWTT findings.

They discovered a strong link between stripping reported in laboratory studies and moisture damage to pavements with established field performance. They also discovered a strong link between stripping inflection points and known stripping performance. Stuart and Izzo [35] used the HWTT to investigate the relationship between binder stiffness and rutting susceptibility. They discovered that stronger binders produced combinations with lesser rutting susceptibility. Izzo and Tahmoressi [36] explored the repeatability of the HWTT.

TxDOT now uses the HWTT as a screening technique for the rutting and moisture susceptibility of HMA mixes [36].

2.5 Bituminous Materials Used in Pavement Construction

Asphalt cement is asphalt that has been carefully polished in terms of quality and consistency to be used directly in the building of asphalt pavement. Asphalt cement must be heated to a sufficiently high temperature before it can be mixed and applied.

2.5.1 Conventional Tests on Asphalt Cements and Their Significance

This section describes the purpose and relevance of the most regularly used asphalt cement testing methods. For a more complete description of the test techniques, readers can turn to the relevant standard test methods.

Penetration Test

The penetration test is one of the oldest and most widely used tests for asphalt cements or leftovers from the distillation of asphalt cuts or emulsions. The established protocol for this test is given in ASTM D5 [41]. It is an empirical test that determines the consistency (hardness) of asphalt under specific test conditions. In the standard test condition, a standard needle with a total load of 100 g is applied to the surface of an asphalt sample at 25°C for 5 seconds. The needle's penetration after 5 seconds is recorded in 0.1 mm units. Softer asphalt will have greater penetration, whilst harder asphalt would have less penetration.
The penetration test may be used to differentiate asphalt cement grades as well as to detect hardness variations caused by age hardening or temperature changes.

Flash Point Test

The flash point test indicates the safe temperature at which asphalt may be heated in the presence of an open flame. The test involves heating an asphalt sample in an open cup at a certain pace and detecting the temperature at which a tiny flame passing over the cup's surface causes the asphalt sample's vapors to momentarily ignite or flash. The Cleveland Open Cup (ASTM D92) and the Tag Open Cup (ASTM D1310) are two widely used flash point test techniques. The Cleveland Open-Cup technique is used on asphalt cements or asphalts with greater flash points, whereas the Tag Open-Cup method is used on cutback asphalts or asphalts with flash values below 79oC.

Solubility Test

Asphalt is mostly composed of bitumen, a kind of high-molecular-weight hydrocarbon that is soluble in carbon disulfide. Bitumen content of a bituminous substance is determined by its solubility in carbon disulfide. The typical bitumen content test (ASTM D4) involves dissolving a small sample of roughly 2 g of asphalt in 100 ml of carbon disulfide and filtering the solution through a filtering mat in a filtering crucible. The material remaining on the filter is then dried and weighed, and the bitumen content is calculated as a percentage of the original asphalt's weight.

Ductility Test

The ductility test (ASTM D113) examines how far a typical asphalt sample can stretch without breaking under regular testing circumstances (5 cm per minute at 25°C). Asphalt with very low ductility is frequently regarded to have weak adhesive properties and hence poor serviceability. Asphalt cement standards sometimes contain minimum ductility requirements.

Viscosity Tests

The viscosity test determines the viscosity of asphalt. Both the viscosity and penetration tests are used to grade asphalts by measuring its consistency at specific temperatures. The viscosity test has an advantage over the penetration test since it evaluates a basic physical characteristic rather than an empirical value. Viscosity is the ratio of a fluid's applied shear stress to its induced shear rate. The link among shear stress, shear rate, and viscosity may be stated as

Shear Rate= Shear Stress/ Viscosity……………….... (2.3)

Thin Film Oven and Rolling Thin Film Oven Tests

When asphalt cement is used in the construction of asphalt concrete, it must be heated to a high temperature and combined with heated aggregate. The heated asphalt mixture is then transported to the project site, where it is poured and compacted. By the time the compacted asphalt concrete cools to typical pavement temperature, the asphalt binder has hardened significantly. The qualities of the asphalt in service alter dramatically from the original asphalt.

Because the performance of asphalt concrete in service is dictated by the properties of the hardened asphalt binder in service rather than the characteristics of the original asphalt, the qualities of the hardened asphalt in service must be recognized and managed.

The Thin Film Oven Test (TFOT) technique (ASTM D1754) was designed to imitate the effects of hot-mix facility heating on asphalt cement. The typical TFOT procedure is pouring the asphalt cement sample to a depth of about 1/8 inch (3.2 mm) onto a flat-bottomed pan. The pan containing the asphalt sample is then placed on a rotating shelf in an oven and cooked at 1630 degrees Celsius for five hours. The asphalt properties are measured before and after the TFOT approach to compute the projected change in properties during a hot-mix plant operation.

The Rolling Thin Film Oven Test (RTFOT) process (ASTM D2872) was created for the same purpose as the TFOT procedure and is intended to have roughly the same effect on asphalt cement. The RTFOT has two benefits over the TFOT: (1) it can test more samples at once, and (2) it takes less time to complete the test. The usual RTFOT technique involves placing the asphalt cement sample in a specially built bottle, which is then put on its side on a rotating shelf in an oven set to 1630C and rolled continuously for 85 minutes.

During each spin, the bottle's aperture passes an air jet, which gives new air to the asphalt in the bottle, increasing its oxidation rate.

While RTFOT and TFOT have typically performed successfully on pure asphalts, difficulties have arisen when modified asphalts are employed. Asphalts treated with crumb rubber and SBR tended to leak from the RTFOT bottles during the RTFOT process. When TFOT was applied to these modified binders, a thin skin formed on the surface of the modified asphalt, reducing homogeneity and aging of the samples.

2.6 Aggregates used in pavement construction

Mineral aggregates influence the performance of asphalt mixes. Aggregates account for around 85% of the overall volume of asphalt mixes. The performance of the mixes is influenced by a variety of characteristics, including the aggregate blend's gradation and maximum size, as well as the aggregates' angularity and surface roughness.

2.6.1 Effects of Aggregate Characteristics on Performance of Asphalt Pavements

Most asphalt paving mixes are composed of 90 to 95% aggregate by weight and 75 to 85% volume. The aggregate supplies the majority of the asphalt mixture's load-bearing capability. Thus, the aggregate qualities have a significant impact on the performance of an asphalt mixture. This section discusses the implications of aggregate qualities on asphalt pavement performance, as well as the most prevalent techniques for determining these aggregate parameters.

Aggregate Gradation

One of the most essential properties of an aggregate that influences the performance of an asphalt mixture is its gradation. The qualities of an asphalt mixture can be significantly affected when the aggregate gradation is varied.

What is a suitable gradation of aggregate for use in an asphalt mixture? Because an asphalt mixture receives its strength mostly from the aggregate, it is better to use well-graded aggregate to achieve the highest amount of material in the mix. However, if the aggregate is overly well-graded, the voids in mineral aggregate (VMA) in the mix may be insufficient to accommodate the required quantity of asphalt to achieve a minimum asphalt film thickness on the aggregate surface.

If the VMA is too low and the appropriate quantity of asphalt is added to the mix, bleeding may occur because there are insufficient voids in the mix to accept the asphalt. However, if a lesser asphalt concentration is employed, the asphalt film thickness on the aggregate may be inadequate. The asphalt concrete formed would not be durable, and raveling might develop. Thus, the ideal aggregate should be fairly well graded to produce a high volume of aggregate in the asphalt mix, but not so well graded that the VMA drops too low.

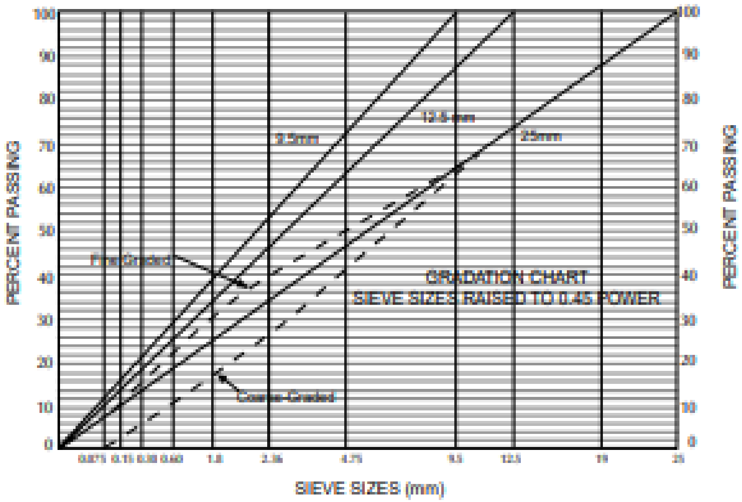


Figure 1 Maximum density gradations plotted on a 0.45 power gradation chart.

Figure 1 shows three different maximum-density aggregate gradations, each with a different top size coarse aggregate. The Federal Highway Administration (FHWA) of the United States developed a 0.45 power gradation chart in 1962 to plot aggregate gradation. The chart was chosen so that a gradation that plots as a straight line on the chart would define the maximum density gradation. The equation for the FHWA's maximum

$$P=100(d/D)^{0.45} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.4)$$

Where P = total percent passing the specific sieve

d = the specific sieve size in question

D = maximum size of the aggregate

Fine-graded asphalt mixtures are those with aggregate gradations that plot above the maximum density line. Mixes with gradations that fall below the maximum density line are known as coarse-graded mixes. When all other conditions remain constant, coarser-graded aggregate requires less asphalt binder in the mix to obtain acceptable coating and mix qualities. It also tolerates higher asphalt concentration than finer-graded combinations. Coarser mixtures, when appropriately constructed, are more resistant to persistent deformation [42].

ASTM Standard Specification D3515 [43] provides recommended aggregate gradation standards for dense-grade asphalt mixes with varying nominal maximum aggregate sizes. For the most part, the FHWA maximum density curves are within the limitations of the gradation standards for the maximum aggregate sizes. This section's subsection "Superpave Mix Design Method" presents the aggregate gradation standard for the Superpave mix design technique.

Maximum Aggregate Size

The maximum aggregate size is the smallest filter through which 100% of the aggregate particles pass. In general, employing a bigger maximum aggregate size in the asphalt mixture increases the pavement's bearing capacity and rutting resistance. Using a greater maximum aggregate size decreases both the design asphalt content and the mix cost. However, combinations containing a bigger stone size are more difficult to position and compact to the appropriate smoothness. The lift thickness also determines the maximum aggregate size that may be employed. The maximum aggregate size is 0.5 times the lift thickness.

Asphalt mixture names often refer to the nominal maximum aggregate size rather than the maximum aggregate size. However, the concept of nominal maximum size varies each agency. The ASTM C125 Standard [43] defines nominal maximum size as the lowest sieve hole through which the total amount of aggregate can pass, with up to 10% of the aggregate retained. In the Superpave mix design system, nominal maximum size is defined as one sieve size greater than the first sieve to retain more than 10%, whereas maximum size is one sieve larger than the nominal maximum size.

Aggregate Shape and Texture

The shape of an aggregate used in an asphalt mixture greatly influences the mix's inclination to distort. Rounded aggregates have no interlocking ability and can simply "slide by" each other under shear loads. Increasing the proportion of crushed coarse and fine particles in an asphalt mixture can greatly improve its resistance to plastic deformation. Thus, in order to improve the rutting resistance of asphalt mixes, several asphalt mixture requirements have required a high proportion of coarse aggregate to have at least one or two crushed faces, while limiting the quantity of natural sand that may be utilized.

Flat or elongated particles are commonly classified as having a maximum-to-minimum dimension ratio of more than five. Flat and elongated particles are undesirable. These particles are easily shattered by traffic compaction, reducing the strength of the asphalt mix. These particles also impair the workability of the asphalt mixture and can interfere with its compaction during construction. ASTM D4791, Standard Test Method for Flat or Elongated Particles in Coarse Aggregate [43], can be used to detect whether particles are flat or elongated.

The surface roughness of aggregate particles has a significant impact on the mix's capacity to withstand plastic deformation. Some scholars believe this element is more essential than particle form. A rough aggregate surface texture can provide superior skid resistance on the pavement surface. Asphalt bonds better to uneven surfaces than smooth ones. Aggregates with flat surfaces, such as gravels, are more likely to rut than crushed limestone aggregate, which has rougher surfaces.

The ASTM D3398 Standard Test for Index of Aggregate Particle Shape and Texture can be used to quantify an aggregate's overall particle shape and texture properties by calculating a particle index value. In this test, the aggregate to be examined is sieved into various size fractions. The aggregate from each size fraction is deposited in three layers in a specific cylindrical steel mold, and each layer is crushed with 10 tamps using a special tamping rod.

This method is repeated with a compaction rate of 50 tamps each layer. The weight of the compacted aggregate and the aggregate's bulk specific gravity are used to calculate the proportion of voids in each condition. The particle index for the aggregate in each size fraction is computed using the following equation:

$$I_a = 1.25\, V_{10} - 0.25\, V_{50} - 32.0 \qquad (2.5)$$

Where Ia = particle index value

V10 = percent voids in the aggregate compacted with 10 tamps per layer

V50 = percent voids in the aggregate compacted with 50 tamps per layer

The particle index of the aggregate is calculated as the weighted average of the particle index values from the various size fractions based on their percentages in the original aggregate. An aggregate having spherical particles with smooth surface texture may have a particle index ranging from 5 to 8, whereas an aggregate containing highly angular particles with rough texture may have a particle index of 15 to 20.

Strength and Toughness

Because the aggregates constitute the majority of the load bearing capacity of asphalt mixes, they must be robust and resistant enough to withstand the applied loads. Insufficiently strong and resistant aggregates in asphalt mixes can be severely fractured and deteriorated by construction loads and traffic throughout service.

The Los Angeles (L.A.) abrasion test is often performed to ensure that the aggregate has the necessary strength and toughness. The ASTM C131 Standard Test Method for Resistance to Degradation of Small-Size Aggregate by Abrasion and Impact in the Los Angeles Machine applies to coarse aggregate less than 37.5 mm (1½ in.). The ASTM C535 Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine is used for coarse aggregate bigger than 19 mm (3/4 in.) and with a maximum aggregate size of 76 mm (3 in.).

The L.A. abrasion test produces results in terms of percentage L.A. abrasion loss. A higher percentage L.A. abrasion loss often indicates a less abrasion-resistant aggregate. The average test result ranges from 10% for extremely hard rocks to more than 60% for gentle pebbles. The maximum permissible L.A. abrasion loss in HMA mixes is frequently limited by aggregate specifications, which can range from 40% to 60% depending on the agency.

It should be noted that the L.A. abrasion loss is primarily a measure of resistance to abrasion. Many aggregates have performed satisfactorily despite having a significant L.A. abrasion loss.

Durability

To guarantee durability, coarse aggregate standards for use in asphalt mixes often include a soundness test using sodium or magnesium sulfate (ASTM C88). The aggregate's various size fractions are submerged in a solution of sodium or magnesium sulfate for 18 hours before being oven dried. The operation is repeated for a set number of cycles. The weight loss for each size fraction is determined, and the weighted average percent loss for the total sample is calculated and presented as percent soundness loss. A higher % soundness loss suggests a less durable aggregate. The ASTM D692 Standard Specification for Coarse Aggregate for Bituminous Paving Mixtures stipulates a maximum loss of 12% after 5 cycles for sodium sulfate and 18% for magnesium sulfate.

The sodium and magnesium sulfate soundness test was first designed to imitate the harmful effects of freezing and thawing on aggregates. However, this test is routinely used to screen aggregates regardless of whether they will be utilized in freezing and thawing environments.

Cleanliness

Clean aggregates that are devoid of harmful substances are ideal for use in asphalt mixes. Clay, dust, friable particles, and organic contaminants are all harmful substances that should be avoided. The sand equivalent test (ASTM D2419) determines the proportions of clay and sand in a fine aggregate. In this test, a sample of the fine aggregate to be analyzed is put in a clear cylinder containing water and a flocculant. The mixture is stirred and let to settle for 20 minutes.

The sand separates from the flocculated clay, and the clay and sand levels in the cylinder are measured. The sand equivalent is the height of sand divided by the height of clay multiplied by 100. A higher sand equivalent value suggests a cleaner aggregate. Aggregates in asphalt mixes are commonly specified with a minimum sand equivalent of 25 to 35.

Clay and friable particles in aggregate may be determined using the ASTM C142 Standard Test Method for Clay Lumps and Friable Particles in Aggregates. Clay lumps and friable particles are normally confined to no more than 1%. The plasticity index (PI) (ASTM D4318) indicates the quantity of plastic particles present in a fine aggregate. The ASTM D1073 Standard Specification for Fine Aggregate for Bituminous Paving Mixtures sets the PI of the proportion passing the No. 40 (425 µmm) at 4.0.

2.7 Superpave Specifications on Aggregates

Unlike Marshall and Hveem mix design approaches, Superpave mix design processes add aggregate criteria by improving on current test methodologies. There are two sorts of aggregate processes specified: consensus and source properties.

Consensus features include coarse aggregate angularity, fine aggregate angularity, flat and elongated particles, and clay content [30]. The angularity of the aggregates provides a high degree of internal friction and shear resistance. Limiting elongated fragments ensures that the mixture is not prone to aggregate fracture during handling, building, and transportation. Limiting the amount of clay promotes a strong adhesive connection between the asphalt binder and the aggregate. Source qualities include toughness, soundness, and harmful materials. These features are source-specific and are used to identify local aggregate sources.

2.7.1 Role of Aggregate Gradation

Gradation is one of the most essential features of the aggregates used in asphalt mixes. Superpave employs the 0.45 power gradation chart with control points and a limited zone to create a design aggregate structure. Control points serve as master ranges through which gradients must pass. They are put on three sieves: the nominal maximum, an intermediate (2.36mm), and the smallest (0.075mm).

The limited zone, located at the maximum density gradation between an intermediate sieve and a 0.3mm sieve, defines a band past which the gradation cannot travel. Gradations that pass through the restricted zone have been dubbed "humped gradations" due to their distinctive hump form in this location. In most circumstances, a humped gradation implies a high amount of fine sand relative to overall sand. This grade causes compaction issues during construction and has little resistance to permanent deformation over its service life.

The limited zone also keeps the gradation from following the maximum density line in the fine aggregate sieves. Gradations that follow this maximum density gradation frequently have insufficient VMA to accommodate enough asphalt content for appropriate durability. These gradations are extremely sensitive to asphalt composition and can rapidly turn plastic with even modest changes.

Air Void Considerations

The packing parameters of asphalt-coated aggregate qualities in an asphalt mixture are determined by both aggregate surface features and gradation. Surface roughness and angularity are two examples of aggregate surface properties. Surface qualities affect stability and skid resistance. Sufficient voids are required to form appropriate thick asphalt layers for adhesion and durability.

Aggregate gradation has a significant role in the creation of intergranular empty space between aggregate particles. The Voids in the Mineral Aggregate (VMA) refers to the volume of the intergranular void space between the aggregate particles of a compacted paving mixture that comprises the air voids and the effective asphalt content, expressed as a percentage of total volume. A gradation with maximal density has no or very few air spaces.

The addition of asphalt to this maximum density gradation just separates the aggregate particles, lowering the mix's shear strength and increasing the likelihood for lateral flow. Too many air gaps make the mixture extremely permeable, reducing resistance to the action of air and water. High air permeability induces oxidative embrittlement of the binder, causing the pavement to break. High water permeability facilitates asphalt peeling from aggregate particles, jeopardizing both the subgrade layer and the base course [44]. Thus, air spaces in the compacted mixture contribute significantly to the durability of asphalt concrete.

As a result, the content of the voids must be carefully chosen to ensure that no vital traits are compromised.

CHAPTER 3 METHODOLOGY

3.1 Introduction

The main objective of this research is to compare the mix volumetric and performance of field produced lab-compacted asphalt mixture with laboratory produced asphalt mixtures using either Marshal or Superpave mix designs. The performances to be evaluated are rutting and moisture sensitivity. These three are very important asphalt performances which will make the pavement resistant to wheel and environmental loads. This requires many steps from preparing enough samples and undergoing extensive laboratory tests carefully. Apart from mixing the AC constitutes, the research also performs quality tests. These tests include aggregate quality and bitumen quality tests. These tests will further simplify the comparison result and will figure out the main consistency problems among field mixes and lab mixes.

The first step of the research was selecting a road construction site which all the materials are collected from. These materials include, field produced asphalt mixture which is ready to paving and compaction, the raw materials used to produce the field mix i.e. aggregate, asphalt cement and fillers. After collecting these materials, a laboratory mix will be prepared and undergo various lab tests to evaluate the performances of both mixes.

This chapter therefore encompasses the materials used and samples prepared with their properties used and the tests and results; using tables, figures, graphs and charts with explanations.

The figure below shows the flow of the experimental design used in the study.

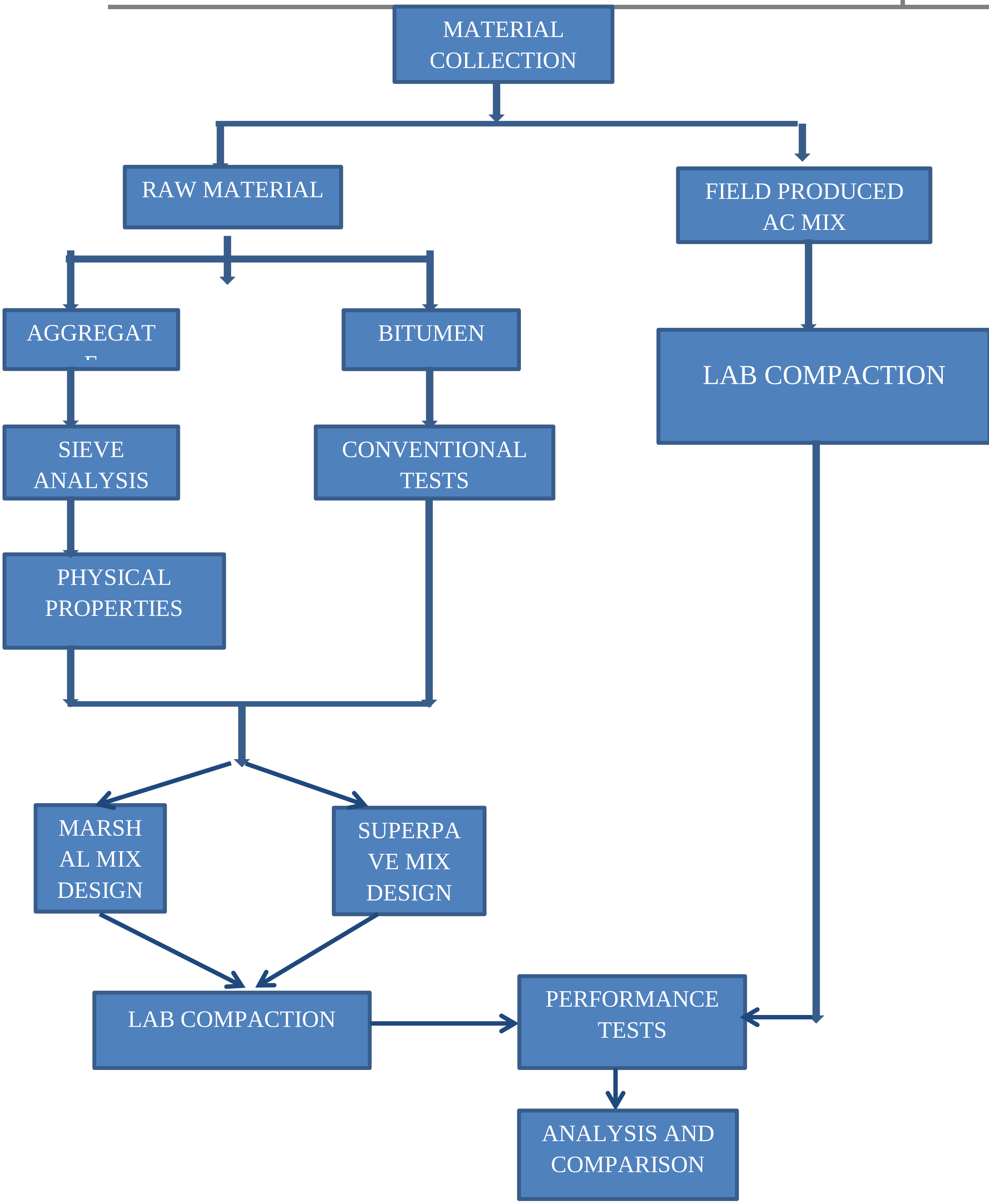


Figure 2 Flow chart of experimental design

3.2 Description of the study area

The study areas are located in Addis Ababa, Ethiopia. They are Entoto Park to African leadership Academy Access Road Project, Imperial and Kadisco Intersection Project and Kality Ring Road Interchange – Tulu Dimtu Roundabout Road Project. They all are full asphalt road projects constructed using Marshal, Superpave and Marshal mix design methods respectively. The first road project is 18km long with 7m wide carriageway, the second road project is 3km and 11m carriage way width and the third project is 10.928km long with 26m carriage way width both direction.

3.3 Study Design

The research methodology was a case study on three road projects. Because it is very difficult and time taking to assess all road projects in Addis Ababa, it is preferred to undergo a case study just on three projects. Enough asphalt concrete mixes were sampled from the three road projects on site just before compaction for performance tests in laboratory. Similarly row materials were collected from the batching plant to prepare an identical laboratory mixes using project specification

3.4 Assessment of Asphalt mix plants of the road projects

The purpose of this study was to compare field produced HMA mixtures and lab produced HMA mixtures in terms of volumetric properties and performances. The control points of the comparing mixtures were their place of production (lab and field) and their method of mix design. Hence to investigate their variation, it was important to consider the control points. One of these control points is their method of production. HMA specimens collected from site were produced on batching plants. Thus the study conducted an assessment on the asphalt batching plants of the study areas to check whether they have significant role on the test results. The result of the assessment is discussed her under.

Asphalt plant is applicable to manufacture paving material that is widely utilized in highway, airports and bridges. They are also found crucial for road construction on country roads and for repairing road surfaces. The asphalt mixing plant is mainly composed of cold aggregate supply system, drum drier, coal burner, coal feeder, dust collector, hot aggregate elevator, vibrating screen, filler supply system, weighting and mixing system, asphalt storage and bitumen supply system.

Preparing quality asphalt mix requires using the right equipment and quality materials. In addition these equipments require regular maintenance for optimum performance. The batching plants of the three case study areas were assessed for age, theoretical capacity and drier capacity. By collecting information on these points from concerned personnel, the following assessment was made.

I. Age

If an asphalt plant is more than 10-15 years old, it is inevitable that parts will wear out and performance will start to decline. Some of the control algorithms may become out dated and getting replacement parts could be tricky, particularly as some suppliers are reluctant to support older products (N.Johnstone, 2021). The batching plant of Kality-Tuludimtu road project owned by IFH Engineering PLC was installed in 2002 which makes the plant 22 years old. The batching plant of Entoto-Kotebe road project owned by ASER Construction was installed in 2007, 17 years ago. The batching plant of the Imperial-Kadisco Intersection project owned by the China First Highway Engineering was installed 12 years ago in 2012.

II. Batching Plant Capacity

Asphalt batching plants are marketed by their hourly capacity by the producers. Capacity of batch plants is up to 300 tons per hour. The batching plant capacity must be proportional to machinery capacity in the construction site so as to avoid High Capacity Effect and Low Capacity Effects. The Kality-Tuludimtu road project and Entoto-Kotebe road projects batching plants have a capacity of 80tph and that of the imperial road project batching plant has a capacity of 12tph. Accordingly the Kality-Tuludimtu road project was affected by Low Capacity Effect. Three of them however were free from High Capacity Effect.

III. Dryer Capacity

Dryer's capacity has the highest effect on plant's capacity. Aggregates which have not totally removed from moisture cannot be used in asphalt concrete. A drier which is not appropriate for plant's capacity, will decrease the capacity and increase fuel consumption. The dryer capacities of the three projects were 100tph for Kality-Tuludimtu and Entoto-Kotebe road projects and 140tph for the imperial-Kadisco road project. As far as these numbers are concerned, the dryer capacities found appropriate for the output capacity for three of them.

3.5 Materials

3.5.1 Aggregate Physical Properties

The aggregates used on the selected site were tested in the laboratory so as to evaluate its quality. The tests undertaken were aggregate physical property tests which are important for suitability of a pavement. The type of tests and their specifications are presented in table 3-1

3.5.2 Aggregate Gradation

Crashed aggregates were obtained from crusher plants of each project. The aggregates were then sieved to four control sieves: the maximum sieve size, the nominal maximum sieve, the 12.5mm sieve, the 2.36mm sieve and the 0.075mm sieve. The details of the sieve values for all projects were attached in the Annex.

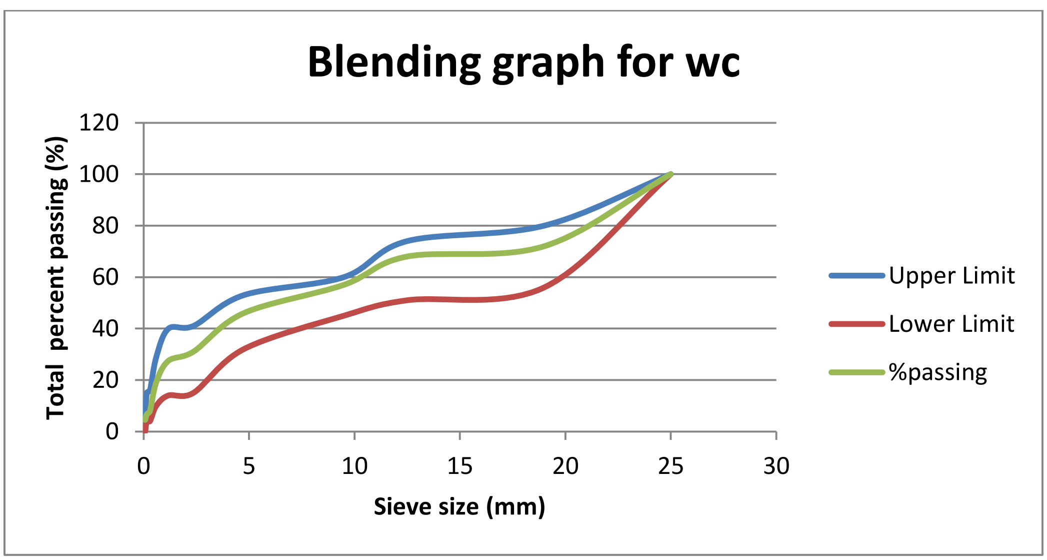


Figure 3 Aggregate Gradation Curve-Entoto-Kotebe Access Road Project

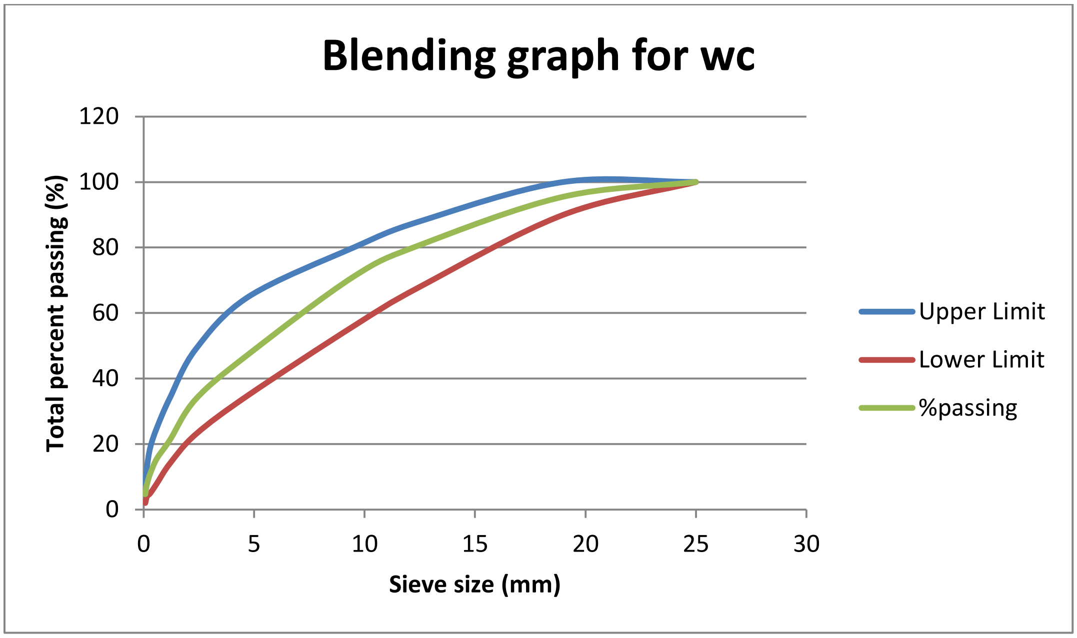


Figure 4 Aggregate Gradation Curve –Imperial and Kadisco Intersection Project

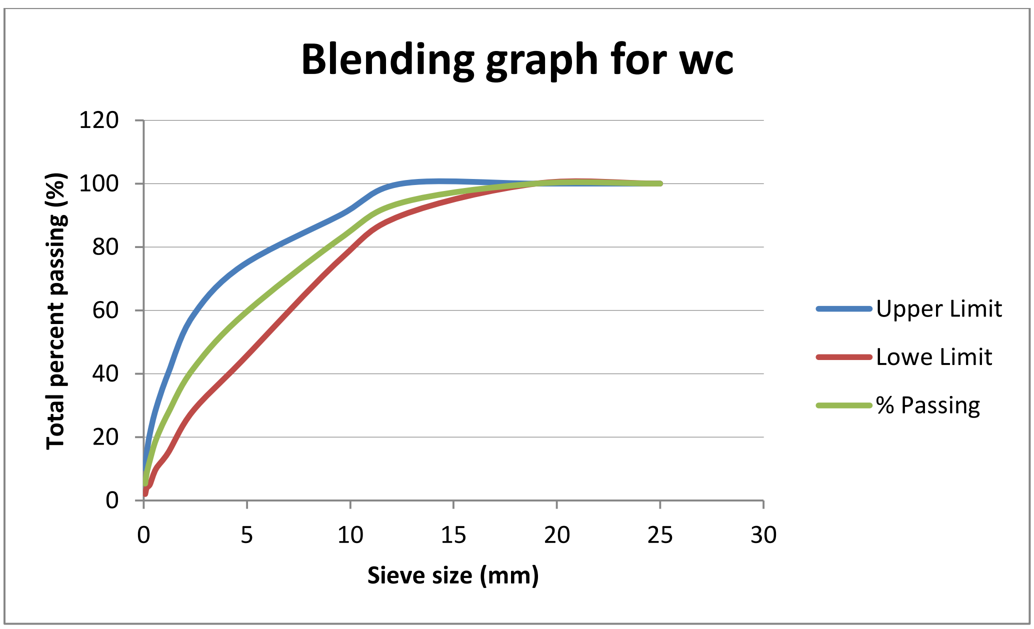


Figure 5 Aggregate Gradation Curve –Kality-Tuludimtu Road Project

3.5.3 Asphalt cement

Similarly this study used asphalt cement taken from the road site which they use to prepare an asphalt concrete. One of the specific objectives of this study was checking the quality of asphalt cement of the case projects. 60/70 grade bitumen was used for all projects. The details of the tests performed on the asphalt cement were attached in Annex. And the respected test results were summarized and discussed on Chapter four.

3.6 Marshal Specimen Preparations

Marshal design method consists of aggregate selection, asphalt binder selection and optimum asphalt binder content determination. Thus using the selected raw materials from the road site and Marshal Mix design result (OBC) of the projects was used to prepare corresponding Marshal Specimens in the laboratory to determine the stability, flow and volumetric properties of the mixtures. The details of these test results were attached in the Annex and discussed in chapter four.

3.7 Superpave Mix Preparation

This mix design method is now a widely accepted method which is exempted from just a specific process or procedure. Superpave is a performance based specification for asphalt binder and volumetric mixture design. The idea was to allow asphalt traffic conditions of a given site. Therfore this design method will eliminate the limitations of penetration test which is highly emprical. It also adresses the problem of high or very low tempreture effects. The Superpave system was developed to give highway engineers and contractors the tools they need to design asphalt pavements that will perform better under extremes of tempreture and heavy traffic loads. The Imerial and Kadisco Intersection Road Project was constructed using Superpave mix design Method. The procedures and methods used to prepare Superpave mixtures is presented.

The field mixes are produced using Superpave design method. Therefore a duplicated lab samples were mixed in lab using project mix design criteria. Here are listed in the table below project super pave mix design criteria.

Table 9 Project Superpave mix design criteria-Imperial and Kadisco Intersection

Volumetric Mix Design Criteria					
Design air voids					4.00%
Fines to effective Asphalt, (AF) ratio					0.6 - 1.2
Tensile Strength ratio, (AASHTO T283)					75% Minimum
Nominal Maximum Size					
Minimum Void in Mineral Aggregate, (VMA) %	37.5 mm	25 mm	19 mm	12.5 mm	9.5 mm
	11	12	13	14	15

Design ESALs (millions)	Percent of Theoretical Maximum Specific Gravity			Percent Void Filled with Asphalt, (VFA)
	$N_{initial}$	N_{design}	$N_{maximum}$	
< 0.3	≤ 91.5	96.0	≤ 98.0	70 - 80
0.3 < 3	≤ 90.5	96.0	≤ 98.0	65 - 78
3 < 10	≤ 89.0	96.0	≤ 98.0	65 - 75
10 < 30	≤ 89.0	96.0	≤ 98.0	66 - 75
≥ 30	≤ 89.0	96.0	≤ 98.0	67 - 75

Gyratory Compaction Criteria			
Design ESALs (millions)	**Compaction Parameters**		
	$N_{initial}$	N_{design}	$N_{maximum}$
< 0.3 (Light Trafic)	6	50	75
0.3 < 3 (Medium Traffic)	7	75	115
3 < 30 (Heavy Traffic)	8	100	160
≥ 30 (Extra Heavy Traffic)	**9**	**125**	**205**

Asphalt Binder Grading System

The Asphalt binder grading system in Super pave is called the performance grading (PG) system. PG Binders are characterized based upon fundamental engineering parameters, it accounts for the impact of climatic factors on binder characteristics at both the hot and cold temperature regimes and In addition to climatic conditions, traffic and aging control the performance of the pavement.

60/70 grade bitumen was selected and quality tests were taken and the results being summarized in next chapter.

Based on the tests taken, a binder classified PG64- 10 was selected which would meet the required physical properties at pavement temperatures as high as 64 ^{o}C and as low as - 10 ^{o}C. The first number in the rating indicates the high temperature grade; the second indicates the low temperature grade.

For predicting the project high pavement design temperatures from seven-day mean high air temperature and geographical latitude of the project location.

$$T_{20mm} = \left(T_{air} - 0.00618Lat^2 + 0.2289Lat + 42.2\right) 0.9545 - 17.78$$

T_{20mm} = (28Oc – 0.00618*(8.98)2 + 0.2289*8.98+42.2)*(0.9545 – 17.78)

T_{20mm} = 50.72^{o}C

Where: T20mm = High pavement design temperature at a depth of 20mm, oC.

T_{air} = Seven – days mean high air temperature, oC.

Lat = Geographical latitude of project location, degree The SHRP low pavement design temperature model is presented in the following formula.

$$T_d = T_{air} - 0.051d - 0.000063d^2$$

Where: Td = Low Pavement Temperature at pavement depth d, oC.

T_{air} = Air temperature, oC

d = Depth below surface, mm

Td= (28Oc – 0.051*485 – 0.00063(485) ^{2}

Td **= -11.55 ^{o}C**

The job mix formula (JMF) gradation target values will be established within the design criteria specified for the particular type of asphalt mixture to be produced. To select the design aggregate structure, trial blends were established by mathematically combining the gradations of the individual materials into a single gradation. The blend gradation is then compared to the specification requirements for the appropriate sieves. There is also a restricted zone that is an area on either side of the maximum density line generally starting at the 2.36 mm sieve and extending to the 0.3 mm sieve. The minimum and maximum values required for the control sieves change (as does the restricted zone) as the nominal maximum size of the mixture changes. The laboratory Mixtures was prepared with PG64-10 grade bitumen and aggregate source from Akaki quarry asphalt batching plant. The aggregate blending proportion for each sieve size for this mix is (14mm-25mm)21%, (6mm-14mm)30%, (3mm-6mm)15%,(0mm-3mm)32%, and filler 2%.

The main purpose of the gradation evaluation is to determine whether a selected gradation which meets the gradation controls is likely to meet the VMA requirements. VMA is influenced predominantly by aggregate characteristics such as gradation, angularity, and surface texture. Paving mix specimens, all containing the selected design aggregate structure, were prepared at project optimum binder content and compacted to Nmax, gyrations and then checked the air content.

Specimens were mixed at the appropriate mixing temperature which is 165°C to 173°C for the selected PG 64-10 binder. The specimens are then short-term aged by placing the loose mix in a fiat pan in a forced draft oven at 135°C for 4 hours. The Specimens are then brought within the compaction temperature range (150°C to 157°C) by placing them in another oven for a short time (generally less than 30 minutes). Finally, the loose mix is removed and either compacted or allowed to cool loose (for maximum theoretical specific gravity determination).

The number of gyrations used for compaction is determined based on the design high air temperature of the paving location (50.72°C) and the traffic (≥ 30 million (Extra Heavy Traffic) ESALs). For these two conditions, the numbers of gyrations was identified as

- ✓ Ninitial = 8 gyrations;
- ✓ Ndesign = 125 gyrations; and
- ✓ Nmaximum = 205 gyrations.

Superpave Gyratory Compaction

The SGC is an electro-hydraulic device consisting of the following system components: reaction frame, rotating base and motor, loading system, loading ram and pressure gauge, height measuring and recording system, and mold assembly.

The reaction frame provides a non-compliant structure against which the loading ram can push while compacting specimens. The base of the SGC rotates and is affixed to the loading frame. It supports the mold while compaction occurs. Reaction bearings are used to position the mold at an internal angle of 1.16 ± 0.02 degrees which is the compaction angle of the SGC. The electric motor drives the rotating base at a constant speed of 30 ± 0.5 revolutions per minute as well as furnishes power to the hydraulic system. A hydraulic or mechanical system applies a load to the loading ram which imparts 600 ± 18 kPa compaction pressures to the specimen. The loading ram diameter nominally matches the inside diameter of the mold, which is usually 150 mm.

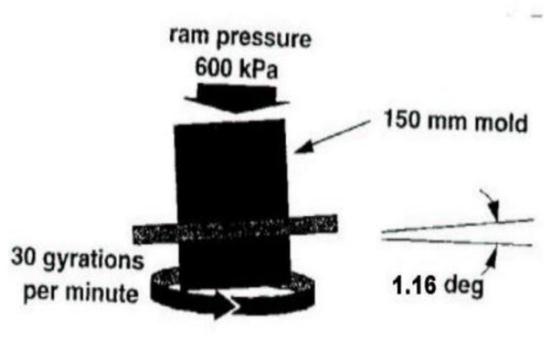


Figure 6 SGC Mold Configuration

Each specimen was compacted to the maximum number of gyrations. During compaction, the height of the specimen is continually monitored. Knowing the initial weight of the mix, the fixed volume of the mold, and the measured height, the density of the specimen were monitored.

Compaction specimens are required to be mixed and compacted under equi-viscous temperature conditions corresponding to 0.170 +/-0.02 Pa·s and 0.280 +/-0.03 Pa·s, respectively. Mixing is accomplished by a mechanical mixer. After mixing in the lab, loose test specimens are subjected to 2 hours +/- 5 minutes of short term aging in a forced draft oven maintained at the compaction temperature. The compaction molds and base plates should also be placed in an oven at compaction temperature for at least 30 to 45 minutes prior to use.

These prepared specimens were then subjected to performance tests. Performance comparison was then realized with test results that belong to laboratory and field samples. The tests and results were discussed on the results and discussion part of the paper.

Superpave Mixture Volumetric

This method covers the compaction of cylindrical specimens of hot mix asphalt (HMA) using the Superpave Gyratory Compactor. The Superpave mix design tests, as we can see the above mixture volumetric requirements consist of air voids (V), voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA). Air void content is an important property because it is used as the basis for asphalt binder content selection. In all cases, the design air void content is four percent. VMA requirements are a function of maximum nominal aggregate size of the mixture. VFA requirements are a function of traffic level (design ESALs). At the selected 4.58% optimum bitumen content, (OBC) all the Mixture volumetric were computed.

3.8 Performance test methods

After all the AC mixture constituent materials were collected and tested, they were mixed in the laboratory with their respective project design specification as discussed above. These laboratory mixtures were then subjected to performance tests. These performance tests were similarly done to field mixtures after compaction. For the Marshal samples flow and stability tests were taken prior to TSR test which indicates the performance of the mixes.

3.8.1 Moisture Susceptibility Test

One of the most environmental factors that greatly affect asphalt pavements is moisture. Every paving mixture is susceptible to moisture induced damage. Hence the esteemed pavement mixture needs to resist moisture damage or stripping. Type of aggregate used and asphalt binder together with pavement surface drainage condition will influence moisture susceptibility of the mixture. This test serves two purposes. First it identifies whether an asphalt aggregate is moisture susceptible. Second, it measures the effect of anti-stripping additives.

$$S_t = \frac{2000 \times P}{\Pi \times t \times D}$$

Where: - St = Tensile Strength, Kpa
P = Maximum Load, N
t = Specimen thickness, mm
D = Specimen diameter, mm

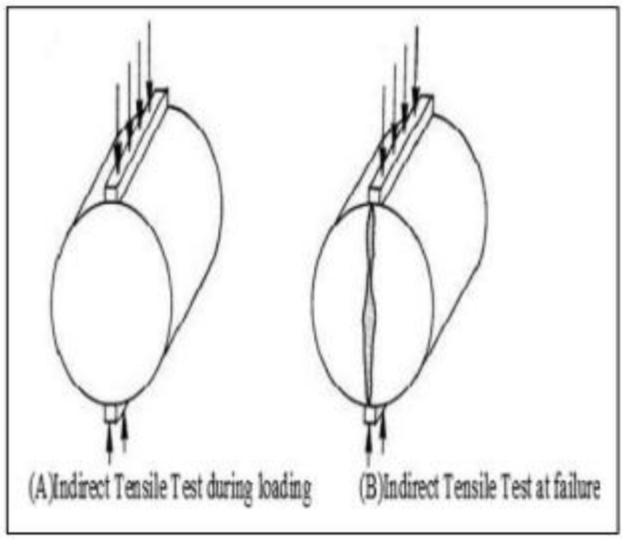


Figure 7 TSR test configuration

In this test, two subsets of test specimens were produced from a loose mixture at design asphalt contents of respective projects. One set was kept at room temperature. The other set was subjected to water conditioning. After conditioning, both subsets were tested for indirect tensile strength at 25^0c. The test result reported is the ratio of average tensile strength of the conditioned subset to that of the unconditioned subset which is referred to as 'Tensile Strength Ratio'. This ratio will then be compare to design requirements.

3.8.2 Wheel Tracking Test

The wheel tracking test device of different sizes and configurations are available to determine or evaluate the resistance of Hot Mix Asphalt (HMA) to permanent deformation or rutting under continuously applied wheel loads. The rut depth formed by the wheel loads will then be recorded. The wheel loads will pass repeatedly over a sample slab prepared in the laboratory. For this purpose asphalt concrete slabs with dimensions of 300mmx300mmx50mm was prepared for both field and laboratory Superpave mixtures as proposed by (EN 1267-Part 22:2003) after compacted to the target density using a roller compaction. The weight of the asphalt mixture required for the preparation of the slab was calculated using the following equation:

$$M = 10^{-6} * L * I * e * \rho_m * \frac{100-V}{100}$$

Where M= is the mass of asphalt concrete slab, Kg

L= is the length of the mold, mm

I= is the width of mold, mm

V= is the air void of the slab in percent

e= is the thickness of asphalt concrete slab, mm

ρm= is the maximum theoretical specific gravity of HMA, Kg/m3

Based on this equation the M value for the Superpave samples was computed as

$M=10^{-6}$ (300*300*50)*2.438*(100-4/100)

=10.53Kg

For the laboratory Superpave mixtures, the aggregate sample and binder were heated to the mixing temperature for more than an hour just before mixing. Then, required amount of asphalt binder and a weighted aggregate sample were mixed by a mechanical mixer taken in by a preheated bowl at the mixing temperature for 3 minutes. After the mixing process was completed, a slab sample was prepared. The contact pressure between the rubber wheel and specimen was set to be 0.7Mpa and the loading speed to be 42 passes per minute.

The loose mixture was then placed in the oven for 2 hours at a temperature equal to the mixture's compaction temperature for short term aging. Then, the mixture was removed from the oven and spread in a preheated mold with a shovel. The mixture was then tamped throughout, including the corners, and compacted to an air void level of 4% using the roller Compactor according to (BS EN 1269733:2003).

The wheel tracking test is a laboratory-controlled rut depth test undertaken by rolling a loaded wheel on the surface of each asphalt concrete slab. The load applied to the wheel is 700 ± 10 N with a frequency of 26.5 ± 1.0 load cycles per 60 seconds. Rotation of the drive shaft from an electric motor is translated to a linear reciprocating motion, the geometry of which fixes at test path of (230±10) mm.

The compacted specimens of dimension (300 mm length, 300 mm width and 50 mm height) were left to cool at room temperature for 24 hours and then placed in the test frame of wheel tracking device. Before testing the slab specimens were conditioned in an environmental chamber at 60oc for 4hr. During testing, the contact pressure between rubber wheel and specimen surface was 0.7 MPa, with a loading speed of 42 passes per minute. After conditioning, the machine was set in motion and the sample deformation measured using linear variable displacement transducers (LVDT).

The test was run for 10,000 cycles (20,000 passes) or until a deformation of 20 millimeters was reached, whichever came first. The wheel tracking test was performed to compare the rutting resistance of different types of asphalt mixtures.

The parameters obtained from wheel track test were the dynamic stability (DS), and rutting depth (RD) and employed to evaluate the performance of asphalt mixtures in terms of rutting resistance. The development of rutting depth was measured and recorded with a linear variable differential transformer. The dynamic stability value was calculated by Equation listed in below:

$$DS = \frac{15N}{d_2 - d_1}$$

Where:- DS = is the dynamic stability (No of cycles /1mm rutting depth)

N = the loading speed (42 cycles/min)

d1 = is the rutting depth, (mm) at 45min

d2 = is the rutting depth, (mm) at 60min

Wheel truck tests at the selected asphalt bitumen content (4.58%) was conducted with three mixes. Based on the dynamic stability test results, the maximum depth rutting was computed by using the above formula at 10000cycles/1hr.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

In this chapter summary of material quality test results and performance tests of field and laboratory mixtures were presented and analyzed. The conventional tests made on bitumen and aggregate from the three case study areas was compared to design specifications and standards. After this task analysis of field lab produced AC mixture volumetric was discussed and so does performance tests using tables and graphical presentation. The details of all test results were attached in the appendix part.

4.2 Material Quality Test Results

4.2.1 Aggregate Physical Properties

Table 4-1 below illustrates selected aggregate physical properties test results for the case study areas with corresponding ERA specification. According to the test results of the five tests taken, all sample aggregates meets design qualifications.

Table 10 Aggregate physical properties

Types of Tests	Results			Specification (ERA,2002)	Remark
	Entoto	Imperial	Kality		
Los Angeles Abrasion (%)	21	15	19	<30	**Qualified!**
Particle Shape, Flakiness (%)	18.5	18	19.54	<25	**Qualified!**
Aggregate Crushing Value (%)	20.23	14	16.03	<25	**Qualified!**
Sand Equivalent (%)	51	84.5	62	>40	**Qualified!**
Water Absorption (%) Course Aggregate Fine Aggregate	 1.807 1.93	 1.9 2	 1.66 1.823	 <2 <2	 **Qualified!**
Bulk Specific Gravity Coarse Aggregate Fine Aggregate	 2.627 2.61	 2.62 2.60	 2.622 2.6	 N/A N/A	

Bulk specific gravities of the aggregate samples were also determined in addition to the five aggregate tests for the three projects because these aggregate properties play a vital role on the volumetric properties of the mixtures during compaction. Even though all the selected aggregate materials lied with in the design specifications, some of the aggregates on field produced asphalt mixtures were found larger than the nominal maximum aggregate size of the mix design. This was one of the reasons for performance variation of field and lab produced AC mixes.

4.2.2 Bitumen Quality Test Result

The virgin bitumen used for the projects were taken to the laboratory and checked for four quality tests. Table 4-2 below summarizes the four quality tests taken for the three case study areas together with standard specifications. The summary result shows again that the projects sites used qualified bitumen at least on the four properties.

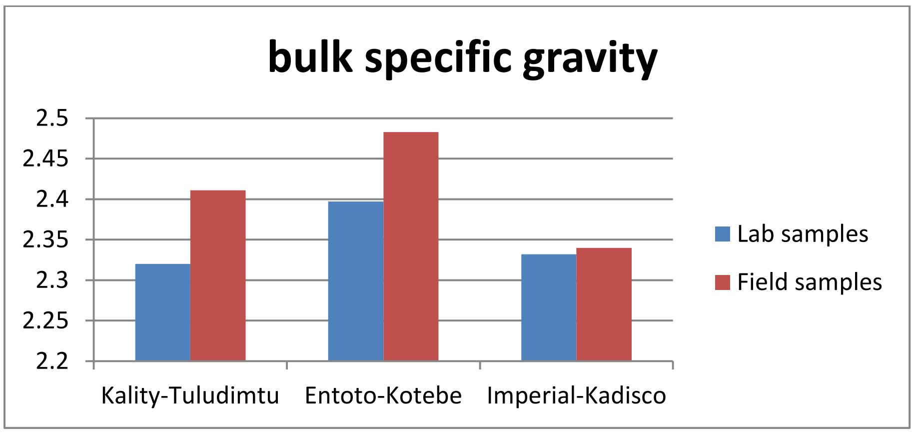
Table 11 Asphalt Cement Quality Test Results

Properties	**Specification**	**Unit**	**Result**			**Remark**
			Entoto	**Imperial**	**Kality**	
Softening Point	46-56	^{0}C	50.65	51	50.2	**Qualified!**
Flashing Point	>232	^{0}C	295	289	307	**Qualified!**
Penetration (25^{o}C)	60-70	0.1mm	63.4	67	62.9	**Qualified!**
Ductility (25^{o}C)	100+	cm	100+	100+	100+	**Qualified!**

4.3 Volumetric Properties of Field and Laboratory Mixtures

Asphalt mixture volumetric properties include the bulk specific gravity (Gmb), theoretical maximum specific gravity (Gmm), air voids (Va), voids in mineral aggregate (VMA) and voids filled with asphalt (VFA). These all volumetric properties of asphalt mixture highly affect its performance if they are not on their acceptable specification range. These mix volumetric properties highly depend on aggregate physical properties and bitumen content. This study computed the volumetric of both field and lab mixtures for the three projects. The results of the three case study areas were summarized on Table 3-4, Table 3-5 and figure 4-1.

The asphalt mixtures of Kality-Tuludimtu and Entoto-Kotebe road projects were designed using Marshal mix design method whereas the Imperial-Kadisco road project was designed using the Superpave mix design method. Thus, after producing corresponding Marshal mix specimens and Superpave mix specimens in the laboratory, the bulk specific gravities and the theoretical maximum specific gravities were all determined which were used to compute the mix volumetric at the projects' optimum binder content. The summary results were discussed on figure 4.1 and table 4-3 below.



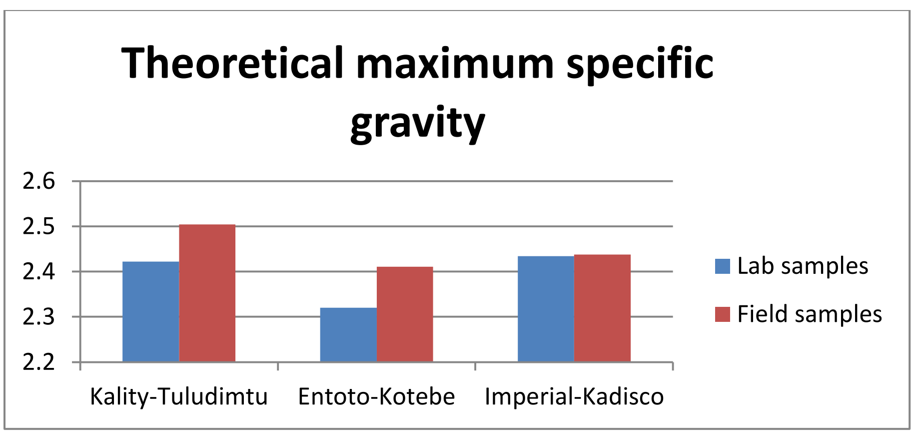


Figure 8 Bulk specific gravity and theoretical maximum specific gravity of case study areas

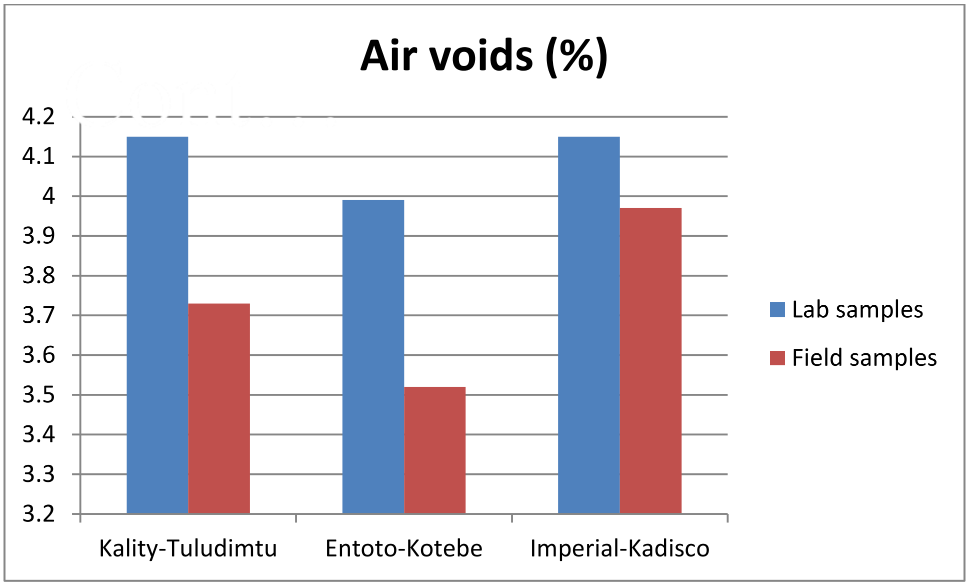
Table 12 Bulk and Theoretical Maximum specific Gravities of Field and Lab mixes

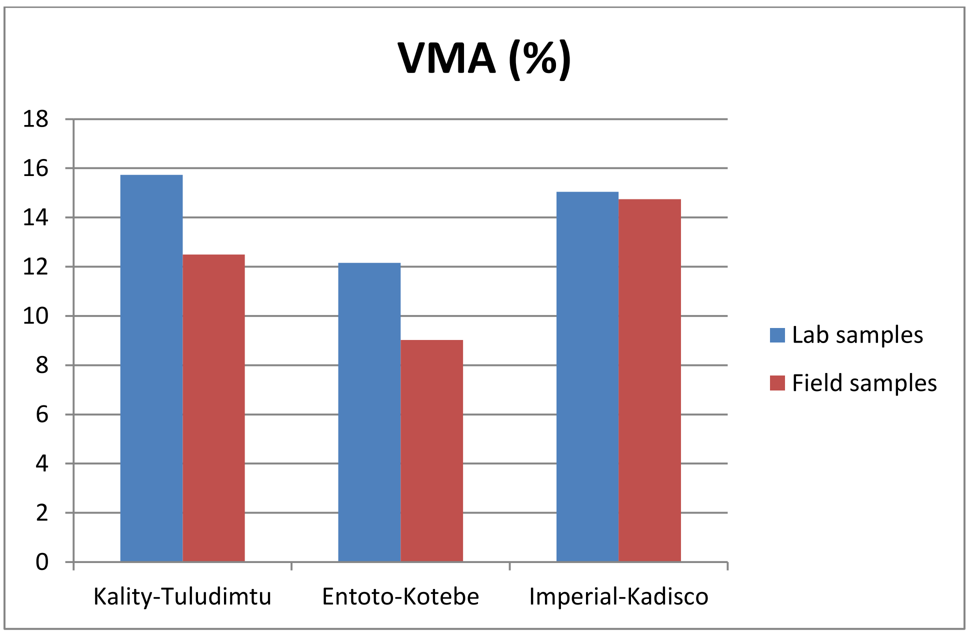
Road Project	Bulk specific gravity (Gmb)		Theoretical maximum specific gravity (Gmm)		Mix-Design Type
	Laboratory Samples	Field Samples	Laboratory Samples	Field Samples	
Kality-Tuludimtu	**2.320**	**2.411**	**2.422**	**2.504**	**Marshal**
Entoto-Kotebe	**2.397**	**2.483**	**2.32**	**2.411**	**Marshal**
Imperial-Kadisco	**2.332**	**2.340**	**2.434**	**2.438**	**Superpave**

According to the above test results shown, the field samples showed an average increment of 3.75 % and 3.65% on bulk specific gravities (Gmb) and maximum specific gravities (Gmm) respectively compared to lab samples. And the field Superpave samples showed a small increment of 0.34% and 0.17% respectively. Thus Marshal samples showed very much higher variation than Superpave samples

Table 13 Volumetric Properties of Field and Lab mixes

	Air voids (Va) (%)		Voids in mineral aggregate (VMA) (%)		Voids filled with asphalt (VFA) (%)		Project OBC (%)
Specification	**3-5**		**>12**		**65-78**		
Road Project	Laboratory Samples	Field Samples	Laboratory Samples	Field Samples	Laboratory Samples	Field Samples	
Kality-Tuludimtu	**4.15**	**3.73**	**15.73**	**12.5**	**73.67**	**70.155**	**4.9**
Entoto-Kotebe	**3.99**	**3.52**	**12.16**	**9.03**	**67.22**	**61.02**	**3.96**
Imperial-Kadisco	**4.15**	**3.97**	**15.04**	**14.74**	**72.41**	**73.03**	**4.58**


Air voids (%)
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
Kality-Tuludimtu
Entoto-Kotebe
Imperial-Kadisco
Lab samples
Field samples


VMA (%)
18
16
14
12
10
8
6
4
2
0
Kality-Tuludimtu
Entoto-Kotebe
Imperial-Kadisco
Lab samples
Field samples

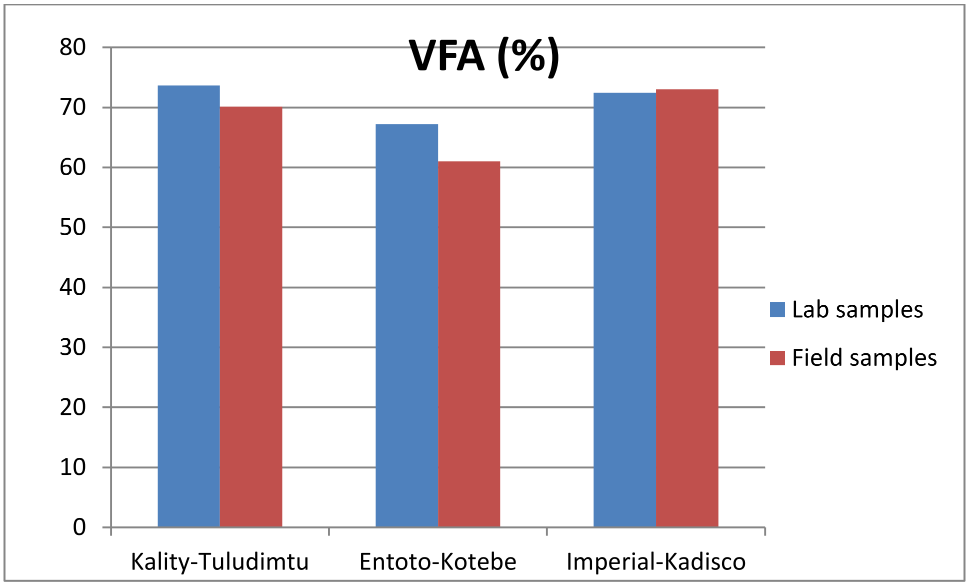


Figure 9 Volumetric properties of field and lab samples

From the above result, the air voids of the field Marshal samples has been decreased by 10.12% and 11.8% and the field Superpave samples decreased by just 4% but yet near to 4% air void. Since their densities have been increased, it is expected that the air voids would be compromised. Therefore by considering an adjustment factor on the compaction method we can improve the air voids. Also the VMA and VFA of the field Marshal samples were found 17.9% lesser than lab samples. And the VFA of Entoto-Kotebe field samples were even below the minimum requirement. This may happen due to insufficient asphalt content and batching mix problems. Consequently aggregate particles of this field mixes will not get enough asphalt film thickness. The VMA of field Superpave samples gave a small margin of decrement from the lab samples and the VFA was found 0.85 times more than lab samples.

4.4 Performance Analysis of Field and Laboratory Asphalt Mixtures

Asphalt mix performance is a wide concept and is affected by various factors such as temperature, traffic load and moisture. Thus Engineers dared to provide a mixture with acceptable performance by using extensive mix design methods. This designed asphalt mix should be resistant to cracking, permanent deformation and moisture damage; which are the three basic pavement distress types. This paper investigated the resistance of lab and field AC samples to permanent deformation and moisture sensitivity using the wheel tracking test and ITS test respectively. For projects with Marshal design the stability and flow of lab and field samples were also determined and compared.

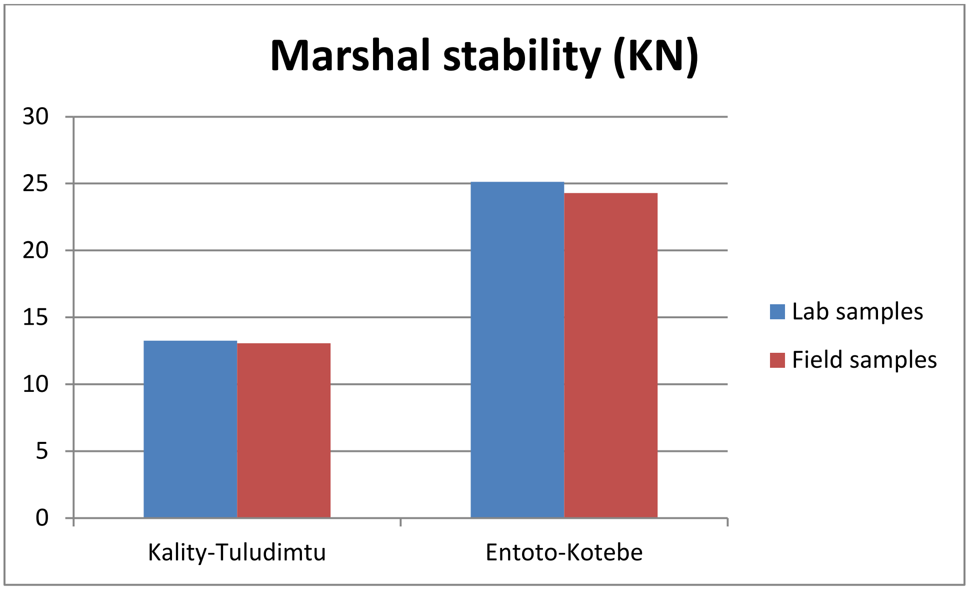
4.4.1 Marshal Stability and Flow Test Results of Lab and Field Mixes

Marshal Stability measures the maximum load sustained by the bituminous material which is mainly a measure of mass viscosity of the aggregate asphalt cement at a standard test temperature of 60^0C. It is significantly affected by the angle of internal friction of the aggregate and asphalt cement viscosity. Mixture with high stability value shows that it has high viscosity and will be resistant to cracking. The flow value, on the other hand, is the deformation that the test specimen undergoes during loading up to the maximum load.

After the loose AC mixtures of field and lab mixes were compacted with Marshal hammer with specified number of blows at the design asphalt content, the samples were then checked for Marshal stability and flow test. Table 4-6 and figure 4-3 below shows the result of lab and field samples.

Table 14 Marshal Stability and Flow Test Result-Kality-Tuludimtu Road Project

Road Project	Marshal Stability (KN)		Specification	Marshal Flow (mm)		Specification
	Lab samples	Field samples		Lab samples	Field samples	
Kality-Tuludimtu	**13.25**	**13.07**	**>12**	**2.81**	**2.69**	**2-4**
Entoto-Kotebe	**25.13**	**24.3**		**3.75**	**3.71**	



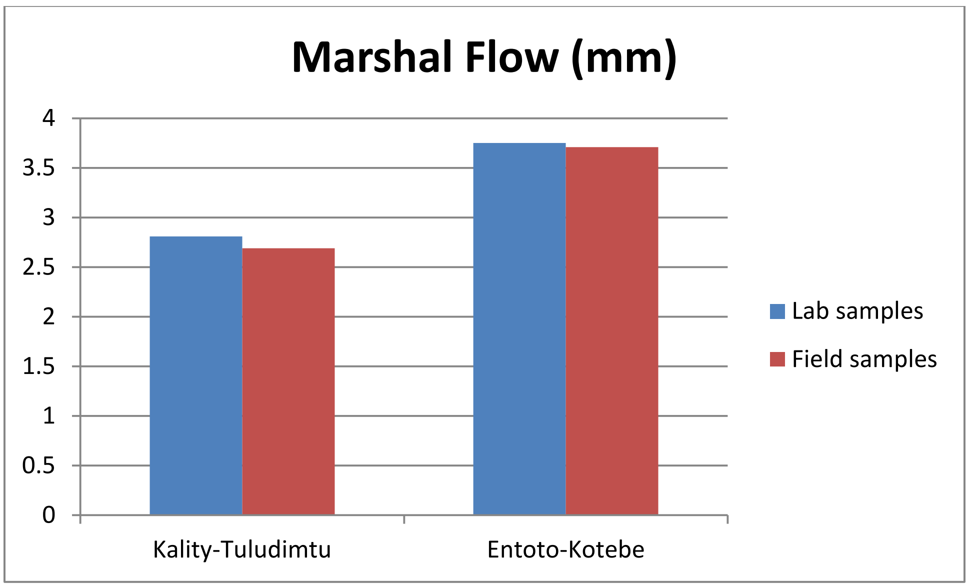


Figure 10 Marshal stability and flow test results

Here the test result shows that both the lab and field mixes fall on the specification range with some differences in terms of stability and flow. The lab samples showed higher strength or good stability than the field and recorded slightly higher flow. Here higher flow value for lab samples, indicates that field samples tend to be more resistant towards permanent deformation. This may be as a result of good mixing mechanism of field samples.

4.4.3 Indirect Tensile Strength Test Result

This test indicates the tensile strength of an asphalt mixture by comparing the conditioned samples to that of the unconditioned or dry samples. This ratio is used for the measurement of the strength loss resulting from damage caused by stripping of the asphalt from the aggregate under laboratory-controlled accelerated water conditioning. Therefore this study paper tested and examined the lab and field mixes for stripping problem. Table 4-8 and figure 4.5 below shows the TSR results of the field and lab mixes.

Table 15 TSR Test Results

Road Project	TSR value (%)		Field Samples
	Lab Samples	Field Samples	
Kality-Tuludimtu	**86.72**	**85.33**	
Entoto-Kotebe	**86.88**	**85.01**	**>75%**
Imperial-Kadisco	**84.83**	**86.38**	

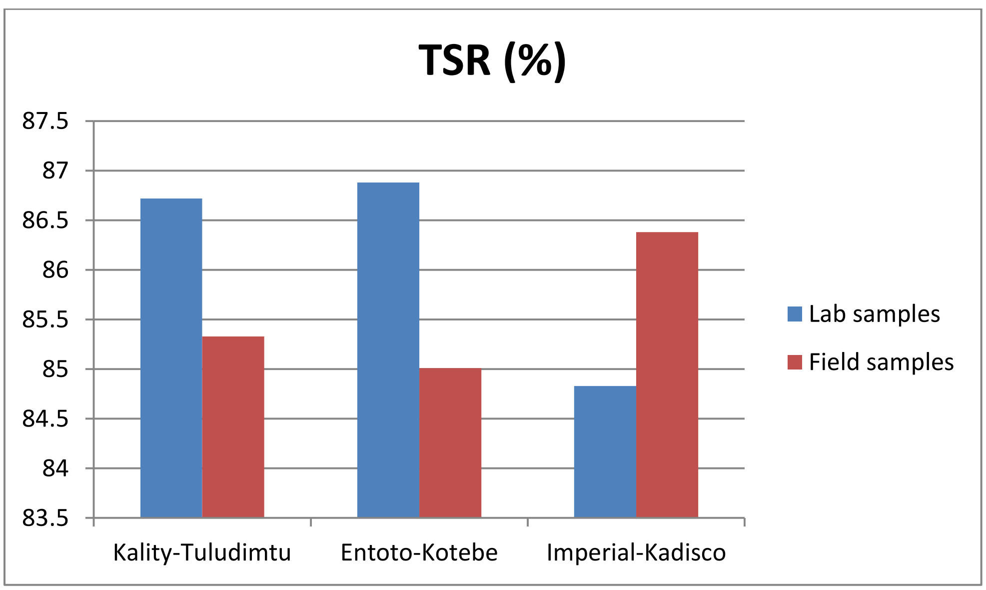


Figure 11 Tensile strength ratio test results

As can be seen from the results, Marshal lab samples showed higher percent of tensile strength improvement than field samples and hence higher resistance of moisture or stripping than the field samples and yet they both fall above the minimum requirement. This may happened as a result of uncontrolled gradation and may be related to the volumetric problem which was manifested on the field samples above. The field Superpave samples on the other hand showed better resistance to moisture damage.

4.4.5 Wheel Tracking Test Result

Laboratory wheel-tracking device was used to run simulative tests that measure the Superpave mixture qualities by rolling a small loaded wheel device repeatedly across a prepared slab specimens prepared from both field and lab produced AC mixtures. This test method was used to predict the rutting extent of the mixes. WTT was done to the Superpave samples of Imperial – Kadisco road project to evaluate and compare the rutting resistance of the lab and field mixes. With details of the test results being attached in the Appendix, the summary test result was shown below.

Table 16 Wheel-tracking Test Result-Imperial and Kadisco Intersection Project

Sample Type	Average Maximum Rut Depth (mm)	Specification
Lab samples	**1.63**	<7mm
Field samples	**2.02**	

According to the wheel-tracking test result, the lab Superpave samples, in contrary to Marshal samples, showed lower rut depth (1.63mm) than the field samples. This indicates that lab samples have good resistance to rutting than the field samples even though they both fall below the maximum rutting value.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study tried to evaluate material qualities, volumetric properties and performance variations of field produced and lab produced asphalt mixtures of three road projects in Addis Ababa. In doing do, different tests was taken carefully to the AC materials as well as field and lab produced mixtures. The results were summarized and discussed in chapter four and from the results obtained the following general conclusions have been drawn.

- The aggregate physical properties and conventional bitumen tests taken on the three projects were all laid on the design specification. But particle sizes greater than the design maximum particle size was seen on the field mixtures, which might be the reason for volumetric and performance variation.
- The bulk specific gravity (Gmb) and the theoretical maximum specific gravity (Gmm) of field produced Marshal samples shown an average increment of 3.75% and 3.65% respectively when compared to the lab samples, while the Superpave samples showed a small increment of 0.34% and 0.17%.
- The air voids of field Marshal samples were found 10.12 and 11.78 times lesser than lab produced samples while the VMA showed a significant average decrement of 17.93% in accordance with the lab samples. So does the VFA, which found to be 7 times lesser than laboratory samples. The Superpave field samples also shown a decrement on air voids and VMA by 4% and 2% respectively.
- Indirect tensile strength test results for laboratory Marshal mixtures were found 1.6 and 2.15 times more in accordance with field samples. This would further imply that lab Marshall mixtures appear to be capable of withstanding larger tensile strains prior to cracking or internal resistance. But the field Superpave samples showed 1.82 times more ITS test result in accordance with laboratory samples which would imply that field Superpave samples withstand stripping problem.

- The wheel-tracking test results also proved the difference between laboratory and field sample performance. Superpave laboratory samples protected their structural integrity during test duration and showed a 24% lesser rut depth from field samples.
- Generally, the magnitude of variation between field and lab samples were found higher among Marshal samples than Superpave samples, that is field Superpave samples performed way better than field Marshal samples.

5.2 Recommendation

Based on the study results of this paper, we can see that laboratory samples were proven better on volumetric properties as well as performance tests. Thus to narrow the variations between field and lab mixes, the following recommendation can be considered.

- Checking and monitoring the aggregate gradation or particle size distribution at the batching plant.
- Avoid using outa dated and older batching plants
- Ensuring the provision of quality assurance programs on asphalt concrete mixtures during production and construction
- Being consistence on selected aggregate quarry source unless another test is taken for alternative quarry sites
- Controlling and making sure that the bitumen content to be kept at the design optimum asphalt content
- Try to avoid longer waiting time of damp trucks carrying asphalt concrete mixes at the project sites waiting to damp on the paving line. This will affect the bitumen viscosity and will lose the paving temperature.
- Cover the asphalt mixtures using plastic membrane or any other covering material while transporting from batching plant to the project site.

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Appendix A-Material Quality Test Results

Table A-1 Specific Gravity and Water Absorption of Coarse (>No.4) Aggregate Kality_Tulu Dimtu Intersection Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Course Agg (14-20mm) Sample from: Hot Bin 1 Material description: Crushed AGG.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Trial	1	2	Average
B= Mass of SSD sample in air (g)	2501	2500	
C= Mass of saturated sample in water (g)	1548.2	1547.2	
A= Mass of oven dry sample in air (g)	2463.5	2462	
Water Temperature Correction at 25^{0}C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B-C)	2.583	2.582	2.582
Bulk Sp.gravity (SSD) Ss=B*K/(B-C)	2.623	2.621	2.622
Apparent Sp.gravity Sr=A*K/(A-C)	2.689	2.689	2.689
Water absorption (%) Aw=(B-A)*100/A	1.52	1.54	**1.53**

Table A-2 Specific Gravity and Water Absorption of Coarse (>No.4) Aggregate Kality-Tulu Dimtu Intersection Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Course Agg (14-20mm) Sample from: Hot Bin 2 Material description: Crushed AGG.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Trial	1	2	Average
B= Mass of SSD sample in air (g)	1840	2500	
C= Mass of saturated sample in water (g)	1143.5	1149	
A= Mass of oven dry sample in air (g)	1807	1818	
Water Temperature Correction at 25^{0}C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B-C)	2.592	2.591	2.582

Bulk Sp.gravity (SSD) Ss=B*K/(B-C)	2.639	2.637	2.622
Apparent Sp.gravity Sr=A*K/(A-C)	2.721	2.715	2.689
Water absorption (%) Aw=(B-A)*100/A	1.83	1.76	**1.795**

Table A-3 Specific Gravity and Water Absorption of Fine Aggregate Kality-Tulu Dimtu Intersection Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Fine Agg(<10mm) Sample from: Hot Bin 3 Material description: Crushed Sand.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Pycnometer	1	2	Average
B= Mass of pycnometer + water (g)	682.6	682.6	
S= Mass of SSD sample (g)	249.8	249.8	
C=Mass of pysnometer + water + sample (g)	831	837	
A= Mass of oven dry sample in air (g)	245	245.3	
Water Temperature Correction at 25^{0}C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B+S-C)	2.41	2.6	2.49
Bulk Sp.gravity (SSD) Ss=S*K/(B+S-C)	2.461	2.6	2.54
Apparent Sp.gravity Sr=A*K/(A+B-C)	2.533	2.7	2.61
Water absorption Aw=(S-A)*100/A	1.959	1.8	**1.90**

Table A-4 Specific Gravity and Water Absorption of Fine Aggregate Kality_Tulu Dimtu Intersection Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Fine Agg (<10mm) Sample from: Hot Bin 4 Material description: Crushed Sand.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Pycnometer	1	2	Average
B= Mass of pycnometer + water (g)	682.6	682.6	

S= Mass of SSD sample (g)	248.8	249.9	
C=Mass of pysnometer + water + sample (g)	838.4	838.5	
A= Mass of oven dry sample in air (g)	244.7	245.4	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B+S-C)	2.63	2.6	2.62
Bulk Sp.gravity (SSD) Ss=S*K/(B+S-C)	2.672	2.7	2.66
Apparent Sp.gravity Sr=A*K/(A+B-C)	2.750	2.7	2.74
Water absorption Aw=(S-A)*100/A	1.676	1.8	1.75

Table A-5 Specific Gravity and Water Absorption of Coarse (>No.4) Aggregate Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Course Agg (14-20mm) Sample from: Hot Bin 1 Material description: Crushed AGG.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Trial	1	2	Average
B= Mass of SSD sample in air (g)	2500	2503	
C= Mass of saturated sample in water (g)	1551	1547.2	
A= Mass of oven dry sample in air (g)	2460	2463	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B-C)	2.589	2.574	2.582
Bulk Sp.gravity (SSD) Ss=B*K/(B-C)	2.63	2.62	2.624
Apparent Sp.gravity Sr=A*K/(A-C)	2.70	2.69	2.695
Water absorption (%) Aw=(B-A)*100/A	1.63	1.62	1.63

Table A-6 Specific Gravity and Water Absorption of Coarse (>No.4) Aggregate Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Course Agg (14-20mm) Sample from: Hot Bin 2 Material description: Crushed AGG.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Trial	1	2	Average
B= Mass of SSD sample in air (g)	1850	1855	
C= Mass of saturated sample in water (g)	1146.5	1152	
A= Mass of oven dry sample in air (g)	1810	1823	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B-C)	2.570	2.590	2.580
Bulk Sp.gravity (SSD) Ss=B*K/(B-C)	2.63	2.64	2.631
Apparent Sp.gravity Sr=A*K/(A-C)	2.72	2.71	2.719
Water absorption (%) Aw=(B-A)*100/A	2.21	1.76	1.985

Table A-7 Specific Gravity and Water Absorption of Fine Aggregate Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Fine Agg(<10mm) Sample from: Hot Bin 3 Material description: Crushed Sand.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Pycnometer	1	2	Average
B= Mass of pycnometer + water (g)	682.6	682.6	
S= Mass of SSD sample (g)	251	250	
C=Mass of pysnometer + water + sample (g)	825	833	
A= Mass of oven dry sample in air (g)	245.3	245.5	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B+S-C)	2.26	2.5	2.36

Bulk Sp.gravity (SSD) Ss=S*K/(B+S-C)	2.309	2.5	2.41
Apparent Sp.gravity Sr=A*K/(A+B-C)	2.381	2.6	2.48
Water absorption Aw=(S-A)*100/A	2.324	1.8	2.08

Table A-8 Specific Gravity and Water Absorption of Fine Aggregate Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Fine Agg(<10mm) Sample from: Hot Bin 4 Material description: Crushed Sand.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Pycnometer	1	2	Average
B= Mass of pycnometer + water (g)	682.6	682.6	
S= Mass of SSD sample (g)	248.8	250	
C=Mass of pysnometer + water + sample (g)	838.4	838.5	
A= Mass of oven dry sample in air (g)	244.7	245.4	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B+S-C)	2.63	2.6	2.62
Bulk Sp.gravity (SSD) Ss=S*K/(B+S-C)	2.672	2.7	2.66
Apparent Sp.gravity Sr=A*K/(A+B-C)	2.750	2.7	2.74
Water absorption Aw=(S-A)*100/A	1.676	1.9	1.78

Table A-9 Specific Gravity and Water Absorption of Coarse (>No.4) Aggregate Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Course Agg (14-20mm) Sample from: Hot Bin 1 Material description: Crushed AGG.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Trial	1	2	Average
B= Mass of SSD sample in air (g)	2510	2507	
C= Mass of saturated sample in water (g)	1548.2	1547.2	
A= Mass of oven dry sample in air (g)	2459	2454	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B-C)	2.554	2.554	2.55
Bulk Sp.gravity (SSD) Ss=B*K/(B-C)	2.61	2.61	2.61
Apparent Sp.gravity Sr=A*K/(A-C)	2.70	2.70	2.70
Water absorption (%) Aw=(B-A)*100/A	2.07	2.16	2.12

Table A-10 Specific Gravity and Water Absorption of Coarse (>No.4) Aggregate Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Course Agg (14-20mm) Sample from: Hot Bin 2 Material description: Crushed AGG.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Trial	1	2	Average
B= Mass of SSD sample in air (g)	1840	1850	
C= Mass of saturated sample in water (g)	1143.5	1149	
A= Mass of oven dry sample in air (g)	1809	1820	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B-C)	2.594	2.593	2.59
Bulk Sp.gravity (SSD) Ss=B*K/(B-C)	2.64	2.64	2.64
Apparent Sp.gravity	2.72	2.71	2.71

Sr=A*K/(A-C)			
Water absorption (%) Aw=(B-A)*100/A	1.71	1.65	1.68

Table A-11 Specific Gravity and Water Absorption of Fine Aggregate Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Fine Agg(<10mm) Sample from: Hot Bin 3 Material description: Crushed Sand.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Pycnometer	1	2	Average
B= Mass of pycnometer + water (g)	682.6	682.6	
S= Mass of SSD sample (g)	251.4	252.8	
C=Mass of pysnometer + water + sample (g)	840	841	
A= Mass of oven dry sample in air (g)	246.1	245.5	
Water Temperature Correction at 25^0C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B+S-C)	2.62	2.6	2.61
Bulk Sp.gravity (SSD) Ss=S*K/(B+S-C)	2.672	2.7	2.67
Apparent Sp.gravity Sr=A*K/(A+B-C)	2.771	2.8	2.79
Water absorption Aw=(S-A)*100/A	2.154	3.0	2.56

Table A-12 Specific Gravity and Water Absorption of Fine Aggregate Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Material type: Fine Agg(<10mm) Sample from: Hot Bin 4 Material description: Crushed Sand.		Test Method: AASHTO T 85-91 Date sample: Date test:	
Pycnometer	1	2	Average
B= Mass of pycnometer + water (g)	682.6	682.6	
S= Mass of SSD sample (g)	248.5	250	
C=Mass of pysnometer + water + sample (g)	810	815	
A= Mass of oven dry sample in air (g)	244.2	247.2	
Water Temperature Correction at 25^{0}C (K)	0.9989	0.9989	
Bulk Sp.gravity (oven dry) Sd=A*K/(B+S-C)	2.01	2.1	2.06
Bulk Sp.gravity (SSD) Ss=S*K/(B+S-C)	2.050	2.1	2.09
Apparent Sp.gravity Sr=A*K/(A+B-C)	2.088	2.2	2.12
Water absorption Aw=(S-A)*100/A	1.761	1.1	1.45

Table A-13 Aggregate LA Abrasion Test Result-Kaliti Tuludimtu Ring Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: LA Abrasion test Material type: Course Agg(>No.4) Material description: Crushed Stone.		Test Method: AASHTO T 96-94 Date sample: Date test:	
Trial	1	2	Average
Number of Revolution	500	500	
Total Weight of Sample (g)	5000	5000	
Weight of sample retained on N0. 12 sieve (g)	4000	4100	
Percent Loss	20	18	19

Table A-14 Aggregate LA Abrasion Test Result-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: LA Abrasion test Material type: Course Agg(>No.4) Material description: Crushed Stone.		Test Method: AASHTO T 96-94 Date sample: Date test:	
Trial	1	2	Average
Number of Revolution	500	500	
Total Weight of Sample (g)	5000	5000	
Weight of sample retained on N0. 12 sieve (g)	3949	3951	
Percent Loss	21.02	20.98	21

Table A-15 Aggregate LA Abrasion Test Result-Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: LA Abrasion test Material type: Course Agg(>No.4) Material description: Crushed Stone.		Test Method: AASHTO T 96-94 Date sample: Date test:	
Trial	1	2	Average
Number of Revolution	500	500	
Total Weight of Sample (g)	5000	5000	
Weight of sample retained on N0. 12 sieve (g)	4200	4300	
Percent Loss	16	14	15

A-16 Aggregate Flakiness Index Test Results Akaki-Tuludimtu Ring Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: Flakiness Index Calculation Material type: Course Agg. Material description: Crushed AGG.		Test Method: BS 812:Section 105.1:1989 Date sample: Date test:	
Sieve Size (mm)		Mass Retained (g) (A)	Mass Passing (g) (B)
100% Passing	100% Retained		
63	50	0	0
50	37.5	0	0
37.5	28	0	0

28	20	790	101
20	14	520	85
14	10	260	95
10	6.3	252	75
TOTAL		1822	356
FI =(B/A)*100%		19.54	

A-17 Aggregate Flakiness Index Test Results Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: Flakiness Index Calculation Material type: Course Agg. Material description: Crushed AGG.		Test Method: BS 812:Section 105.1:1989 Date sample: Date test:	
Sieve Size (mm)		Mass Retained (g) (A)	Mass Passing (g) (B)
100% Passing	100% Retained		
63	50	0	0
50	37.5	0	0
37.5	28	0	0
28	20	795	96
20	14	532	85
14	10	242	95
10	6.3	302	70
TOTAL		1871	346
FI =(B/A)*100%		18.5	

A-18 Aggregate Flakiness Index Test Results Imperial and Kadisko Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: Flakiness Index Calculation Material type: Course Agg. Material description: Crushed AGG.		Test Method: BS 812:Section 105.1:1989 Date sample: Date test:	
Sieve Size (mm)		Mass Retained (g) (A)	Mass Passing (g) (B)
100% Passing	100% Retained		
63	50	0	0
50	37.5	0	0
37.5	28	0	0
28	20	800	90

20	14	545	85
14	10	242	95
10	6.3	302	70
TOTAL		1889	340
FI =(B/A)*100%		18.0	

A-19 Aggregate Crushing Value Test Kality-Tuludimtu Ring Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: ACV Material type: Course Agg. Material description: Crushed Stone.	Test Method: BS 812:Part 110 (1990) Date sample: Date test:	
Trial	1	2
Mass of Sample passing 12mm sieve (g) (W1)	2000	1900
Mass of sample passing 2.36mm sieve (g) (W2)	315	310
ACV=(W2/W1)*100%	15.75	16.32
Average ACV (%)	16.03	

A-20 Aggregate Crushing Value Test- Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: ACV Material type: Course Agg. Material description: Crushed Stone.	Test Method: BS 812:Part 110 (1990) Date sample: Date test:	
Trial	1	2
Mass of Sample passing 12mm sieve (g) (W1)	1800	1600
Mass of sample passing 2.36mm sieve (g) (W2)	346	342
ACV=(W2/W1)*100%	19.22	21.38
Average ACV (%)	20.30	

A-21 Aggregate Crushing Value Test- Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: ACV Material type: Course Agg. Material description: Crushed Stone.	Test Method: BS 812:Part 110 (1990) Date sample: Date test:	
Trial	1	2
Mass of Sample passing 12mm sieve (g) (W1)	2300	2270
Mass of sample passing 2.36mm sieve (g) (W2)	321	319
ACV=(W2/W1)*100%	13.96	14.05
Average ACV (%)	14.0	

A-22 Aggregate Sand Equivalent Test Kality-Tuludimtu Ring Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: Sand Equivalent	Test Method: AASHTO T 176 Date sample: Date test:	
Trial	1	2
Sand Reading (mm) (A)	89	92
Clay Reading (mm) (B)	140	152
Sand Equivalent = (A/B)*100%	63.58	60.53
Average SE (%)	62.0	

A-23 Aggregate Sand Equivalent Test - Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: Sand Equivalent	Test Method: AASHTO T 176 Date sample: Date test:	
Trial	1	2
Sand Reading (mm) (A)	88	85
Clay Reading (mm) (B)	167	173
Sand Equivalent = (A/B)*100%	52.69	49.13
Average SE (%)	51	

A-24 Aggregate Sand Equivalent Test – Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Akaki Quary Test type: Sand Equivalent	Test Method: AASHTO T 176 Date sample: Date test:	
Trial	1	2
Sand Reading (mm) (A)	100	105
Clay Reading (mm) (B)	118	124.5
Sand Equivalent = (A/B)*100%	84.75	84.34
Average SE (%)	84.5	

A-25 Bitumen Quality Test Result-Akaki Ring Road Project

Location: AASTU HIGHWAY LAB. Source: Kality Asphalt Plant Grade: 60/70 Test type: Quality Test	Test Method: AASHTO M20-70 Date sample: Date test:

Penetration	Frequency	Test Temperature (^{0}C)	Time of test (s)	Test Load (g)	Reading Date (0.1mm) First Time	Second Time	Third Time	Average Penetration (0.1mm)
	1	25	5	100	65.6	68.6	64.1	66.1
	2	-	-	-	63.2	62.5	62.9	**62.9**
	3	-	-	-	58.7	60	60.8	59.8

Ductility	Frequency	Test Temperature (^{0}C)	Speed (cm/min)	Ductility (cm) 1	2	3	Average Ductility (cm)
	1	25	5	100+	100+	100+	100+
	2	25	5				

Softening Point	Frequency	Initial temperature	Record of liquid temperature in beaker every one min 1	2	3	4	5	6	7	8	Softening Point (0C)	Average SP (^{0}C)
	1	5^{0}C				~					49.8	**50.2**
	2	5^{0}C				~					50.6	

Flashing and Fire Point	Frequency	Flash Point Temperature (^{0}C)	Fire Point Temperature (^{0}C)	Flash Point (^{0}C)	Fire Point (^{0}C)
	1	305	340	**307**	**342**
	2	310	345		

A-26 Bitumen Quality Test Results-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Source: Kality Asphalt Plant Grade: 60/70 Test type: Quality Test				Test Method: AASHTO M20-70 Date sample: Date test:							
Penetration	Frequency	Test Temperature (^{0}C)	Time of test (s)	Test Load (g)	Reading Date (0.1mm)						Average Penetration (0.1mm)
					First Time		Second Time		Third Time		
	1	25	5	100	66.3		68.8		64.5		66.53
	2	-	-	-	63.7		63		63.2		**63.33**
	3	-	-	-	59.4		61		60.9		60.4
Ductility	Frequency	Test Temperature (^{0}C)	Speed (cm/min)		Ductility (cm)						Average Ductility (cm)
					1		2		3		
	1	25	5		100+		100+		100+		100+
	2	25	5								
Softening Point	Frequency	Initial temperature	Record of liquid temperature in beaker every one min							Softening Point (0C)	Average SP (^{0}C)
			1	2	3	4	5	6	7	8		
	1	5^{0}C				~					50.4	**50.65**
	2	5^{0}C				~					50.9	
Flashing and Fire Point	Frequency	Flash Point Temperature (^{0}C)		Fire Point Temperature (^{0}C)						Flash Point (^{0}C)	Fire Point (^{0}C)
	1	290		339						**295**	**341.5**
	2	300		344							

A-27 Bitumen Quality Test Results-Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Source: Kality Asphalt Plant Grade: 60/70 Test type: Quality Test				Test Method: AASHTO M20-70 Date sample: Date test:				
Penetration	Frequency	Test Temperature (^{0}C)	Time of test (s)	Test Load (g)	Reading Date (0.1mm)			Average Penetration (0.1mm)
					First Time	Second Time	Third Time	
	1	25	5	100	69	69.4	68.5	68.97
	2	-	-	-	66.5	67.5	67.1	**67.0**
	3	-	-	-	64.9	65.3	65.1	65.1
Ductility	Frequency	Test Temperature (^{0}C)	Speed (cm/min)		Ductility (cm)			Average Ductility (cm)
					1	2	3	

	1	25	5				100+		100+		100+	100+
	2	25	5									
Softening Point	Frequency	Initial temperature	Record of liquid temperature in beaker every one min								Softening Point (0C)	Average SP (^{0}C)
			1	2	3	4	5	6	7	8		
	1	5^{0}C				~					50.5	**51**
	2	5^{0}C				~					51.5	
Flashing and Fire Point	Frequency	Flash Point Temperature (^{0}C)			Fire Point Temperature (^{0}C)						Flash Point (^{0}C)	Fire Point (^{0}C)
	1	294			339						**289**	**340**
	2	284			341							

APPENDIX B Aggregate Gradation

Table B-28 Aggregate Gradation-Akaki Ring Road Project

Source: Akaki Quary

Purpose: Agg. For Asphalt Mix Design

Material Description: Wearing Coarse

Sieve Size(mm)	Average Cumulative Passing					Total	Construction Specification		
	14-25 mm	6-14mm	3-6mm	0-3mm	Filler		Up	Down	Middle Range
25	100	100	100	100	100	**100**	100	100	100
19	100	100	100	100	100	**100**	100	100	100
12.5	29.2	99.2	100	100	100	**94**	100	90	95
9.5	7.9	74.8	100	100	100	**82.6**	90	76	83
4.75	2.1	18.2	90.9	100	100	**58.2**	74	44	59
2.36	0.5	8.4	18.6	92.3	100	**41.2**	58	28	43
1.18	0.5	3.5	12.6	62	100	**27.5**	40	15	27.5
0.6	0.5	1.8	6.3	43.2	100	**19.2**	29	10	19.5
0.3	0.5	1.8	1.5	26.8	100	**12.6**	21	5	13
0.15	0.5	1.8	1	15.9	98.3	**8.6**	15	4	9.5
0.075	0.5	1.8	1	6.9	94.6	**5.3**	10	2	6
Blended Proportion	**8%**	**40%**	**14%**	**36%**	**2%**				

Table B-29 Aggregate Gradation-Entoto-Kotebe Access Road Project

Source: **Akaki Quary**

Purpose: Agg. for Asphalt Mix Design

Material Description: Wearing Coarse

Sieve Size(mm)	**Average Cumulative Passing (%)**					**Total**	**Construction Specification**		
	14-25 mm	**6-14mm**	**3-6mm**	**0-3mm**	**Filler**		**Upper Limit**	**Lower Limit**	**Middle Range**
25	100	100	100	100	100	**100**	100	100	100
19	100	100	100	100	100	**72**	80	56	68
12.5	27.3	97.4	100	100	100	**68**	74	51	95
9.5	7.3	75	97.9	100	100	**57**	60	45	83
4.75	1.9	15.1	89.6	100	100	**46**	53	32	38
2.36	0.4	7.9	17.8	90.3	100	**31**	41	15	28
1.18	0.4	3.0	11.0	59.2	100	**27.5**	40	14	27.5
0.6	0.4	1.5	5.4	40.5	100	**19.2**	29	10	19.5
0.3	0.4	1.5	1.1	25	100	**8**	16	4	10
0.15	0.4	1.5	1	14.3	98.6	**6.7**	15	4	9.5
0.075	0.4	1.5	1	5.7	95.1	**4.5**	6	0	6
Blended Proportion	**12%**	**38%**	**16%**	**32%**	**2%**				

Table B-30 Aggregate Gradation-Imperial and Kadisco Intersection Project

Source: **Akaki Quary**

Purpose: Agg. For Asphalt Mix Design

Material Description: **Wearing Coarse**

Sieve Size(mm)	Average Cumulative Passing (%)					Total	Construction Specification		
	14-25 mm	6-14mm	3-6mm	0-3mm	Filler		Upper Limit	Lower Limit	Middle Range
25	100	100	100	100	100	**100**	100	100	100
19	78.7	100	100	100	100	**95.52**	100	90.0	95.0
12.5	9.9	98.9	100	100	100	**80.76**	88.0	68.0	78.0
9.5	0.6	73.9	98.9	100	100	**71.11**	80.0	56.0	68.0
4.75	0.1	2.5	85.1	100	100	**47.46**	65.0	35.0	50.0
2.36	0.0	0.2	8.5	95.0	100	**33.73**	49.0	23.0	36.0
1.18	0.0	0.1	3.7	58.0	100	**21.17**	34.0	14.0	24.0
0.6	0.0	0.0	2.3	41.4	100	**15.60**	25.0	8.0	16.5
0.3	0.0	0.0	1.0	27.8	100	**11.04**	19.0	5.0	12.0
0.15	0.0	0.0	0.4	17.8	98	**7.73**	13.0	4.0	8.5
0.075	0.0	0.0	0.0	8.7	95	**4.68**	8.0	2.0	5.0
Blended Proportion	**21%**	**30%**	**15%**	**32%**	**2%**				

APPENDIX C Performance Test and Volumetric Analysis of Marshal Specimens

Table C-31 Theoretical Maximum Specific Gravity of Lab Produced Marshal Specimens at OBC-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.9% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A Mass of Dry Sample in Air (g)	1008	1007	1009
B Mass of Jar Filled with Water (g)	2668.6	2668.4	2668.5
C Mass of Jar Filled with Water Plus Sample	3259	3260	3262
Water Temperature Correction (K)	1.000	1.000	1.000
Maximum Theoretical Sp. Gravity(Gmm)=A/(A+B-C)	2.414	2.424	2.428
Average Gmm	**2.422**		

Table C-32 Theoretical Maximum Specific Gravity of Field Produced Marshal Specimens at -Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.9% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A Mass of Dry Sample in Air (g)	1000	1000	1000
B Mass of Jar Filled with Water (g)	2668.6	2668.4	2668.5
C Mass of Jar Filled with Water Plus Sample	3269.1	3268.5	3269.6
Water Temperature Correction (K)	1.000	1.000	1.000
Maximum Theoretical Sp. Gravity(Gmm)=A/(A+B-C)	2.503	2.501	2.507
Average Gmm	**2.504**		

Table C-33 Theoretical Maximum Specific Gravity of Lab Produced Marshal Specimens at OBC-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 3.96% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A Mass of Dry Sample in Air (g)	1000	1000	1000
B Mass of Jar Filled with Water (g)	2668.6	2668.4	2668.5
C Mass of Jar Filled with Water Plus Sample	3270	3270.5	3269.6
Water Temperature Correction (K)	1.000	1.000	1.000
Maximum Theoretical Sp. Gravity(Gmm)=A/(A+B-C)	2.509	2.513	2.507
Average Gmm	**2.510**		

Table C-34 Theoretical Maximum Specific Gravity of Field Produced Marshal Specimens - Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 3.96% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A Mass of Dry Sample in Air (g)	1002	1001	1000
B Mass of Jar Filled with Water (g)	2668.6	2668.4	2668.5
C Mass of Jar Filled with Water Plus Sample	3283	3282	3280.5
Water Temperature Correction (K)	1.000	1.000	1.000
Maximum Theoretical Sp. Gravity(Gmm)=A/(A+B-C)	2.585	2.584	2.577
Average Gmm	**2.582**		

Table C-35 Bulk Specific Gravity of Lab Produced Marshal Specimens-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.9% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A: Mass of dry specimen in air (g)	1180	1175	1178

B:Mass of SSD sample in air (g)	1206	1206.8	1209
C: Mass of volumeter filled with water(g)	5350.8	5350.8	5350.8
D: Mass of volumeter filled specimen and water (g)	6050	6050.1	6051
Bulk Specific Gravity(Gmb)=A/(B+C-D)	2.328	2.315	2.315
Average Gmb	**2.320**		

Table C-36 Bulk Specific Gravity of Field Produced Marshal Specimens-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.9% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A: Mass of dry specimen in air (g)	1187.3	1184.9	1190.2
B:Mass of SSD sample in air (g)	1190.5	1190.6	1195.9
C: Mass of volumeter filled with water(g)	5350.8	5350.8	5350.8
D: Mass of volumeter filled specimen and water (g)	6048.8	6049.8	6053.5
Bulk Specific Gravity(Gmb)=A/(B+C-D)	2.411	2.410	2.413
Average Gmb	**2.411**		

Table C-37 Bulk Specific Gravity of Lab Produced Marshal Specimens-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 3.96% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A: Mass of dry specimen in air (g)	1185	1183	1185.8
B:Mass of SSD sample in air (g)	1193	1195	1198
C: Mass of volumeter filled with water(g)	5350.8	5350.8	5350.8
D: Mass of volumeter filled specimen and water (g)	6052	6053	6051
Bulk Specific Gravity(Gmb)=A/(B+C-D)	2.410	2.401	2.382
Average Gmb	**2.397**		

Table C-38 Bulk Specific Gravity of Field Produced Marshal Specimens-Entoto-Kotebe Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.9% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A: Mass of dry specimen in air (g)	1197	1195	1198
B:Mass of SSD sample in air (g)	1179	1181.5	1180
C: Mass of volumeter filled with water(g)	5350.8	5350.8	5350.8
D: Mass of volumeter filled specimen and water (g)	6049	6048	6050
Bulk Specific Gravity(Gmb)=A/(B+C-D)	2.490	2.467	2.492
Average Gmb	**2.483**		

Table C-39 Volumetric Analysis of Lab Produced Marshal Specimens at OBC-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced OBC: 4.9% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	Average
A: Bitumen Content (Pb) (%)	4.9	4.9	
B: Bulk Specific Gravity of Aggregate(Gsb)	2.62	2.62	
C: Bulk Specific Gravity of Compacted Mix (Gmb)	2.328	2.315	
D: Theoretical Maximum Specific Gravity (Gmm)	2.422	2.422	
Air Void (%) Va = (D-C)/D*100	3.88	4.41	**4.15**
Voids In the Mineral Aggregate (%) VMA = 100-(100-A)/B*C	15.50	15.97	**15.73**
Voids Filled with Asphalt (%) VFA = (VMA-Va)/VMA*100	74.96	72.38	**73.67**

Table C-40 Volumetric Analysis of Field Produced Marshal Specimens at OBC-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Project site Kality OBC: 4.9% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	Average
A: Bitumen Content (Pb) (%)	4.9	4.9	
B: Bulk Specific Gravity of Aggregate(Gsb)	2.62	2.62	
C: Bulk Specific Gravity of Compacted Mix (Gsb)	2.411	2.410	
D: Theoretical Maximum Specific Gravity (Gmm)	2.504	2.504	
Air Void (%) Va = (D-C)/D*100	3.71	3.75	**3.73**
Voids In the Mineral Aggregate (%) VMA = 100-(100-A)/B*C	12.48	12.52	**12.5**
Voids Filled with Asphalt (%) VFA = (VMA-Va)/VMA*100	70.27	70.04	**70.155**

Table C-41 Volumetric Analysis of Lab Produced Marshal Specimens at OBC-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced OBC: 3.96% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	Average
A: Bitumen Content (Pb) (%)	3.96	3.96	
B: Bulk Specific Gravity of Aggregate(Gs)	2.63	2.63	
C: Bulk Specific Gravity of Compacted Mix (Gsb)	2.41	2.401	
D: Theoretical Maximum Specific Gravity (Gmm)	2.510	2.510	
Air Void (%) Va = (D-C)/D*100	3.98	4.342	**4.16**
Voids In the Mineral Aggregate (%) VMA = 100-(100-A)/B*C	12.0	12.32	**12.16**
Voids Filled with Asphalt (%) VFA = (VMA-Va)/VMA*100	66.78	64.8	**65.77**

Table C-42 Volumetric Analysis of Field Produced Marshal Specimens at OBC-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Project site Entoto OBC: 3.96% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	Average
A: Bitumen Content (Pb) (%)	3.96	3.96	
B: Bulk Specific Gravity of Aggregate(Gs)	2.63	2.63	
C: Bulk Specific Gravity of Compacted Mix (Gsb)	2.49	2.492	
D: Theoretical Maximum Specific Gravity (Gmm)	2.582	2.582	
Air Void (%) Va = (D-C)/D*100	3.56	3.48	**3.52**
Voids In the Mineral Aggregate (%) VMA = 100-(100-A)/B*C	9.07	9.0	**9.03**
Voids Filled with Asphalt (%) VFA = (VMA-Va)/VMA*100	60.75	61.3	**61.02**

Table C-43 Marshal Stability and Flow Test Results of Lab Produced Mixtures at OBC-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab Produced OBC: 4.9% Material description: Wearing Course.			Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:
Sample	Stability (KN)		Flow (mm)
	Load (KN)	Adjusted Load	
A	12.13	12.86	2.77
B	12.4	13.15	2.82
C	12.98	13.75	2.84
Average		**13.25**	**2.81**

Table C-44 Marshal Stability and Flow Test Results of Field Produced Mixtures-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Project site Kality Material description: Wearing Course.			Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:
Sample	Stability (KN)		Flow (mm)
	Load (KN)	Adjusted Load	
A	12.55	13.3	2.63
B	11.95	12.66	2.9
C	12.5	13.26	2.54
Average		**13.07**	**2.69**

Table C-45 Marshal Stability and Flow Test Results of Lab Produced Mixtures-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab Produce OBC: 3.9% Material description: Wearing Course.			Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:
Sample	Stability (KN)		Flow (mm)
	Load (KN)	Adjusted Load	
A	22.75	24.12	3.7
B	23.33	25.44	3.8
C	23.69	25.83	3.75
Average		**25.13**	**3.75**

Table C-46 Marshal Stability and Flow Test Results of Field Produced Mixtures-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Project site Entoto OBC: 3.9% Material description: Wearing Course.			Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:
Sample	Stability (KN)		Flow (mm)
	Load (KN)	Adjusted Load	
A	22.45	23.8	3.69
B	23.49	24.9	3.75
C	22.83	24.2	3.71
Average		**24.3**	**3.71**

Table C-47 Indirect Tensile Strength Test of Lab Produced Marshal Mixtures-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced Material description: Wearing Course.					
	Maximum Load (N) (P)	Specimen Thickness (mm) (t)	Specimen Diameter (mm) (D)	Pie (π)	S = 2000*P / Π*t*D
S1: Tensile Strength Conditioned Subset	22520	102.5	150	3.1415	932.49
S2: Tensile Strength Unconditioned Subset	25968	102.5	150	3.1415	1075.26
Tensile Strength Ratio (TSR)= S2/S1*100%					**86.72**

Table C-48 Indirect Tensile Strength Test of Field Produced Marshal Mixtures-Kality Ring Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Project site Kality Material description: Wearing Course.					
	Maximum Load (N) (P)	Specimen Thickness (mm) (t)	Specimen Diameter (mm) (D)	Pie (π)	S = 2000*P / Π*t*D
S1: Tensile Strength Conditioned Subset	21795.9	102.5	150	3.1415	**902.5**
S2: Tensile Strength Unconditioned Subset	25543.1	102.5	150	3.1415	**1057.67**
Tensile Strength Ratio (TSR)= S2/S1*100%					**85.33**

Table C-49 Indirect Tensile Strength Test of Lab Produced Marshal Mixtures-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced Material description: Wearing Course.					
	Maximum Load (N) (P)	Specimen Thickness (mm) (t)	Specimen Diameter (mm) (D)	Pie (π)	S = 2000*P / Π*t*D
S1: Tensile Strength Conditioned Subset	21910	102.5	150	3.1415	**907.23**
S2: Tensile Strength Unconditioned Subset	25220	102.2	150	3.1415	**1044.23**
Tensile Strength Ratio (TSR)= S2/S1*100%					**86.88**

Table C-50 Indirect Tensile Strength Test of Field Produced Marshal Mixtures-Entoto-Kotebe Access Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Project site Entoto Material description: Wearing Course.					
	Maximum Load (N) (P)	Specimen Thickness (mm) (t)	Specimen Diameter (mm) (D)	Pie (π)	S = 2000*P / Π*t*D
S1: Tensile Strength Conditioned Subset	21340	150	150	3.1415	**883.63**
S2: Tensile Strength Unconditioned Subset	25100	102.5	150	3.1415	**1039.33**
Tensile Strength Ratio (TSR)= S2/S1*100%					**85.01**

APPENDIX D Performance Test and Volumetric Analysis of Superpave Specimens

Table D-51 Theoretical Maximum Specific Gravity of Lab Produced Superpave Specimens at OBC-Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.58% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A Mass of Dry Sample in Air (g)	1001	1001.5	1000
B Mass of Jar Filled with Water (g)	2668.6	2668.4	2668.5
C Mass of Jar Filled with Water Plus Sample	3257.9	3258	3258.4
Water Temperature Correction (K)	1.000	1.000	1.000
Maximum Theoretical Sp. Gravity(Gmm)=A/(A+B-C)	2.431	2.431	2438
Average Gmm	**2.434**		

Table D-52 Theoretical Maximum Specific Gravity of Field Produced Superpave Specimens at OBC-Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.58% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A Mass of Dry Sample in Air (g)	1000	1000	1000
B Mass of Jar Filled with Water (g)	2668.6	2668.4	2668.5
C Mass of Jar Filled with Water Plus Sample	3258.7	3257.8	3258.6
Water Temperature Correction (K)	1.000	1.000	1.000
Maximum Theoretical Sp. Gravity(Gmm)=A/(A+B-C)	2.440	2.435	2.440
Average Gmm	**2.438**		

Table D-53 Bulk Specific Gravity of Lab Produced Superpave Specimens- at OBC-Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.58% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A: Mass of dry specimen in air (g)	4500	4470	4480
B:Mass of SSD sample in air (g)	4514	4503	4511
C: Mass of volumeter filled with water(g)	5350.8	5350.8	5350.8
D: Mass of volumeter filled specimen and water (g)	7937	7936	7941
Bulk Specific Gravity(Gmb)=A/(B+C-D)	2.334	2.331	2.332
Average Gmb	**2.332**		

Table D-54 Bulk Specific Gravity of Field Produced Superpave Specimens- at OBC-Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture OBC: 4.58% Material description: Wearing Course	Test Method: ASTM DES. D 2041-90 Date sample: Date test:		
Trial	1	2	3
A: Mass of dry specimen in air (g)	4502.8	4481.1	4497.5
B:Mass of SSD sample in air (g)	4508.9	4495.4	4512.3
C: Mass of volumeter filled with water(g)	5350.8	5350.8	5350.8
D: Mass of volumeter filled specimen and water (g)	7933.8	7934.2	7939.5
Bulk Specific Gravity(Gmb)=A/(B+C-D)	2.338	2.344	2.338
Average Gmb	**2.340**		

Table D-55 Volumetric Analysis of Lab Produced Superpave Specimens at OBC- Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced OBC: 4.58% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	Average
A: Bitumen Content (Pb) (%)	4.58	4.58	
B: Bulk Specific Gravity of Aggregate(Gsb)	2.62	2.62	
C: Bulk Specific Gravity of Compacted Mix (Gmb)	2.334	2.331	
D: Theoretical Maximum Specific Gravity (Gmm)	2.434	2.434	
Air Void (%) Va = (D-C)/D*100	4.1	4.2	**4.15**
Voids In the Mineral Aggregate (%) VMA = 100-(100-A)/B*C	14.99	15.10	**15.04**
Voids Filled with Asphalt (%) VFA = (VMA-Va)/VMA*100	72.65	72.18	**72.41**

Table D-56 Volumetric Analysis of Field Produced Superpave Specimens at OBC- Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced OBC: 4.58% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	Average
A: Bitumen Content (Pb) (%)	4.58	4.58	
B: Bulk Specific Gravity of Aggregate(Gsb)	2.62	2.62	
C: Bulk Specific Gravity of Compacted Mix (Gmb)	2.338	2.344	
D: Theoretical Maximum Specific Gravity (Gmm)	2.438	2.438	
Air Void (%) Va = (D-C)/D*100	4.101	3.85	**3.97**
Voids In the Mineral Aggregate (%) VMA = 100-(100-A)/B*C	14.85	14.63	**14.74**
Voids Filled with Asphalt (%) VFA = (VMA-Va)/VMA*100	72.38	73.68	**73.03**

Table D-57 Indirect Tensile Strength Test of Lab Produced Superpave Mixtures- Imperial and Kadisco Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced Material description: Wearing Course.					
	Maximum Load (N) (P)	Specimen Thickness (mm) (t)	Specimen Diameter (mm) (D)	Pie (π)	S = 2000*P / Π*t*D
S1: Tensile Strength Unconditioned Subset	21,927.15	102.5	150	3.1415	**907.92**
S2: Tensile Strength conditioned Subset	18,602.77	102.5	150	3.1415	**770.27**
Tensile Strength Ratio (TSR)= S2/S1*100%					**84.83**

Table D-58 Indirect Tensile Strength Test of Field Produced Superpave Mixtures- Imperial and Kadisco Intersection Road Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced Material description: Wearing Course.					
	Maximum Load (N) (P)	Specimen Thickness (mm) (t)	Specimen Diameter (mm) (D)	Pie (π)	S = 2000*P / Π*t*D
S1: Tensile Strength Unconditioned Subset	24188	102.5	150	3.1415	**1001.56**
S2: Tensile Strength conditioned Subset	20893.9	102.5	150	3.1415	**865.16**
Tensile Strength Ratio (TSR)= S2/S1*100%					**86.38**

Table C-59 Wheel Tracking Test Result of Lab produced Superpave Mixtures-Imperial and Kadisco Intersection Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced OBC: 4.58% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	3
N: Loading speed(cycles/min)	42	42	42
d1: Rutting depth at 45 min (mm)	1.412	1.031	1.236
d2: Rutting depth at 60 min (mm)	1.516	1.127	1.345
DS: Dynamic Stability= (15*N)/d1-d2	6058	6562	5780
Required number of cycles per 1 hr at maximum rutting depth	10000	10000	10000
Maximum rutting depth (mm)	**1.65**	**1.52**	**1.73**
Average maximum rut depth (mm)	**1.63**		

Table D-60 Wheel Tracking Test Result of Field produced Superpave Mixtures-Imperial and Kadisco Intersection Project

Location: AASTU HIGHWAY LAB. Material type: Bituminous Mixture Sample from: Lab. Produced OBC: 4.58% Material description: Wearing Course.	Test Method: ASTM D 1559 - AASHTO T 245 Date sample: Date test:		
Trial	1	2	3
N: Loading speed(cycles/min)	42	42	42
d1: Rutting depth at 45 min (mm)	1.705	1.394	1.802
d2: Rutting depth at 60 min (mm)	1.832	1.5158	1.935
DS: Dynamic Stability= (15*N)/d1-d2	4960.63	5180.92	4719.1
Required number of cycles per 1 hr at maximum rutting depth	10000	10000	10000
Maximum rutting depth (mm)	**2.01**	**1.93**	**2.12**
Average maximum rut depth (mm)	**2.02**		

APPENDIX E: SAMPLE PHOTOS

E 1 Collecting AC mixtures from project site

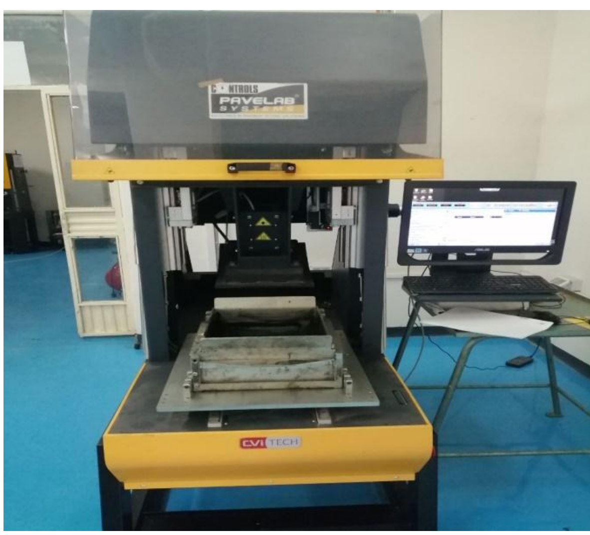
D-2 Cylindrical sample preparation

D-3 Slab sample preparation

D-4 Testing Machines


CONTROLS


GYROCOMP
CONTROLS


PAVELAB


UNIFRAME
Used to Test
① CBR
② UCS
③ ITS
④ Marshal
- Subgrade
- Subbase Material
Asphalt Concrete