JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

HIGHWAY ENGINEERING STREAM

SUITABILITY OF VOLCANIC ASH AS A FILLER MATERIAL IN HOT MIX ASPHALT

A Thesis submitted to Jimma University School of Graduate Studies as a Partial Fulfillment for the Requirements of Degree of Master of Science in Highway Engineering

By: Achalu Kebede

March, 2021

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Co-advisor: Engr. Basha Fayissa (MSc.)

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DECLARATION

I, the undersigned student, declare that the thesis entitled as "**Suitability of volcanic ash as a filler material in hot mix asphalt**" is my original work which has not been presented at any university for the award of any degree.

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As a research advisor, we have reviewed and approved for examination, the research entitled as "**Suitability of volcanic ash as a filler material in hot mix asphalt**" which is done by **Achalu Kebede** under our guidance.

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ABSTRACT

Now a day, the scarcity of conventional filler material needs a quick solution in the production of hot mix asphalt. Hence, this study investigated the suitability of volcanic ash as an alternative filler material in hot mix asphalt. The study used purposive method of sampling materials. An experimental research method was used to investigate the partial replacement of volcanic ash in hot mix asphalt based on Marshall Mix design method. Marshall Specimens were prepared with bitumen content of 4 to 6% at 0.5% increments using crushed stone dust as a control mix. Forty five Marshall Specimens were prepared to determine optimum bitumen content. This optimum bitumen content was used to prepare Marshall Specimen with replacement of volcanic ash from 10 to 100% at 10% increments. Thirty three specimens were prepared to evaluate the effects of volcanic ash on Marshall Properties of hot mix asphalt. Marshall Immersion test method was used to determine tensile strength ratio of both filler to evaluate Moisture susceptibility of the mix.

The plastic index and specific gravity of volcanic ash are 0.92% and 2.44 respectively. The chemical composition analysis indicated the volcanic ash can be classified as class – N pozzolana. All the mixes prepared with 5.15% optimum bitumen content at different proportions of volcanic ash met Marshall Criteria for asphalt concrete wearing course. Maximum stability of 11.38 kN was obtained at full replacement of volcanic ash. Marshall Immersion test resulted, tensile strength ratio of 82 and 98% for mix with crushed stone dust and fully replaced volcanic ash respectively. This result showed higher moisture resistance of volcanic ash than crushed stone dust filler in hot mix asphalt.

This study concluded, all the mixes with different proportions of volcanic ash had no significant effect on performance or volumetric properties of hot mix asphalt. Hence, volcanic ash can be used for hot mix asphalt pavement either fully replacing or in combination with crushed stone dust filler. Further study on hot mix asphalt with different bitumen contents and grades, performance test (rutting) and economic analysis are recommended.

Keywords*: Filler, hot mix asphalt, Marshall Mix, tensile strength ratio, volcanic ash*

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ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ASTM	American Society for Testing and Materials
BC	Binder Content
BS	British Standard
CSD	Crushed Stone Dust
EAPA	European Asphalt Pavement Association
ERA	Ethiopian Roads Authority
ERCC	Ethiopian Roads Construction Corporation
FC	Filler Content
HL	Hydrated Lime
HMA	Hot Mix Asphalt
JIT	Jimma Institute of Technology
JMF	Job Mix Formula
MS-2	Asphalt Institute's Manual Series – 2
NAPA	National Asphalt Pavement Association
NMAS	Nominal Maximum Aggregate Size
NP	Non Plastic
OBC	Optimum Bitumen Content
TSR	Tensile Strength Ratio
VA	Volcanic Ash

CHAPTER ONE

INTRODUCTION

1.1 Background

Flexible Pavements are the major parts of Global road network, which utilize asphalt concrete mixes as their binder and wearing courses. This asphalt concrete mixes mainly consists of aggregates (coarse and fine), filler and bitumen binder. The quality of pavements should be engineered to have requirements for the properly selected asphalt binder grades for the climate and traffic, aggregate characteristics including material quality and gradation, HMA volumetric requirements and HMA performance criteria (Asphalt institute, 2014).

Numerous research studies showed that the strength of hot mix asphalt (HMA) depends on different factors such as aggregate, filler and bitumen binder. Aggregates provide mixture stability by forming a skeleton to resist traffic load whereas asphalt provides the binding action and durability to asphalt mixes. Fillers are fine particles passing the No. 200 sieve added in the asphalt mix to a maximum of 10% by mass, which affects the load-carrying capacity and stability of the mixture (ERA, 2013). Filler fills the gaps between larger aggregates in bituminous mixes, providing stability, lowering the optimal bitumen content, and increasing impermeability. It also affects the workability, moisture sensitivity, stiffness, durability, fatigue behavior, and long-term characteristics of HMAs (Yan, et al., 2013). Physical and chemical properties, shape and texture, size, and gradation all differ among fillers. As a consequence, choosing the right filler is crucial for optimal HMA efficiency (Muniandy & Aburkaba, 2011).

In the construction of HMA, filler materials like crushed stone dust, cement, lime and hydrated limes have been using traditionally. However, due to insufficiency, economic and environmental concern regarding to production of these material, recent studies focuses on the utilization of alternative filler materials. In recent years, it can be seen that the growth in the mining industry and the raised consumption of raw materials have caused a rapid limitation in available natural resources (Arabani & Tahami, 2017; Blasl, et al., 2017). The high volume of resource extraction and shortage of raw materials lead to developed waste recycling and management (Angelone, et al., 2016). In these regard, several researchers have studied the performance of asphalt mixes incorporated with waste fillers. Jayvant, (2020), investigated the suitability and performance of more than 20 different types of wastes obtained from various sources as fillers in place of conventional material in dense graded bituminous macadam mix. Similarly, numerous researchers investigated waste material like; Bauxite residues (BR), fly ash (FA) and diatomite (Li et al., 2018; Tang et al., 2019; Woszuk et al., 2019). Rice husk ash (RHA) and date seed ash (DSA) (Seyed, et al., 2018), brick dust powder (Mei-zhu, et al., 2011), Coal fly ash, waste glass beads, local loam red brick and (Ali & Alaa, 2018), rice husk ash (Al-Hdabi, 2016; Tuba & Sezai, 2013),construction and demolition waste (Gedik, 2020), coal bottom ash and carbonized rice husk (Rengarasu, et al., 2020), copper industry waste as filler (Choudharya, et al., 2019), etc. According to their studies, all these wastes were satisfactorily used as filler material in different proportion to produce economical and sustainable asphalt mixes. Hence, this thought is becoming outstanding to introduce new wastes, which have physical and chemical composition similar to the conventional fillers to produce economical and sustainable asphalt mixes.

Pozzolan is siliceous or siliceous and aluminous material, which possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (ASTM C125, 2000). Pozzolan materials are natural (volcanic ash, volcanic tuff, pumice or burned clay) and artificial (silica fume, fly ash, blast furnace and so on). According to previous studies artificial pozzolan like silica fume, fly ash and blast furnace are widely used as alternative construction material in construction industries. Volcanic ash is natural pozzolonic material with size below 2mm formed due to volcanic activities in various parts of the world like Europe, Central America, China, Southeast Asia, East and Central Africa (Eritrea, Djibouti, Kenya, Ethiopia and Cameroon), Iran and Saudi Arabia (Alemayehu & Lennartz, 2009; Liao, 2016).

Previous studies explored the potential use of volcanic ash as raw material in the construction industries in the production of concrete, cement, mortar, geopolymers, and ceramics. Volcanic ashes mainly comprised of the minerals of Silicon, Aluminum, Magnesium and Calcium (Taylor & Lichte, 1980; Crowley, et al., 1989). However, studies concerning the utilization of volcanic ash as mineral filler for asphalt concrete mixes are very limited and this area is open for wide speculation. Therefore, this study geared toward evaluating some of the Marshall Mix properties of volcanic ash partially replaced with crushed stone dust in hot mix asphalt concrete. The study is aimed at investigating the physical properties and chemical composition of volcanic ash, effect on the Marshall Mix properties and moisture sensitivity. This study is aimed to reduce time, cost of production and environmental pollution

1.2 Statement of the Problem

In the production of HMA fine sand, cement, hydrated lime, crushed stone dust and marble dust are using as filler material. However, production of consumes natural resources, which brings tremendous pressure on the decreasing resources (Xu & Shi, 2018). One of the main problem in the production of HMA is scarcity of conventional fillers. On the other hands, high production cost and environmental pollution are the other concern.

Recently researchers investigated different industrial waste materials as alternative filler material in HMA mix. However, these industrial waste products needs care, long period to store and obtain sufficient quantity. Therefore, it is mandatory to find an alternative non-conventional HMA filler material which is locally available and ecofriendly. Hence, the use of volcanic ash is found an alternative option for replacing crushed stone dust as a filler material in HMA.

1.3 Rational of the Study

The justification for conducting this study provides locally available materials to decrease the scarcity of conventional filler materials with environmental friendly and economically feasible. Hence, the use of this alternative material in HMA reduces production cost, time and environmental pollution, it is very important in giving attention toward the effective use of locally available materials in the construction industry. This study benefits the road construction industry, government, Local community and further researchers for further investigation on volcanic ash in HMA mix. Also, this study provides ground basis for other countries with abundant of this volcanic material.

1.4 Research Questions

1. What are the physical properties and chemical compositions of volcanic ash?
2. What are the potential effects of volcanic ash on Marshall Mix properties?
3. What is the effect of volcanic ash on moisture susceptibility of HMA?

1.5 Objective

1.5.1 General Objective

The purpose of the study is to evaluate the suitability of volcanic ash as partial replacement of crushed stone dust in HMA.

1.5.2 Specific Objectives

The specific objectives of the study are:

1. to determine physical properties and chemical compositions of volcanic ash
2. to determine the potential effects of volcanic ash on Marshall properties of HMA
3. to examine the effect of volcanic ash on moisture susceptibility of HMA

1.6 Scope of the Study

The study focused on the evaluation of Marshall Mix properties and Moisture susceptibility. However, the findings are limited to the effects of volcanic ash on HMA mixture produced by Marshall Mix design method with material specified in this study. Hence, the results are also specific to the source, type, chemical compositions and content of volcanic ash used and test procedures that have been adopted in the experimental work.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

Asphalt concrete pavement is a mixture of aggregates, filler, and bituminous binder that is used to construct roads, airports, sidewalks, parking lots, and other structures. Construction of AC pavement involve huge national asset to design, construct and maintain in order to provide durable and high level of services. Hence, selecting high quality paving material that can extend pavement service life is a main objective. Many experts, engineers, and researchers have been assigned to select paving materials that can reduce the magnitude and density of distress while also enhancing the overall performance of asphalt pavements in order to achieve this goal (Muniandy, et al., 2013).

Hot mix asphalt concrete is the most popular pavement material utilized for binder and wearing course on the world. Asphalt concrete is a mixture of coarse aggregate, fine aggregate, binder, and filler in various relative amounts that determine the substantial characteristics of the mix. Among these, filler material plays a major role in various properties of HMA, particularly those related to mixture compatibility and aggregate bitumen adhesion (Gardiner, 2009). In construction of asphalt concrete pavement fine sand, cement, hydrated lime, crushed stone dust and marble dust are using as filler material. However, this materials are not sufficiently obtained and requires high production cost and leads environmental pollution.

This study was concentrated on the Marshal properties of hot mix asphalt mixtures prepared using various replacement rate of volcanic ash on hot mix asphalt concrete. In this chapter, review of previous study conducted on the effect of mineral fillers on hot mix asphalt performance will be discussed.

2.2 Asphalt Concrete

Asphalt concrete commonly called hot mix asphalt (HMA) in Europe or asphalt Concrete (AC) in the U.S. is a predetermined mix proportion of aggregates (coarse and fine), filler and bituminous binder. Asphalt binder holds the aggregate in HMA together, without asphalt binder; HMA would simply be crushed stone or gravel. Asphalt binder is the thick, heavy residue remaining after kerosene, gasoline, diesel oil, and other fuels and lubricants are refined from crude oil. Aggregate typically makes up about 95% of an HMA mixture by weight. Because HMA mixtures are mostly aggregate, aggregates used in HMA must be of good quality to ensure the resulting pavement will perform as expected. This mineral aggregate bounded together with bitumen, lay in layers, and compacted to form asphalt concrete pavement. When used in the construction of highway pavements, it must resist deformation from imposed traffic loads, be skid resistant even when wet and not affected easily by weathering forces. Filler fills the gaps between larger aggregates in bituminous mixes, providing stability, lowering the optimal bitumen content, and increasing impermeability.

Due to the different requirements, the respective mix used needs to have a sufficient stiffness and resistance to deformation in order to cope with the applied pressure from vehicle wheels on the one hand, yet on the other hand, the need to have an adequate flexural strength to resist cracking caused by the varying pressures exerted on them. Moreover, good workability during application is essential in order to ensure that they can be fully compacted to achieve optimum durability (EAPA, 2015)

2.3 Composition of Asphalt concrete

The main constituents of asphalt mix are aggregate (coarse and fine), filler and bitumen binder. It is crucial that the properties of the component materials of HMA meet minimum standards to ensure the material has a satisfactory performance.

2.3.1 Aggregate

Aggregates are hard inert material used in highway construction obtained from natural rock like igneous, sedimentary and metamorphic rock. Aggregates are the dominant ingredient of HMA, by making roughly 90 to 95% of the mixture by weight. Hence, aggregates are principal load supporting component of asphalt concrete pavements. Because HMA mixtures are mostly aggregate, aggregates used in HMA must be of good quality to ensure the resulting pavement will perform as expected. Aggregates are generally divided into coarse, fine, and filler fractions. Coarse aggregate are aggregates that are retained on 2.36 mm sieve and fine aggregates that are passing 2.36 mm and retain on 0.075 mm whereas fillers are fine particles with at least 75% passing sieve size 0.075 mm (ERA, 2013).

i. Properties of Aggregates

The physical properties of aggregates those are important to the asphalt pavement are gradation, particle shape, toughness, durability, cleanliness, absorption and adhesion. The aggregate should be: angular and not excessively flaky, clean and free of clay and organic material, strong enough, resistant to abrasion and polishing, non-absorptive and good affinity with bitumen (hydrophilic aggregates may be acceptable only where protection from water can be guaranteed or a suitable adhesion agent is used).Aggregates for HMA are required to be hard, tough, strong, durable, clean and properly graded.

Table 2.1: Required properties for HMA aggregates (ERA, 2013)

Property	Test	Properties	
		Wearing course	Binder course
Cleanliness	Sand equivalent [1]: for < 4.75 mm fraction < 1.5 x 10E6 ESA > 1.5 x 10E6 ESA	> 35 > 40	
	Material passing 0.425 mm sieve Plasticity index [2] Linear shrinkage %	< 4 < 2	
Particle shape	Flakiness index [3]	< 35	
Strength	Aggregate crushing value (ACV) [4]	< 25	
	Aggregate impact value (AIV) [4]	< 25	
	10% FACT(dry) KN[4]	> 160	
	Los Angeles Abrasion Value(AAV) [5]	< 30	< 35
Water absorption	Water absorption [6]	< 2	
Soundness [7] (5 cycles,% loss)	Sodium sulphate Test: Coarse Fine Magnesium sulphate Test: Coarse Fine	< 10 < 16 < 15 < 20	
Bitumen affinity	Immersion Mechanical Test: Index of retained Marshall stability Static Immersion Test [8] Retained indirect Tensile strength [9]	> 75 > 95% coating retained > 79% (at 7% VIM)	

Notes: [1] AASHTO T176-86
[2] BS 1377:Part 2 (1990)
[3] BS 812,part 105 (1990)
[4] BS 812,Part 3 (1985)
[5] ASTM C131 and C535
[6] BS 812, part 2 1975
[7] AASHTO T104-99
[8] D Whiteoak (1990)
[9] AASHTO T283

ii. Aggregate gradation

The stability of asphalt mixture is affected by several features such as aggregate gradation, size, and amount of filler materials. Gradation is one of the aggregates characteristics affecting the performance of HMA. Laboratory result by Amir, et al., (2012), showed that, reducing percentage air voids and VMA up to the certain amount, increases resilient modulus of the mixture and decreases deformation and non-recoverable strain. Hence, Gradation bands placed in the upper limits of asphalt mixture design gradation chart show the best performance against rutting while lower bands have the highest permanent deformation. Whereas the selected gradations are almost parallel with the job mix formula, when it gets near to upper limit curve permanent deformation is reduced and rutting resistance will be increased and when the gradation is near to the lower limit curve, the permanent deformation increases and rutting resistance will be decreased.

Amir, et al., (2012) Performed the study on the investigation of the effect of variation in gradation of aggregate on the properties of asphalt mixture. According to the researchers, five different gradations were tested to investigate the impacts of variation in gradation of aggregate on the HMA properties. The gradation was such as JMF gradation, coarse, fine, fine- coarse, and coarse-fine and their respective effects on the performance of asphalt mixture are concluded as follows: fine-coarse and coarse-fine gradation variation cause higher and lower Marshall Air void, void in mineral aggregates (VMA) respectively. In addition, the aforementioned gradation variation results lowest and highest Marshall Flow, respectively. Generally, the Marshall stability is affected by gradation variation with the fine gradation produced the highest stability, whereas the fine- coarse gradation variation resulted in the lowest stability.

Mohammad & Mohammad, (2020), evaluated the effect of nominal maximum aggregate size and aggregate gradation on the surface friction properties of HMA mixtures. Their study showed that the surface friction properties of mixtures at top surface were significantly affected by the NMAS and aggregate gradation. According to this context, by increasing the NMAS in the mix, the top surface exhibits improved micro texture and lessened micro-textures for both types of aggregate gradations. On the other hand, the friction properties of the bottom surfaces were only affected by the aggregate gradation type due to the migration of fine material. Generally, According to several researcher investigation showed that aggregate gradation plays a major role in HMA performance. Hence aggregate gradation in HMA helps to determine property including stiffness, durability, stability, permeability, workability, fatigue resistance, and resistance to moisture damage. Gradation is often measured by sieve analysis, and different aggregate specification was provided in local and global pavement manual standards.

Table 2.2: Particle size distributions for asphalt concrete courses (ERA, 2013)

Layer		Road base		Binder course		Wearing course					
Sieve No	Sieve size (mm)	Nominal maximum stone size (mm)									
		Percentage passing sieve size									
		37.5 mm		25 mm		19 mm		12.5 mm		9.5 mm	
		min	max	min	max	min	max	min	max	min	Max
2"	50	100	100	-	-	-	-	-	-	-	-
1 1/2"	37.5	90	100	100	100	-	-	-	-	-	-
1"	25	-	-	90	100	100	100	100	100	100	100
3/4"	19	56	80	-	-	90	100	100	100	100	100
1/2"	12.5	-	-	56	80	-	-	90	100	100	100
3/8"	9.5	-	-	-	-	56	80	-	-	90	100
No.4	4.75	23	53	29	59	35	65	44	74	55	85
No.8	2.36	15	41	19	45	23	49	28	58	32	67
No.16	1.18	-	-	-	-	-	-	-	-	-	-
No.30	0.6	-	-	-	-	-	-	-	-	-	-
No.50	0.3	4	16	5	17	5	19	5	21	7	23
No.100	0.15	-	-	-	-	-	-	-	-	-	-
No.200	0.075	0	6	1	7	2	8	2	10	2	10

2.3.2 Bitumen

Bitumen is dark brown to black cementitious material, which holds aggregate in HMA together. Bitumen is a co-product either naturally occurring or refining crude petroleum. At ambient temperature, asphalt is black, sticky semisolid and highly viscous material.it is strong and durable with excellent adhesive and water proofing characteristics. The largest use of asphalt concrete is in the production of HMA, which is primary used in the construction of flexible pavements. The asphalt can readily be liquefied by applying heat for mixing with mineral aggregates to produce HMA. Being very sticky, it adheres to the aggregates particles and binds them to form HMA. Three methods based on penetration, viscosity or performance are used to classify asphalt cement in to different grades.

Table 2.3: Requirements for penetration grade bitumen (ERA, 2013)

Test	Test Method (ASTM)	Penetration Grade		
		40/50	60/70	80/100
Based on original bitumen				
Penetration at 25˚C	D 5	40-50	60-70	80-100
Softening Point (˚C)	D 36	49-59	46-56	42-51
Flash point (˚C) Min	D 92	232	232	219
Solubility in trichloroethylene (%) Min	D 2042	99	99	99
TFOT heating for 5h at 163 ˚C	D 1754	-	-	-
a) Loss by mass (%) Max	-	0.5	0.5	0.8
b) Penetration (% of original) Min	D5	58	54	50
c) Ductility at 25˚C Min	D 113	-	50	75

2.3.3 Filler

Filler is mineral particle finer than 75 μm in size used as one of the main constituents in asphalt mixture. Conventionally crushed stone dust, lime, hydrated lime and cement have been using as filler material in asphalt concrete mixture. Filler plays a major role in determining the properties and the behavior of the mixture especially the binding and aggregate interlocking effects. Fillers not only fill voids in the mixture, but also affect the ageing characteristics of the mix. Filler has ability to increase the resistance of particle to move within the matrix and or works as an active material when it interacts with the asphalt cement to change the properties of the mastic (Eltaher, et al., 2013). Mineral filler greatly influences the design, and performance of the mixture by the nature and amount, excess quantity of filler tends to increase stability, brittleness, and proclivity to cracking. Deficiency of filler tends to increase void content, lower stability, and soften the mix. The filler content is particularly important as it has a significant impact on technical properties and, hence on potential end use. The gradation, shape, and texture of the mineral filler significantly influence the performance of hot mix asphalt regarding permanent deformation, fatigue cracking, and moisture susceptibility. A better understanding of the effects of fillers on the properties of mastics and HMA mixtures is crucial to good mix design and high performance of HMA mixtures (Eltaher & Ratnasamy, 2016).

Now a day due to environmental and economic concerns, several researchers investigated different non-conventional alternative filler material for asphalt concrete mix. Amir & Morteza, (2014), investigated the application of coal waste powder as filler material in HMA, comparison to reference mix (i.e. a mix containing limestone powder) the coal west and its ash resulted in higher stability and resilient modulus. Furthermore, the combination of coal waste and limestone powders in equal proportion resulted in a desirable mix with high water resistance. Moreover, coal waste powder and especially its ash also improved the water sensitivity of mixes. Raja & Tapas, (2016), investigated the effect of fly ash as alternative filler in HMA through Marshall Mix design. According to obtained Marshall Parameters, the addition of fly ash up to 4% in dense bitumen mix, by replacing conventional mineral filler like HL shows a 7.5% reduction in OBC compared to the control mix, which may provide a considerable economy of bitumen in resulting mixture. According to this context, replacement of HL by Fly Ash in HMA not only satisfies all the standard specification but also gives better strength with lesser deformation compared to that of the conventional mix. Hence, especially in the areas where fly ash generally dumped may be used as replacement of common filler to support global sustainability. Today, waste material have been increasingly utilized as alternative raw material in asphalt mixture in order to decrease construction costs, conserve natural resources and reduce environmental problems. Seyed, et al., (2018), investigated the potential usage of rice husk ash (RHA) and date seed ash (DSA), as filler material in hot mix asphalt by replacing conventional filler. They found that, asphalt mixtures with DSA and RHA fillers showed higher stability and stiffness modulus in comparison with the control mixture. Also using biomass ashes improved the thermal sensitivity of mixtures and adhesive force between asphalt and aggregates, which caused an enhancement in rutting resistance and fatigue life of HMA mixtures. (Al-Hdabi, 2016) Study on the properties of HMA with Rice Husk Ash (RHA) as filler material instead of conventional filler (OPC), showed that Marshall Stability increases by 65% more than conventional filler (OPC).

2.4 Pozzolanic Materials

Pozzolana is a siliceous or siliceous and aluminous material, which in itself possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pumice is a finely divided volcanic ash composed of angular and porous particles of siliceous glass and varying proportions of crystal fragments differing from pumice only in grain size.

Pozzolana are classified based in their origin namely natural Pozzolana and artificial Pozzolana. Natural Pozzolana represent all those naturally occurring materials such as volcanic ash or Pumicite, Diatomaceous earth, Shales, opaline, Chert, and tuffs. Artificial Pozzolan represents all those Pozzolan formed from processing of materials originally without Pozzolanic properties such as fly ash, blast furnace slag, bumed clay or shale, micro silica or silica fumes.

2.4.1 Uses of Pozolonic Materials

Today, volcanic tuffs and Pumicite are still uses as Pozzolan throughout the world and often referred to as Pozzolana in the literature. Pozzolana use in worldwide as a cement replacement material due to the fact that they improve the durability of cement, reduce the cement production costs and also reduces the environmental degradation associated with cement production as well as disposal of various industrial wastes effectively. Common Pozzolanic materials that have been utilized are fly ash, sludge and in some countries, natural pozzolana. Many researcher Results on pozzolans showed that it could partially replace ordinary Portland cement.

2.4.2 Volcanic Ash

Deposits of volcanic ash likely found wherever there are volcanic activities in various parts of the world and due to frequent volcanic eruption, volcanic debris such as: volcanic ash and pumice are found abundantly. Volcanic ashes are pyroclastic materials commonly found in many regions of the world (Patrick N., et al., 2018). The deposits of pyroclastic materials are generally readily accessible and have the advantage that they can be naturally mined with enormous benefits from low cost mining. The physical condition of volcanic ashes may range from loose fine material to coarse deposits containing quite large particles. Deposits may be loose, with an appearance and texture similar to a compacted coal or wood ash. Other deposits were cemented, sometimes with appearance and properties similar to stone, and in this form, they are normally referred to as tuffs or trassy. The colour of deposits can vary from off-white to dark grey (Saroni, 2014). Once the deposits have been excavated most volcanic ashes will require only minor processing before use as a pozzolana. Many ashes are only loosely cemented and can easily be excavated by hand, although others may need mechanical or pneumatic equipment. Volcanic ash is a non-generic term which refers to fine fragments of pyroclastic materials. Typical volcanic ashes are pyroclastic debris with size below 2 mm (Dingwell, et al., 2012). Most pyroclastic materials present pozzolanic activity that at ambient temperature, can combine with lime in the presence of water to form compounds that behave like hydraulic binders (al-swaidani, et al., 2016).

They are pozolonic material, hence in the presence of moisture; chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. A comprehensive research program was carried out with motivation from local cement and construction industries, in an attempt to explore the possible utilization of volcanic debris in cement and concrete production. Patrick N., et al., (2018), investigated the potential use of volcanic ashes in the fields of cements and concretes, geopolymers, ceramics, low grade refractory materials, lunar soil simulants and adsorbents. The use of this local material provide low cost concrete but also help to decrease environmental hazards. Research suggested the manufacture of blended PVAC (Portland volcanic ash cement) and PVPC (Portland volcanic pumice cement) similar to PFAC (Portland fly ash cement) with maximum replacement of up to 20% (Hossain, 2003). Durability of concrete is one of its most important desirable properties and it is essential that the concrete made with VA and

VP blended cement should be capable of preserving its durability throughout the life of structures like other pozzolanic concretes made with SF, FA, PFA and BFS (Hossain & Lachemi, 2004). Hence, it is very important to know the pozzolanic, alkali-silica reaction and autoclave expansion characteristics of volcanic ash (VA) and finely ground volcanic pumice (VP) to evaluate their potential use as cement additives and this paper will concentrate on these issues.

Ethiopia is one of the volcanic tuff rich countries in Africa (Akahashi & Hoji, 1998). However, there were no researches conducted in the area of using volcanic ash as alternative filler material in hot mix asphalt pavement.

2.5 Hot Mix Asphalt Design Methods

Asphalt concrete mix design is to determine the combination of asphalt cement and aggregate that will give long-lasting performance to pavement structure. This mix design involves laboratory procedures to determine an appropriate blend of aggregate sources (or gradation) and selecting type and amount of asphalt cement. A properly designed asphalt mixture provides a balance of engineering properties and economics that ensures a durable pavement. The mix design is just the starting point to assure that an asphalt pavement layer will perform as required. Together with proper construction practice, mix design is an important step in achieving well-performing asphalt pavements. Correct mix design involves adhering to an established set of laboratory techniques and design criteria.

The design of asphalt paving mixes, as with other engineering materials designs, is largely a matter of selecting and proportioning materials to obtain the desired properties in the finished construction product. The overall objective for the design of asphalt paving mixes is gradation of aggregates and binder content that yields a mix having:

- **i.** Sufficient asphalt to ensure a durable pavement
- **ii.** Sufficient mix stability to satisfy the demands of traffic without distortion or displacement
- **iii.** Sufficient air voids in the total compacted mix to allow for a slight amount of additional compaction under traffic loading and a slight amount of thermal binder expansion without flushing, bleeding and loss of stability

iv. A maximum void content to limit the permeability of harmful air and moisture into the mix

v. Sufficient workability to permit efficient placement of the mix without segregation and without sacrificing stability and performance and

vi. Aggregate texture and hardness to provide sufficient skid resistance in unfavorable weather conditions.

The final goal of mix design is to select a unique design binder content that will achieve a balance among all of the desired properties.

2.5.1 Marshall Mix Design Method

The Marshall Stability and flow test provides the performance prediction measure for the Marshall Mix design method. In this method, the resistance to plastic deformation of a compacted cylindrical specimen of bituminous mixture is measured when the specimen is loaded diametrically at a deformation rate of 50 mm per minute. There are two major features of the Marshall method of mix design. i.e., density-voids analysis and stability-flow tests. The Marshall stability of the mix is defined as the maximum load carried by the specimen at a standard test temperature of 60°C. The flow value is the deformation that the test specimen undergoes during loading up to the maximum load. Flow is measured in 0.25 mm units. This design procedure includes a density-voids analysis of the compacted specimens to determine the percent air voids and percent voids filled with asphalt (VFA). After these determinations, the specimens are tested at 60°C (140°F), and the Marshall Stability (maximum load observed in the test) and flow value (deformation corresponding to the maximum load) are obtained. Data resulting from these mix evaluations are plotted as a series of curves and include density versus asphalt content, percent air voids versus asphalt content, percent VFA versus asphalt content, Marshall Stability versus asphalt content, and flow value versus asphalt content. The design asphalt content is determined as the average of the four contents selected corresponding to the peak density, 4 percent air voids, 75 percent VFA, and maximum Marshall Stability. This asphalt content is then checked to ensure that the resulting air void content and percent VFA fall within prescribed limits, that the Marshall stability exceeds a specified minimum level, and that the flow value does not exceed a prescribed maximum value.

According to (Asphalt institute, 2014), the binder content corresponding to 4 percent air voids is selected (on the basis of a compactive effort representative of the traffic to be applied). Compactive efforts range from 35 to 75 blows per side for traffic ranging from light to heavy. Other mix properties, including the Marshall stability, flow value, and VMA, are then checked to determine whether specified criteria have been satisfied.

Table 2.4: Mechanical Properties of binder and wearing course (Asphalt institute, 2014)

Total Traffic (10E6 ESA)	< 1.5		1.5 - 10		> 10	
Traffic Class	Light Traffic		Medium Traffic		Heavy Traffic	
Mixture Parameters	Min	Max	Min	Max	Min	Max
Stability (kN at 60˚C)	3.5	-	6	-	7	-
Compaction level (No of blows)	2*35		2*50		2*75	
Flow (mm)	2	4	2	4	2	4
Air void (%)	3	5	3	5	3	5
VFA (%)	70	80	65	78	65	75
VMA (%)	13	-	13	-	13	-

2.6 Moisture Susceptibility of Hot Mix Asphalt

Premature failure may result due to stripping when critical environmental conditions act together with poor and/or incompatible materials and traffic. Moisture susceptibility is a problem that typically leads to the stripping, loss in strength and durability due to the presence of water and this stripping makes an asphalt concrete mixture ravel and disintegrate. Moisture damage can occur due to three main mechanisms: loss of cohesion of the asphalt film, failure of the adhesion between the aggregate particles and the asphalt film, and degradation of aggregate particles due to freezing (Brown & Kandhal, 2001)

Pavements are susceptible to low temperature cracking. Particularly in colder area the tensile strength of pavements at low temperature should be adequate enough to resist cracking. The retained stability value for asphalt mixes prepared with Rice husk ash and Slag fillers satisfy the minimum retained stability requirement of AASHTO standard specification (75%). It indicates that mixes containing Stone dust, Slag, and Rice husk ash as filler had good resistance to moisture-induced damages (Akter & Hossain, 2017)

Many variables affect the amount of moisture damage which occurs in an asphalt concrete mixture. Some of these are related to the materials forming hot mix asphalt such as aggregate and asphalt binder. Others are related to mixture design and construction (air void level, film thickness, permeability and drainage), environmental factors, traffic conditions and type, and properties of the additives. The presence of moisture, combined with the repeated action of traffic, accelerates damage to the AC pavement (Santucci, 2010).To combat stripping, proper mix design is essential and proper field compaction with specified air void which prevent water entering into the AC layer. Many tests methods have been developed in the past to predict the moisture susceptibility of HMA mix however; no test has any wide acceptance. This is due to their low reliability and lack of satisfactory relationship between laboratory and field conditions. Selected test methods used by some agencies will be discussed briefly (Roberts, et al., 1996). The first two test methods are subjective tests while the reaming are strength tests. The test methods mentioned below are not the only ones and other tests are still being used throughout the world.

i. **Boiling water test (ASTM D3625):-** Loose HMA mix is added to boiling water. ASTM specified a 10minute boiling period. The percentage of the total visible area of the aggregate that retains its original coating after boiling is estimated as above or below 9%
   Static immersion test (AASHTO T182):- HMA mix is immersed in distilled water at 25°c for 16 to 18 hours. The percentage of total visible area of the aggregate which remains coated will be estimated as above or below 95%.

ii. **Lottman test (NCHRP 246):-** This is a strength test developed by Lottman under National Cooperative Highway Research Program 246. Nine specimen 102mm in diameter and 64mm high are compacted at expected field air void content. The specimen are divided into three, three specimen per group. Group 1 is control group. Group 2 are vacuum saturated (660 mm Hg) with water for 30minutes. Groups 3 are also vacuum saturates subjected to freeze at -180c for 15hours and thaw for 24 hours at 60°c. All nine specimen are tested for resilient modulus or indirect tensile strength. Retained tensile strength (TSR) is the quotient of indirect tensile strength of conditioned specimen to indirect tensile strength of control specimen. A minimum TSR of 0.7 is used as a guideline.

iii. **Modified Lottman Test (AASHTO T283)**:- uses the Lottman test with some modification. The sample size is reduced to six and grouped into two containing three specimen. The specimen are compacted to 6 to 8% air void. Group 1 is a control specimen while group 2 are vacuum saturated (55 to 80% saturation) with water and then subjected to one cycle freeze and thaw. All specimen are tested for indirect tensile strength at 25°c at a loading rate of 51mm/minute. TSR is determined based on the Lottman test and a minimum value of 0.7 is usually specified.

iv. **Marshall Immersion test (ASTM D1075):-** Six Marshall specimen are prepared for this test. The specimens are grouped into two groups, each with three specimens. Group 1 is the control specimen maintained in air at 250c while group 2 is immersed in water for 24 hrs at 60°c or at 49°c for four days. Group 2 specimen is then transferred to 25°c water bath for 2hrs and compressive strength of both groups is determined. Index of retained strength is determined just like TSR in Lottman test. A value of at least 70% is specified as a requirement in many agencies. Super pave design guideline requires a minimum of 80% retained strength.

2.7 Summary

Generally, this chapter describes the literature review about what the researcher was focused on. The review of literature includes basic concepts of hot mix asphalt which includes aggregates and asphalt binder, basic concepts of mineral fillers, the effect of mineral filler in hot mix asphalt. Therefore by taking this issue into account, this study is required to investigate the effects of volcanic ash on Marshall Properties and Moisture susceptibility of HMA.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Sampling Area

For this study sample of volcanic ash was collected from Wanci district, South West Shoa, Oromia, Ethiopia located at 08^{o} 50' 34'' N and 38^{o} 00'40''E. This sample area is located at 22 km from Ambo, 42 km from Waliso, 98 km west of Finfinnee and 13.5 km from mount Dandi, Ethiopians second highest volcano. The sample is found from Wanci volcano which is the highest volcano in Ethiopia (3,450 m above msl). The volcano has a 4km by 4.8 km caldera, and single creator Lake Wanci Lake, about 450 m below the rim of the volcano. Source: https://en.m.Wikipedia.org/wiki/Wonchi_(volcano). The sampling site point location map is shown in Figure 3.1

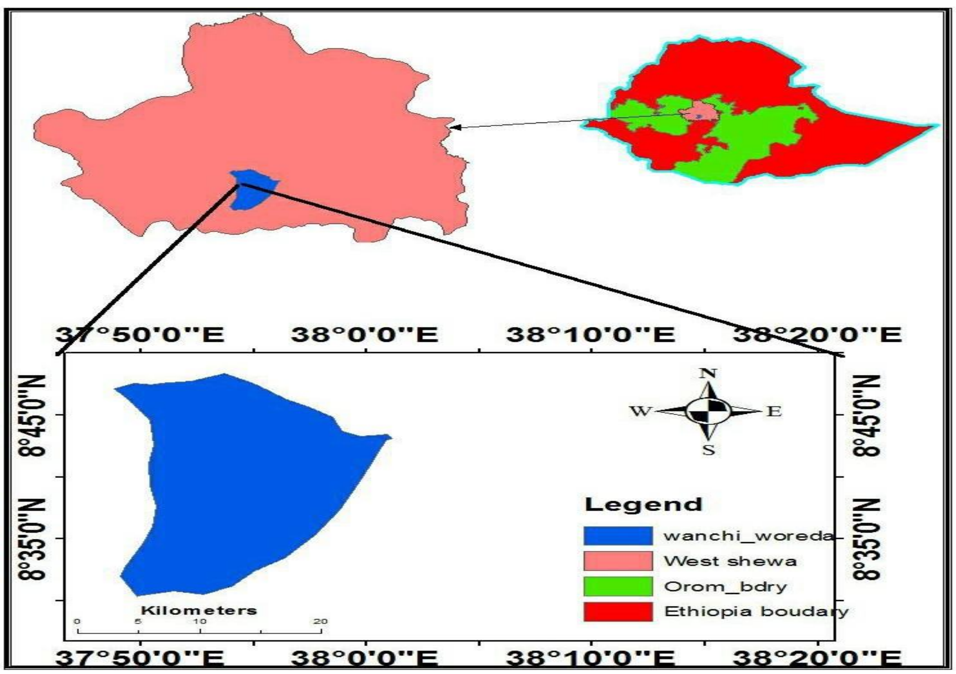


Figure 3.1: volcanic ash sample location map

3.2 Study Design

This study was designed to meet the objective based on experimental procedure. The experimental procedure was performed following the ERA, ASTM, AASHTO, and BS material testing standards and guidelines. The study design follows sample collection and preparation, experimental set up, data analyses and interpretation to draw conclusions based on the finding.

The representative samples of aggregate was collected manually in accordance with AASHTO T2 and sampling for bituminous materials, AASHTO T 40. The collected samples were prepared to ensure that the applicable test results accurately reflect the true characteristics of the material according to AASHTO T 248 and AASHTO T 87.

The experimental set up compromised the material characterization, Marshall Mix design and Moisture susceptibility test. The material characterization was performed for aggregates, bitumen and fillers. In Marshall Mix design, aggregate gradation was performed according to ASTM D1535 and Marshall Specimens were conducted according to ASTM D1559. Three Marshall Mix specimens were prepared with bitumen content of 4 to 6% at 0.5% increments for the aggregate gradation of 5, 5.5 and 6% CSD. Forty five specimens were prepared to determine OBC and the corresponding volumetric properties of HMA. NAPA procedure is used to determine the OBC in the mix. Thirty three specimens were prepared with VA at percentage replacement of 10 to 100% at 10% increments. The performance of the HMA specimen against external effect of water was analyzed with twelve (12) specimens to evaluate for Moisture resistivity. The results are analyzed and interpreted through discussing the effect of volcanic ash on the Marshall properties of the mix and performance of HMA. In this phase, the suitability of volcanic ash in HMA was evaluated for stability, flow, unit weight, Air void, void in mineral aggregate, and void filled with asphalt. Also, moisture susceptibility of hot mix asphalt was also discussed. Finally, conclusions and recommendations are made based on findings. Figure 3.2 shows the overall study design flow chart for this study.

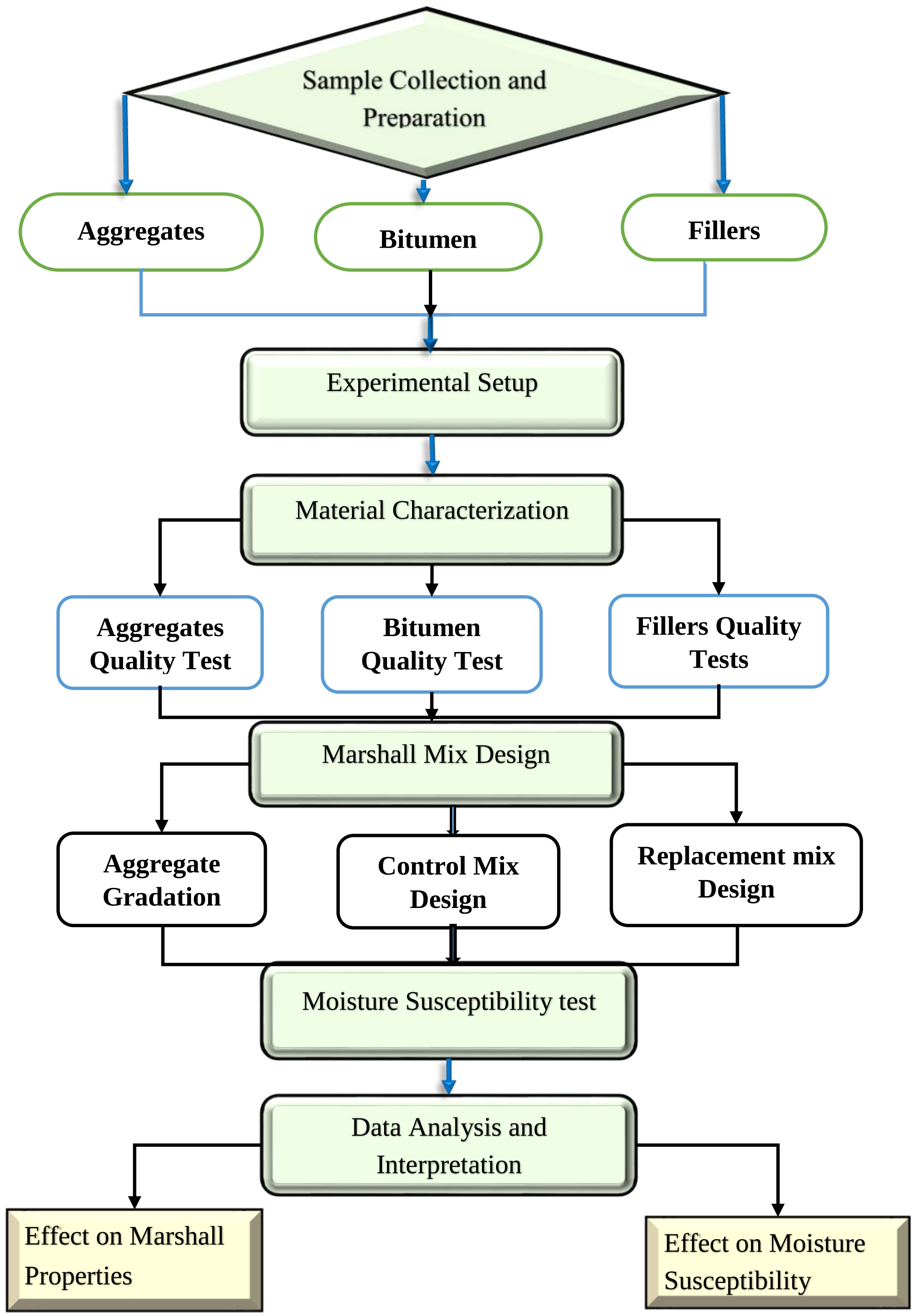


Figure 3. 2: Study method flow chart

3.3 Sampling Techniques and Preparation

This study followed a purposive sampling, which is non-probability method. Disturbed sample of volcanic ash was collected from test pits manually by hand tools. Based upon the changes in moisture condition, color consistency, type and structure, the sides of the test pit was inspected to their full depth and any observable change is recorded with depth. Any vegetation growing around the upper edge of the test pit was removed and distinguishable sample layer was separately sampled. Three test pit samples were collected from several locations within a field, properly composited (mixed) and taken to laboratory.

Representative sample of aggregates was collected manually in accordance with AASHTO T2 methodology for sampling from stockpiles and AASHTO T40, Sampling for bituminous Materials.

The samples were prepared properly to ensure that the applicable test results accurately reflect the true characteristics of the material. The samples obtained from the field in accordance with AASHTO T2 were reduced to the test size in accordance with AASHTO T248. Samples were dried to a constant mass in an oven maintained at 110 ± 5°C (230 ± 9°F) according to AASHTO T87 Practice for dry preparation of soil samples. Finally, the samples were evaluated for physical test, mechanical analysis and moisture density.

3.4 Methods of Data Collection

From early development of this Study topic, various data were collected and processed to achieve the objective of this study. These were conducted first by reviewing previous related literature and different international & local standard specification, secondly by laboratory tests regarding the preparation of HMA. Specifically, both primary and secondary data were used in this study.

3.4.1 Primary Source of Data

These sources of data were obtained through laboratory tests on aggregates, filler and bitumen and Marshall Property's results.

3.4.2 Secondary Source of Data

The secondary data were collected from previous studies, scientific researches, national and international pavement design manuals & standards.

3.5 Study Variables

3.5.1 Dependent Variable

The dependent variable is effect of volcanic ash on hot mix asphalt

3.5.2 Independent Variables

The independent variables are amount of volcanic ash added to the mix, material properties, Marshall Mix properties and moisture resistivity.

3.6 Materials

Hot mix asphalt mixture is a combination of different size of aggregates with mineral filler, uniformly mixed and coated with bitumen. This mixture requires selection, characterization and proportioning of ingredients to provide the required quality and properties of the mix. The overall mix design procedure starts with the selection and evaluation of aggregates and bitumen binder. The aggregates, crushed stone dust and bitumen used in this study were collected from ERA, Own force road maintenance, Deneba site located at 80 km from Jimma town.

3.6.1 Aggregates

Aggregates used for HMA are generally required to be hard, tough, strong, durable, clean, rough and hydrophobic surface (ERA, 2013). The physical properties of aggregates used for HMA is determine by evaluating size and gradation, cleanliness, hardness, durability, surface texture, particle shape and water absorption. Various quality tests were conducted on the physical properties of aggregates to ensure its suitability in HMA. Sieve analysis, Specific gravity, water absorption, Los Angles abrasion, Flakiness index, Aggregate crushing value, Aggregate impact Value were the tests performed for aggregates following their respective test methods. The physical properties of aggregates are shown in Table 4.1

3.6.2 Bitumen

Performance characterization of asphalt specifically depends on its physical properties. Typically, the physical properties of the asphalt binder are a direct outcome of its chemical properties. In this study, 60/70, penetration grade bitumen was used as it is a common type of bitumen which is mostly used in tropical areas. The physical characteristics of the bitumen were determined conformed to AASHTO and ASTM standards and compared with ERA standard specification. The properties bitumen such as penetration, ductility, softening point, specific gravity and flashpoint were performed and evaluated as per ASTM standards experimentally. The test results for bitumen is shown in Table 4.2.

3.6.3 Mineral Filler

The effects of filler on the mechanical properties of the asphalt mixture are remarkable as it is one of the crucial ingredients in the HMA. Filler plays a vital role in determining the performance and properties of mixes, especially it's interlocking and binding effects (Zulkati, et al., 2012). In this study, crushed stone dust (as control) and volcanic ash (as replacement) were used as mineral filler in the preparation of HMA. The physical properties of crushed stone dust and volcanic ash were conducted according to AASHTO T84-95. The chemical compositions of volcanic ash was performed using complete silicate analysis and evaluated for pozolanic properties following ASTM C 618. The analytical methods used to analysis the chemical composition of volcanic ash are $LiBo_2$, fusion, HF attack, gravimetric, colorimetric and AAS. Similarly, plasticity index was conducted using cone penetrometer following BS 1377: Part 2 1990, whereas an apparent specific gravity was performed following ASTM D 854. The physical property and chemical compositions test results are as shown in Table 4.3 and Table 4.4 respectively.

3.7 Experimental Setup

This study was performed based on laboratory tests to evaluate the suitability of volcanic ash in HMA. In this study Marshall Mix design and Moisture susceptibility tests were performed. The physical characterization of aggregates, bitumen and fillers were evaluated experimentally. Also the chemical compositions of volcanic ash was conducted. To evaluate these material properties different quality control tests were performed and compared with ERA, AASHTO, ASTM, and BS standards. The experimental procedures, considerable data concerning the Marshall parameters of HMA were obtained from the test results. These data were recorded on the standard formats of laboratory reports and used as input for the analysis of the study results and findings of the research.

3.7.1 Marshall Mix Design

The overall procedure for mixture design always begins with acceptance tests performed on aggregates and bitumen binder considered for the design. HMA is a homogenous substance formed when aggregate and bitumen are combined with new physical properties but not similar to the physical properties of its components. It is the procedure of determining what aggregate to utilize, what bitumen to use, and what the best blend of these both ingredients should be. After determining the quality and quantity of all mixture constituents, the asphalt mix design proceeds. Generally, HMA mix design has included some laboratory tests that use various critical procedures to provide characterizations of each trial HMA blend.

In this step, several trial blends of aggregates gradation were prepared According to ASTM D1535 specification to obtain the design aggregate gradation. Afterward, the several specimens of HMA mixture were prepared at bitumen content of 4 to 6% by 0.5% increments for aggregate gradation of 5, 5.5 and 6% filler content. A total of forty five Marshall Specimens were prepared to obtain OBC. These Marshall specimens were subjected to Marshall Stability and flow test as per AASHTO T 1559 or ASTM D 6927 standards. Marshall Stability parameters such as stability, flow, air void, void filled with asphalt, and void in mineral aggregates were determined and evaluated following ERA (2013) standards. The OBC and optimum filler content were determined based on the maximum stability of the mixtures. For all the mixes, keeping OBC and design gradation constant, crushed stone dust was replaced by volcanic ash from 0 to 100% at 10% increments. A total of 33 specimens were prepared to for replacement to obtain the acceptable percentage of volcanic ash. HMA design requires aggregate gradation, preparing Marshall Specimen and determination of optimum bitumen content.

i. Aggregate gradation

Aggregate gradation is the distribution of particle sizes expressed as a percent of the total weight. This can be determined by sieve analysis, through series of sieves stacked with progressively smaller openings from top to bottom, and weighing the material retained on each sieve. Gradation of aggregate is expressed as total percent passing sieve sizes and represented by a gradation curve for which the ordinate is the total percent by weight passing a given size on an arithmetic scale, while the abscissa is the particle size plotted to a logarithmic scale. In this study sieve opening; 25, 19, 12.5, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15, and 0.075 mm standard sieve were used. The coarse aggregate, fine aggregate, and the filler material were proportioned so as to fulfill the requirements of the relevant standards. The required quantity of the mix is taken so as to produce compacted bituminous mix specimens of thickness 63.5 mm approximately 1200 gm. of aggregates and filler are required to produce the desired thickness. In the designing of aggregate blending, any number of the trial could be attempted. However, three trials is the standard number of blends. For this study, aggregates were sieved and three trial blends were prepared in the laboratory according to ASTM D3515 specifications shown in *Appendix A*

ii. Marshall Specimens preparation (Control mix)

Marshall Specimens for HMA were prepared for the desired aggregate gradation and binder content in bulk to provide a sample for Marshall Parameter determination procedure in accordance of ASTM D1559.

The coarse aggregate, fine aggregate, and the filler material were proportioned so as to fulfill the requirements of the relevant standards. The required quantity of the mix is taken so as to produce compacted bituminous mix specimens of thickness 63.5 mm approximately 1200 gm. of aggregates and filler. The aggregates were heated to a temperature of approximately 160-170°C, the compaction mold assembly and rammer are cleaned and kept pre-heated. The bitumen was heated to a temperature of 140°C to 170°C. Marshall Specimens were prepared at bitumen content of 4 to 6% at 0.5% increments for aggregate gradation of 5, 5.5 and 6% filler content. The mix were placed in a mold and compacted with a compaction effort of 75 blows on each side. Finally, the specimens were permitted to cool overnight and removed from the mold with the help of extrusion jack and the compacted specimens were subjected to determination of bulk density and Marshall Stability and flow tests. The Marshall stability and flow data collected were graphically plotted to determine the OBC. This OBC was used for the replacement mix following the Marshall Specimen preparation above. The Marshall properties of the asphalt mix such as stability, flow, air voids in the total mix, density, void in mineral aggregates and voids filled with bitumen were determined. Finally, the results were analyzed and compared with standard specifications of bituminous wearing course as per (Asphalt institute, 2014)

iii. Optimum bitumen content determination

The main intention of the Marshall Mix design is to determine the OBC that satisfy the required values of design parameters. In this study the NAPA procedure was used to determine the optimum bitumen content. Finally, the Marshall parameters were determined based on optimum bitumen content and compared with the specification for acceptability as indicated in Table 4.5

3.7.2 Marshall Mix Design for Volcanic Ash

The design gradation and OBC determined in Marshall Mix design were used for the examination of Marshall Properties and moisture susceptibility of volcanic ash. The crushed stone dust was replaced with volcanic ash from 10 to 100% at increments of 10%. The Marshall Mix specimens were prepared, compacted, and tested according to ASTM D 1559. Marshall Mix specimens were produced for each filler proportion, and the average values of bulk specific gravity, Marshall Stability, flow, air void, void in mineral aggregate, void filled with asphalt were determined. Marshall Specimens at full replacement of volcanic ash are given in Table 4.6. Details are given in *Appendix E.*

3.7.3 Volumetric Parameters of HMA Mixtures

HMA mixture design determines the volume of bitumen and aggregate necessary to a mixture with the desired properties. Since weight, measurements are typically much easier; weights are taken and then converted to volume by using specific gravities. The volumetric properties of a compacted paving mixture provide some indication of the mixture's probable pavement service performance. The properties that are to be considered include: theoretical maximum specific gravity (Gmm), bulk specific gravity (Gmb), air voids (VIM), volume of bitumen (Vb), voids in mineral aggregate (VMA), voids filled with asphalt (VFA) and effective asphalt content (Pbe). The performance of the hot mix asphalt could be determined from the computation of the volumetric properties of the compacted mixture.

Bulk specific gravity of compacted specimen (Gmb): is the ratio of mass of compacted specimen in air to volume of permeable material (including both permeable and impermeable voids). The bulk specific gravity is determined for the compacted specimens after extruded from the mold taking the weight in air, in water and in saturated surface dry. This value is used to determine the mass per unit volume of the compacted mixture. The bulk specific gravity of the compacted specimen increases with increasing asphalt content up to certain point, after which it decreases.

In this study, the bulk specific gravity of compacted mixtures was determined by using saturated surface dry specimen as per AASHTO T 166 or ASTM D 2726. The standard bulk specific gravity of compacted specimen is expressed in Eq. (1).

$$\text{Gmb} = \frac{\text{Wd}}{\text{Wssd} - \text{Ww}} \qquad \text{.. (1)}$$

Where; Gmb =bulk specific gravity of compacted asphalt mixture, Wd = weight of sample in air, Wssd = weight of saturated surface dry of sample, Ww = weight of sample in water

Theoretical Maximum specific gravity of loose specimen (G_{mm}): is the ratio of the weight in air of a unit volume of loose asphalt mixture at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature. The theoretical maximum specific gravity (G_{mm}) at various asphalt binder content was used to determine the air void percentage in the mix. The theoretical maximum specific gravity of loose mix is defined as in Eq. (2).

$$\mathrm{Gmm} = \frac{\mathrm{A}}{(\mathrm{A}+\mathrm{B})-\mathrm{C}} \qquad (2)$$

Where; A = weight of loose asphalt sample (g), B = weight of pycnometer filled with water (g) C = weight of pycnometer filled with water and lose asphalt sample (g)

Voids in the Mineral Aggregates (VMA): is the total volume of inter-granular void space between the mineral aggregate particles of a compacted mixture expressed as a percentage of the total mix volume. It represents the volume of air void and volume of effective asphalt binder (non-absorbed by aggregates).VMA significantly affects the performance of mixture. Hence, too small VMA leads the durability problem whereas too large VMA shows stability problem and un-economical to produce. The VMA has two components: the volume of the voids filled with asphalt and the volume of voids remaining after compaction. Generally, the VMA for any given mix must be sufficiently high to ensure that there is room for the asphalt cement plus the required air voids. The VMA generally decreases to a minimum value then increase with increasing asphalt contents. Specifically, a minimum value of VMA is described in different standard specifications, whereas a maximum VMA may or may not be specified. VMA is expressed mathematically as in Eq. (3).

$$\mathrm{VMA} = 100 - \left(\frac{\mathrm{Gmb}}{\mathrm{Gsb}}\right) * \mathrm{Ps} \qquad (3)$$

Where; VMA = void in the mineral aggregates (%), Gmb = bulk specific gravity of compacted mixture (g/cm^3), Gsb = bulk specific gravity of total aggregate and Ps = aggregate content, the percentage by mass of the total mixture

Air voids (VIM): is the total volume of the small pockets of air between the coated aggregate particles in the compacted asphalt mixture. The amount of air voids in a mixture is particularly vital and closely related to stability and durability. The percent of air voids decreases with increasing bitumen contents. It is given mathematically by, Eq. (4).

$$\text{VIM} = \left(\frac{\text{Gmm}-\text{Gmb}}{\text{Gmm}}\right) * 100 \quad (4)$$

Where; VIM = percentage of Air Void in the compacted mixture, Gmm = maximum specific gravity of the loose mixture, Gmb = bulk specific gravity of the compacted mixture (g/cm^3)

Voids Filled with Asphalt (VFA): is the portion of the voids in the mineral aggregate that contain asphalt binder. VFA is the percentage of inter-granular void pocket between the aggregate particles filled with asphalt binder and can expressed as the ratio of the difference of VMA and VIM to VMA. The VFA value increases with increasing bitumen contents

Mathematically computed as in Eq. (5).

$$\text{VFA} = \left(\frac{\text{VMA}-\text{VIM}}{\text{VMA}}\right) * 100 \quad (5)$$

Where; VFA = percentage of void filled with asphalt binder, MA = percentage of void in mineral aggregate, VIM= percentage of air voids in the compacted mixture

Volume of absorbed Bitumen (Pba): is the volume of bitumen expressed by percentage in the mixture that has been absorbed by the pore space of the aggregate. It is expressed as in Eq. (6).

$$\text{Pba} = \text{Gb} * \left(\frac{\text{Gse}-\text{Gsb}}{\text{Gse}*\text{Gsb}}\right) * 100 \quad (6)$$

Where; Pba = percentage of absorbed asphalt binder, Gb = specific gravity of asphalt binder, Gse = effective specific gravity of total aggregate, Gsb = bulk specific gravity of total aggregate

Effective Asphalt Content (Pbe): is the total asphalt content of the HMA less the portion of asphalt binder that is lost by absorption into the aggregate. The effective asphalt content is the measure of the asphalt film around the aggregate. The asphalt film thickness around the aggregate particle can be correlated to the durability, fatigue and moisture damage.

The effective asphalt content is calculated as in Eq. (7).

$$\text{Pbe} = \text{Pb} - \frac{\text{Pba}}{100} * \text{Ps} \quad (7)$$

Where; Pbe = effective asphalt content, percent by total weight of the mix, Pb = asphalt content, percent by total weight of mix, Ps = aggregate content, percent by total weight of mixture, Pba = absorbed asphalt, percent by weight of aggregate

3.8 Moisture Susceptibility

Marshall Immersion test (ASTM D1075) was used for this study to evaluate HMA against moisture susceptibility**.** A total of 12 Marshall Specimens were prepared at optimum asphalt binder content for aggregate gradation with crushed stone dust and volcanic ash. The specimen is grouped in to two groups, each with three specimens. The first group, control group were kept at a temperature of 25°C for a period of 2 hours without soaking. The second group, conditioned samples were immersed in a water bath at 60°C, for a period of 24 hours. The samples were then removed from the water bath and kept in a water bath maintained at a temperature of 25°C for a period of 2 hours. These specimens are then attached between two load stripes and are loaded radially at a speed of 50mm/min and the load at failure is recorded at each case. Then the tensile strength of water conditioned as well as an unconditioned specimen for each mix was determined. A value of at least 70% is specified as a requirement in many agencies. Then the tensile strength ratios were calculated using the following equation:

$$TSR = \frac{\mathrm{St(\,cond)}}{\mathrm{St(\,un\,cond)}} * 100 \qquad (9)$$

Where; TSR= Tensile Strength Ratio (%), St (cond.) = Average tensile Strength of Conditioned Sample (kpa), St (uncond.) = Average tensile Strength of Unconditioned Sample (kpa). The material at optimum asphalt content is subjected to moisture sensitivity test. The test results are as indicated in Table 4.7

3.9 Data Quality Management

The quality of data is assured through the replication of measurements and standard specifications. To check the accuracy and validity of data instrument calibration and verification was carried out. Laboratory test data recording formats were prepared in order to avoid error of data. Finally, duplicate and triplicate measurements of parameters were conducted and mean ± standard deviation values are reported or presented in a figure.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Materials Properties

4.1.1 Aggregates physical properties

The physical properties of the aggregates are shown in Table 4.1. The water absorption, flakiness index, aggregate crushing value, Loss Angeles Abrasion test and aggregate impact value are 1.4, 23, 14.9, 11.56 and 8.06%, respectively. The water absorption of the aggregates is less than 2% indicated that the aggregate has low water absorption with durable and economic mix. Similarly, the aggregate crushing value is less than 25% which shows that the aggregate had resistance to crushing under a gradually applied compressive load. Also, the aggregate impact value indicates the aggregate is strong. The Los Angeles Abrasion loss values indicated that an aggregate is tough and resistant to abrasion. Therefore, the aggregate used for this study is applicable for HMA wearing course. The Details of the aggregate physical properties are given in *Appendix A.*

Table 4.1: Aggregate physical properties

Properties	Test method	Values			ERA (2013) Specification
		9.5 to 25 (mm)	2.36 to 9.5 (mm)	0 to 2.36 (mm)	
Gsb	AASHTO T84-95	2.563	2.583	2.594	-
Gss		2.600	2.627	2.643	-
Gsa		2.660	2.701	2.729	-
WA (%)	AASHTO T85	1.4	1.696	1.896	< 2
SE (%)	AASHTO T176-86	75.6	-	-	> 40
FI (%)	BS 812,part 105	23	-	-	< 35
ACV (%)	BS 812, part 110	14.9	-	-	< 25
LAA (%)	AASHTO T 96	11.58	-	-	< 35
AIV (%)	BS 812, part 112	8.06	-	-	< 25

Where; Gsb = Bulk dry specific gravity, Gss = Bulk Saturated Surface dry specific gravity, Gsa = apparent specific gravity, WA = Water Absorption, SE = Sand Equivalent, FI = Flakiness Index, ACV = Aggregate Crushing Value, LAA = Loss Angeles Abrasion, AIV = Aggregate Impact Value

4.1.2 Bitumen

The results of penetration, ductility, softening point, specific gravity and flash point are 65.1 mm, 108 cm, 47.2 ˚C, 1.025, and 320 ˚C respectively as shown in Table 4.2. Based on the standard specification, the bitumen used for this study is applicable for asphalt concrete mix design. Details of bitumen properties are given in *Appendix B.*

Table 4.2: Bitumen quality test results

Test	Test method	Value	ERA (2013) specification
Penetration @ 25˚C (0.1 mm)	AASHTO T 49	65.1	60 - 70
Ductility @ 25˚C (cm)	AASHTO T 51	108	Min 50
Softening point (˚C)	AASHTO T 53	47.2	46 - 56
Specific gravity @ 25˚C	ASTM D 70	1.018	1.01 - 1.06
Flash point (˚C)	ASTM D 92	320	Min 232

4.1.3 Mineral Filler

The filler materials used in this study are crushed stone dust as control and volcanic ash as an ingredient. The results of gradation, plasticity index and apparent specific gravity of crushed stone dust and volcanic ash are summarized as Table 4.3 and that of the chemical composition of volcanic ash is presented in Table 4.4. The result of plastic index of volcanic ash is 0.92% which is less than 4% showing that it is a non-plastic material.

The chemical compositions of volcanic ash determined by complete silicate analysis are given in Table 4.4. The combined ingredients by weight of silica (SiO_2), aluminum (Al_2O_3) and iron oxides (Fe_2O_3) is more than 70% which reveals that the material is classified as Class-N Pozolana. The result of Loss on ignition is less than 10% which shows that the material is not sensitive weather action. The moisture content of volcanic ash is 2.21% which is less than 3%. Therefore, the complete silicate analysis resulted volcanic ash can be classified as Class-N Pozolana. Hence, the material had no significant effect on the aggregate inter granular bondage in HMA. The details of test results are given in *Appendix C.*

Table 4.3: Physical properties of mineral fillers

Sieve size	Passing (%)		Specification	
	CSD	VA	ASTM D242	ERA (2013)
No 30 (600 µm)	100	100	100	
No 50 (300 µm)	100	96	95 – 100	
No 200 (75 µm)	100	83.3	70 – 100	
PI	NP	0.92	-	< 4
Gsa	2.68	2.44	-	

Table 4.4 : Chemical composition of volcanic ash (*Appendix C*)

Composition	Weight (%)	Class - N Pozolana (ASTM C618)	Remarks
SiO_2	55.18	-	
Al_2O_3	20.85	-	
Fe_3O_3	5.48	-	
$SiO_2 + Al_2O_3 + Fe_3O_3$	81.52	≥ 70 %	OK
CaO	1.9	-	
MgO	0.42	-	
Na_2O	5.46	-	
K_2O	2.12	-	
MnO	0.18	-	
P_2O_5	0.1	-	
TiO_2	0.18	-	
H_2O	2.21	≤ 3%	OK
LOI	5.24	≤ 10 %	OK

4.2 Marshall Mix Properties

4.2.1 Aggregate Gradation

Figure 4.1 shows percentage passing at each corresponding sieve size for three different aggregate gradations with 5%, 5.5%, and 6% filler contents for bituminous paving wearing course. The combined aggregate of the three gradations on the basis of three different percentages of fillers is applicable for HMA wearing course. The details of the analysis are given in *Appendix A.*

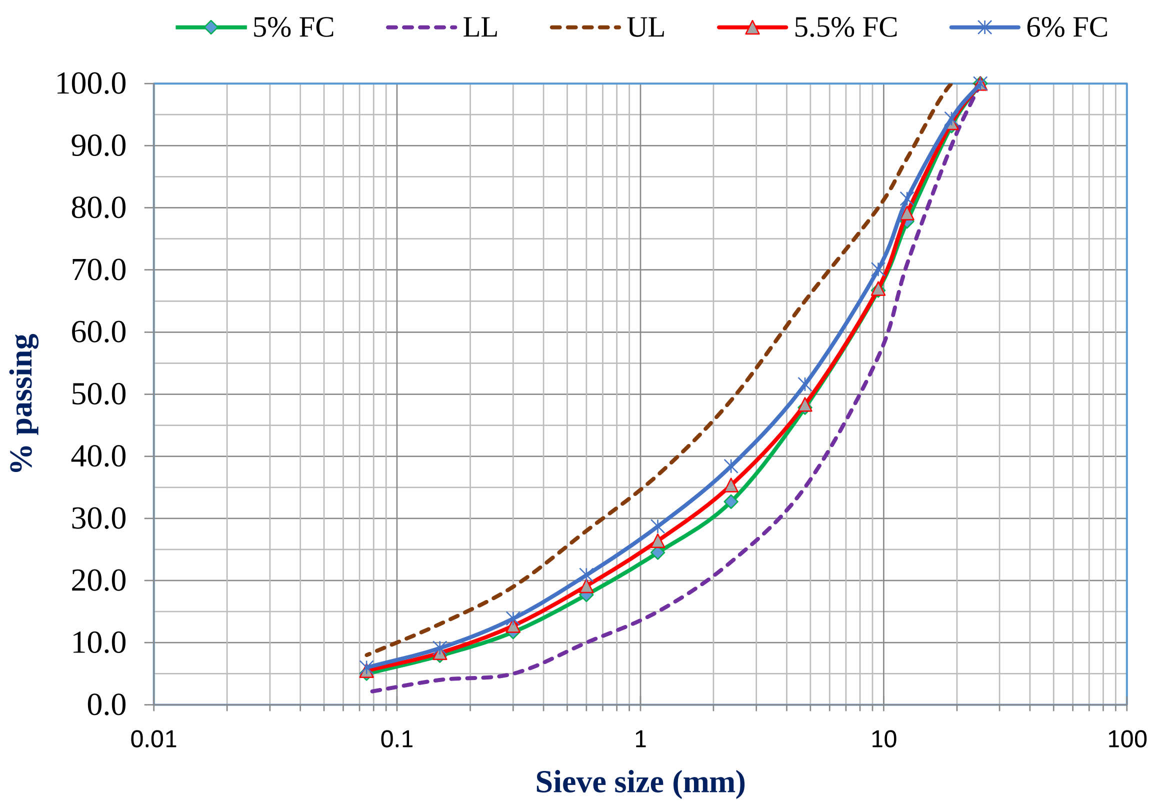


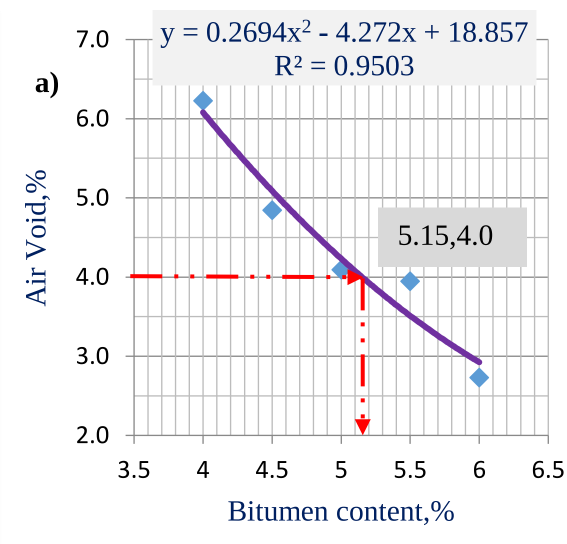
Figure 4.1: Aggregate gradation curve

4.2.2 Marshall Mix Properties of Control Mix

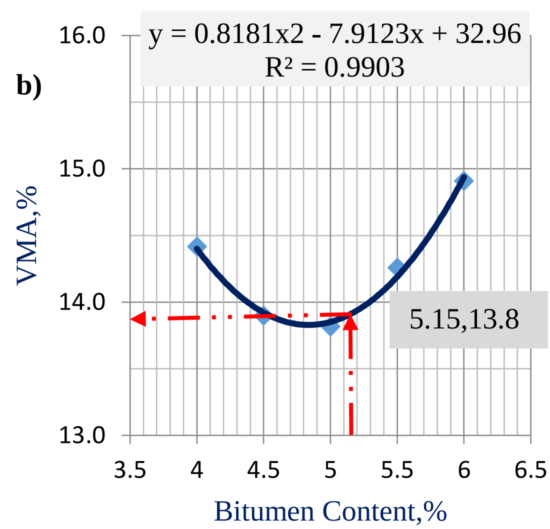
The variation of Marshall Mix properties at bitumen contents 4 to 6% at 0.5% increments for mixes containing different proportion of filler 5, 5.5 and 6% are given as Figure 4.2 to 4.4 consequently. Details are presented in *Appendix E*.

i. Marshall Mix properties of 5% CSD

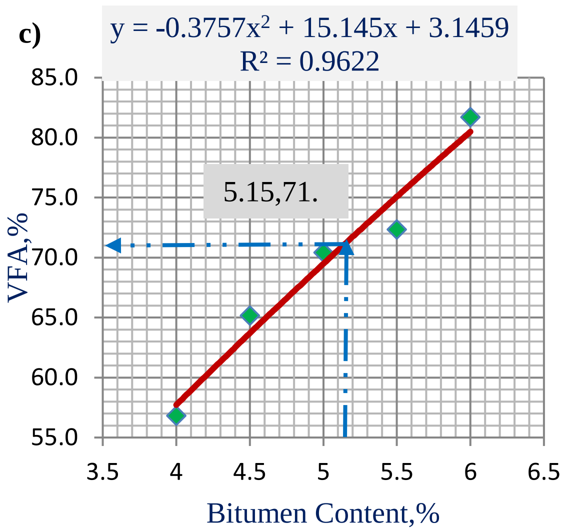
The air void in the mix decreased as bitumen content increases as shown on Figure 4.2a. The air void curve showd the usual concave up wards. This indicate that as bitumen content increases hot bitumen lubricates the aggregates allowing closer together in which air void decreases hence density increases. Figure 4.2b presents the graph for bitumen content versus void in mineral aggregates which is flattened U-shape. With the increase in bitumen content, the mix became workable and compacted easily, which increases density. However, as the bitumen content increases more than bitumen content at maximum density the thicker films around the individual aggregates were formed there by resulting low density and high VIM. The graph of bitumen content versus void filled with asphalt is as presented on Figure 4.2c. The graph showed the usual convex upward, as bitumen content increased void filled with asphalt also increased. This indicated that the void in the mineral aggregates were filled with bitumen while the air void in the mix decreases. The stability increased with increase bitumen up to a maximum of 13.1 kN after which the stability decreased as presented on Figure 4.2d. This indicated as bitumen content increases hot bitumen lubricates the aggregates allowing closer together in which the density increases. The flow value increased with the increase of bitumen content as shown on Figure 4.2e. The curve showed the usual concave up wards which indicates as the bitumen content increases the mix became plastic and loss stability. Figure 4.2f indicated the bulk specific gravity slightly increased to 2.341 g/cm^3 with increase bitumen content, after which it decreases. The Details of the analysis are given in *Appendix E*



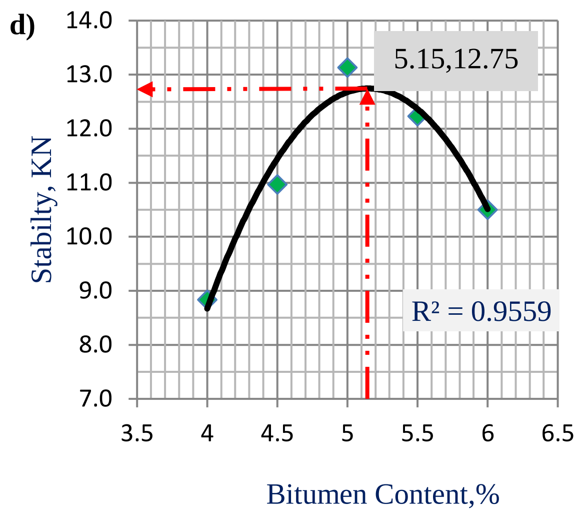
a) Air void Vs Bitumen content



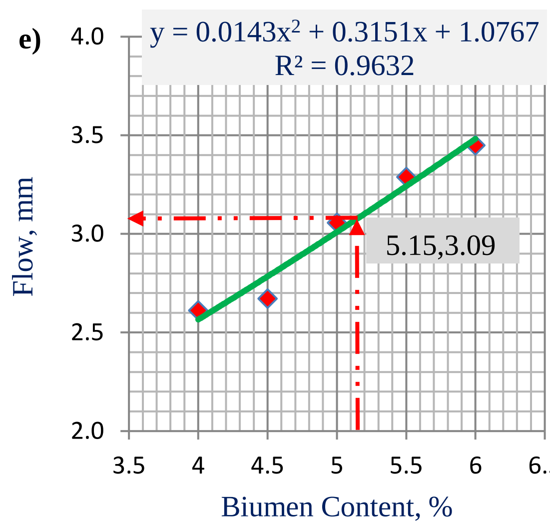
b) Bitumen content Vs VMA



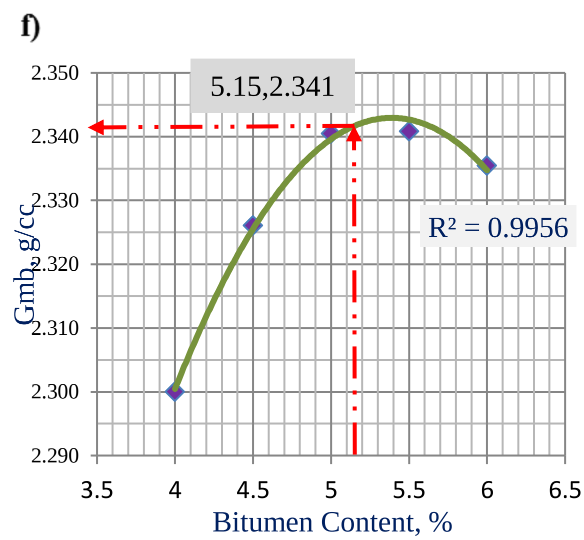
c) Bitumen content Vs VFA



d) Bitumen content Vs Stability



e) Bitumen content Vs VFA



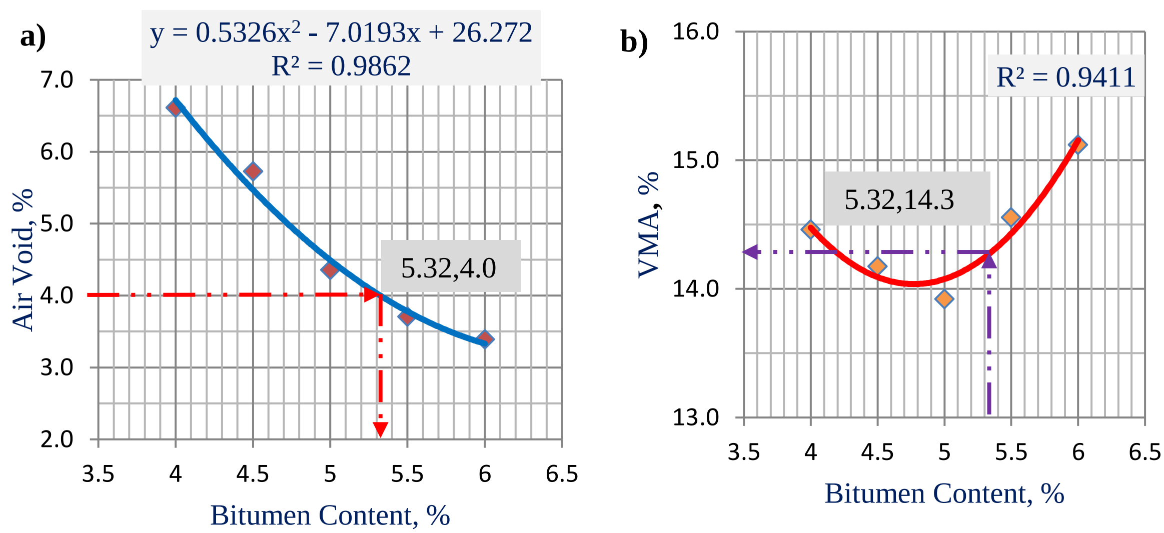
f) Bitumen content Vs Stability

Figure 4.2: Marshall Mix property of 5% CSD

ii. Marshall Properties of 5.5% CSD

The graph of bitumen content versus air void indicated that the void in mix decreased as bitumen content increases as shown on Figure 4.3a. The air void curve showed the usual concave up wards. This indicates that as bitumen content increases hot bitumen lubricates the aggregates allowing closer together in which air void decreases hence the density increases. The graph of bitumen content versus void in mineral aggregates is as shown on Figure 4.3b.

The graph showed flattened U-shape, decreased void in mineral aggregates to a minimum value of 13.9% then increased with increase bitumen content. With the increase in bitumen content, the mix became workable and compacted easily, which increases density. However, as the bitumen content increases more than bitumen content at maximum density the thicker films around the individual aggregates were formed there by resulting low density and high VIM. Therefore, up to lower VIM value, the bulk density of the mix increase to maximum value of 2.338 g/cm^3. Figure 4.3c presents the graph of bitumen content versus Void filled with asphalt. The graph showed the usual convex upward which indicates the void in the mineral aggregates were filled with bitumen while the air void in the mix decreases. The stability increased to a maximum value of 11.7 kN with increase of bitumen after which the stability decrease as shown on Figure 4.3d. This indicated as bitumen content increases the density increases because hot bitumen lubricates the aggregates allowing closer together. The graph of bitumen content versus flow shown on Figure 4.3e indicated the flow value increased with increase of bitumen content. The concave up wards curve of bitumen content versus flow indicated as the bitumen content increases the mix became plastic and loss stability. Figure 4.3f shows the graph of bitumen content versus bulk specific gravity. The graph showed that bulk specific gravity slightly increased to 2.338 g/cm^3 with increase bitumen content, after which it decreases. The Details of the analysis are given in *Appendix E*



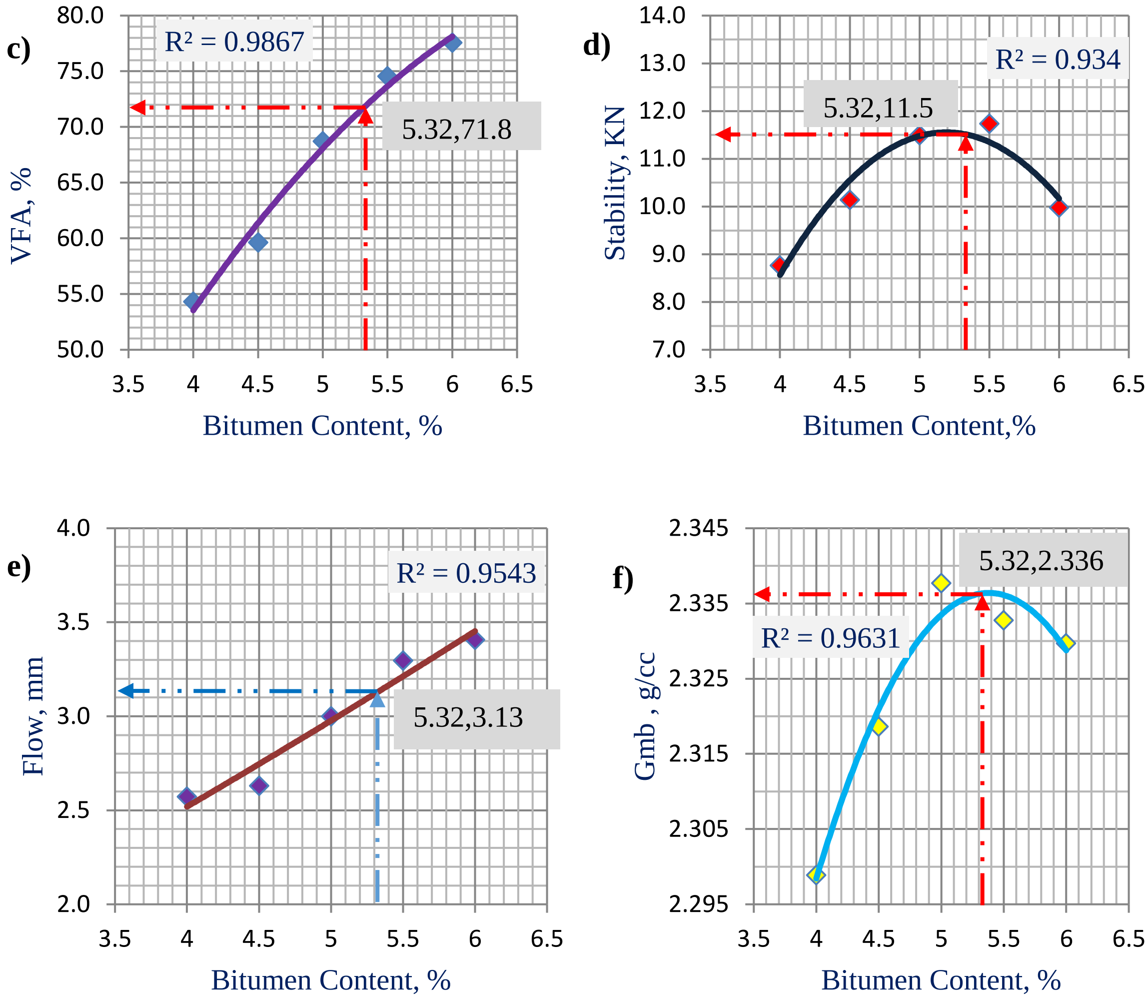
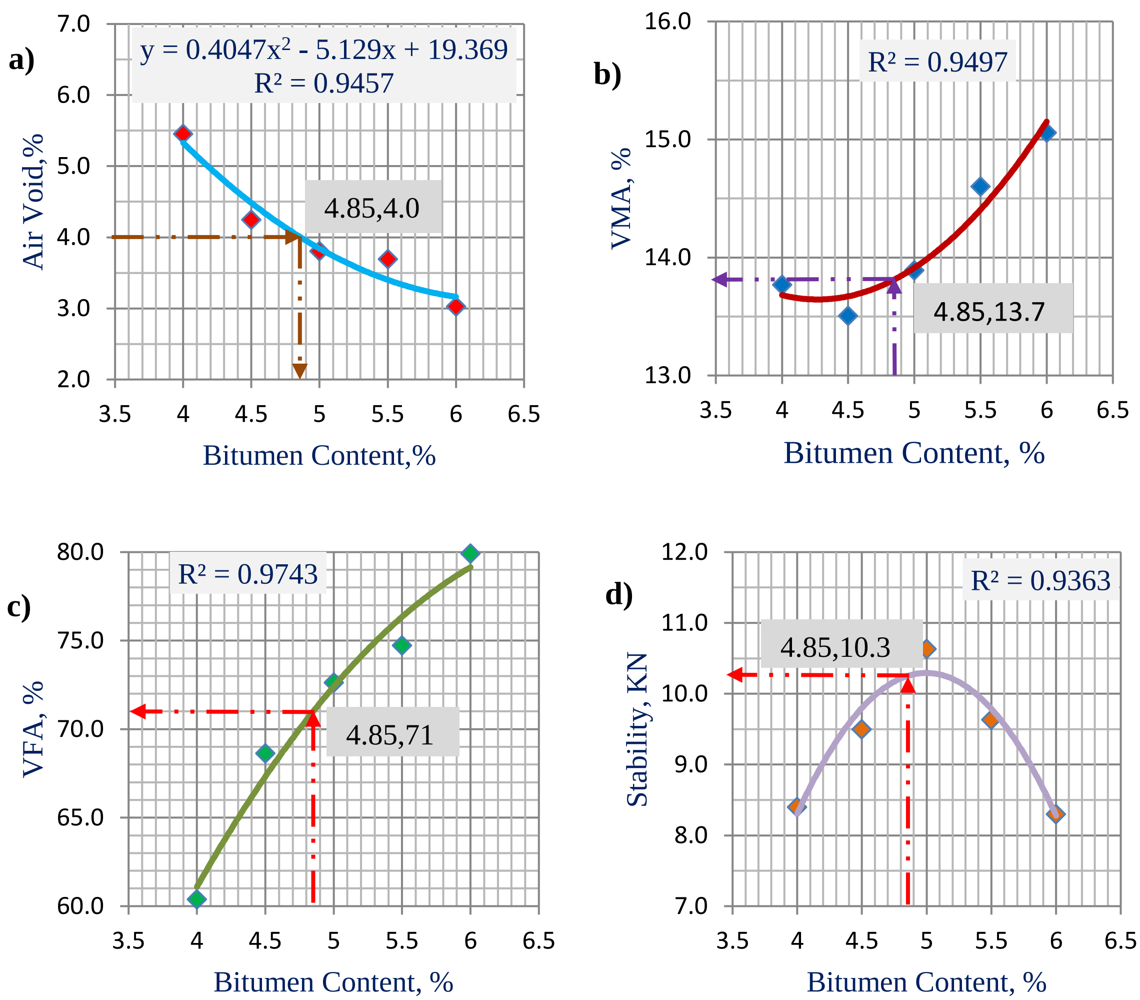
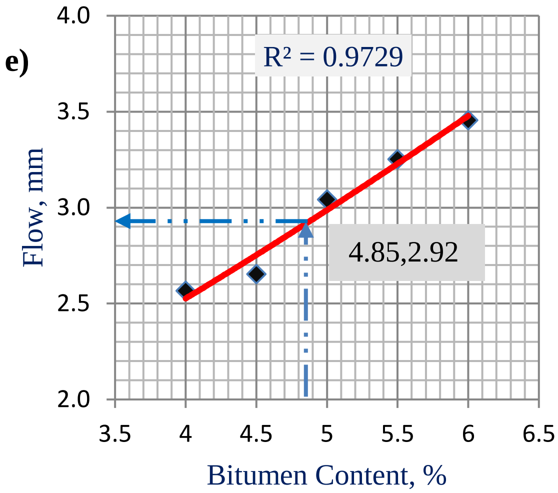


Figure 4. 3: Marshall Mix property of 5.5% CSD

iii. Marshall properties of 6% CSD

The graph of bitumen content versus air void shown on Figure 4.4a indicated the void in mix decreased as bitumen content increased. The relationship showed the usual concave up wards curve which indicate that as bitumen content increases density increases while air void decreases. Figure 4.4b shows the graph for bitumen content versus void in mineral aggregates which is flattened U-shape. The curve showed a minimum value of 13.5% then increases with increasing bitumen content. With the increase in asphalt, the mix actually became more workable and compacts more easily, meaning more weight can be compressed into the unit volume. Therefore, the bulk density of the mix increases to 2.339g/cm^3 while VMA decreases to a minimum value of 13.5%. The void filled with asphalt increased as the bitumen content increases as presented on Figure 4.4c. The graph showed the usual convex upward which indicates the void in the mineral aggregates were filled with bitumen while the air void in the mix decreases. The graph of bitumen content versus stability presented on Figure 4.4d indicated Marshall Stability increased with increase bitumen content to a maximum value of 10.6 kN after which the stability decreases. This indicate that as bitumen content increases hot bitumen lubricates the aggregates allowing closer together which increasing the density. Figure 4.4e shows the graph of bitumen content versus flow. The flow increased with the increase of bitumen content. The concave up wards curve of bitumen content versus flow indicated as the bitumen content increases the mix became plastic and loss stability. The result of bulk specific gravity shown on Figure 4.4f slightly increased to 2.339 g/cm^3 with increasing bitumen content, after which it decreases. Details of the analysis are given in *Appendix E*





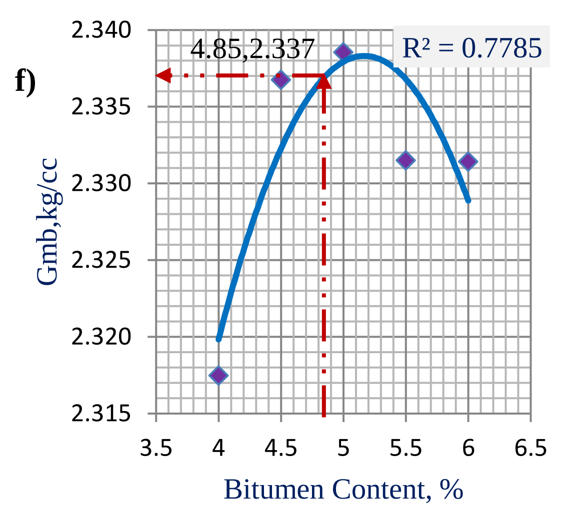


Figure 4.4: Marshall Mix property of 6% CSD

iv. Optimum bitumen content

The Marshall Parameters relationships, bitumen content along x-axis and Marshall Parameters along y-axis for different gradation are shown on Figure 4.2 to 4.4. The graph plot indicated the OBC for different gradation according to NAPA procedure. Accordingly, Marshall Stability, flow, VMA, VFA, and VIM with corresponding OBC for each gradations were indicated. As Figure 4.2 shows, the OBC for aggregate gradation with 5% filler content at 4% Air voids is 5.15% and the corresponding VMA, VFA, Stability, flow and Gmb value are 13.8%,71%,12.75 kN,3.09 mm and 2.432 g/cm3 respectively. All the results obtained shows Marshall Parameters satisfies the specification requirements. Figure 4.3 shows, the OBC of aggregate gradation with 5.5% filler content at 4% Air voids is 5.32% and the corresponding VMA, VFA, Stability, flow and Gmb value are 14.3%,71.8%,11.5 kN,3.13 mm and 2.336 g/cm^3 respectively. The result shows all the Marshall parameters satisfies specification requirements. Figure 4.4 shows, the OBC of aggregate gradation with 6% filler content at 4% Air voids is 4.85% and the corresponding VMA, VFA, Stability, flow and Gmb value are 13.7%,71%,10.3 kN,2.92 mm and 2.337 g/cm3 respectively. The result shows all the Marshall parameter satisfies the specification requirements. Summary of this section is as shown on Table 4.5. Details of Marshall Mix properties are given in *Appendix E*

Table 4.5: Summary of Marshall Mix properties at OBC

Marshall property	Marshall Mix Result			ERA (2002) Specification		Asphalt Institute (1996)		Remark
	5% FC	5.5% FC	6% FC	Lower	Upper	Lower	Upper	
BC (%)	5.15	5.32	4.85	4	10	4	10	Ok
Air Void (%)	4	4	4	3	5	3	5	Ok
VMA (%)	13.8	14.3	13.7	13	-	13	-	Ok
VFA (%)	71	71.8	71	65	75	65	75	Ok
Stability (kN)	12.75	11.5	10.3	7	-	8.006	-	Ok
Flow (mm)	3.09	3.13	2.92	2	4	2	3.5	Ok
Gmb (gm/cm^3)	2.432	2.336	2.337	-	-	-	-	Ok

v. Design bitumen content

Marshall Mix properties of three different gradations at their respective OBC are shown in Table 4.5. Accordingly, stability of three gradation with 5, 5.5 and 6% filler content was obtained 12.75, 11.5, and 10.3 kN respectively. From this result, the maximum Marshall stability of 12.75 KN was found from gradation mixtures with 5% filler content. The Marshall Flow values of 3.09, 3.13, and 2.92 mm corresponding to their OBC were obtained for gradation with 5, 5.5 and 6% filler content respectively. The bulk density of all mixtures produced from gradation with different filler content of 5, 5.5, and 6% was 2.432, 2.336, and 2.337 g/cm^3 respectively. The results shows HMA mixture with 5% filler content was relatively provided highest values of bulk density. Thus the mixture with 5% optimum filler content was selected as design gradation. The percentage of VMA corresponding to OBC was 13.8, 14.3, and 13.7% for the mixture gradation with 5, 5.5, and 6% filler content respectively. The percentage of void filled with asphalt (VFA), which controls the quantity of bitumen-filled micro voids at OBC for gradation with 5, 5.5 and 6% filler content were obtained 71, 71.8, and 71% respectively.

Generally, depending on stability, gradation with 5% CSD filler demonstrated greater stability than all other mixtures. Thus, for this study, mixture with gradation of 5% optimum filler content was considered as design aggregate gradation with 5.15% OBC.

4.3 Marshall Mix Properties of Volcanic Ash

The selected OBC of 5.15% and design gradation with 5% optimum filler content, CSD was substituted with VA at replacement rate of 10% increment from 10 to 100%. The Marshall parameters like bulk density, VIM, VMA, VFA, stability and flow for different proportion of volcanic ash replacement is shown in *Appendix E*

Generally, the effects of volcanic ash on the Marshall properties of HMA are discussed in this sub-sections.

4.3.1 Bulk Specific Gravity of the Mixture

Bulk specific gravity of different percentage replacement of volcanic ash at OBC resulted slightly decreased with increase percentage replacement from 0 to 100% at OBC as show in figure 4.5. The reason is the specific gravity of crushed stone dust is greater than specific gravity of volcanic ash which is 2.68 and 2.44 respectively. Volcanic ash has porous siliceous glass which absorbs bitumen and decreases the density of the mix. However density can be achieved by increased compaction, by increased bitumen content, by increased filler content and other method that reduces air voids. Because as the air void in the mix decreases the density increases. Details are given in *Appendix E.*

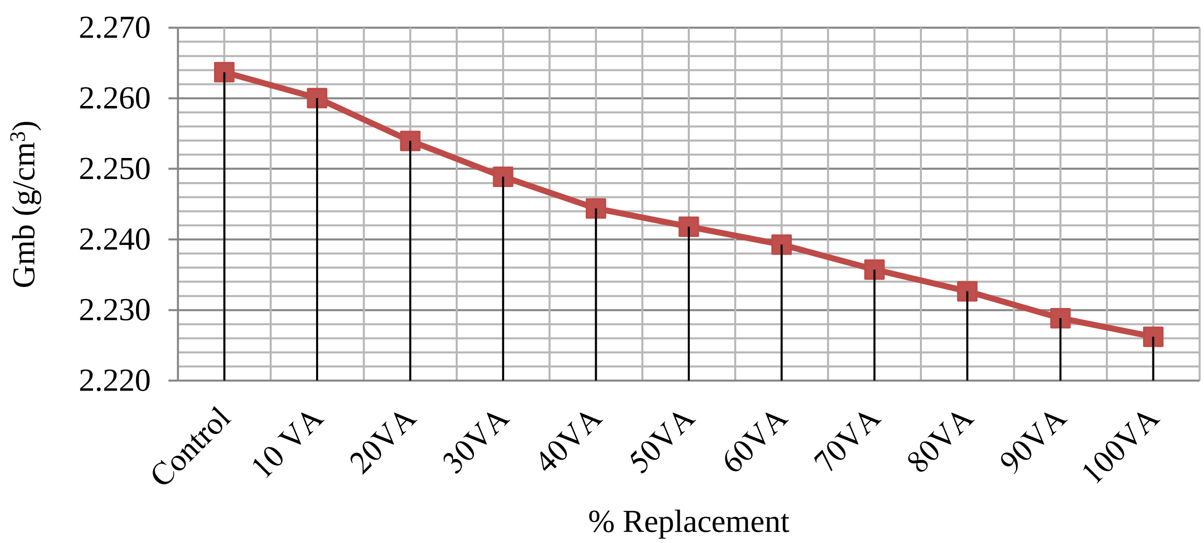


Figure 4.5: Gmb at different percentage replacement of VA

4.3.2 Air Void

The void in mix increased from 4.3 to 4.95% as percentage replacement increases as shown on Figure 4.6. Higher air void of 4.95% was obtained from the mix with full replacement of volcanic ash. This indicated the air void is close to the upper limits of laboratory air void requirements of ERA (2013), 3 to 5%. Decrease in density increases the Air void because of the porous particle of siliceous glass of the volcanic ash. However, too high VIM value indicates, the pavement may be too permeable to air and water, resulting in significant moisture damage and rapid age hardening. Also when air void contents are too low, the asphalt binder content may be too high, resulting in a mixture prone to rutting and shoving. But, all the results are within the limit of the Marshall criteria. The effect of air void can be adjusted by field compaction. Details are given in *Appendix E.*

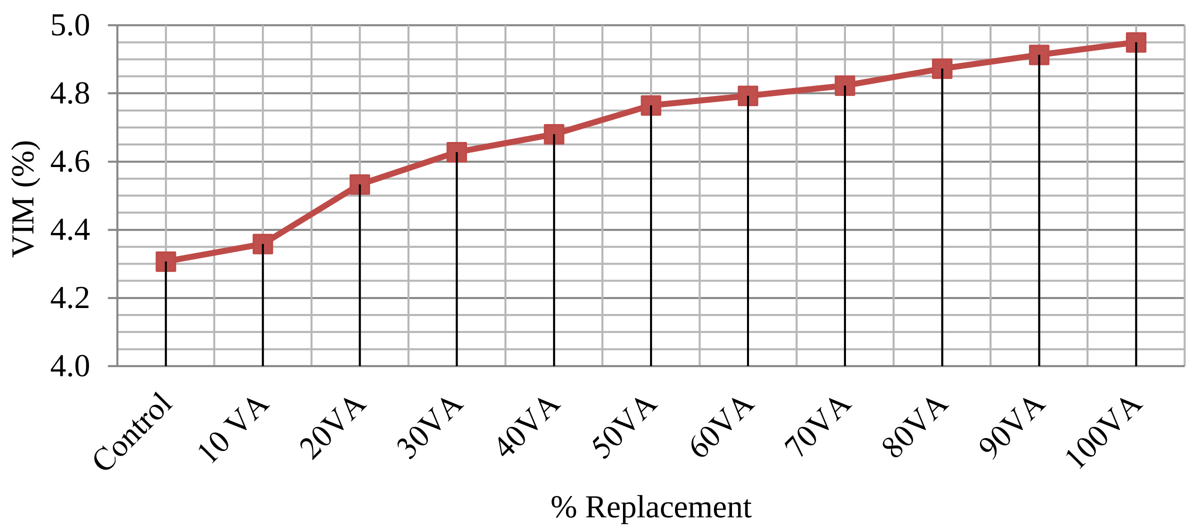


Figure 4. 6: Air void at different percentage replacement of VA

4.3.3 Void in Mineral Aggregate

The value of VMA increased from 16.8 to 18.2% as the volcanic ash filler replacement increases as shown in Figure 4.7. Higher voids in mineral aggregate were obtained from mixes prepared by volcanic ash. This is due to the fact that volcanic ash is finer than crushed stone dust and as density decreased, Air void increase which increases the VMA. Too small VMA value less than the specification limit suffer durability problem and too large VMA results stability problem and un-economical mix. The increasing value for VMA indicates that the absorbance of bitumen could be increased due to a high level of porosity in the surface of the volcanic ash particle. Also, increasing VMA can also decrease rut resistance. However, for all proportion VMA value satisfied the standard requirement of ERA and asphalt institute which is greater than 13%. Details are given in *Appendix E.*

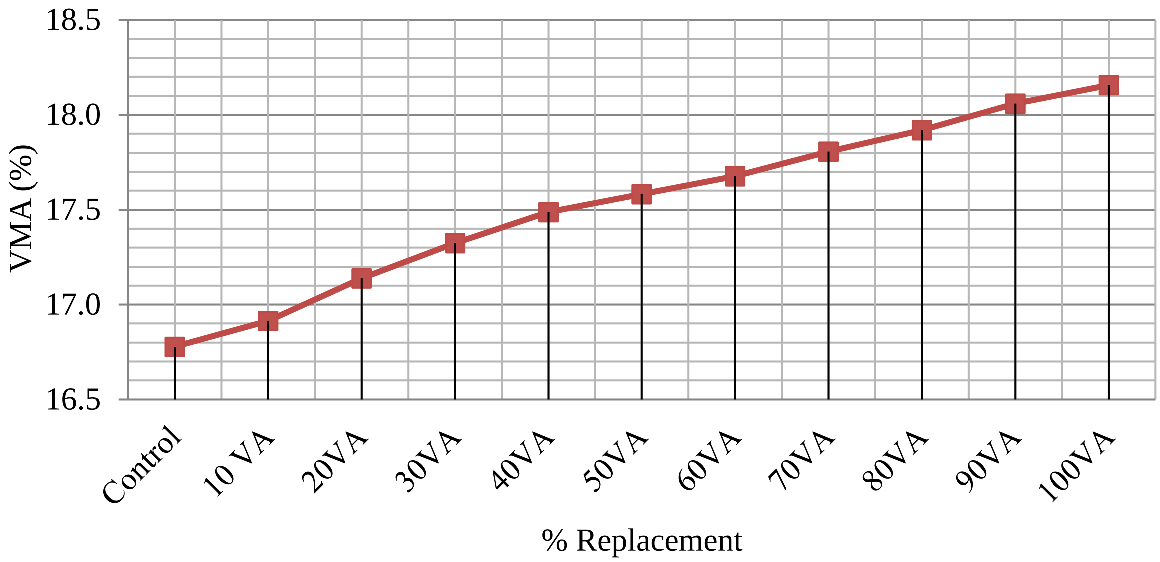


Figure 4.7: Void in mineral aggregate at different percentage replacement of VA

4.3.4 Void Filled with Asphalt

Effect of volcanic ash on the voids filled with asphalt is indicated on Figure 4.8. The graph shows void filled with asphalt decreased with increasing percentage replacement of volcanic ash replacement. This indicates the decrease in density, increases VIM and VMA leading to the decreasing of VFA. The Marshal Criteria is important for the durability of mixes hence the lower VFA value than the limit indicates, there will be less asphalt film around the aggregate particles. Lower asphalt films are more subjected to moisture and weather effects where they can be detached from the aggregate particles and subsequently lower performance. On the other hand, if the limit is exceeded, more voids are filled with asphalt than required for durability. However, for all the mix at different proportions of VA, the VFA value ranges from 72.7 to 74.3% which conforms to the Marshal Criteria, 65 to 75%. Details are given in *Appendix E.*

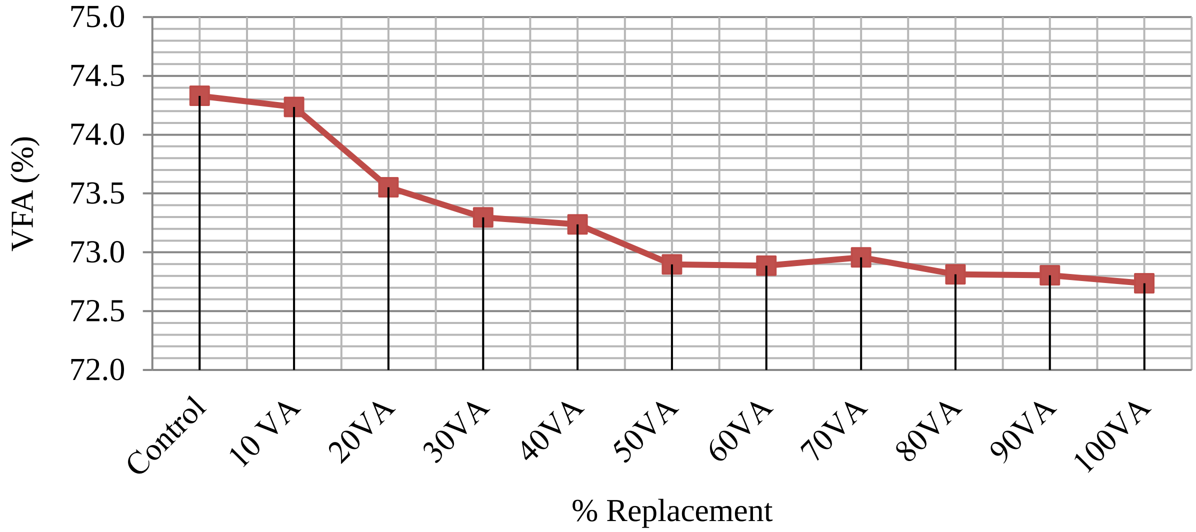


Figure 4.8: Void filled with asphalt at different percentage replacement of VA

4.3.5 Marshall Stability

Marshall Stability with different percentage of volcanic ash at OBC is shown in Figure 4.9. As the figure shows the stability increased from 10.2 to 11.38 kN as percentage replacement of VA increases from 0 to 100%. This indicates volcanic ash has high internal friction than CSD. All the mix proportions conforms the specification requirement of ERA (2002), Min.7 kN and asphalt institute, Min.8.006 kN. Maximum stability of 11.38 kN was obtained at full replacement of volcanic ash which is greater than the control mix stability, 10.2 kN. This indicates that, the mixture with full replacement of volcanic ash has high resistance to traffic loading. Details are given in *Appendix E.*

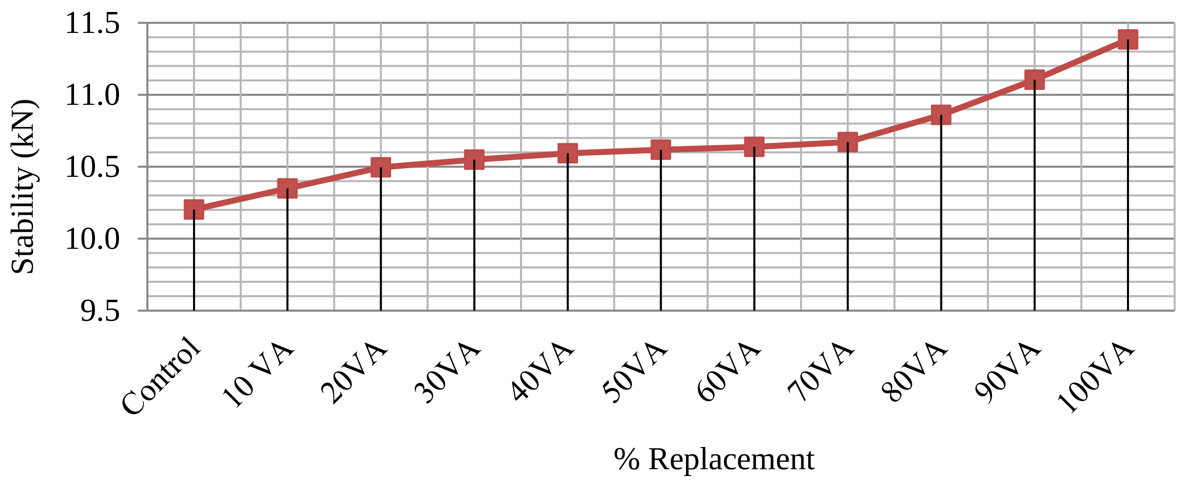


Figure 4.9: Marshall Stability at different percentage replacement of VA

4.3.6 Flow

Flow value increases from 3.04 to 3.47 mm as percentage replacement of volcanic ash increases from 0 to 100% at OBC as shown on Figure 4.10. The result indicated that al the flow value were within the acceptable range of ERA, 2 to 4% and asphalt institute, 2 to 3.5% specification requirement. Also the result indicated the mix had capable to resist vertical deformation corresponding to maximum load. However, maximum flow value was obtained at full replacement of volcanic ash. This indicated that the plastic mix that will experience permanent deformation will occur for filler content and bitumen content more than the optimum for this study. Details are given in *Appendix E.*

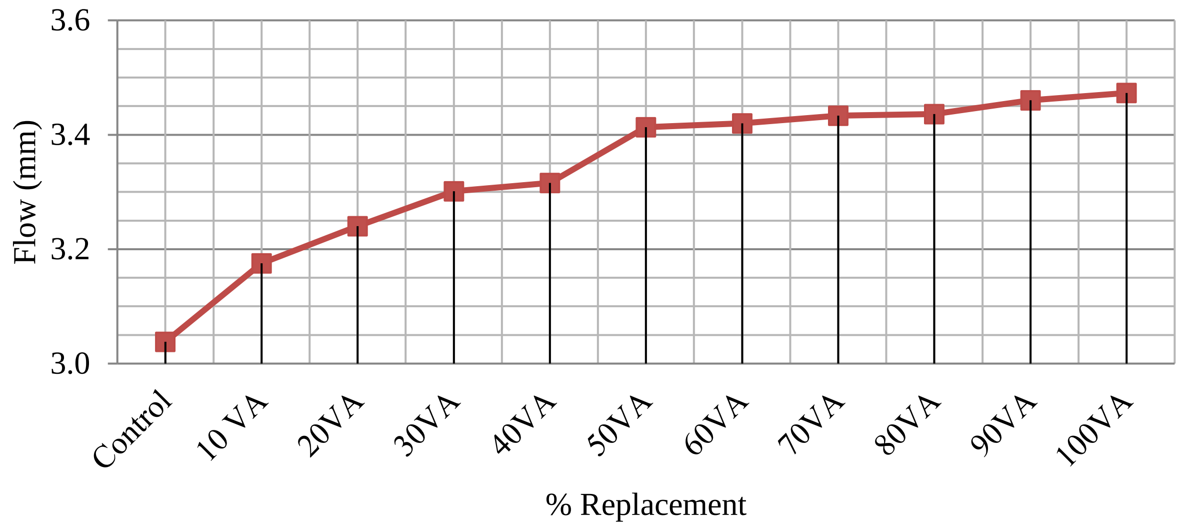


Figure 4. 10: Marshall Flow at different percentage replacement of VA

4.3.7 Optimum Percentage of Volcanic Ash

In order to find the optimum filler content that produces an HMA mixture with the best marshal properties, a combination of mechanisms and control are suggested. All the Marshall properties satisfied the specification requirement of asphalt concrete wearing course. However, the maximum stability value was obtained from the mixture corresponding to 100% volcanic ash filler relative to other proportions. Also corresponding to this proportion, air void, and bulk density values were 4.95% and 2.226 gm/cm3, respectively, which are satisfactory. As Table 4.6 shows the Marshall properties with full replacement of volcanic ash satisfied the national (ERA, 2002) and international (Asphalt institute, 1996) specification requirement. Therefore, volcanic ash can be used as an alternative non-conventional filler at full replacement of conventional filler. Details are given in *Appendix E.*

Table 4. 6: Marshall Properties at full replacement of volcanic ash

Marshall property	Test Result	ERA(2002) Specification		Asphalt Institute (1996) specification		Remarks
		Lower	Upper	Lower	Upper	
OBC (%)	5.15	4	10	4	10	Ok
VIM (%)	4.95	3	5	3	5	Ok
VMA (%)	18.2	13	-	13	-	Ok
VFA (%)	72.7	65	75	65	75	Ok
Stability (kN)	11.38	7	-	8.006	-	Ok
Flow (mm)	3.47	2	4	2	3.5	Ok
Gmb (gm/cm^3)	2.226	-	-	-	-	Ok

4.4 Moisture Susceptibility of HMA

Table 4.7 presents the test results of the tensile strength ratio (TSR) for mixes prepared with crushed rock and full replacement of volcanic ash at 5.15% OBC and 5% filler content. From the marshal immersion test result, the tensile strength ratio values were obtained as a ratio of conditioned to unconditioned tensile strength. As Marshall Immersion test result indicated, asphalt mixes with volcanic ash and crushed stone dust gives tensile strength ratio of 98% and 82% respectively. The test result shows mixes prepared with volcanic ash provide higher tensile strength ratio relative to conventional crushed rock. Thus, mixes prepared with volcanic ash provide better resistance to moisture induced damage. Details of the analysis are given in *Appendix F*

Table 4. 7: Tensile strength ratio test result

Sample type	Filler type	Weight of specimen (gm)			Gmb (g/cm^3)	Maximum load (kN)	TSR (%)
		in air	in water	SSD			
Control	CSD	1249.1	699.1	1250.9	2.264	8.5	82.0
Conditioned		1249.5	698.8	1251.2	2.262	7.0	
Control	VA	1250.6	698.7	1256.1	2.243	9.8	98.0
Conditioned		1253.5	698.9	1257.9	2.243	9.6	

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the objective this study the obtained findings are concluded as follows:

The plastic index and specific gravity of volcanic ash are 0.92% and 2.44 respectively. The combined compositions of silica, aluminum and iron oxides is 81.51%. The loss on ignition and moisture content are 5.24% and 2.21% respectively. Therefore, the chemical composition analysis indicated that the volcanic ash can be classified as Class - N pozzolana.

All the mixes prepared at different proportions of volcanic ash has no significant effect on performance or volumetric properties of hot mix asphalt. Maximum stability value of 11.38 kN was obtained at full replacement of volcanic ash in the mix. The air void increases from 4.3 to 4.95% as percentage replacement of volcanic ash increases from 10 to 100%. Void in Mineral aggregate increases from 16.8 to 18.2% as the percentage replacement of volcanic ash filler increases from 10 to 100%. Void filled with asphalt decreased from 74.3 to 72.7 % as percentage replacement of volcanic ash increases. Marshall Flow result for different percentage of volcanic ash increases from 3.04 to 3.47 mm.

The mix with fully replaced volcanic ash resulted higher moisture resistance compared to the mix produced with crushed stone dust at optimum bitumen content.

Therefore, volcanic ashes can be used as either fully replacing or in combination with crushed stone dust filler for hot mix asphalt pavement.

5.2 Recommendations

In Ethiopia, construction of asphalt pavement is still in infant stage and needs much more effort to make construction materials. The awareness about the different alternative locally available, economically feasible as well as environmentally friendly filler material for HMA materials and their advantages is negligible. Therefore, based on the findings of this study, the following recommendations are forwarded:

- Volcanic ash can be used as a filler material in hot mix asphalt either fully replacing or in combination with crushed stone dust.

- Volcanic ash investigated in this study can be used as crushed stone replacement. Therefore concerned government and private companies like contractors and consultants should have to made awareness about.
- Finally the researcher recommends the Ethiopian Road Authority to apply the potential use of this material on asphalt concrete pavements.

The following further investigations are required:

- Evaluation of the suitability of volcanic ash in hot mix asphalt at different bitumen content and grade.
- Rutting effect investigation of volcanic in HMA mixture.
- The economic analysis on the use of volcanic ash as alternative material
- Evaluation of HMA mixture with different super-pave gradation using volcanic ash.
- Analysis of pozzolanic reaction and chemical structure of volcanic ash needs further investigation.

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APPENDICES

Appendix A: Aggregate Test Results

Table A1: Particle size distribution for coarse aggregate (9.5-25 mm)

Test method: Sieve analysis (AASHTO T 27)

Material type:-Crushed stone coarse aggregate(9.5-25 mm)									
Dry sample Weight,(gm)				5010	5050				
washed dry sample,(gm)				4999.6	5039.1				
Sieve size,mm	Weight Ret.,g	% Ret.	Comm. Ret. %	% Passing	Weight Ret.,g	% Ret.	Comm. Ret. %	% Passing	Av.comm. Pass %
25	0.0	0.0	0	100.0	0.0	0.0	0	100	100.0
19	1122.2	22.4	22.4	77.6	1096.0	21.7	21.7	78.30	77.9
12.5	2497.0	49.8	72.2	27.8	2568.6	50.9	72.6	27.43	27.6
9.5	1207.4	24.1	96.3	3.7	1196.9	23.7	96.3	3.73	3.7
4.75	130.3	2.6	98.9	1.1	131.3	2.6	98.9	1.13	1.1
2.36	25.1	0.5	99.4	0.6	25.3	0.5	99.4	0.63	0.6
1.18	10.0	0.2	99.6	0.4	12.6	0.2	99.6	0.39	0.4
0.6	5.1	0.1	99.7	0.3	5.8	0.1	99.7	0.27	0.3
0.3	2.5	0.0	99.8	0.2	2.7	0.1	99.8	0.22	0.2
0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.075	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0
Pan									
W.loose	10.4				10.9				
Total	5010.0				5050.0				

Table A2: Particle size distribution for intermediate aggregate (2.36-9.5 mm)

Material type:-Crushed stone intermediate aggregate(2.36-9.5 mm)									
Dry sample Weight, gm			4900		4800				
washed dry sample, gm			4873.6		4776.4				
Sieve size, mm	Weight Ret.,g	% Ret.	Comm. % Ret.	% Pass	weight Ret.,g	% Rett.	Comm. % Ret.	% Pass	Av. comm. Pass,%
25	0.0	0.0	0	100	0.0	0.0	0	100	100
19	0.0	0.0	0.0	100	0.0	0.0	0	100	100
12.5	0.0	0.0	0.0	100	0.0	0.0	0	100	100
9.5	720.3	14.7	14.7	85.3	700.8	14.6	14.6	85.4	85.4
4.75	2389.3	48.8	63.5	36.5	2338.0	48.7	63.3	36.7	36.6
2.36	1460.2	29.8	93.3	6.7	1440.0	30.0	93.3	6.7	6.7
1.18	137.2	2.8	96.1	3.9	134.4	2.8	96.1	3.9	3.9
0.6	122.5	2.5	98.6	1.4	120.0	2.5	98.6	1.4	1.4
0.3	34.3	0.7	99.3	0.7	33.6	0.7	99.3	0.7	0.7
0.15	9.8	0.2	99.5	0.5	9.6	0.2	99.5	0.5	0.5
0.075	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pan									
W.loose	26.4				23.6				
Total	4900.0				4800.0				

Table A3: Particle size distribution for fine aggregate (0-2.36 mm)

Material	Crushed stone fine aggregate 0-2.36 mm								
Dry Wt,g	4000				4000				
Washed,g	3481.1				3521.3				
Sieve size, mm	Weight Ret.,g	% Ret.	Comm. % Ret.	% Pass	weight Ret.,g	% Rett.	Comm. % Ret.	% Pass	Av. comm. Pass,%
25	0.0	0.0	0	100	0.0	0.0	0	100	100
19	0.0	0.0	0.0	100	0.0	0.0	0.0	100	100
12.5	0.0	0.0	0.0	100	0.0	0.0	0.0	100	100
9.5	0.0	0.0	0.0	100	0.0	0.0	0.0	100	100
4.75	38.1	1.0	1.0	99.0	38.1	1.0	1.0	99.0	99.0
2.36	236.2	5.9	6.9	93.1	238.1	6.0	6.9	93.1	93.1
1.18	896.9	22.4	29.3	70.7	895.7	22.4	29.3	70.7	70.7
0.6	719.8	18.0	47.3	52.7	720.1	18.0	47.3	52.7	52.7
0.3	700.1	17.5	64.8	35.2	698.5	17.5	64.8	35.2	35.2
0.15	480.0	12.0	76.8	23.2	480.2	12.0	76.8	23.2	23.2
0.075	310.0	7.8	84.5	15.5	300.6	7.5	84.3	15.7	15.6
Pan	100.0	2.5			150.0	3.8	88.0	12.0	
W.loose	518.9				478.7				
Total	4000.0				4000.0				

Table A4: Aggregate gradation for 5% CSD filler

Aggregate type	9.5-25 mm		2.36-9.5 mm		0-2.36 mm		Total blend	middle value	specification limit
Blending,%	31		37		32				
Sieve size	% pass	% Blend	% pass	% Blend	% pass	% Blend	A+B+C		
		A		B		C			
25	100	31.0	100	37.0	100	32.0	100.0	100.0	100.0
19	77.9	24.2	100	37.0	100	32.0	93.2	95.0	90-100
12.5	27.6	8.6	100	37.0	100	32.0	77.8	79.5	…..
9.5	3.7	1.1	85.4	31.6	100	32.0	66.7	68.0	56-80
4.75	1.1	0.3	36.6	13.5	99.0	31.7	47.8	50.0	35-65
2.36	0.6	0.2	6.7	2.5	93.1	29.8	32.7	36.0	23-49
1.18	0.4	0.1	3.9	1.4	70.7	22.6	24.5	26.0	……
0.6	0.3	0.1	1.4	0.5	52.7	16.9	17.7	19.0	……
0.3	0.2	0.1	0.7	0.3	35.2	11.3	11.7	12.0	5-19
0.15	0.0	0.0	0.5	0.2	23.2	7.4	7.9	8.5	……
0.075	0.0	0.0	0.0	0.0	15.6	5.0	5.0	5.0	2-8

Table A5: Aggregate gradation for 5.5% CSD filler

Aggregate type	9.5-25 mm		2.36-9.5 mm		0-2.36 mm		Total blend	middle value	specification limit
Blending,%	28.8		36		35.2				
Sieve size	% pass	% Blend	% pass	% Blend	% pass	% Blend			
		A		B		C	A+B+C		
25	100.0	28.8	100	36	100	35.2	100	100	100
19	77.9	22.4	100	36	100	35.2	93.6	95	90-100
12.5	27.6	7.9	100	36	100	35.2	79.1	79.5	…..
9.5	3.7	1.1	85.4	30.7	100.0	35.2	67.0	68	56-80
4.75	1.1	0.3	36.6	13.2	99.0	34.9	48.4	50	35-65
2.36	0.6	0.2	6.7	2.4	93.1	32.8	35.4	36	23-49
1.18	0.4	0.1	3.9	1.4	70.7	24.9	26.4	26	……
0.6	0.3	0.1	1.4	0.5	52.7	18.6	19.1	19	……
0.3	0.2	0.1	0.7	0.3	35.2	12.4	12.7	12	5-19
0.15	0.0	0.0	0.5	0.2	23.2	8.2	8.4	8.5	……
0.075	0.0	0.0	0.0	0.0	15.6	5.5	5.5	5	2-8

Table A6: Aggregate Gradation for 6% CSD filler

Aggregate type	9.5-25 mm		2.36-9.5 mm		0-2.36 mm		Total blend	middle value	specification limit
Blending,%	25.6		35.9		38.5				
Sieve size, mm	% pass	% Blend	% pass	% Blend	% pass	% Blend			
		A		B		C	A+B+C		
25	100.0	25.6	100	35.9	100	38.5	100.0	100.0	100
19	77.9	20.0	100	35.9	100	38.5	94.4	95.0	90-100
12.5	27.6	7.1	100	35.9	100	38.5	81.5	79.5	…..
9.5	3.7	0.9	85	30.6	100	38.5	70.1	68.0	56-80
4.75	1.1	0.3	37	13.1	99.0	38.1	51.6	50.0	35-65
2.36	0.6	0.2	6.7	2.4	93.1	35.9	38.4	36.0	23-49
1.18	0.4	0.1	3.9	1.4	70.7	27.2	28.7	26.0	……
0.6	0.3	0.1	1.4	0.5	52.7	20.3	20.9	19.0	……
0.3	0.2	0.1	0.7	0.3	35.2	13.6	13.9	12.0	5-19
0.15	0.0	0.0	0.5	0.2	23.2	8.9	9.1	8.5	……
0.075	0.0	0.0	0	0.0	15.6	6.0	6.0	5.0	2-8

Table A7: specific gravity and water absorption of coarse aggregate (9.5-25 mm)

Test method AASHTO T85-91

Trial No	1	2	Average
A= Weight of oven dry sample in air, gm	2464.8	2465.5	
B=Weight of SSD sample in air, gm	2500	2500	
C=Weight of saturated sample in water,gm	1538.7	1537.9	
Bulk sp.gravity(oven dry) ,Gsb=A/(B-C)	2.564	2.563	2.563
Bulk sp.gravity(SSD), Gss=B/(B-C)	2.601	2.598	2.600
Apparent specific gravity ,Gsa=A/(A-C)	2.661	2.658	2.660
Water Absorption ,%=(B-A)/A*100	1.428	1.399	1.414

Table A8. Specific gravity and water absorption of intermediate aggregate (2.36-9.5 mm)

Test method AASHTO T85-91

Trial No	1	2	Average
A= Weight of oven dry sample in air, gm.	1968.2	1965.1	
B=Weight of SSD sample in air, gm.	2000	2000	
C=Weight of saturated sample in water, gm.	1238.2	1239.1	
Bulk sp. gravity(oven dry) ,Gsb=A/(B-C)	2.584	2.583	2.583
Bulk sp. gravity(SSD), Gss=B/(B-C)	2.625	2.628	2.627
Apparent specific gravity ,Gsa=A/(A-C)	2.696	2.707	2.701
Water Absorption ,%=(B-A)/A*100	1.616	1.776	1.696

Table A9: specific gravity and water absorption of fine aggregate (0-2.36 mm)

Test method AASHTO T84-95

Trial No	1	2	Average
A= Weight of oven dry sample in air, gm.	249.1	243.6	
B=Weight of Pycnometer+ Water, gm.	700	695	
C=Weight of Pycnometer + water + sample, gm.	856.8	850.3	
S=Weight of SSD sample, gm.	252	250	
Bulk Sp.gravity(oven dry) ,Gsb=A/(B+S-C)	2.617	2.572	2.594
Bulk Sp.gravity(SSD), Gss=S/(B+S-C)	2.647	2.640	2.643
Apparent specific gravity ,Gsa=A/(A+B-C)	2.699	2.759	2.729
Water Absorption ,%=(S-A)/A*100	1.164	2.627	1.896

Appendix B: Bitumen Test Results

Table B1: Penetration test (Test method: AASHTO T49)

Test No	Test Temp. °c	Time of test(s)	Test Load(g)	Reading (0.1mm)			Average (0.1mm)
				1st time	2nd time	3rd time	
1	25	5	100	64.2	65.1	63.5	64.3
2	25	5	100	67.2	63.8	62.7	64.6
3	25	5	100	65.7	67.3	66.2	66.4
Average Penetration							65.1

Table B2: Ductility test (Test method AASHTO T51)

Test No	Test Temp °c	Speed (cm/min)	Ductility (cm)	Average(cm)
1	25	5	109	
2	25	4	107	
3	25	5	108	
Average			108	

Table B3: Softening point (Test method AASHTO T53)

Test No	Temp. when starting to heating(°c)	Record of liquid temp.in beaker			Softening point (°c)
		4min	5min	6min	
1	24	32	40	46	46.15
2	24	32	40	46	48.25
Average					47.2

Table B4: Specific Gravity of bitumen (Test Method ASTM D70-97 or AASHTO T-228)

Group	Wt. of pycnometer (g) =A	Wt. Of Pycnometer + distilled Water (g) =B	Wt. Pycno+ partially filled with Bitumen (g)=C	Wt. Pycno+ water + bitumen (g)=D	Relative Density=(C-A)/((B-A)-(D-C))	Specific gravity=Relative density *density of water (0.997gm/cm3)
	A	B	C	D		
1	31.89	130.43	108.06	132.49	1.028	1.025
2	32.1	131.23	107.5	132.3	1.014	1.011
Average						1.018

Appendix C: Mineral Filler Test Results

Table C1: Particle size distribution of CSD filler (Test method: AASHTO T 11)

Material	Crushed stone dust,<0.075 mm								
Dry Wt,g	360				370				
Washed,g	0				0				
Sieve size, mm	Weight Ret.,g	% Rett.	Comm. % Ret.	% Pass	weight Ret.,g	% Ret.	Comm. % Ret.	% Pass	Av. comm. Pass,%
1.18	0	0	0	100	0	0	0	100	100
0.6	0	0	0	100	0	0	0	100	100
0.3	0	0	0	100	0	0	0	100	100
0.15	0	0	0	100	0	0	0	100	100
0.075	0	0	0	100	0	0	0	100	100
Pan	0				0				
W.loose	360				370				
Total	360				370				

Table C2: Particle size distribution of VA filler

Sieve Size(mm)	Mass Retained (g)	% Retained	% pass	Specification (ASTM D242)
2.36	0	0	100	-
1.18	0	0	100	-
0.6	0	0	100	100
0.3	60.5	4.0	96.0	95-100
0.15	250.6	16.7	83.3	70-100
0.075	761.3	50.8	49.2	-
pan	427.6	28.5		-
Total Mass	1500	100.0		-

Table C3: Specific gravity of CSD mineral fillers (Test method: AASHTO T84-95)

Material type	Crushed stone dust	
Pycnometer No	1	2
Mass of dry clean & calibrated pycnometer, g	29.84	30.88
A=Mass of oven dry sample in air,g	25	25
B=Mass of pycnometer + Water,g	122.37	125.42
C=Mass of pycnometer +water + sample, g	138.03	141.1
observed Temp.of H20,Ti	23	23
K for TX	1	1
Apparent specific gravity Gsa=A*K/(A+B-C)	2.68	2.68
Average	2.680	

Table C4: Specific gravity of VA mineral fillers

Material type	Crushed stone dust	
Pycnometer No	1	2
Mass of dry clean & calibrated pycnometer,g	30.5	31.38
A=Mass of oven dry sample in air,g	25	25
B=Mass of pycnometer + Water,g	127.76	125.93
C=Mass of pycnometer +water + sample,g	142.54	140.64
observed Temp.of H20,Ti	26	26
K for TX	0.9997	0.9997
Apparent specific gravity Gsa=A*K/(A+B-C)	2.445	2.43
Average	2.44	

Table C5: Chemical composition of volcanic ash

	GEOLOGICAL SUPERVISION OF ETHIOPIA	Doc.Number: GLD/F5.10.2	Version No: 1
	GEOCHEMICAL LABORATORY DIRECTORATE		Page 1 of 1
Document Title:	Complete Silicate Analysis Report	Effective date:	May, 2017

Issue Date: -21/01/2021

Customer Name:- Achalu Kebede

Request No:- GLD/RQ/483/20

Report No:- GLD/RN/77/21

Sample type :- Volcanic Ash Rock

Sample Preparation: - 200 Mesh

Date Submitted :- 18/12/2020

Number of Sample:- One (01)

Analytical Result: In percent (%) Element to be determined Major Oxides & Minor Oxides

Analytical Method: $LiBO_2$ FUSION, HF attack, GRAVIMETERIC, COLORIMETRIC and AAS

Collector's code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
Volcanic Ash	55.18	20.85	5.48	1.90	0.42	5.46	2.12	0.18	0.10	0.18	2.21	5.24

Note: - This result represent only for the sample submitted to the laboratory.

Analysts	Checked By	Approved By	Quality Control
Lidet Endeshaw		Lidet	
Nigist Fikadu	Tizita Zemene	For Yohannes Getachew	Gosa Haile

Geological Survey of Ethiopia Central Geological Laboratory

Table C6: Plasticity index of VA filler

Test Method: Cone penetrometer (BS 1377: part 2:1990)

	Liquid Limit, LL				Plastic Limit, PL			
Test No	1	2	3	4	1	2	3	4
penetration, mm	16.1	23.80	26.2	28.4	14.9	19.34	22.61	26.77
Container No	A17	T1	4	3-3	A7	A3-3	T1	4
Mass of wet soil + container, g	47.44	37.51	48.5	55.01	31.7	48.18	21.9	54.78
Mass of dry soil + container, g	39.52	27.74	38.56	45.3	27.5	40.85	17.05	42.6
Mass of container, g	21.94	6.43	16.98	24.31	17.5	24.31	6.43	16.98
Mass of moisture, g	7.92	9.77	9.94	9.71	4.23	7.33	4.85	12.18
Mass of dry soil, g	17.58	21.31	21.58	20.99	9.98	16.54	10.62	25.62
Moisture content ,%	45.05	45.85	46.06	46.26	42.4	44.32	45.67	47.54

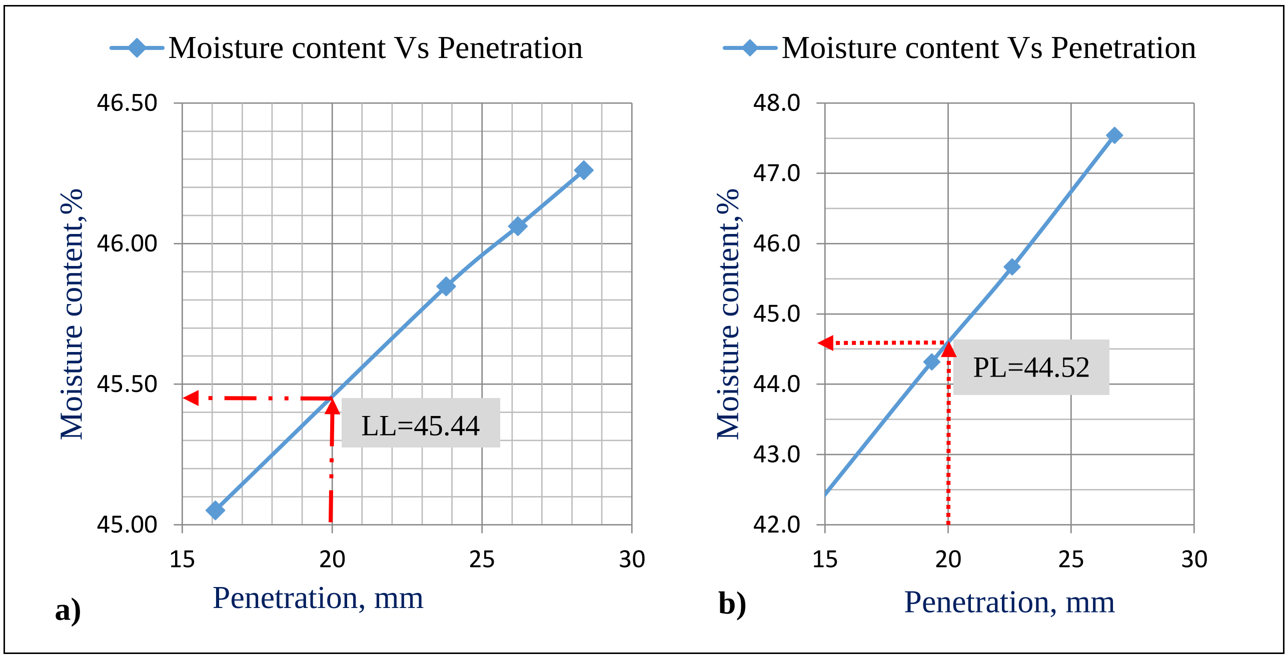


Figure C1: a) Liquid Limits, b) Plastic Limits

PI=LL-PL=45.44 – 44.52=0.92%

Where; PI=plasticity index, LL= liquid Limit and PL= plastic Limit

Appendix D: Maximum Theoretical Density

Test Method: ASTM Designation: D 2041 -90

Table D1: Theoretical maximum specific gravity of un compacted mixture with 5 % CSD

BC %	4		4.5		5		5.5		6	
Trial No	1	2	1	2	1	2	1	2	1	2
A	1230.2	1230.5	1232.5	1237.6	1243.3	1245.4	1226.7	1221.3	1235.1	1233.6
B	2427.6	2429.4	2427.6	2429.4	2427.6	2429.4	2427.6	2429.4	2427.6	2429.4
C	3159.8	3154.6	3157.4	3159.2	3162	3163.9	3150.7	3149.8	3150.4	3147.1
Gmm=A/(A+B-C)	2.470	2.435	2.452	2.437	2.443	2.438	2.436	2.438	2.411	2.391
Avg. Gmm	2.453		2.444		2.440		2.437		2.401	

Table D2: Theoretical maximum specific gravity of un compacted mixture with 5.5 % CSD

BC %	4		4.5		5		5.5		6	
Trial No	1	2	1	2	1	2	1	2	1	2
A	1250.6	1251.9	1252.7	1252.3	1254.6	1253.1	1255.7	1253.8	1254.9	1250.1
B	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6
C	3171.3	3169.8	3170.8	3170.9	3168.9	3169.8	3164.8	3164	3160.1	3161.3
Gmm=A/(A+B-C)	2.467	2.456	2.459	2.460	2.444	2.453	2.422	2.423	2.402	2.421
Avg. Gmm	2.462		2.459		2.444		2.423		2.411	

Table D3: Theoretical maximum specific gravity of un compacted mixture with 6% CSD

BC %	4		4.5		5		5.5		6	
Trial No	1	2	1	2	1	2	1	2	1	2
A	1231.5	1230.2	1232.1	1231.7	1233.8	1235.6	1236.8	1237.3	1236.5	1233.3
B	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6	2427.6
C	3156.5	3156.1	3155.1	3154.3	3153.2	3155.6	3153.2	3154.1	3150.1	3147.6
Gmm=A/(A+B-C)	2.450	2.452	2.442	2.439	2.428	2.434	2.419	2.422	2.406	2.403
Avg. Gmm	2.451		2.440		2.431		2.421		2.404	

Where; A=Mass of Dry Sample in Air, B=Mass of Jar filled with water (@ 25 ºc and

C=Mass of Jar + Sample + Water (@ 25 ºc

Appendix E: Marshall Mix Design Test Result

Table E1: Marshall Mix Properties of Asphalt mix with 5% CSD

Project : **MSc Thesis** | **Test Name:** ____________ | **Bulk specific gravity of Aggregate:** **2.580**
Location : **Jimma University,JIT** | **Test Number:** ____________ | **Bitumen Grade:** **60/70 penetration grade**
Sample : **Asphalt Concrete Mix** | **Date Tested:** ____________ | **Filler Material:** **Crushed stone dust**
Tested by : **Achalu kebede** | **Checked by:** ____________ | **Test Method:** **ASTM D1559/AASHTO T 245**

Spec. No	% AC .	Spec .height (mm)	Weight of specimen (g)			Volume of spec. cc	Gmb (g/cm^3)	Unit wt. (kg/m3)	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
			in Air	in water	in SSD									
1	4	70	1208.8	695.2	1220.7	525.5	2.300	2300		6.2	14.4	56.9	8.5	2.6
2		70.5	1212.1	696.7	1224.9	528.2	2.295	2295		6.4	14.6	55.9	8.5	2.7
3		70	1214.5	694.8	1221.7	526.9	2.305	2305		6.0	14.2	57.7	9.5	2.6
Mean ± St Dev.		70.2	1211.8	695.6	1222.4	526.9	2.300±0.005	2300.0	2.453	6.2±0.2	14.4±0.2	56.8±0.9	8.8±0.6	2.6±0
1	4.5	70	1216.2	695.1	1217.5	522.4	2.328	2328		4.8	13.8	65.6	9.8	2.8
2		70.5	1215.6	692.2	1215.7	523.5	2.322	2322		5.0	14.0	64.4	10.5	2.7
3		69.5	1213.9	692.7	1214.1	521.4	2.328	2328		4.8	13.8	65.6	12.6	2.6
Mean ± St Dev.		70.0	1215.2	693.3	1215.8	522.4	2.326±0.004	2326.1	2.444	4.8±0.1	13.9±0.1	65.2±0.7	11.0±1.5	2.7±0.1
1	5	70	1212.8	697.1	1213.5	516.4	2.349	2349		3.8	13.5	72.2	12.6	3.0
2		71	1210.6	693.3	1212.7	519.4	2.331	2331		4.5	14.2	68.3	12.7	3.1
3		69.5	1211.9	694.7	1212.1	517.4	2.342	2342		4.0	13.8	70.8	14.1	3.0
Mean ± St Dev.		70.2	1211.8	695.0	1212.8	517.7	2.341±0.009	2340.5	2.440	4.1±0.4	13.8±0.3	70.4±2	13.1±0.8	3.1±0.1
1	5.5	70.5	1208.2	695.1	1209.5	514.4	2.349	2349		3.6	14.0	74.1	12.5	3.2
2		70	1209.6	692.2	1210.7	518.5	2.333	2333		4.3	14.6	70.6	12.3	3.3
3		70.5	1208.9	692.7	1209.1	516.4	2.341	2341		3.9	14.3	72.4	11.9	3.3
Mean ± St Dev.		70.3	1208.9	693.3	1209.8	516.4	2.341±0.008	2340.9	2.437	3.9±0.3	14.3±0.3	72.4±1.7	12.2±0.3	3.3±0.1
1	6	69	1217.2	698.1	1217.9	519.8	2.342	2342		2.5	14.7	83.2	10.6	3.5
2		69.5	1216.6	696.2	1217.9	521.7	2.332	2332		2.9	15.0	80.9	10.5	3.5
3		69.5	1214.9	695.7	1216.5	520.8	2.333	2333		2.8	15.0	81.1	10.4	3.4
Mean ± St Dev.		69.3	1216.2	696.7	1217.4	520.8	2.335±0.005	2335.5	2.401	2.7±0.2	14.9±0.2	81.7±1.3	10.5±0.1	3.5±0

Table E2: Marshall Mix Properties of Asphalt mix with 5.5% CSD

Project : **MSc Thesis**					**Test Name:** ______				**Bulk Sp. of Aggregate:** **2.581**					
Location : **Jimma University,JIT**					**Test Number:** ______				**Bitumen Grade:** **60/70 penetration grade**					
Sample : **Asphalt Concrete Mix**					**Date Tested:** ______				**Filler Material:** **Crushed stone dust**					
Tested by : **Achalu kebede**					**Checked by:** ______				**Test Method:** **ASTM D1559/AASHTO T 245**					
Spec. No	% AC.	Spec.height (mm)	Weight of specimen (g)			Volume of specimen cc	Bulk Density (g/cc)	Unit Weight (kg/m3)	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
			in Air	in Water	in SSD									
1	4	71.5	1238.5	703.3	1245.2	541.9	2.285	2285		7.2	15.0	52.2	8.8	2.6
2		71.0	1232.3	702.6	1237.3	534.7	2.305	2305		6.4	14.2	55.2	8.6	2.5
3		70.5	1240.2	708.5	1246.2	537.7	2.306	2306		6.3	14.2	55.5	8.9	2.6
Mean ± St Dev.		71.0	1237.0	704.8	1242.9	538.1	2.299±0.012	2299	2.462	6.6±0.5	14.5±0.4	54.3±1.9	8.8±0.2	2.6±0.04
	4.5	70.0	1233.5	704.0	1235.5	531.5	2.321	2321		5.6	14.1	60.0	9.8	2.7
		70.5	1235.7	701.3	1236.6	535.3	2.308	2308		6.1	14.6	57.8	10.0	2.7
		69.5	1232.7	703.5	1233.3	529.8	2.327	2327		5.4	13.9	61.1	10.7	2.6
Mean ± St Dev.		70	1234	702.93	1235.1	532.2	2.319±0.009	2319	2.459	5.7±0.4	14.2±0.3	59.6±1.7	10.1±0.5	2.6±0.04
1	5	70.0	1242.5	713.3	1243.5	530.2	2.343	2343		4.3	13.7	68.7	11.0	2.9
2		70.0	1248.7	715.1	1249.5	534.4	2.337	2337		4.6	14.0	67.3	11.8	3.1
3		69.5	1247.5	714.5	1249.2	534.7	2.333	2333		4.7	14.1	66.6	11.7	3.0
Mean ± St Dev.		69.8	1246.2	714.3	1247.4	533.1	2.338±0.005	2338	2.448	4.5±0.2	13.9±0.2	67.5±1.1	11.5±0.5	3.0±0.1
1	5.5	70.5	1241.5	713.1	1246.5	533.4	2.328	2328		3.9	14.7	73.4	11.6	3.3
2		70.0	1239.7	712.6	1243.3	530.7	2.336	2336		3.6	14.4	75.3	12.2	3.3
3		70.0	1238.4	711.8	1242.2	530.4	2.335	2335		3.6	14.5	75.0	11.4	3.3
Mean ± St Dev.		70.2	1239.9	712.5	1244.0	531.5	2.333±0.005	2333	2.423	3.7±0.2	14.6±0.2	74.6±1	11.7±0.4	3.3±0.04
1	6	70.0	1237.5	709.6	1240.7	531.1	2.330	2330		3.4	15.1	77.6	10.3	3.4
2		69.5	1238.1	710.3	1241.5	531.2	2.331	2331		3.3	15.1	77.8	10.1	3.4
3		69.5	1236.8	706.1	1237.3	531.2	2.328	2328		3.4	15.2	77.3	9.6	3.5
Mean ± St Dev.		69.7	1237.5	708.7	1239.8	531.2	2.330±0.001	2330	2.411	3.4±0.1	15.1±0.05	77.6±0.3	10.0±0.3	3.4±0.1

Table E3: Marshall Mix Properties of Asphalt mix with 6% CSD

Project : MSc Thesis | **Test Name:** ________ | **Bulk Sp. of Aggregate:** 2.582
Location : Jimma University,JIT | **Test Number:** ________ | **Bitumen Grade:** 60/70 penetration grade
Sample : Asphalt Concrete Mix | **Date Tested:** ________ | **Filler Material:** Crushed stone dust
Tested by : Achalu kebede | **Checked by:** ________ | **Test Method:** ASTM D1559/AASHTO T 245

Spec. No	% AC by wt. of mix.	Spec.height (mm)	Weight of specimen (g)			Volume of specimen cc	Bulk Density (g/cc)	Unit Weight (kg/m3)	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
			in Air	in Water	in SSD									
1	4	69.5	1227.5	699.8	1229.7	529.9	2.316	2316		5.5	13.8	60.2	8.4	2.6
2		69	1225.5	699.6	1227.5	527.9	2.321	2321		5.3	13.6	61.2	8.3	2.5
3		69	1226.7	698.5	1228.5	530.0	2.315	2315		5.6	13.9	59.8	8.5	2.6
Mean ± St Dev.		69.2	1226.6	699.3	1228.6	529.3	2.317±0.004	2317.5	2.451	5.5±0.1	13.8±0.1	60.4±0.7	8.4±0.1	2.6±0.03
1	4.5	69	1218.5	697.5	1220.6	523.1	2.329	2329		4.5	13.8	67.0	9.2	2.6
2		69.5	1217.6	696.3	1219.3	523.0	2.328	2328		4.6	13.8	66.7	9.5	2.7
3		68.5	1222.5	703.5	1223.1	519.6	2.353	2353		3.6	12.9	72.2	9.8	2.7
Mean ± St Dev.		69.0	1219.5	699.1	1221.0	521.9	2.337±0.014	2336.8	2.44	4.2±0.6	13.5±0.5	68.6±3.1	9.5±0.3	2.7±0.1
1	5	68	1223.7	701.1	1223.7	522.6	2.342	2342		3.7	13.8	73.3	10.2	3.0
2		68.5	1218.8	697.5	1219.5	522.0	2.335	2335		4.0	14.0	71.8	10.6	3.0
3		68.5	1217.8	699.6	1220.2	520.6	2.339	2339		3.8	13.9	72.8	11.1	3.1
Mean ± St Dev.		68.3	1220.1	699.4	1221.1	521.7	2.339±0.003	2338.6	2.43	3.8±0.1	13.9±0.1	72.6±0.8	10.6±0.5	3.0±0.1
1	5.5	68.5	1215.9	695.1	1216.5	521.4	2.332	2332		3.7	14.6	74.8	9.9	3.2
2		68	1215.1	694.2	1215.3	521.1	2.332	2332		3.7	14.6	74.8	9.7	3.2
3		68	1217.8	696.3	1218.8	522.5	2.331	2331		3.7	14.6	74.6	9.3	3.4
Mean ± St Dev.		68.2	1216.3	695.2	1216.9	521.7	2.332±0.001	2331.5	2.42	3.7±0.03	14.6±0.03	74.7±0.2	9.6±0.3	3.3±0.1
1	6	67.5	1218.1	698.1	1220.1	522.0	2.334	2334		2.9	15.0	80.4	8.5	3.4
2		68	1216.5	695.2	1218.4	523.2	2.325	2325		3.3	15.3	78.5	8.3	3.5
3		67	1219.2	699	1221	522.0	2.336	2336		2.9	14.9	80.9	8.1	3.45
Mean ± St Dev.		67.5	1217.9	697.4	1219.8	522.4	2.331±0.006	2331.4	2.40	3.0±0.2	15.1±0.2	79.9±1.3	8.3±0.2	3.5±0.02

Table E4: Marshall Mix Properties of Asphalt mix with volcanic ash at 5.15% OBC and 5% FC

Project : **MSc Thesis** | **Test Name:** ____________ | **Bulk Sp. of Aggregate:** **2.58**
Location : **Jimma University,JIT** | **Test Number:** ____________ | **Bitumen Grade:** **60/70 penetration grade**
Sample : **Asphalt Concrete Mix** | **Date Tested:** ____________ | **Filler Material:** **CSD & Volcanic Ash**
Tested by : **Achalu kebede** | **Checked by:** ____________ | **Test Method:** **ASTM D1559/AASHTO T 245**

Spec. No	% Blend	Spec.height (mm)	Weight of specimen (g)			Volume of specimen cc	Bulk Density (g/cc)	Unit Weight (kg/m3)	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
			in Air	in Water	in SSD									
1	0	69	1248.4	699.1	1250.7	551.60	2.263	2263		4.33	16.80	74.24	10.99	3.55
2		69.3	1249	699.15	1250.8	551.65	2.264	2264		4.29	16.76	74.41	10.20	3.04
3		69.5	1248.9	699.2	1250.9	551.70	2.264	2264		4.31	16.78	74.34	9.42	2.53
Mean + St Dev.		69.3	1248.8	699.2	1250.8	551.7	2.264±0	2263.7	2.366	4.31±0.02	16.78±0.02	74.33±0.09	10.2±0.78	3.04±0.51
1	10	69	1239.3	694.6	1243.3	548.70	2.259	2259		4.42	16.97	73.96	10.61	3.22
2		69	1242.9	697	1247	549.95	2.260	2260		4.36	16.91	74.23	10.35	3.18
3		69	1246.5	699.4	1250.6	551.20	2.261	2261		4.30	16.86	74.51	10.09	3.13
Mean + St Dev.		69	1242.9	697	1247	549.95	2.260±0.001	2260	2.363	4.36±0.06	16.91±0.05	74.23±0.27	10.35±0.26	3.18±0.05
1	20	70	1250	700.3	1255	554.70	2.253	2253		4.55	17.16	73.46	10.64	3.25
2		69.5	1251.3	700.65	1255.8	555.15	2.254	2254		4.53	17.14	73.55	10.50	3.24
3		69	1252.6	701	1256.6	555.60	2.254	2254		4.51	17.12	73.65	10.35	3.23
Mean + St Dev.		69.5	1251.3	700.65	1255.8	555.15	2.254±0.001	2254	2.361	4.53±0.02	17.14±0.02	73.55±0.1	10.5±0.15	3.24±0.01
1	30	69.5	1247.7	694.6	1251.2	556.60	2.242	2242		4.93	17.59	71.95	10.25	3.25
2		69.5	1247.1	695.85	1250.4	554.55	2.249	2249		4.63	17.32	73.28	10.55	3.30
3		68	1246.5	697.1	1249.6	552.50	2.256	2256		4.32	17.06	74.67	10.85	3.36
Mean + St Dev.		69.0	1247.1	695.9	1250.4	554.6	2.249±0.007	2248.9	2.358	4.63±0.31	17.32±0.27	73.3±1.36	10.55±0.3	3.3±0.06
1	40	68.5	1250	696.8	1253.1	556.30	2.247	2247		4.57	17.39	73.72	11.05	3.36
2		69.0	1249.4	698.15	1254.8	556.65	2.244	2244		4.68	17.49	73.24	10.59	3.32
3		70	1248.7	699.5	1256.5	557.00	2.242	2242		4.79	17.58	72.76	10.14	3.28
Mean + St Dev.		69.2	1249.4	698.2	1254.8	556.7	2.244±0.003	2244.4	2.355	4.68±0.11	17.49±0.09	73.24±0.48	10.59±0.46	3.32±0.04

Spec. No	% Blend	Spec.height (mm)	Weight of specimen (g)			Volume of specimen cc	Bulk Density (g/cc)	Unit Weight (kg/m3)	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
			in Air	in Water	in SSD									
1	50	69	1245.5	696.2	1251.7	555.50	2.242	2242		4.75	17.57	72.95	10.60	3.49
2		69.5	1248.3	697.4	1254.2	556.80	2.242	2242		4.77	17.58	72.90	10.62	3.41
3		70	1251	698.6	1256.7	558.10	2.242	2242		4.78	17.59	72.84	10.64	3.34
Mean + St Dev.		69.5	1248.3	697.4	1254.2	556.8	2.242±0.000	2242	2.354	4.77±0.01	17.58±0.01	72.90±0.05	10.62±0.02	3.41±0.08
1	60	69.5	1251.3	698.4	1257.1	558.70	2.240	2240		4.78	17.66	72.96	9.49	3.34
2		69	1247.6	698.1	1255.3	557.20	2.239	2239		4.80	17.68	72.85	11.79	3.50
3		69.5	1250.1	697.3	1255.6	558.30	2.239	2239		4.80	17.68	72.86	10.64	3.42
Mean + St Dev.		69.3	1249.7	697.9	1256.0	558.1	2.239±0.000	2239	2.352	4.79±0.01	17.68±0.01	72.89±0.06	10.64±1.15	3.42±0.08
1	70/30	69	1250.2	696.4	1257.3	560.90	2.229	2229		5.11	18.1	71.68	10.68	3.48
2		69.5	1246.1	695.1	1254.6	559.50	2.227	2227		5.19	18.1	71.37	10.59	3.36
3		70	1250.5	698.3	1253.8	555.50	2.251	2251		4.17	17.2	75.82	10.74	3.46
Mean + St Dev.		69.5	1248.9	696.6	1255.2	558.6333	2.236±0.013	2236	2.349	4.82±0.57	17.81±0.49	72.96±2.49	10.67±0.08	3.43±0.06
1	80/20	69.5	1250.5	697.6	1258.6	561.00	2.229	2229		5.03	18.05	72.16	10.56	3.35
2		70	1252.6	700.3	1260.6	560.30	2.236	2236		4.75	17.81	73.35	11.45	3.40
3		69.5	1250.2	699.3	1259.1	559.80	2.233	2233		4.84	17.90	72.93	10.57	3.56
Mean + St Dev.		69.7	1251.1	699.1	1259.4	560.4	2.233±0.003	2232.6	2.347	4.87±0.14	17.92±0.12	72.81±0.6	10.86±0.51	3.44±0.11
1	90/10	69.5	1251.2	694.1	1254.7	560.60	2.232	2232		4.78	17.95	73.35	11.54	3.40
2		69	1250.1	693.5	1253.5	560.00	2.232	2232		4.76	17.93	73.43	10.54	3.43
3		69.5	1246.5	695.9	1256.8	560.90	2.222	2222		5.19	18.30	71.63	11.23	3.55
Mean + St Dev.		69.3	1249.3	694.5	1255.0	560.5	2.229±0.006	2229	2.344	4.91±0.24	18.06±0.21	72.81±1.02	11.1±0.51	3.46±0.08
1	100	69	1251	694.6	1256.7	562.10	2.226	2226		4.98	18.18	72.62	12.72	3.48
2		68	1247.3	692.5	1252.3	559.80	2.228	2228		4.87	18.09	73.08	11.38	3.47
3		70	1244.2	692.7	1251.9	559.20	2.225	2225		5.00	18.20	72.51	10.05	3.47
Mean + St Dev.		69.0	1247.5	693.3	1253.6	560.4	2.226±0.002	2226	2.342	4.95±0.07	18.16±0.06	72.74±0.3	11.38±1.34	3.47±0

Appendix F: Moisture Susceptibility Test

Table F1: Moisture Susceptibility Test (Test Method: ASTM C 618)

Sample Type	Filler Type	Weight of specimen (gm)			Bulk density (g/cm3)	Maximum load (kN)	TSR (%)
		in air	in water	SSD			
Control	CSD	1249.4	698.5	1251.7	2.258	8.5	82.0
		1249.0	699.2	1250.8	2.264	8.4	
		1248.9	699.6	1250.1	2.269	8.7	
Average		1249.1	699.1	1250.9	2.264	8.5	
Conditioned	CSD	1249.2	697.8	1251.4	2.257	7.2	
		1248.5	699.2	1251.4	2.261	6.7	
		1250.8	699.4	1250.7	2.269	7.1	
Average		1249.5	698.8	1251.2	2.262	7.0	
Control	VA	1250.2	699.3	1255.2	2.249	9.8	98.0
		1250.1	697.6	1256.0	2.239	10.1	
		1251.4	699.1	1257.1	2.243	9.4	
Average		1250.6	698.7	1256.1	2.243	9.8	
Conditioned	VA	1255.4	700.5	1260.7	2.241	9.6	
		1251.0	697.6	1255.6	2.242	9.8	
		1254.2	698.7	1257.3	2.245	9.3	
Average		1253.5	698.9	1257.9	2.243	9.6	

Where; VA= volcanic ash and CSD = crushed stone dust filler, TSR= Tensile Strength Ratio

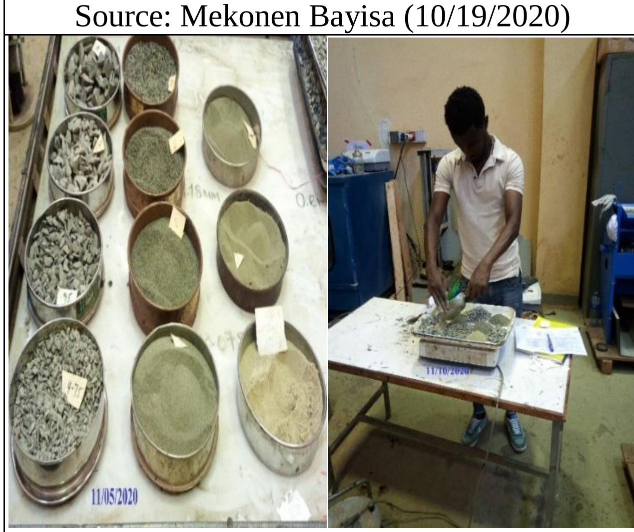
Appendix G: Sample Photos during the Study

Source: Biruk Duri (9/28/2020)

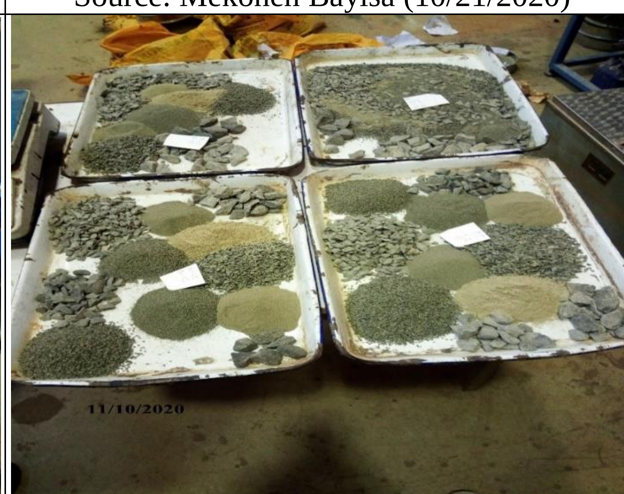

Source: Mekonen Bayisa (9/30/2020)

Source: Mekonen Bayisa (10/19/2020)


Source: Mekonen Bayisa (10/21/2020)



Source: Kinfe W/georges (11/05/2020)



Source: Kinfe W/georges (11/05/2020)

Source: Dejene Dereje(11/06/2020)

Source:Dejene Dereje (11/06/2020)

Source: Kinfe W/georges (11/06/2020)

Source: Dejene Dereje (11/06/2020)

Source: Dejene Dereje (11/07/2020)

Source: Dejene Dereje (11/07/2020)

Source:Dniel Gizachew (11/14/2020)


Source: Daniel Gizachew (11/15/2020)

Source:Belisuma Lemmi (11/15/2020)

Source: Dejene Dereje (12/01/2020)


Source: Dejene Dereje (12/01/2020)


Source:Belisuma Lemmi (12/01/2020)