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EFFECT OF FILLER AND BINDER CONTENTS ON AIR VOIDS IN HOT-MIX ASPHALT FOR ROAD PAVEMENT CONSTRUCTION

BY

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DECLARATION

I, Isooba John, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text and reference list.

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CERTIFICATION

We, the undersigned certify that we have read and hereby recommend for acceptance by Kyambogo University a research dissertation titled: ‘’Effect of Filler and Binder Content on Air Voids in Hot-Mix Asphalt for Road Pavement Construction’’, in fulfilment of the requirements for the award of a degree of Master of Science in Construction Technology and Management of Kyambogo University.

Dr. Mugume Rodgers Bangi (Supervisor)

Date: 07/06/2021

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Date: -----------------------------

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DEDICATION

I thank the almighty God for the strength he has given me during this very challenging moment of my life and I go through this final performance as regards my Master program.

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LIST OF ABBREVIATIONS

μm	Micro-meter
AIM	Asphalt Institute Manual
BS	British Standard
CA	Coarse aggregate
DBM	Dense bituminous macadam
DMF	Design mix formula
E	East
FA	Fine aggregate
FM	Fineness modulus
Gb	Bitumen
Gmb	Bulk density
Gmm	Maximum specific gravity
Gsb	Bulk specific gravity
Gse	Effective specific gravity
HMA	Hot mix asphalt
MoWT	Ministry of Works and Transport
MS	Manual Series
N	Newton

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N	North
NE	North East
NMAS	Nominal maximum aggregate size
NR	No requirements
NW	North West
OBC	Optimum binder content
Pb	Bitumen content
PCS	Primary control sieve
RMSE	Root-Mean-Square
rpm	Revolutions per minute
S	South
SAS	Statistical Analysis System
SE	South East
SSD	Saturated surface dry
SW	South West
TRL	Transport Research Laboratory
VA	Air voids
VFB	Voids filled with bitumen
VMA	Voids in mineral aggregate
W	West

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DEFINITION OF TERMS

The following terms and abbreviations were used in this research report:

- **Air voids (Va)**: are small airspaces that occur between coated aggregate particles in the final compacted asphalt mix.
- **Voids in mineral aggregate (VMA):** is the intergranular space occupied by asphalt binder and air in a compacted asphalt mixture.
- **Voids filled with bitumen (VFB):** is the percentage of voids in the mineral aggregate (VMA) filled with bitumen.
- **Nominal maximum aggregate size (NMAS):** One sieve size larger than the first sieve to retain more than 10 percent of the aggregate by weight.
- **Fineness modulus (FM):** The sum of the percentages retained in a sieve analysis divided by 100, using standard sieves (0.150 mm, 0.300 mm, 0.600 mm, 1.18mm, 2.36 mm, 4.75 mm, 9.5 mm, 19 mm, and 37.5 mm)
- **Coarse aggregate (CA):** The percentage of material retained on the 4.75 mm sieve by weight.
- **Fine aggregate (FA):** The percentage of material passing the 4.75 mm sieve by weight.
- **Optimum binder content (OBC):** The binder content meeting the normal Marshall requirements and giving minimum 3% air voids at refusal density

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ABSTRACT

Filler and binder make up a small proportion of bituminous mixtures, hence they are considered as important ingredients of mixtures. Sometimes due to equipment error during production, some mixtures retain extra or a reduced amount of filler or binder as compared to the design mix formula. It is thought that the poor performance of bituminous mixtures is a result of inadequate proportioning of materials and the use of inappropriate compaction tools. This study was intended to appreciate the influence of contents of filler and binder in relation to durability of asphalt mixtures. Filler used was crushed stone passing 0.075 mm sieve, while the binder was 35/50 penetration grade. Several trial mixes were prepared following Ugandan specifications for Road and Bridge Works, and the Asphalt Institute in MS-2. Marshall design method was used, studying volumetric properties with an average stability value of 22.3 kN, average flow value of 3.7 mm, Va of 4.4 %, VFB of 69.3 %, and VMA of 14.2 %. Also, compaction of mixtures to assess its performance at optimum filler and binder contents was done. Compaction was done using an Automatic Impact Hammer, a Vibrating Hammer, and a Superpave Gyratory compactor aimed at simulating secondary compaction by traffic and assessing the retained air voids which was 3.3 %, 1.3 %, and 0.7 % respectively. Generally, in bituminous mixtures when a vibrating hammer or a gyratory compactor is recommended for compaction, coarser mixes would be the best choice.

Key words: Aggregate gradation, Dense bituminous macadam, Marshall properties

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Dense bituminous macadam (DBM) is a binder course used for roads with a greater number of heavy commercial vehicles and a close-graded premix material. This material has increased in popularity causing pavements to perform almost well in all situations. DBM is a mixture of coarse aggregate, fine aggregate, and asphalt binder, mixed, placed and compacted at elevated temperatures basing on the binder type (IRC, 2017). It is also, important that a DBM mix design developed at any time satisfies all the minimum requirements set (Darshna and Patel, 2013). The performance of any DBM mixture is achieved by careful aggregates selection (RRM, 2008).

Some aggregates used in DBM mix design have some porosity which tends to absorb bitumen into the pore structure and the absorbed bitumen is not considered as a binder in the asphalt mixtures (SHRP, 1990). The right proportioning of aggregates to be used for DBM production is a key factor in achieving a good workable mix (Stephen, 2001). It has also been noted that variations in the aggregate gradation within the limits specified can affect the DBM mix design properties (Lodhi, 2016).

Bitumen bonds the particulate mineral aggregates together to form a cohesive mass at working temperature between 150 and 190 ^{o}C (Cesare & Ruggero, 2017). When all are mixed together and compacted it acts as a single uniform unit mass that provides strength and toughness. In good climatic conditions where the quality of aggregates is sound and asphalt binder is obtainable, traffic loading is the only major contribution to deterioration (El-Maaty, 2013).

The amount of binder and filler contents are the two components that most affect air voids in the asphalt mix (Scott, 2019). Insufficient air voids (air voids less than 3%) resulting from binder content being higher than the optimum is one of the common causes of bleeding in asphalt mixtures (Chu, 2011). Hot Mix Asphalt (HMA) mixes should have sufficient binder content for durability and enough air voids under increased densification for better stability of the mixes. Therefore, at the design stage, it is essential to ensure that these two components are closely controlled.

Road pavements are also constructed such that they provide sufficient safety to road users (Sharad and Gupta, 2013). Some road projects are directly funded by the Ugandan government while others are constructed using borrowed funds from World Bank and European Union. Borrowed funds are paid back with the high interest of which all tax payers are affected. A good road network in any country is essential in boosting economic development, enhances social cohesion and integration by providing citizens with equal access to opportunities and promotes poverty alleviation in societies (Muriel, et al. 2001).

Premature failure after major constructions is commonly experienced in DBM Paved roads. In Uganda, this happened on the Eastern Roads and Bridge Development Project, Malaba-Bugiri-Busia road. The road is part of the international highway running from Malaba through Kenya and Uganda to Rwanda and DR Congo.

Therefore, there is a need to study how small alterations of inert filler and binder contents can affect DBM engineering properties.

1.2 STATEMENT OF THE PROBLEM

In general, there is an increasing number of axles, wheel loads and traffic on road pavements in Uganda today. It is expected that this situation will continue as long as there is a continued expansion of the road network. This is a challenge to asphalt experts to make decisions on what type of a mix can resist such pavement loading and tire pressures.

For better performance of pavements under these increasingly severe conditions, considering both present and future transportation growth, asphalt experts and pavement engineers who are responsible for designing and construction of pavement structures must search continually to come up with better mix designs to avoid premature failures in asphalt pavements. Also, there is a need for improvement in the choice of laboratory compaction equipment that can appropriately simulate field conditions on secondary compaction.

An asphalt mixture is a combination of materials, small alterations in the contents of filler and binder yield diverse engineering properties. When all ingredients which form an asphalt mixture are optimally proportioned, the expected outcome is a mix with engineering properties that conforms with the specification requirements.

Even though research work has been done on the effects of coarse and fine aggregates, the effects of contents of inert filler and binder are not well defined. In-spite of the small quantities it represents in the mix, it has been proved of critical importance in the performance of the paved mixtures.

The use of mineral dust commonly known as an inert filler in asphalt mixtures, and the use of petroleum asphalt commonly known as bitumen in a variety of applications of asphalt, long has been common practice. The engineer has to select the quantity of mineral filler and the amount of bitumen best suited for following the specification. This selection of both filler and binder has been a matter of empirical practice. Therefore, the purpose of this study was to appreciate how small changes in the contents of filler and binder can affect asphalt mixtures. DBM mixtures were considered in this research because DBMs can be used as base course, binder course, and as well wearing course.

1.3 MAIN OBJECTIVE

The primary objective of this study was to assess the effect of filler and binder contents on volumetric properties which relate to durability in hot-mix asphalt for road pavement construction. An additional aspect of this study was to assess the impact of compaction methods on air voids content.

1.3.1 Specific Objectives

The specific objectives of this research were;

i) To identify an appropriate DBM sensitive mixture to recognize the Marshall design method to obtain optimum filler and binder contents.

ii) To determine the effect caused by altering contents of either filler or binder on air voids in DBM mixtures for pavement construction.

iii) To evaluate the refusal density laboratory compaction test methods to simulate realistic field compaction levels and performance characteristics.

1.3.2 Research Questions

i) What effect is caused by altering contents of either filler or binder on air voids in a DBM mixture for pavement layer construction?

ii) When does the DBM mixture become tender and difficult to compact when filler content is altered from the optimum binder content?

iii) How will the DBM mixture behave when air voids requirement is not met at the design stage when all material properties comply?

1.4 RESEARCH JUSTIFICATION

Filler and binder are the principal contributors to early pavement failures where its contents in the HMA have a significant effect on mixture performance. This research seeks for a more functional, performance-based mixture which also addresses cost and safety.

Selecting filler and binder contents in their precise optimums in an asphalt mix can reduce premature failures in road pavements. Besides, other benefits in having good pavements like reduction in travel time over longer distances, minimizing cases of accidents, and reduction in vehicle repair costs can be related to choosing a mixture with better functional and performance. The research results can be used by the Ministry of Works and Transport (MoWT) of Uganda, to improve on the guidelines in regard to extended compaction as a way of minimizing air voids which is a function of the compaction tools and methods used in the laboratory to predict secondary compaction on pavements.

1.5 SIGNIFICANCE OF THE STUDY

Asphalt mixtures ought to be optimally proportioned for the paved mixture to last for the anticipated period of time with minimal maintenance. Even though proper workmanship and construction practices are perfectly exercised, poorly proportioned mixtures will fail prematurely.

This research aims to provide direct technical support to agencies, whereby it will provide agencies and asphalt practitioners with direct information about the effect of individual mix property parameters on mix performance.

Also, it will investigate the interaction of the effects of the parameters on mixture performance, which could be more important than the individual effect. Even though the study is put in the context of the construction variation effect and with the purpose of aiming to improve construction quality, the knowledge gained here can be utilized in the mix design process. Mix design engineers will be able to compare the predictive performance of various mixes, and make sure the best mix is chosen for the project.

Other information from this study will aid in a better understanding of asphalt mix properties and the related laboratory test methods. This shall give the position of other studies to come following recommendations and conclusions drawn.

1.6 SCOPE OF THE STUDY

Testing procedures used in this study were chosen to analyze the effect of varying contents of filler and binder in a single aggregate gradation. The tests used in this study included; maximum specific gravity, bulk density, and Marshall stability and flow. Compaction methods in the process of preparing the specimens included; Normal Marshall compaction by applying 75 blows on each face, Extended Marshall compaction using an automatic impact hammer, Extended Marshall compaction using a vibrating hammer, and Compaction using a Gyratory mechanism.

All tests in this study were prepared and performed in the laboratory. No specimens were taken from the field nor were any test performed in the field. This implied that tests in this study were conducted in a conducive atmosphere.

The selected aggregate gradation contained 20-28 mm, 14-20 mm, 6-14 mm, 0.075-6 mm, and passing 0.075 mm sizes, material passing 0.075 mm was used as filler. The aggregates and filler were sampled so that all sizes came from the same location in the quarry and thus thought to have the same properties.

A sample of bitumen manufactured by ENI-Italy refineries (Reffinaria di Livorno ENI-Italy) was used for all tests. Thus, every single precaution was taken to ensure that the test results focused on the effect of varying the contents of filler and binder only.

1.7 CONCEPTUAL FRAMEWORK

The conceptual framework in Figure 1.1 gives an insight into the study, plan and interconnectivity of all the conceptual variables. The study focused on the effect of contents of filler and binder on engineering properties in DBM mixtures. Filler and binder in DBM mixtures formed the independent variables. The process of optimizing DBM mixtures involved aggregates (coarse and fine), filler, and binder, by means of the Marshall mix design method. This process was influenced by intervening factors such as compaction levels and test standards. The dependent variables were the mix properties, which were compared with the DBM mixture parameters in MoWT (2005) specification and the performance indicators.

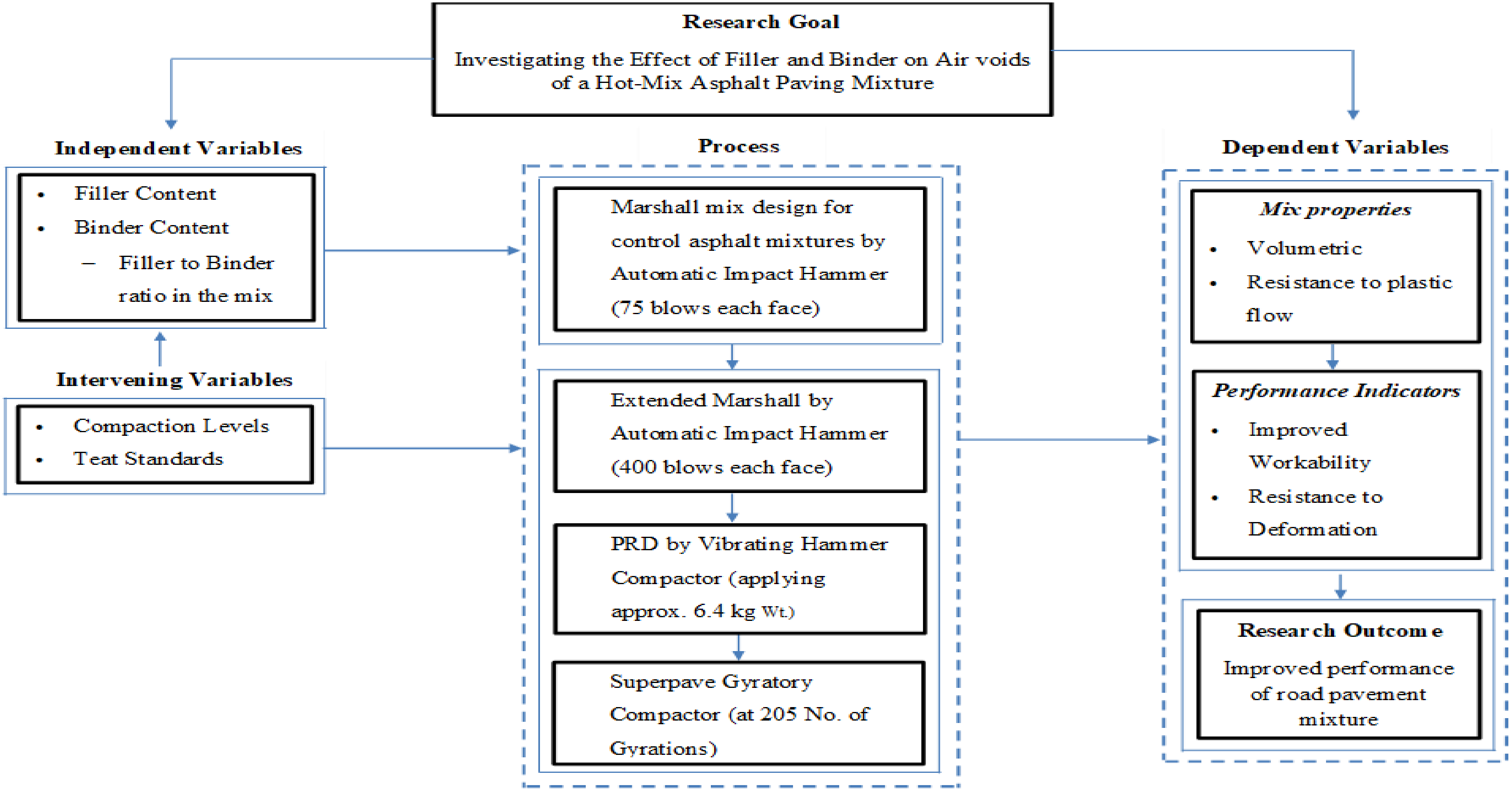


Figure 1.1: Conceptual Framework of the Research

1.8 CHAPTER SUMMARY

The behaviour of a well-designed asphalt mixture should conform to the requirements of the specifications. Obtaining adequate air voids in an asphalt mixture is an important part of the mix design which must be met. Filler and binder content are the major influencing elements on-air voids. The challenge is always during design where some designers with experience find it easy to get it right at one trial mix. Other designers redesign or alter the mix they have designed after discovering a problem in the mix.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter covers a review of concepts that relate to filler and binder contents assimilated into the asphalt mixtures. Kumar and Yadav (2016) reported that the performance of a bituminous mixtures depends on external and internal conditions; where traffic load and environmental being external conditions while properties of the mixture and process of construction being the internal condition. Diab and Enieb (2017) in their study found out that the blend of mineral filler and asphalt binder forms the asphalt mastic which plays a major role in controlling the mechanical behaviour of the mixture. Qasim et. al., (2017) also added that filler is the major contributor to the failure process in asphalt properties and it has a great effect on the hot-mix asphalt properties. In their research work, they remarked that asphalt pavement layers consist of mineral filler, coarse and fine aggregates, all bonded together by the asphalt binder and blended at pre-specified weight proportions determined from the mix design.

2.2 MINERAL FILLER

Diab & Enieb (2017) found out that incorporation of mineral filler in asphalt mix production is essential and can alter the engineering properties of the mixtures. The same research work also found out that the blending of mineral filler and bitumen forms the asphalt mastic which is intended to play a major role in controlling the mechanical behaviour of the mixture. Speculation was made that the quality of the mineral filler is an important factor that controls the lifetime of roads.

Sady (2013), also found out in research that better asphalt mixture performance is considered when filler asphalt ratio is in the range between 1.2 and 1.5 in all respects. Also, it was further mentioned that in some aspects the asphalt mixture performance needs to be modified, by adjusting filler and/or binder quantities.

Remisova et. al., (2015) in a study of mineral filler effect on asphalt mixtures properties emphasized that mineral filler in addition to affecting the mechanical properties of asphalt is also important with respect to stripping or moisture damage. Furthermore, it was mentioned that mineral filler plays an important role in stiffening and toughening asphalt binder, and that filler content, surface area and surface absorption capacity affect the optimal content of the binder in a mixture. In their study, it was also mentioned that the limits of filler to mass ratio do not exist in current asphalt mix design procedures. It is expected that the optimal ratio mass of filler to 1 mass unit of binder is from 1.5 to 1.75. Accordingly, the higher mass of filler in a mixture improves cohesion and internal stability of the mixture and increases bitumen stiffness and influence the workability of the mixture. On the other hand, low filler content and high bitumen binder content can increase mixture sensitivity to rutting. Conclusion was made that filler influences the amount of asphalt content; filler affects workability during mixing and compaction, and hence final properties of asphalt mixture.

According to Wasim (2014), fine aggregates only fill the voids in course aggregates and stiffen the bitumen while the mineral filler material fills the voids between the fine aggregates. Furthermore, Qasim et. al., (2017) also discussed that filler content has a significant effect on the mixture stiffness, and thereby it affects the HMA pavement performance. Moreover, filler content has some additional effects on HMA properties like; extending the content of asphalt binder, stiffening of asphalt binder, ageing properties affecting the mixture, affecting compaction characteristic and workability on the asphalt, and changing the moisture resistance of the HMA. It was further emphasized by McDaniel (2014) who concluded that poor durability of asphalt mixtures is caused by high filler to binder ratio.

2.3 ASPHALT BINDER

Asphalt binder is a valuable engineering material for the following reasons:

i. It assists in the lubrication of asphalt mixtures, comprised of aggregate, liquid bitumen, and sometimes additives.
ii. It has an extra ordinarily excellent adhesive property to aggregate.
iii. It is waterproof to aggregate and under layers.
iv. It can resist any environmental conditions and is a durable pavement material.
v. It is resistant to acids, alkalis and salts reactions.

This was supported by Majeska (2016), where he emphasized that the role of bitumen binder in road construction is to glue aggregates together that form a pavement in a way that does not induce rutting and cracking of pavements when it gets cold, aged, and increase in traffic loads.

Wasim (2014), made some research studies on Marshall and Modified Marshall Specimens using Crumb Rubber Modified Bitumen and concluded that the binder plays a very important role in the performance of dense bituminous macadam mixture for pavement construction. The conclusion made was bitumen used for DBM mixtures should not be highly temperature susceptible in that when used, the mixture does not become too soft and unstable and during cold weather, the mix does not become too brittle causing cracks. Basing on this argument, a harder type of bitumen binder of penetration grade 35/50 was used for the research.

Sudhakara et. al., (2010) also recommended the use of penetration grade 35/50 bitumen because this type of binder is stiff and suitable for use in warmer temperature regions and can withstand very heavy traffic volume. TRL (1993), supported the idea and said that since in the tropics temperatures are higher, DBM mixtures are prone to early deformations and ageing and for that reason, harder bitumen types are recommended. The choice of bitumen source and type is very significant for DBM mixture construction. Hicks, Curren & Lundy (1998), identified that bleeding or flushing in asphalt pavement is caused by excess bitumen in the asphalt mixtures. It is expected that other contributing factors included an insufficient coarse aggregate, excessive rolling during placement, stripping of the bitumen from the aggregate, and low air voids.

A research carried out by McDaniel (2014), observed that poor durability is also caused by low binder content in asphalt mixtures and it specifically results in ravelling, cracking and brittleness of pavements. The research was to prove by checking DBM mixtures with relatively low, optimum and higher binder contents.

2.4 AGGREGATE

Aggregates can be mined, quarried, crushed, and graded by separating using screens in different sizes. Wasim, 2014, stated that different sizes and kinds of aggregates can be used in the manufacture of asphalt mixtures as long as their properties comply with the specifications. The choice of aggregate sizes depends on the performance characteristics required of the proposed pavement to be constructed. Using a large size of aggregates in the base course or binder layers minimizes or eliminates rutting of heavily-trafficked pavements.

The Asphalt Institute (2014) discussed the importance of course aggregates as to provide compressive and shear strength in aggregates, whereby strength is said to be dependent on the resistance to movement and friction between aggregate particles. In their research work, they also remarked that rough textured aggregates provide more resistance than rounded and smooth-textured aggregates. Moreover, angular pieces and rounded pieces of aggregate can retain the same material strength, angular aggregate particles tend to lock tighter, resulting in a stronger mass of material. In the same study, they observed that rounded aggregate particles tend to slide past each other. Basing on that, a conclusion was made that the internal friction in aggregates improves the ability to interlock and create a mass that is almost as strong as the individual pieces.

It was revealed by Afaf (2014) in a study conducted that aggregates comprise the vast bulk of the asphalt mixture, so they exert significant influence on the resulting engineering properties of the structure. Coarse aggregate was evaluated as the material which substantially retains on a 2,36 mm sieve. Accordingly, the research revealed the different ways how aggregate properties affect the mix properties; when aggregate used are weak, they disintegrate in the process of Marshall compaction and contribute to the fines, consequently, the fines and filler content in the mix increases and leads to higher stability of the mix. Diab and Enieb (2017) in their study supported the same by saying that coarse and fine particles act as the structural skeleton of the constructed pavement.

2.5 AGGREGATE GRADATION

Michael (2011) referred to the term asphalt to describe mixtures of bitumen with mineral aggregates. It was mentioned that the optimum binder content of the asphalt mix is highly dependent on aggregate characteristics. The combined aggregate particle size distribution is directly related to optimum binder content. It is known that the finer the mix gradation, the larger the total surface area of the aggregate and the greater the amount of binder required to uniformly coat the particles. Conversely coarser mixes have fewer total aggregates surface area and they demand less bitumen to coat the particles. Moreover, that is where the proper relationship between aggregate surface area and optimum binder content is better observed when filler material is added to the mix.

The Asphalt Institute (1996) revealed that aggregate characteristics contribute to either poor or good asphalt mixture performance. The study also, stated that a gradation below the restricted zone is encouraged because it has better shear resistance provided by the coarse aggregate skeleton. Aggregate gradation then was classified as above through and below the restricted zone (AASHTO, 2004). A combined aggregate gradation passing below the primary control sieve is classified as coarse-graded: If the gradation curve passes above the primary control sieve, it is classified as fine-graded. Agencies are using a broad band to confine the specific aggregate size into a certain range, as evidenced by the (MoWT, 2005) specification.

Wenbin (2011), also found out that most agencies are specifying that it is the contractor's responsibility to conduct the mix design following the current specification. This is simply because the gradation broad band gives contractors the freedom of developing a master gradation curve that can meet all the mix design parameter requirements, such as VMA, VFB, VA, Stability and Flow values. The band is also large enough to allow two types of aggregate gradation to be designed with the same aggregate source for the project; coarse- graded and fine-graded. Due to these two gradations, the mix properties could be distinctly different. Contractors might prefer one type of gradation to another type just because the selected one could be easier to comply with the gradation requirement of the quality assurance program. This raises the concern that a gradation with better performance, such as higher rutting resistance would not be selected by the contractor. Therefore, to produce a good performing pavement, it seems equally important to address the aggregate gradation issue by selecting a proper gradation in the mix design phase and to control the gradation deviation in the production phase.

Afaf (2011) conducted research on the effect of aggregate gradation and type on hot asphalt concrete mix properties. The conclusion was that deformations in placed asphalt mixes are minimised in well-graded aggregate than in poorly graded aggregates. Moreover, continuously- graded aggregates when used in asphalt mixes, it resists rutting. It was also revealed that the maximum aggregate particle size and its gradation affect the rut depth and it is influential in compaction and a determinant to the thickness of pavements. Pavement Interactive (2012), stated in their publication that aggregate gradation also influences on HMA parameters such as stiffness, stability, durability, permeability, workability, fatigue resistance, friction resistance, and resistance to moisture damage.

AASHTO (2001) revealed that since it is not easy to achieve the desired aggregate gradation crushed in a single size, several and different aggregate sizes are to be blended in ratios to achieve a desired and acceptable gradation for the mix design. Another conclusion that is worth noting is that a filler-to-binder ratio up to 1.6 can be used in dense-graded mixes.

The Asphalt Institute (2014) showed that there is no specific standard for blending aggregates for asphalt mix design to come up with the right gradation curve. For the mix design to be successful, aggregates for the mix should be completely dry prior to blending. If they contain some moisture especially the fine aggregates, they alter the batching weights. Gradation and other physical and chemical tests should be performed on each individual aggregate size. Weaker and softer aggregates degrade in the production process of asphalt and produce a finer mix. However, the mix design should follow the project specification.

2.6 IMPORTANCE OF COMPACTION ON AIR VOIDS

- To minimize additional densification by traffic,
- To minimize permeability,

- To limit oxidation of the asphalt mixture when paved, and
- To provide adequate shear strength

2.7 MARSHALL MIX DESIGN CONCEPTS

The Asphalt Institute MS-2 (2014) itemised three principle methods of designing dense-graded mixes, that is the Marshall method, Hveem method, and Superpave method. The objective of a mix design is to determine the combination of asphalt binder and aggregate that will give long-lasting performance as part of the pavement structure. The mix design involves laboratory procedures developed to establish the necessary approximate blend of aggregates to produce a proper gradation of mineral aggregate and amount of bitumen content as a binder for that gradation. In many cases, the causes of poorly performing pavements have been attributed to a poor or inappropriate mix design or are due to the production of a mixture different from what was designed in the laboratory. The Asphalt Institute added that the mix design compaction should generate the same air void content as the one achieved after secondary compaction by the traffic loadings. Muhammad (2014) briefly introduced the history of Marshall mix design as developed by Bruce G. Marshall (1939) of the Mississippi Highway Department, hence the name Marshall Mix Design. Then later the Marshall mix design was refined by the U.S. Army for use on airfield pavements. This was because of the drastic increase in military aircraft wheel loads and tire pressure. The U.S Army Corps of Engineers revised by adding modifications, a deformation measuring device, traffic loading variables, and weather variables. The American Society for Testing Materials (ASTM) adopted the resulting laboratory mix design and compaction procedure as used today. The Marshall mix design at first was applicable with an aggregate maximum size up to 25mm and later modified to incorporate up to aggregate maximum size 38 mm.

Pavement Interactive (2012) stated that the mix design is a laboratory simulation of the actual production, construction and performance of the laid pavement. It is from this simulation that we can predict what type of a mix design can be adopted for application and how it will perform. Moreover, conducting a mix design can provide cost-effective and relative simulations that are useful in decision making.

Tom and Krishna (2007) showed that Marshall Stability and flow test predicts the performance of the Marshall mix design. Furthermore, it was stated that laboratory specimens are used to simulate field conditions. However, some limitations were observed like small compaction machines and other testing devices used in mix design cannot fully reflect the actual production, construction and performance standards.

2.8 DENSE BITUMINOUS MACADAM MIXTURES

Garcia and Hanse (2001) described dense-graded hot-mix asphalt as a bituminous construction material that can be used effectively in all pavement layers for all traffic conditions. It serves in a multitude of traffic and environmental conditions, provided that the materials and design meet specific engineering requirements.

Ganapati and Adiseshu (2013) defined Dense Bituminous Macadam (DBM) mixes as mixtures consisting of bitumen as an adhesive to bind the mineral aggregate which provides strength and toughness to the mix. Bituminous macadam must be internally strong and resistant to compressive and shear stress to prevent permanent deformation within the mixture. The load applied to a bituminous mixture create stress that is transmitted to the entire thickness as vertical compressive stress, shear stress within the asphalt layer and horizontal tensile stress at the bottom of the asphalt layer. Furthermore, it was found out that the properties of bituminous macadam are altered with temperature whereby the mixtures are stiffer at lower temperatures and that is why testing is done at recommended temperatures. Bitumen macadam is stiffer with a shorter period of loading time. The dependence of asphalt binder behaviour on temperature and load duration means these two factors can be used interchangeably (Asphalt Institute Manual, 2014).

AASHTO (2002) in relating compaction effort and percent air voids in the compacted specimens confirmed that the test is performed using the Saturated Surface Dry (SSD) procedure. Moreover, the efficiency of compaction in the process of reducing air voids at a given mix was found to be a function of the filler and binder content with respect to the compaction tool used. Asphalt Institute MS-2 (2014) showed that the selection of proper compaction level during the mix design phase is critical for proper mix performance. Therefore, the designer is held responsible since the mix design density should closely approach the maximum density obtained in the pavement under traffic. Chen and Li (2013) in their research confirmed that compaction characteristics of asphalt mixtures describe how easy or difficult to compact a mixture. Moreover, hot-mix asphalt mixture compaction has a great influence on its strength and durability. Similarly, good compaction can make asphalt mixtures to acquire enough carrying capacity to meet the need for heavy traffic. In the same research, a conclusion was drawn that mixtures having more binder densities are higher compared with mixtures with low binder content. That it is easier to compact mixtures with more binder content and such mixtures retain smaller air voids when the gradation is the same.

Swiertz et. al., (2010) under mix design and compaction methods explained the advantage of the Marshall compaction method for its focus on air voids, strength and durability; the method recognises sufficient bitumen to ensure durability; sufficient stability to satisfy structural requirements under loading, sufficient air voids content (an upper limit to prevent environmental damage and a lower limit to allow for additional compaction by traffic), and workability to facilitate effective compaction. Also, revealed by saying that air voids content is a direct result of gradation, bitumen content, compaction effort, and compaction type.

Bukowski et. al., (2010) assessed the test method used in determining the Gmb especially for coarse-graded mixes, the test method impacts several HMA mix properties, including VA, VMA, VFB, Gmm and density. The air voids were calculated in accordance to AASHTO T 166 (2016) and ASTM D 2726 (1996) standards. Both methods calculate the specific gravity of samples basing on the fundamental density equations, mass over volume. The problem of determining Gmb by Archimede's principle is that the technique does not favour specimens with higher water absorption. Specimens with large permeable voids, such as coarse-graded, gap-graded, open-graded mixtures, water enter the voids when the specimen is submerged, drains out when the specimen is removed from the water bath and the surface water wiped out with a damp towel. The result of the water drainage is an error in the SSD mass and thereby the volume determination of the specimen. Consequently, a higher specific gravity value that the specimen has is determined.

2.9 DESIRABLE PROPERTIES OF ASPHALT MIXTURES

Bituminous mixtures must be designed, manufactured and placed to obtain the following desirable properties:

Structural strength: The structural layers compose of; bituminous wearing course, bituminous binder course, and bituminous base course as stated by Constructor (2017), are layers designed purposely for structural strength provision. These layers distribute loads throughout the pavement layer as expected and these loads can be dynamic or static in nature.

Surface drainage: Resistance to moisture-induced damage. Impermeability is the resistance of asphalt pavement to the passage of air and water into or through it. This characteristic is related to the void content of the compacted mixture. Even though void content is an indication of the potential for passage of air and water through pavement, the character of these voids is more important than the number of voids. The size of voids, the interconnection of the voids, and the access of the voids to the surface of the pavement all determine the degree of impermeability.

Surface friction: Skid resistance is the ability of an asphalt surface to minimize slipping of vehicle tires, particularly when wet as expressed by Civilblog (2017). Good skid resistance, tire tramp must be able to maintain contact with the aggregate particles instead of riding on a film of water on the pavement surface. Skid resistance is measured in the field at 40 mi/hr with a standard tramp tire under controlled wetting of the pavement surface. A rough pavement surface with many little peaks and valleys will have greater skid resistance than a smooth surface. Best skid resistance is obtained with rough-textured aggregate in a relatively open-graded mixture. Besides having a rough surface, the aggregates must resist polishing (smoothing) under traffic.

Durability: The asphalt mix should contain sufficient binder to ensure an adequate film thickness around the aggregate particles. This reduces the chances of the paved mixture from rutting and cracking when laid and compacted at the required temperatures. Also, the compacted mix should not have high air voids, which accelerates the ageing process.

2.10 CHAPTER SUMMARY

During the mixing process, bitumen coats a fraction of fine aggregate particles and forms cement. In the DBM mixture, there exists a mineral filler in addition to aggregate skeleton and bitumen.

In HMA mix design, selecting bitumen grade and its properties are important steps. Bitumen with better properties improves the mix performance. So, identifying bitumen with good potential is an important task. Softer bitumen is generally avoided as mixes with these binders are expected to have poor performance in DBM mixtures. It was identified that the selection of optimal materials used in asphalt mixtures is also an important task in the mix design. In all conditions, mixing and compaction temperature is found to be important. Usually, trial bitumen content between 4.0 and 4.5 percent by weight of dry aggregates are applied to find optimum mixture characteristics.

The presence of bitumen and filler plays an important role in the strength and stiffness behaviour of DBMs. As the filler content defines the amount of bitumen, the addition of too much quantity of filler is not recommended. As it is assumed that aggregate particle interlock is a major factor in DBMs, the aggregate characterization needs to be considered in the mix design. During the mixing of aggregates, filler and bitumen, the bitumen acts as a lubricant to improve the workability and compactability of the mix. Bitumen and filler contents are important factors that affect strength characteristics (Kranthi, 2015). Also, the presence of filler affects the optimum binder content whereby additions to the mix changes the OBC.

Therefore, selecting filler and binder contents in their precise optimums as well as choosing the best laboratory compaction method which simulates the field conditions, is related to durability and performance of the paved asphalt mixes.

CHAPTER THREE

MATERIALS AND METHODS

3.1 INTRODUCTION

The main objective of the study was to determine the effect of filler and binder contents on the physical properties of various filler-binder Dense Bituminous Macadam (DBM) mixtures. Material characterization involved testing of mineral aggregates (coarse and fine), mineral filler and bitumen binder to determine their physical properties following standard test procedures. Activities like material sampling, material testing, preparation of testing specimens were conducted in accordance with the Ministry of Works and Transport (2005) General Specifications for Road and Bridge Works of Uganda.

3.2 RESEARCH DESIGN AND RESEARCH APPROACH

The steps followed by this study outlined in Figure 3.1, aimed at a sensitive optimized DBM mixture which acted as a basis to develop other mixtures. The steps were based on the mix design procedures described by the Marshall method in the Asphalt Institute MS-2 (2014). Literature was reviewed and the information is available on how contents of filler and binder can affect asphalt mixtures. Some findings emphasise that the physical properties of asphalt mixtures are dependent on the concentration of mineral filler. Other parts of the research steps comprised of material identification and sampling, evaluation of collected material and methods that could permit the accomplishment of the objectives of this study. The quality of materials and sample preparations were carried out using standard methods. The test results were graphically plotted to come up with the optimum binder content. All test results were measured against the standard limits provided by the MoWT (2005) General Specifications for Road and Bridge Works of Uganda.

This research followed an experimental approach as the main method of obtaining data, and also considered some secondary data for backing up the information. Emphasis was placed on performing tests as a method of collecting numerical data, the summary of those data and the drawing of inferences from the data by comparing it with the specification requirements.

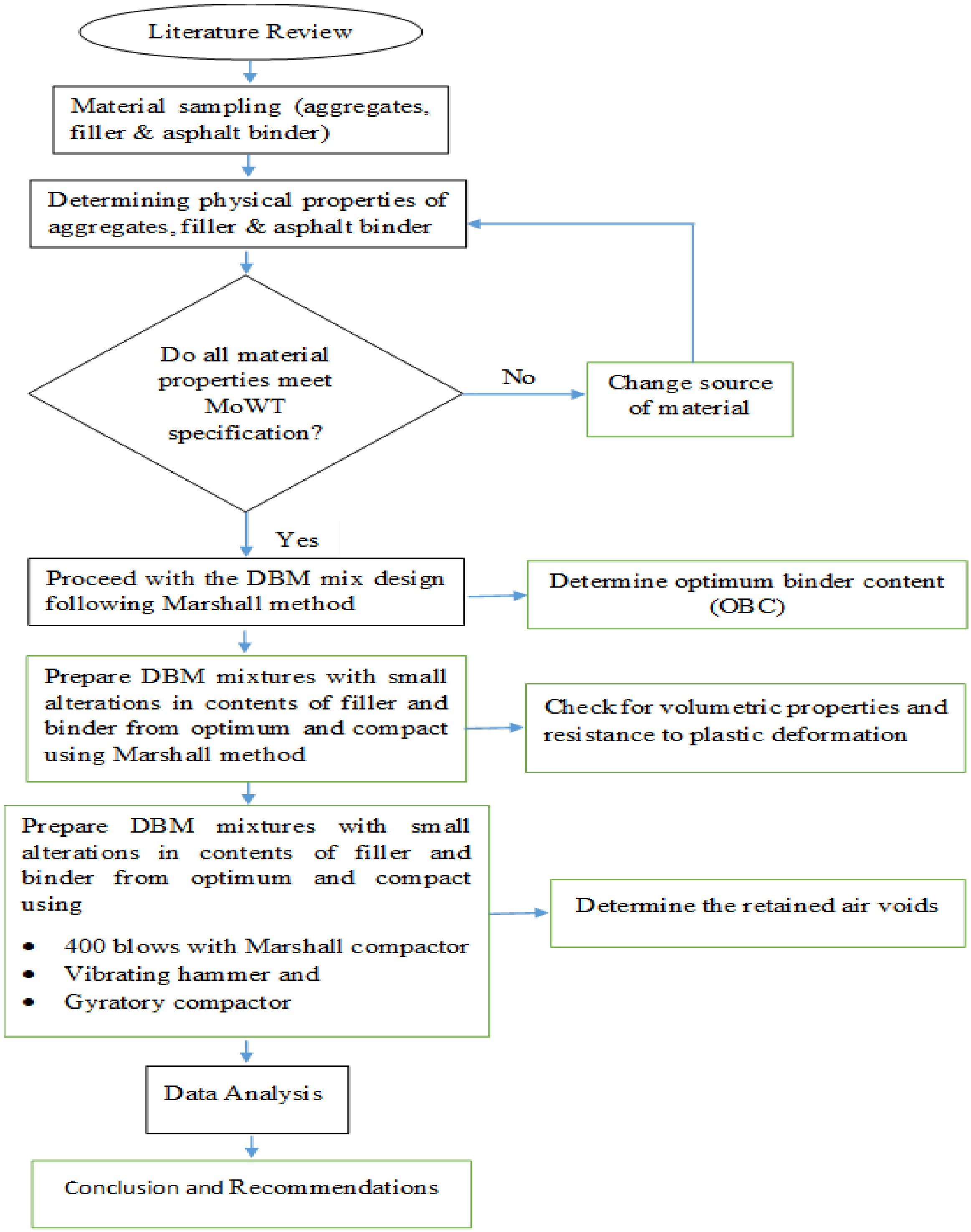


Figure 3.1: Flow Diagram Indicating the Research Steps

3.3 MATERIALS

3.3.1 Introduction

The physical properties of the materials used within this study are discussed in this chapter. Characterization of materials was restricted to aggregates (coarse and fine), mineral filler and bitumen binder. This is important as the characteristics of these materials have a considerable effect on asphalt mixtures. However, studies revealed that the contents of filler and binder have a great impact on bituminous mixtures. Also, studies communicate that coarse aggregates are the structural skeleton of bituminous mixtures. It is from the previous studies that we learnt about testing of materials before use in bituminous mixtures being helpful.

3.3.2 Aggregates

Quarried rock was processed to make it suitable for use in asphalt production. Large stone boulders were crushed resulting in fractured particle faces. The crushed stone was sized by screening, and the dust resulting from the crushing was removed by washing. Aggregates used in the study were obtained from Nakasajja quarry which belonged to Motar-Engil, a Contractor based in Uganda for the construction of a 21 km road. A wheel loader (Figure 3.2) was used in sampling aggregates because the height of the material outlet from hot-bins could not be reached from the ground. Aggregates were placed close to the stockpiles for visual assessment to confirm if there was no mixing of different sizes during conveyance as shown in Figure 3.3. Aggregate sizes 28 to 20 mm, 20 to 14 mm, 14 to 6 mm, and 6 to 0.075 mm were sampled following BS 812: Part 101 standard procedure from hot-bins as shown in

Figures 3.4 and 3.5. For subsequent laboratory testing, quartering of the sampled aggregate material was carried out following AASHTO T 248 (2016) standard test procedure.

Figure 3.2: Collecting hot aggregate

Figure 3.3: Aggregate close to the stockpile

Figure 3.4: Sampling hot aggregate

Figure 3.5: Loading hot aggregate on pickup

3.3.3 Mineral Filler

Finer material commonly known as mineral filler from the crushing of stones, typically the material passing 0.075 mm sieve was sampled. Filler was added to the aggregate blend to meet the target gradation curve. The source of filler material was the same where aggregates were sampled. A filler material is a collection of dust during the crushing of aggregates to appropriate sizes. The function of filler in asphalt mixtures is to fill the voids in the sand to make the total voids as small as possible as determined by the gradation of the sand. An approximate quantity of 50 kg was collected and used in the research after being subjected to tests.

3.3.4 Bitumen Binder

The bitumen binder, 35/50 penetration grade was used as a binding agent to glue aggregates into a coherent mass. Bitumen penetration grade 35/50 was used because it is adequately stiff and performs well in asphalt mixtures under moderate temperature and for all traffic loading conditions (MoWT,2005). Solid asphalt binder was sampled by cutting it from the storage tank as shown in Figure 3.6. An approximate quantity of 4 kilograms was sampled from each container and tested after mixing.

a) Sampling b) Storage tanks c) Sampling tins

Figure 3.6: Bitumen sampling and storage

3.4 METHODS

Mineral aggregates, mineral filler and asphalt binder were assessed for DBM mixture suitability using standard tests listed in Tables 3.1, 3.2 and 3.3 respectively. The DBM mixtures prepared following the experimental design and testing matrix were examined for volumetric using standard tests. Results were compared for conformity with the MoWT, general specification for Uganda.

3.4.1 Material Characterization

a) Aggregate Properties

Aggregates were obtained by extracting them from a large rock formation typically reduced to usable sizes by mechanical crushing. Aggregates are recommended for testing and their physical properties are categorized into consensus and source properties as highlighted by the Asphalt Institute MS-2 (2014). The gradation property was determined using wet sieving for both individual and blended aggregates. Blending of aggregates was determined using the graphical method and adjustments were done to shift the curve close to the target gradation following the DBM 30 envelope. Aggregates were also tested for strength, toughness, hardness, shape, clay content, specific gravity and water absorption properties. To ensure good internal friction, the aggregate was tested for shape. The limiting flatness of aggregate reduces the chances of particle breakage and sliding under load and limiting the clay content enhances the bonding between bitumen and aggregate particles. The physical properties of coarse and fine aggregates used in asphalt mixtures together with the standards used to prepare tests are shown in Table 3.1 and 3.2.

Table 3.1: Physical Properties of Fine Aggregates

Material	Test Description	International Standard
Fine Aggregate	Relative density and Water Absorption	BS 812: Part 2: 1995
	Liquid Limit - LL	BS 1377: Part 2: 1990
	Plastic Limit - PL	BS 1377: Part 2: 1990
	Plasticity Index - PI	BS 1377: Part 2: 1990
	Sand Equivalent Test	AASHTO: T 176-02 (1986)

Table 3.2: Physical Properties of Coarse Aggregate

Material	Test Description	International Standard
Coarse Aggregate	Relative Density and Water Absorption	BS 812: Part 2: 1975
	Los Angeles Abrasion Test – LAA	ASTM C 131 - 09
	Soundness by use of Sodium Sulphate	ASTM C 88 - 90
	Flakiness Index	BS 812 - 105.1: 1989
	Ten Percent Fines Value Test -TFV	BS 812: Part 111: 1990
	Aggregate Crushing Value – ACV	BS 812: Part 110: 1990
	Aggregate Impact Value - AIV	BS 812: Part 112: 1990
	Coating and Stripping Test	AASHTO T 182-84 (1993)

b) Filler Properties

In the current study, inert material in form of dust extracted from other aggregate material sizes during processing was used as mineral filler. The mineral filler material used in DBM mixtures was evaluated in terms of density, gradation and plasticity index following standard test procedures as shown in Table 3.3.

Table 3.3: Physical Properties of Filler

Material	Test Description	Standards
Filler	Bulk Specific gravity	BS 812: Part 2:1995
	Percent Passing 0.075 mm Sieve	BS 1377: Part 2:1990
	Plasticity Index	BS 1377: Part 2:1990

c) Aggregate Grading

Gradation of aggregates was done using the following BS sieve sizes; 37.5 mm, 28.0 mm, 20.0 mm, 14.0 mm, 10.0 mm, 5.00 mm, 2.00 mm, 1.18 mm, 0.425 mm, 0.300 mm, and 0.075 mm. Individual aggregate gradation was done first and since it could not comply, aggregates were blended to have a uniform gradation that satisfied the specification limits. Blending of aggregates was carried out on a weight basis by assigning percent weight of the coarse aggregate, fine aggregate and mineral filler, to come-up with a gradation curve which lied almost at the midpoint of the DBM 30 gradation limits criteria. Limiting chances of mixture failure due to poor or gap grading, a suitable gradation for the design mix was chosen to avoid effects on engineering properties of the DBM mixtures. This was made effective by establishing a gradation whose curve passes in a grading zone of appropriateness. The aggregate blends included coarse, medium and fine to reduce on the void in between particles. According to the failure mechanism, gradation of aggregates was restricted between the upper limit and lower limit as required by the MoWT specification shown in Figure 3.7.

Limits on a Semi-Log Grading Chart

Sieve sizes (mm)	**37.5**	**28**	**20**	**14**	**10**	**5.0**	**2.0**	**1.18**	**0.425**	**0.3**	**0.075**	
Upper Limit	100	100	95	82	73	56	40	35	25	21	9	GENERAL SPEC. Table 4202/6
Lower Limit	100	90	70	58	52	40	24	19	9	7	2	

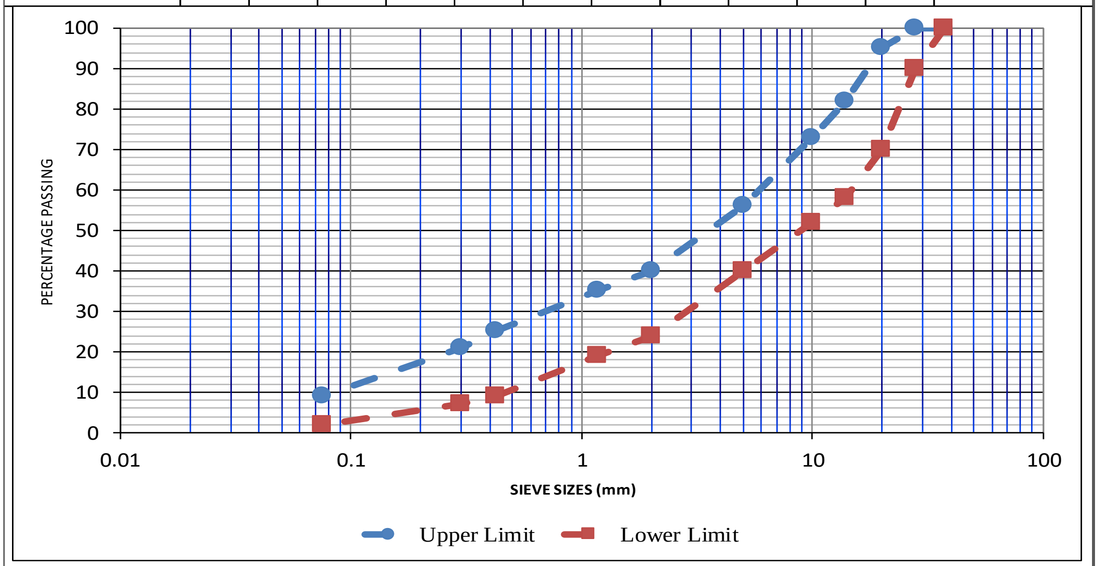


Figure 3.7: Gradation envelope for dense bitumen macadam (DBM 30)

d) Theoretical Gradation

Mineral aggregates (coarse and fine) and filler were separately sieved to determine the theoretical blend which provided the final grading that satisfied the DBM 30 aggregate grading limits. Three repeated sieve analyses were performed to ensure consistency in gradation of each aggregate size fraction. The average percentages passing individual sieve sizes were used to develop a characteristic graphical representation. The graphical method considers the equivalence in distance from the first curve to the x-axis and an equivalent distance between the next two curves above the largest gradation size as applied by the Ministry of Works, United Republic of Tanzania Manual (2000) as shown in Figure 3.8. Also, these proportions were further used to compute actual blending proportions in the total mixture.

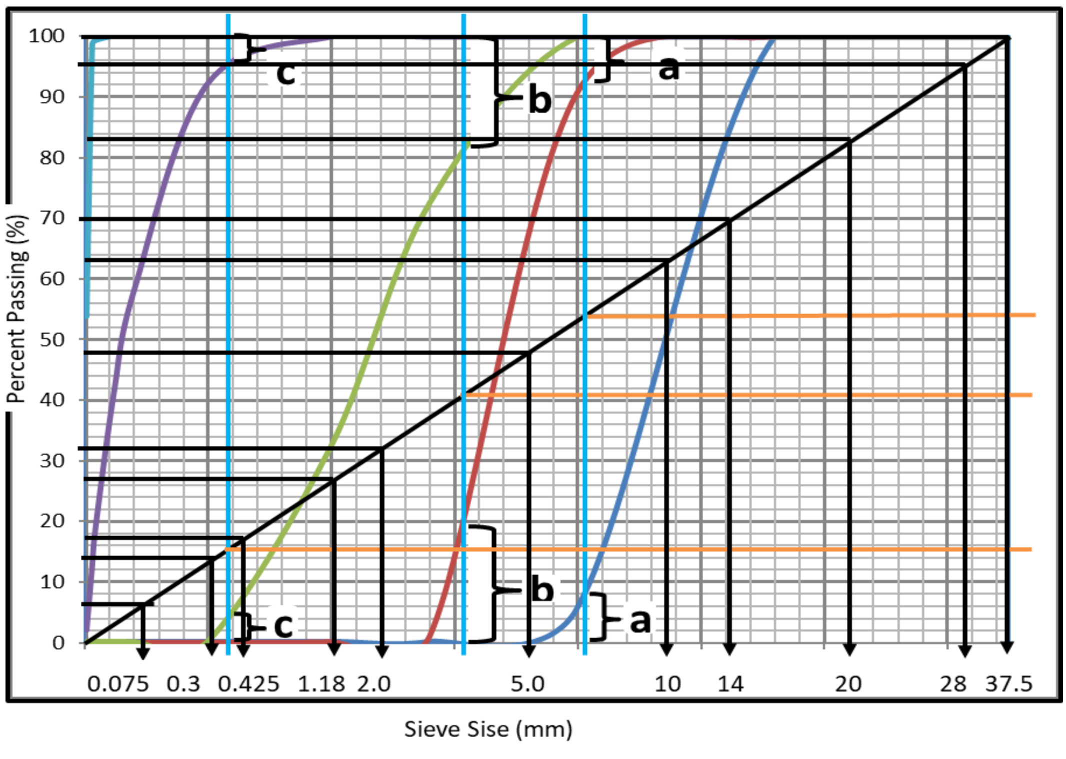


Figure 3.8: Graphical method to estimate aggregate proportions in the mix

e) Asphalt Binder Properties

Asphalt binders are most commonly characterized by their physical properties. This is because an asphalt binder's physical properties directly describe how it will perform as a constituent in HMA pavement. An asphalt binder (35/50 penetration grade) material obtained from the same source, was used as the binder to prepare all the DBM mixtures for this research. Different quality tests were carried out on asphalt binder during this study to assess its basic physical properties through various laboratory steps on listed tests demonstrated in Table 3.4.

Table 3.4: Physical Properties of Binder

Bitumen Type	Test Description	International Standard
35/50	Penetration	AASHTO: T49-84
	Softening Point	AASHTO: T53
	Flush and Fire Point	BS EN ISO 2592
	Specific Gravity	ASTM C127-88
	Viscosity	EN 12596
	Solubility	PN-EN 12592
	Mass Change	PN-EN 12607-1

3.4.2 Specific Gravity of Total Aggregates

The specific gravity of aggregates is needed to determine the weight-to-volume relationships and to calculate the many volume-related quantities such as VMA and VFB in the asphalt mixture. The lower specific gravity of aggregates indicates that there is a relatively high volume of aggregates at a similar weight as compared to aggregate of higher specific gravity. Thus, higher volume aggregate needs higher volume bitumen to coat all the aggregate particles (Berhe, 2007). The volumetric design of compacted HMA is affected by:

i. the proportion of the different aggregates and filler

ii. the specific gravity of the different materials

iii. the amount of bitumen absorbed; and

iv. the amount of non-absorbed bitumen.

Absorption is used as an indicator of the aggregate durability and how much bitumen is most likely to be absorbed (Overseas Road Note-19, 2002). Aggregate specific gravities for different material fractions are presented in Table 4.6. The theoretical specific gravity G is the specific gravity without considering air voids, and is given by:

$$\mathbf{G = [(P1 + P2 \ldots + Pn)] / [(P1/G1) + (P2/G2) \ldots + (Pn/Gn)]} \qquad \text{(Eq. 3.1)}$$

Where,

G = Average specific gravity;

G1, G2, . . . Gn = Specific gravity values for fraction 1, 2, . . ., n; and

P1+ P2, . . . +Pn = Weight percentages of fraction 1, 2, . . ., n

High values of absorption indicate non-durable aggregate. The absorptiveness (ability to absorb binder) of the aggregates used in the asphalt mixture is critical in determining optimum binder content. Effective binder content is the volume of binder not absorbed by the aggregate. It is calculated based on the aggregate bulk specific gravity (Gsb) and the aggregate effective specific gravity (Gse).

3.5 MARSHALL MIX DESIGN

A DBM mix design was carried out following the Marshall procedures. The Marshall test is used to measure the physical properties of asphalt specimens that relate to the plastic deformation properties of asphalt mixtures. The aim of generating the mix design was to determine the optimum blend of materials using a single selected aggregate gradation. The characteristics of aggregates, filler, bitumen and the air voids content of the compacted DBM mixture determine the physical properties of the mixture. Determining the optimum bitumen content (OBC), variations of bulk density, Marshall stability, flow values and voids in the compacted mix against bitumen contents graphs were plotted. The binder content corresponding to 4.0 percent air voids was selected as the OBC. The OBC was used to prepare a working mix which was compacted and verified for conformity with the DBM requirements of the MoWT Specification of Uganda. The proposed steps for the design of bituminous mixtures are given below;

(a) Select a grading to adopt
(b) Select aggregates to be used in the mix
(c) Determine each aggregate proportion required to produce the design grading
(d) Determine the specific gravity of the aggregate combination and bitumen
(e) Determine the bulk density of each compacted specimen
(f) Perform stability tests on the compacted specimens
(g) Calculate the percentage of Va, VMA, and VFB in each specimen
(h) Select the OBC from the property plots
(i) Check the values of Marshall Stability, Flow, Va, VMA and VFB obtained at OBC against the specification.

Preparation of samples followed the Marshall method and afterwards volumetric and resistance to plastic flow was determined using standard procedures and tools as shown from Figure 3.9 to Figure 3.18.

A mix design was performed using the Marshall method by preparing and compacting samples based on 0.5 percent increments of bitumen, with two bitumen contents below and two above the expected bitumen content. This was done in accordance with

AASHTO T 245 (1994) and ASTM D 1559 (1989) Test Methods for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus. In addition, basing a mix design on a single trial bitumen percentage would allow no check on the reliability of the test results (Asphalt Institute MS-02, 2014). For that reason, 3.5, 4.0, 4.5, 5.0, and 5.5 percent bitumen contents by the dry weight of combined aggregates were used. The ultimate aim of considering a range of bitumen contents was to prepare batches that bracket the anticipated optimum binder content. Bitumen penetration grade 35/50 was used in preparing specimens. Approximately 1200g of aggregates and filler put together was measured, placed in an oven set at a temperature of 165^{o} C for approximately four hours.

The specimens were compacted using a machine with a hammer tamping face diameter of 98.5 mm, utilizing free falling weight of 4536 ± 9 g, at a drop height of 457 ± 3 mm, with a dropping frequency of 55 ± 5 (blows/min.) giving 75 blows on each face at a temperature of 155^{o} C. Three duplicate samples were prepared for each bitumen content and the average value was considered if no big difference was observed in the test result.

Figure 3.9: Preheated mould

Figure 3.10: Compaction of specimen

Figure 3.11: Marshall compacted specimens

Figure 3.12: Extruding specimen from the moulds

Figure 3.13: Compacted specimens

Figure 3.14: Measuring specimen heights

Figure 3.15: Maximum Specific Gravity

Figure 3.16: Bulk Specific Gravity

Figure 3.17: Specimens in the water bath at 60º C

Figure 3.18: Marshall Stability and Flow Measurement

3.6 DEVIATED DBM MIXTURES

In this study, the behaviour of DBM mixtures was studied with small alterations in filler and binder contents. Filler was added in increment quantities of 0.4 percent i.e. 5.3, 5.7, 6.1, and 6.5 percent, while binder was added in increment quantities of 0.15 percent i.e. 4.2, 4.35, 4.5, 4.65, and 4.8 percent.

Since the aim of this study was to appreciate the influence of filler and binder on the engineering properties, the following were investigated; Marshall Tests, Stability, Flow, Percent of Air Voids (VA), Voids in Mineral Aggregate (VMA), and Percent Voids Filled with Bitumen (VFB).

The study also aimed at checking the following to confirm the applicability in comparison to the MoWT Specification requirements and the selection was based on three criteria:

i. the selection must fall within the recommended range of filler to binder ratio (0.8 - 1.6 by mass), and should not have a big impact on coarse graded asphalt mixtures (Asphalt Institute MS-2, 2014)

ii. the variation of bitumen content from the optimum at construction by ± 0.3 percent, should not have an impact on the asphalt mixtures (MoWT, 2005),

iii. the gradation of the overall aggregate blend must be within the specified limits given in Table 4202/6 (MoWT, 2005).

To reasonably address the possible variation of mixture mechanistic properties with respect to the variation of filler content, the aggregate compositions was kept the same but the amount of mineral filler was changed. To do so, an average gradation which conformed with the gradation envelope was selected. The combined aggregate gradation for both coarse and fine was maintained for all DBM mixtures, only contents of filler and binder were altered.

Also due to equipment error, sometimes more bitumen is released at the mixing stage hence lead to a significantly high value. As well bitumen might not get into the mix due to blockage of nozzles and/or sticking to the walls during mixing this may lead to a significantly low value. Sometimes the aggregates 0/6 mm might have more fine material finer than 0.075 mm during batching, this significantly increases the filler content in the asphalt mixtures. The last observation is dust coatings on coarse aggregate which can accumulate and increase on filler content in the asphalt mixtures. The DBM mixtures were checked for their performance using the test standards indicated in Table 3.5.

Table 3.5: Performance Tests used to Investigate DBM Mixtures

Asphalt Type	Test Description	International Standard
DBM 30	Volumetric Properties	AASHTO T-245
	Resistance to Plastic Flow	AASHTO T-245
	Percentage Refusal Density (PRD)	TRL Overseas Road Note 31

3.6.1 Experimental Design and Testing Matrix

In the experimental design, four sets of samples were prepared with equal aggregate weights (coarse and fine), but with varying filler content in increments of 0.4 percent starting with 5.3 percent. Each set had five design matrices prepared using similar filler content in the mix, but with varying bitumen content in increments of 0.15 percent starting with 4.2 percent. Bitumen content 4.5 percent was assumed to be the optimum for DBM 30 mixtures (MoWT, 2005). In the whole arrangement, 20 different mixtures were developed and considered in this research as shown in Table 3.6.

Table 3.6: Experimental design and testing matrix

RANGE OF FILLER-TO-BINDER RATIO					
Percent		Filler Content			
		5.3	5.7	6.1	6.5
Binder Content	4.2	1.26	1.36	1.45	1.55
	4.35	1.22	1.31	1.40	1.49
	4.5	1.18	1.27	1.36	1.44
	4.65	1.14	1.23	1.31	1.40
	4.8	1.10	1.19	1.27	1.35

3.6.2 Sample Preparation

For a one design matrix, a total of 20.1 kg of a dry aggregate blend comprising of 20/28, 14/20, 6/14 and 0/6 mm sizes was weighed and placed in a mixing bowl. Mineral filler was also weighed and added into the dry aggregates blend. The bowl containing dry aggregates and filler was placed in an oven set at a temperature of 165^{o} C for a minimum of four hours.

A portion of penetration grade bitumen 35/50, just enough for a one-time mixing was placed in another oven set at 165^{o} C for about two hours. Bitumen after two hours in the oven could easily flow and coat the hot blended aggregate.

The hot aggregates and filler together at a constant weight and temperature were removed and placed on an electronic weighing scale. A crater was formed in the hot aggregate material to contain bitumen and to eliminate bitumen from sticking to the walls of the bowl. Specifically, an intended amount of bitumen at 165^o C was added directly into the hot blended aggregate material by weight using an electronic scale readable to 0.1g as shown in Figure 3.19a.

The bowl containing hot aggregates, filler and bitumen was removed from the weighing scale and placed on a circular stand where mixing started as shown in Figure 3.19b. Under the mixing bowl, a gas cylinder mounted with a burner was positioned for producing regulated fire. The fire was placed to maintain the mixing temperature required of about 160^o C as shown in Figure 3.19c.

Manual mixing of materials started and the process continued until all aggregates were uniformly coated with bitumen. After mixing exhaustively in the shortest time possible, the bowl containing the bituminous mixture was removed from the mixing stand. The mixture was immediately transferred into the riffle box of 50 mm slot to homogenously reduce to smaller masses just enough for specific test specimens as shown in Figure 3.19d. Two parallel specimens and each weighing approximately 2500 g were riffled for the Maximum theoretical density (Gmm) test. Three parallel specimens and each weighing approximately 1200 g were prepared for 102 mm diameter mould for the Marshall test (75 blows each face). Three parallel specimens and each weighing approximately 1205 g were prepared for 102 mm diameter moulds for extended Marshall test using an automatic impact hammer (400 blows each face).

Three parallel specimens and each weighing approximately 4196 g were prepared for the PRD test using an electrically operated vibrating hammer (15 ± 2 minutes each face), and three parallel specimens and each weighing approximately 4700 g were prepared for Superpave gyratory compaction test using 205 gyrations.

After placing the required quantity of DBM mixture into the respective moulds (Figure 3.19e), the moulds plus the DBM mixture were placed back in the oven set at a temperature of 160^{o} C for about two hours for mixture conditioning as shown in Figure 3.19f. Afterwards, moulds containing the DBM mixture were removed one after the other and compacted as required.

(a) Weighing bitumen (b) Mixing (c) Checking temperature

(d) Riffling (e) Mixture in moulds (f) Mixture conditioning

Figure 3.19: Preparing the DBM mixture for compaction

3.7 COMPACTION TO REFUSAL DENSITY

The second part of this study was to evaluate the different compaction efforts in predicting the mixture's behaviour after field secondary compaction by traffic. DBM mixtures were subjected to extended compaction effort, whereby compaction was continued until no further densification of specimens were obtained. The objective of compaction to refusal density is to design asphalt mixtures that can retain the minimum air voids content requirement. Three compaction efforts using different tools and methods were applied in this study and specimens were analyzed for retained air voids. The following three compaction tools were used for compacting specimens:

i) Automatic Marshall Impact Hammer,

ii) Electrically Operated Vibrating Hammer and

iii) Gyratory Compactor

3.7.1 Automatic Marshall Impact Hammer Compaction

Three parallel test specimens were prepared through riffling. Each specimen weighed approximately 1205g of bituminous material. The mass required was adjusted so that the test specimen had a height of 63.5 ± 1.3 mm after compaction as recommended by (Mariki, 2000). The mixture was transferred into the specimen preheated moulds and the surface was levelled. The preheated moulds containing the bituminous material were again placed back in the oven maintained at 160^{o} C for mixture conditioning.

When the temperature of the bituminous mixture inside the moulds attained a temperature of 160^{o} C, the moulds containing the bituminous mixture were removed one after the other and immediately placed into the Marshall compaction machine.

The specimens were compacted using 400 blows to each face. The mould containing the compacted specimen was removed from the compaction machine, labelled and left to cool to room temperature.

The compacted specimens were extruded from the moulds, cleaned, and measured to the nearest 0.1 mm using a Vernier calliper and values recorded. The compacted specimens were analysed volumetrically to determine the retained air voids content in that mixture.

3.7.2 Electrically Operated Vibrating Hammer Compaction

Three parallel test specimens were prepared through riffling. Each specimen weighed approximately 4196 g of bituminous material. The mass required was adjusted so that test specimens had a thickness approximately the same as will be laid on the road (TRL, 1993). The mixture from the mixing bowl was transferred into the oven set at a temperature of 160^{o} C and when the bituminous material gained the required temperature, it was removed and placed in a preheated compaction split mould of 153 mm diameter and the surface levelled.

The mould and the tamping feet were preheated in an oven before starting the test. Two tamping feet were used, one having a diameter of 102 mm and the other 146 mm. The small tamping foot was used for most of the compaction sequence because it provides a kneading action to ensure an absolute refusal density is achieved. Compaction of the bituminous material started using a vibrating hammer attached with a tamping foot, holding it firmly in a vertical position and moved North, South, West, East, North West, South East, South West, and North East. Each point could receive compaction for about 2 to 10 seconds. The compaction sequence using a 102 mm diameter foot continued up to 2 minutes ± 5 seconds. The large tamping foot of 146 mm diameter was used to smooth out the uneven surface of the specimen left by 102 mm tamping foot as seen in Figure 3.20. After compaction a spare base was fixed on top of the mould then turned over for more compaction of the second face. The compaction sequence was repeated for the remaining other specimens.

Figure 3.20: Electrically operated vibrating hammer compaction

3.7.3 Gyratory Compaction

A gyratory compactor is used to provide a method of compaction that is more representative than the Marshall hammer compactor. The purpose of compacting specimens was to determine the bulk density of the mixture and ultimately use this number to determine the air voids of the mixture. Sets of test specimens were prepared and compacted as follows:

a) The gyratory compactor was switched on and left to warm-up (Figure 3.21). Once the gyratory compactor had cycled through the warm-up period, next was to make sure that the machine was in correct settings. The basic requirements for the gyratory compactor are: (i) A constant vertical pressure of 600 kPa on the compacting ram, (ii) A constant rate of rotation of the mould at 30 gyrations per minute, and (iii) The mould is positioned at a compaction angle of 1.25 degrees. The number of gyrations was based on the traffic level of greater than 30 million ESA. Mixtures that are exposed to higher temperatures and high traffic levels in the field will densify more and therefore must be obtained in the laboratory to a higher density (Brown et. al., 2009).

b) Moulds were heated to the desired compaction temperature between 155 and 160^{o}C. The heating of the moulds was intended not to have temperature reduction of the asphalt mixture due to the cold surface of the moulds.

c) A thermometer was placed into the mixture such that temperature could be accurately monitored. It is recommended that once the material has become workable, the desired amount of material for each of the specimens be weighed out and placed in a small pan and heated to compaction temperature. The mixture was reduced to smaller masses of approximately 4700 g using a riffle box to have homogenous test specimens. A flat bottom scoop was used to scoop out the mixture. The specimen weight of 4700 g was measured and placed into separate pans, thermometers were placed in each of the pans to monitor the temperature.

d) After the mixture had reached the compaction temperature, a heated mould was placed on the work table and a piece of filter paper was inserted into the bottom of the mould. The mixture at a temperature of 160^{o} C was removed one after the other and placed in a preheated compaction mould (150 mm diameter) in one lift, taking care to avoid segregation of the mix. The mixture inside the mould was levelled, placed a piece of filter paper and a top plate on the top surface of the material.

e) The mould containing the bituminous mixture was immediately placed inside the gyratory compactor and centring the mould under the loading ram. The start button was pressed for the Gyratory Compactor to automatically lower the ram to reach the pressure of 600 kPa, application of the angle, and progressed with 205 gyrations.

f) Once compaction was completed, the specimen in the mould was removed from the gyratory compactor for extrusion. The filter papers from the top and bottom of the specimen were removed. The specimen was placed on a smooth flat surface and allowed to cool overnight at room temperature.

g) The steps above were repeated as necessary by compacting additional specimens. Once the specimens had cooled, the bulk density of the specimens were determined.

Figure 3.21: Gyratory Compactor and its recordation system

3.8 VALIDITY AND RELIABILITY OF RESULTS

Validity and reliability are concepts used to evaluate how well a method measures the quality of research. According to Phelan and Wren (2007), Validity refers to the accuracy of a measure (whether the results do represent what they are supposed to measure). Reliability refers to the consistency of a measure (whether the results can be reproduced under the same condition). To ensure repeatability and reproducibility of results recorded in the laboratory for the tests carried out, the following measures were employed during laboratory tests;

i) Regular presence of the researcher during testing;

ii) Use of skilled technicians;

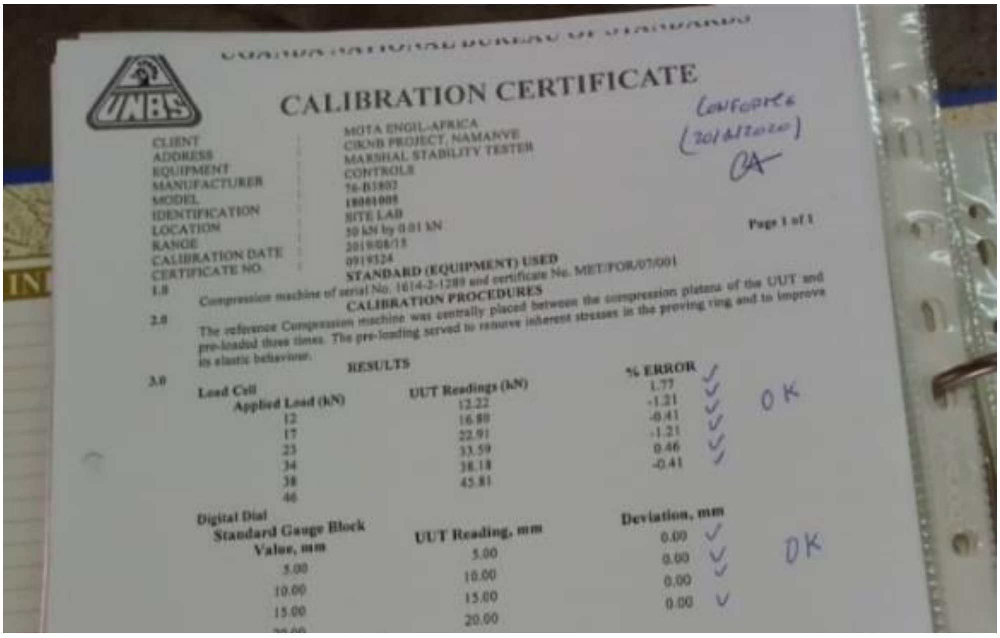
iii) Use of calibrated laboratory equipment as shown in Figure 3.22 for one calibration certificate;

iv) Critical observation of all standard test procedures used (BS, ASTM, and AASHTO);

v) Use of precise weighing scales;

vi) Processing temperature during mixing was monitored and regulated using thermometers and;

vii) Three trial samples for each test determined were used to average each property value.



CALIBRATION CERTIFICATE

Page 1 of 1

CLIENT : MOTA ENGIL-AFRICA
ADDRESS : CIKNB PROJECT, NAMANVE
EQUIPMENT : MARSHAL STABILITY TESTER
MANUFACTURER : CONTROLS
IDENTIFICATION : SITE LAB
RANGE : 50 kN by 0.01 kN

1.0 STANDARD (EQUIPMENT) USED

2.0 CALIBRATION PROCEDURES

3.0 RESULTS

Load Cell Applied Load (kN)	UUT Readings (kN)	% ERROR
12	12.22	1.77
17	16.80	-1.21
23	22.91	-0.41
34	33.59	-1.21
38	38.18	0.46
46	45.81	-0.41

Digital Dial Standard Gauge Block Value, mm	UUT Reading, mm	Deviation, mm
5.00	5.00	0.00
10.00	10.00	0.00
15.00	15.00	0.00
[illegible]	20.00	0.00

Figure 3.22: Calibration certificate of the laboratory equipment used

3.9 DATA ANALYSIS

Analysis of data for independent variables were done in order to identify which factor significantly contributed to the dependent variables. The independent variables analyzed included filler and binder dosages. All test data were analyzed using Excel-based program and, some data was analyzed using a statistical regression method. The objective was to investigate the effect of filler and binder on air voids in DBM mixtures basing on conformity to the engineering requirements.

3.10 CHAPTER SUMMARY

The physical properties of the materials used in this study have been presented in this chapter. Alongside aggregates, filler and bitumen were tested but particular emphasis was given to the characterization of the resultant mixture. The physical properties were conducted on mixtures with small changes in both filler and binder contents. Considering the effect of mineral filler on the properties of DBM mixtures, the amount of filler and binder was the essential parameters in the mix design to ensure better performance. The influence of mineral filler and binder also was verified using the PRD test, to check the retained air voids. The verification aimed at checking DBM mixtures for their performance when exposed to traffic. Accordingly, secondary compaction by traffic on DBM mixtures was simulated in the laboratory using the following tools; Marshall compactor, vibrating hammer compactor and gyratory compactor.

CHAPTER FOUR

DISCUSSION AND ANALYSIS OF RESULTS

4.1 INTRODUCTION

This chapter provides information about the research findings as planned at the beginning of this study. Analysis of data for independent variables was done to identify which factors contributed to the dependent variable. The results on material properties were compared with the MoWT (2005) General Specifications for Road and Bridge Works of Uganda. Compaction to refusal density results especially the retained air voids in DBM mixtures are also presented in this chapter. All test data were analyzed using Microsoft Excel-based program.

4.2 MATERIAL CHARACTERIZATION

The physical properties of coarse and fine aggregates used to evaluate the suitability of the materials in preparing the bituminous mixtures included; strength, toughness, hardness, shape, clay content, specific gravity and water absorption. Those used for filler included; gradation, specific gravity and plasticity index. For bitumen binder, penetration at 25^{o}C, softening point, flush and fire point, specific gravity, viscosity at 135^{o}C, solubility and mass change were used for characterization. A Dense Bituminous Macadam mix of Grade 30 with a nominal maximum size of 28 mm was considered in this study. As per MoWT specifications, DBM 30 necessitates an asphalt content of 4.5 percent of the total mix.

4.2.1 Aggregate Properties

Since aggregate properties play a big role in overcoming permanent deformation, asphalt mixtures constitute approximately 95 percent of aggregates (Asphalt Institute MS-2, 2014; Overseas Road Note 19, 2002). The physical properties of aggregate materials were tested to check the aggregate suitability for bituminous mixtures and test results are shown in Table 4.1, 4.2 and 4.3. The maximum particle size in the aggregate blend was 37.5 mm. Thus, the analysis of aggregate sizes and gradation results were based on DBM bituminous material specifications. Also, since the gradation of individual aggregate sizes could not fall within the DBM gradation specified limits, blending of different aggregate size fractions to obtain the desired continuous dense-graded type was done. This gradation for the combined aggregate conformed with the gradation specified limits for DBM 30 as shown in Figure 4.1.

Ministry of Works and Transport (MoWT) General Specification for Road and Bridge Works of Uganda, has two categories of gradation limits to be achieved before the design of DBM mixtures. Gradation of combined aggregate materials for bituminous mixtures is aimed to pass in the middle of the upper and lower limits shown in Figure 4.1.

In general, based on the findings after testing, the physical properties of aggregates met the specification requirements following MoWT (2005) General Specification for Road and Bridge Works of Uganda. Thus, the aggregate material was suitable for use in the mix design and production of asphalt mixtures in this study.

Table 4.1: Aggregate gradation for DBM 30 mixture

AGGREGATE THEORETICAL GRADING FOR DBM30								
Sieve sizes (mm)	Av. Aggregate % Passing Individual Sieves					Adopted Grading (%) A: B:C:D:E 12:12:27:43:6	Specified Limits for DBM 30	
	20/28 mm (A)	14/20 mm (B)	6/14 mm (C)	0/6 mm (D)	Filler (E)		Lower	Upper
37.5	100	100	100	100	100	**100**	100	100
28.0	100	100	100	100	100	**100**	90	100
20.0	6	91	100	100	100	**88**	70	95
14.0	0	1	73	100	100	**69**	58	82
10.0	0	0	32	100	100	**58**	52	73
5.00	0	0	0	92	100	**46**	40	56
2.00	0	0	0	58	100	**31**	24	40
1.18	0	0	0	41	100	**24**	19	35
0.425	0	0	0	19	99	**14**	9	25
0.300	0	0	0	13	99	**11**	7	21
0.075	0	0	0	2	54	**4**	2	9

AGGREGATE COMBINATION ON A SEMI-LOG GRADING CHART												
Sieve sizes (mm)	**37.5**	**28**	**20**	**14**	**10**	**5.0**	**2.0**	**1.180**	**0.425**	**0.300**	**0.075**	
Upper Limit	100	100	95	82	73	56	40	35	25	21	9	GENERAL SPEC. Table 4202/6
Lower Limit	100	90	70	58	52	40	24	19	9	7	2	
Total Aggregate Combination %	**100**	**100**	**88**	**69**	**58**	**46**	**31**	**24**	**14**	**11**	**4**	
Upper Limit (with permissible deviation)	100	100	95	79	67	56	39	29	19	16	7	GENERAL SPEC. Table 4213/2
Lower Limit (with permissible deviation)	100	90	77	59	52	40	29	19	9	7	2	

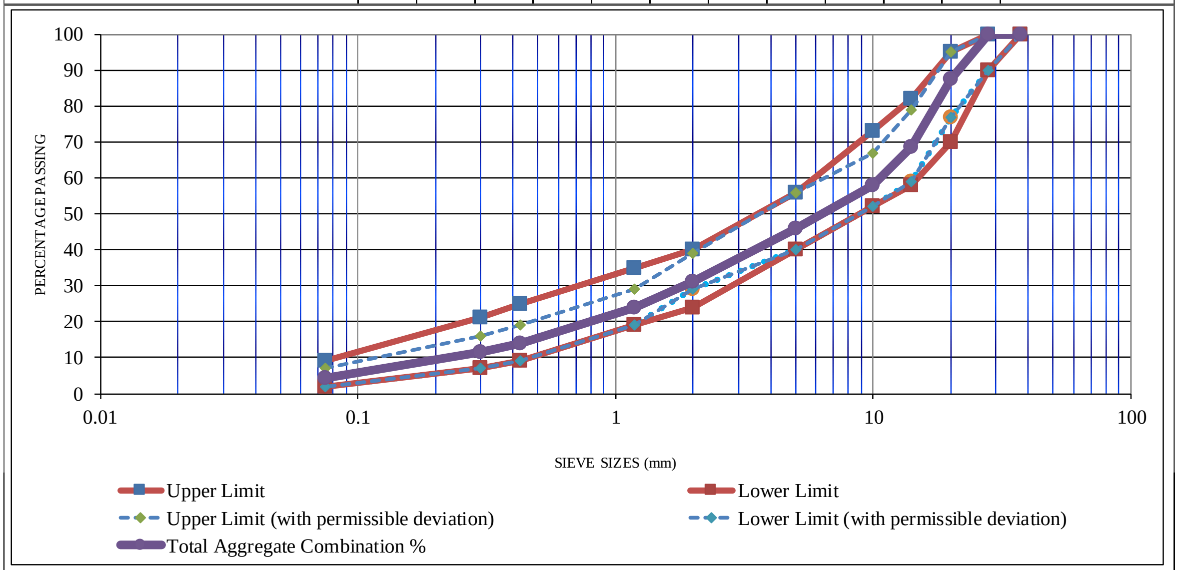


Figure 4.1: Final aggregate gradation with permissible limits

Table 4.2: Physical properties of coarse aggregates

No.	Laboratory Test	Designation	Test Results	Specification Limits
1	Bulk specific gravity (oven-dry basis)	BS 812: Part 2: 1975	2.627	Not Specified
4	Water absorption, %	BS 812: Part 2: 1975	0.29	Max. 2
5	Los Angeles abrasion, %	ASTM C 131 - 89	20.6	Max.50
6	Soundness loss by SSS, %	ASTM C 88 - 98	0.06	Max.12
7	Flakiness Index, %	BS 812-105.1: 1989	15.1	Max.25
8	Ratio of TFV_{soaked} & $TFV_{dry,}$ (%)	BS 812-111:1990	92.7	Min.75
9	Aggregate Crushing Value, %	BS 812-110:1990	23.4	Not Specified
10	Aggregate Impact Value, %	BS 812-112:1990	14.3	Max. 35
11	Coating and Stripping Test, %	AASHTO T 182	98	Min. 95

Table 4.3: Physical properties of fine aggregates

No.	Laboratory Test	Standards	Results	Specification Limits
1	Bulk specific gravity (oven-dry basis)	BS 812-2:1995	2.61	Not Specified
4	Water absorption, %	BS 812-2:1995	0.47	Max. 2
5	Plasticity Index, %	BS: 1377-2:1990	Non-Plastic	Non-Plastic
6	Sand equivalent, %	AASHTO: T176-02	88	Min.50

4.2.2 Mineral Filler Properties

The non-plastic material passing sieve 0.075 mm from sieving of aggregate is called a mineral filler. ASTM D 242 specification requires that filler passes through 1.18 mm, 0.600 mm, 0.300 mm, and 0.075 mm sieves with the requirements of 100%, 97-100%, 95-100%, and 70-100% passing, respectively (ASTM International, 2019). In this research crushed rock dust was used as mineral filler which consisted of finely mineral matter of crusher fines. At the time of use, filler was sufficiently dry to flow freely and free from agglomerations. The mineral filler used conformed with the MoWT General Specifications for Roads and Bridge Works of Uganda. The physical properties are presented in Table 4.4.

Table 4.4: Physical properties of mineral filler

No.	Laboratory Test	Standards	Results	Specification Limits
1	Bulk Specific gravity	BS 812-2:1995	2.606	Not Specified
2	Percent Passing 0.075 mm Sieve	BS 1377-4:1990	82.9	Min. 70 %
3	Plasticity Index, %	BS 1377-2:1990	Non-Plastic	Max. 4

4.2.3 Bitumen Properties

The results of the paving grade bitumen 35/50 used in this research are given in Figure 4.2 and Table 4.5. The (MoWT, 2005) general specifications specify the mixing temperature for the bitumen type 35/50 ranging between 140-165^{o}C. In addition, Overseas Road Note 19 (2002) specifies mixing temperature for paving grade bitumen 35/50 ranging between 150-180^{o}C. While the manufacturer Eni refineries, recommended the appropriate temperatures for asphalt mixtures with 35/50 paving grade bitumen to range between 160-180^{o}C for mixing and 150-170^{o}C for compacting. The research considered the manufacturer's recommendations for mixing and compaction temperatures since manufacturers monitored the bitumen behaviour for a long time. The viscosity determined at 135^{o}C was 0.945 Pa.s as seen in Figure 4.2. The density value of 1.028 of the bitumen was achieved which was later used for volumetric computations of the asphalt mixtures in Table 4.5. The result generally complied with the MoWT, specification requirements and it was suitable for use in this study.

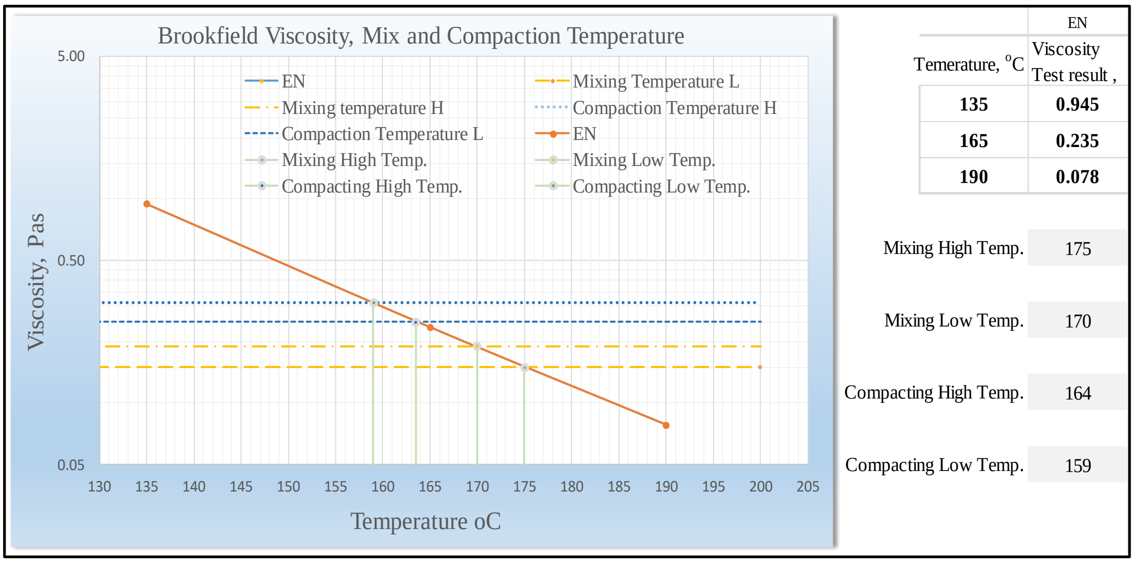


Figure 4.2: Temperature-viscosity for mixing and compaction

Table 4.5: Properties of bitumen

No.	Laboratory Test	Standards	Results	Spec. Limits
1	Penetration at 25° C, 100g, 5 Sec. (0.1mm)	AASHTO: T49-84	43.9	35-50 max.
2	Softening Point, (° C)	AASHTO: T 53	50.6	50-58 max.
3	Flush and Fire Point, (° C)	EN ISO 2592	250	≥ 240
4	Specific Gravity	ASTM C 127-88	1.028	Not Specified
5	Dynamic Viscosity 60°C mm^2/s	EN 12596	235	≥ 225
6	Solubility, % (m/m)	PN-EN 12592	100	≥ 99
7	Change of mass, % (m/m)	PN-EN 12607-1	0.1	≤ 0.5

4.3 SPECIFIC GRAVITY OF TOTAL AGGREGATES

The combined bulk and apparent specific gravity values were used to calculate the effective specific gravity. This was achieved by using the attained average test values in Table 4.6. The higher the aggregate absorption, the greater the difference between Gse and Gsb as represented.

Table 4.6: Aggregate Specific Gravities

AGGREGATE SPECIFIC GRAVITIES							
Bulk Specific Gravity							
Material Fractions	Trial 1		Trial 2		Trial 3		Average
20-28 mm	2.641	2.642	2.636	2.626	2.629	2.631	2.634
14-20 mm	2.624	2.626	2.624	2.625	2.624	2.626	2.625
6-14 mm	2.618	2.621	2.619	2.620	2.613	2.611	2.617
0-6 mm	2.618	2.611	2.614	2.613	2.604	2.602	2.610
Filler	2.606	2.607					2.607
Apparent Specific Gravity							
Material Fractions	Trial 1		Trial 2		Trial 3		Average
20-28 mm	2.662	2.657	2.653	2.648	2.647	2.649	2.653
14-20 mm	2.645	2.646	2.643	2.644	2.653	2.664	2.649
6-14 mm	2.640	2.648	2.640	2.641	2.635	2.633	2.640
0-6 mm	2.644	2.640	2.643	2.644	2.641	2.642	2.642
Filler	2.62	2.62					2.620

$$\text{Bulk Specific Gravity} = \frac{12+12+27+43+6}{\frac{12}{2.634}+\frac{12}{2.625}+\frac{27}{2.617}+\frac{43}{2.610}+\frac{6}{2.607}} = \frac{100}{38.221} = \mathbf{2.617}$$

$$\text{Apparent Specific Gravity} = \frac{12+12+27+43+6}{\frac{12}{2.653}+\frac{12}{2.649}+\frac{27}{2.640}+\frac{43}{2.642}+\frac{6}{2.620}} = \frac{100}{37.846} = \mathbf{2.642}$$

$$\text{Effective Specific Gravity} = (2.617+2.642)/2 = \mathbf{2.629}$$

4.4 MARSHALL DESIGN VALUES

The main aim was to identify an appropriate DBM sensitive mixture to recognize the Marshall design method to obtain optimum filler and binder contents and other engineering properties in compliance with specification requirements. The Marshall test is a repetitive test that enables one to determine strength indexes such as stability and flow for the design of HMA mixtures (Ganapati & Adiseshu, 2013). Once material physical properties met the MoWT specification requirements, the aggregate blend combination met the gradation requirements, the specific gravity of aggregates and bitumen determined, specimen preparations started. The Marshall method uses standard test specimens of 63.5 mm height by 101.6 mm diameter (Anderson, 2011). Following the two principle features of the Marshall method of mix design, measures such as density, air voids, voids filled with bitumen (VFB), and voids in mineral aggregate (VMA) were obtained from the test. As well the stability-flow test of the compacted specimens was performed. The values attained from testing the design mixture were plotted on graphs to choose the optimum binder content and the findings are presented in Table 4.7 read from Figure 4.3. All the data presented in Table 4.7 were considered in deciding on the optimum binder content. Choosing the bitumen content at the mid-point of the percent air voids limits, which is 4.0 percent was considered (Asphalt Institute MS-2, 2014). Thus, the binder content recorded from the graphs (Figure 4.3), was 4.5 percent by weight of the total mix. As well VFB (%), VMA (%), G_{mb} (g/cc), Stability (N), and Flow (mm) corresponding to 4.5 percent binder content were recorded from the matching graphs in Figure 4.3. The values were compared with the MoWT General Specification requirements shown in Table 4.8.

Table 4.7 Marshall Design Values

SUMMARY OF MARSHALL PROPERTIES (75 blows each face)							
Bitumen Content, Pb (%)	Gmb (g/cc)	VMA (%)	Va (%)	VFB (%)	Stability (N)	Flow (mm)	Stability/Flow (N/mm)
3.5	2.299	15.2	5.7	62.6	9087	2.5	3634.8
4.0	2.314	15.1	5.0	67.2	9842	3.1	3174.8
4.5	2.321	15.3	4.1	73.4	11084	3.3	3358.8
5.0	2.338	15.1	2.8	81.7	12487	3.5	3567.7
5.5	2.366	14.5	1.4	90.1	12690	3.4	3732.4

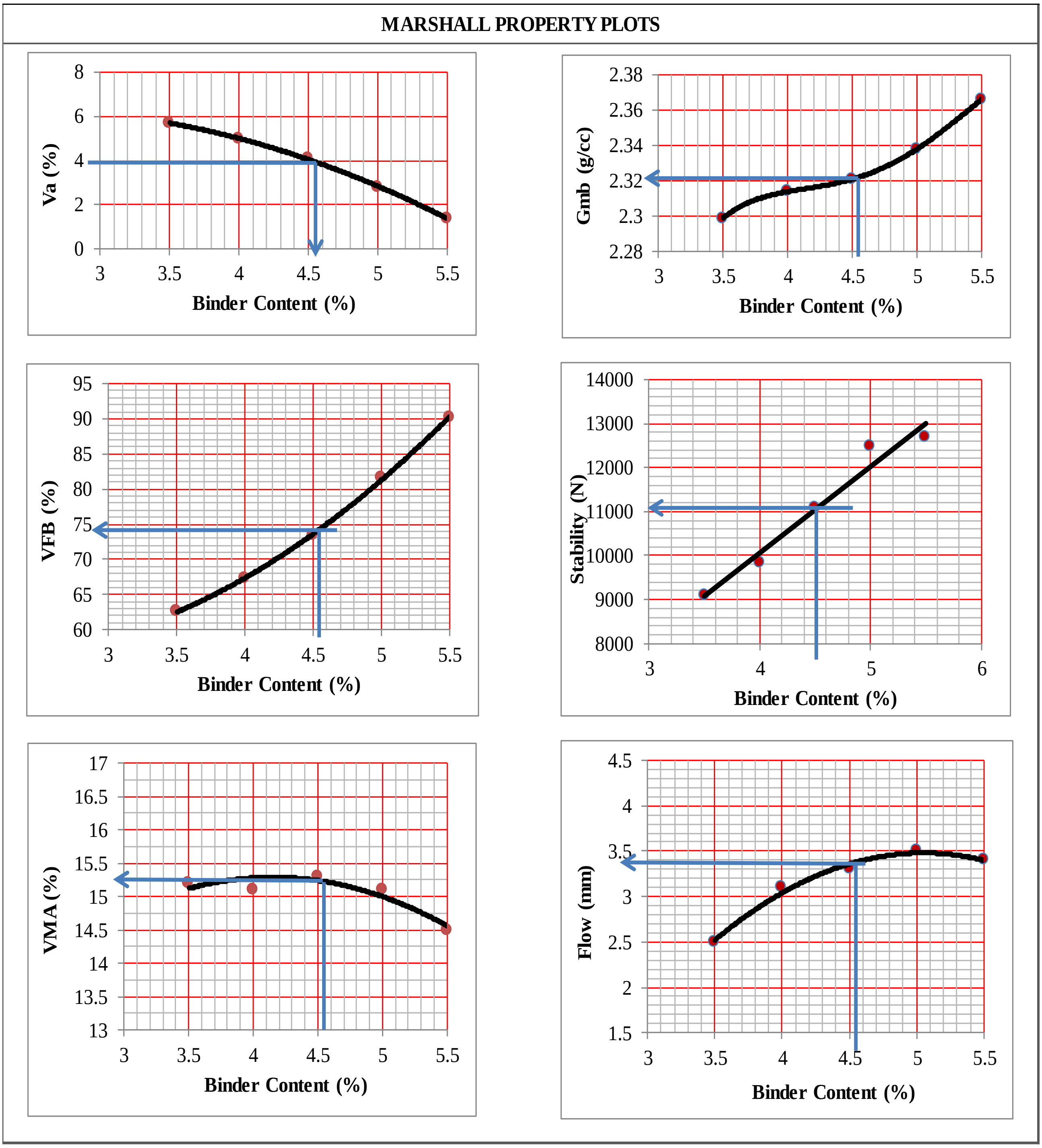


Figure 4.3: Influence of Binder Against Marshall properties

Table 4.8: Values from property plots against the specification

DESIGN REQUIREMENTS FOR DENSE BITUMEN MACADAM MARSHALL MIX DESIGN		
Property description	**Mixture properties at 4 percent air voids**	**Specification Limits (Table:4203/4 Gen. Spec.), (Table 8.5 Overseas Road Note 31)**
Binder Content, %	4.5	4.5 (for bidding purposes)
Marshall stability, N	11,084	Min. 9000
Marshall flow, 0.25 mm	3.4	2 - 4
Voids in mineral aggregate (VMA), %	15.3	Min. 12.5
Voids filled with bitumen (VFB), %	74.0	65 - 75

4.5 MARSHALL PROPERTIES AT OPTIMUM BINDER CONTENT

Deciding whether the DBM mix was satisfactory at the selected design binder content, a special mix was prepared at optimum binder content. The aggregates (coarse, fine and filler) in the mix were reduced by the magnitude of the selected binder 4.5 percent.

The Marshall properties of the asphalt mixture prepared at optimum binder content (4.5 percent), and 95.5 percent total aggregates (coarse, fine and filler) in the mix is shown in Table 4.9. Marshall properties were determined and checked for conformity with the limits specified in the MoWT (2005) general specifications for roads and bridge works of Uganda. Since all measured values for the design mixture at 4.5 percent bitumen content met the design requirements, this was considered as the DBM sensitive control mixture for a subsequent research study.

Table 4.9: Mixture properties at optimum binder content

MARSHALL TEST RESULTS AT OPTIMUM BINDER CONTENT 4.5 %		
Property description	**Mixture properties at optimum binder content**	**Specification Limits (Table:4203/4 Gen. Spec.), (Table 8.5 Overseas Road Note 31)**
Marshall stability, N	22,332	Min. 9000
Marshall flow, 0.25 mm	3.7	2 - 4
Air Voids (Va), at 75 blows on each face, %	4.4	4 - 8
Voids in mineral aggregate (VMA), %	14.2	Min. 12.5
Voids filled with bitumen (VFB), %	69.3	65 - 75

4.6 DESIGN MIX FORMULA (DMF)

The design mix formula provides the aggregate ingredients (coarse, fine and filler) to incorporate in the mix and the summation of all aggregate proportions add up to 95.5 percent as indicated in Table 4.10. Also, the inclusion of 4.5 percent bitumen amounts to 100 percent volume and mass required in the total bituminous mixture. The selection of the DMF was done after confirming that all the measured DBM mixture properties met the specification requirements. Hence, the aggregate content (coarse, fine and filler) and the optimum binder content constituted the design mix formula as shown in Table 4.10. The aggregate proportions in the final mix were reduced using the equation below:

RAP = [(100 – OBC)/ 100] * IAP (Eq. 4.1)

Where; **RAP** is the Reduced Aggregate Proportion to be used in the final mix,

OBC is the Optimum Binder Content,

IAP is the Initial Aggregate Proportion used to determine the optimum binder content. Hence the application of the Equation 4.1 shown above was as follows:

i) 20/28 mm $= \frac{100 - 4.5}{100} \times 12 = 11.5$

ii) 14/20 mm $= \frac{100 - 4.5}{100} \times 12 = 11.5$

iii) 6/14 mm $= \frac{100 - 4.5}{100} \times 27 = 25.8$

iv) 0/6 mm $= \frac{100 - 4.5}{100} \times 43 = 41.1$

v) Filler $= \frac{100 - 4.5}{100} \times 6 = 5.7$

Table 4.10: Adopted Design Mix Formula

THE DESIGN MIX FORMULA FOR DENSE BITUMEN MACADAM							
Optimum Binder Content	4.5						
Total Percent of aggregate in the mix	95.5						
Total percentage of the mixture	100						
Aggregate sizes	20/28 mm	14/20 mm	6/14 mm	0/6 mm	Filler	OBC (%)	Total
Individual percent of aggregate in the mix	12	12	27	43	6	-	100
Reduced aggrgate percentages in the mix by 4.5 % optimum binder content	11.5	11.5	25.8	41.1	5.7	4.5	100

Thus, the design mix formula using the aggregate proportionate sizes 20/28 mm, 14/20 mm, 6/14 mm, 0/6 mm, filler and binder remained 11.5%, 11.5%, 25.8%, 41.1%, 5.7% and 4.5% respectively, did not require any adjustment since the mixture properties met the specification requirements.

4.7 DEVIATED DBM MIXES

The objective of designing DBM mixtures with small range alterations in contents of filler and binder from the job mix formula, was based on observations during production. Sometimes due to equipment error during production, some mixtures retain extra or a reduced amount of filler or binder as compared to the Design Mix Formula (DMF).

The design mix formula for Dense Bituminous Macadam (DBM) was decided on after assessing the right quantities of materials in the mix. The DBM mixtures were subjected to a level of compaction related to traffic in terms of equivalent standard axles.

Mixtures prepared with filler and binder contents altered from the optimum contents as determined by Marshall mix design criteria were considered as deviated mixtures. The volumetric properties of the HMA are highly dependent on filler and binder contents. Basing on the achieved results from the Marshall mix design conducted, the optimum filler content of 5.7 percent and optimum binder content of 4.5 percent by weight of total mix remained the basis to prepare altered DBM mixtures. The altered DBM mixtures were prepared by varying filler and binder contents from the DMF as stated in Section 4.6. Accordingly, both mechanical and volumetric analysis was conducted on the prepared specimens. Basing on the principle that filler proportion in the asphalt mixtures is characteristically allowed in the range of 0.6-1.2 except (1) for 4.75 mm mixes which allows 0.9-2.0 and (2) for coarse-graded mixes which may be raised from 0.8-1.6 (Asphalt Institute MS-2, 2014). The filler proportion addresses the workability of asphalt mixtures. A low proportion in the mix results in a tender mix and is difficult to compact because it tends to move laterally under the compactor. A high proportion results in a stiff mix, but too much also result in a tender mix. Filler proportions indicated in Table 4.11, illustrates that the amount of filler in DBM mixtures have a demonstrative impact on the stability of the mixture, hence affect the performance.

The compaction effort of 75 blows on each side was used in preparing specimens with deviated contents of filler and binder. The specimens were used to determine the bulk density, air voids, voids in mineral aggregate, voids filled with bitumen, stability and flow. Table 4.11 illustrates the relationship between filler and binder contents altered from the optimum contents.

Table 4.11: Marshall properties after 75 blows each face

MARSHALL VOLUMETRIC PROPERTIES AFTER 75 BLOWS EACH FACE										
Sample height	Filler Content	Bitumen Content of mix, Pb	Dust to Binder ratio, P0.075/Pb	Maximum SG, Gmm	Bulk Density of compacted mix, Gmb	VA	VMA	VFB	Marshal Stability	Marshal Flow
mm	%	%			(g/cc)	%	%	%	N	mm
64.1	5.3	4.2	1.26	2.504	2.252	10.0	17.5	42.6	18870	4.7
64.2	5.3	4.35	1.22	2.497	2.275	8.9	16.8	47.1	12666	3.2
64.7	5.3	4.5	1.18	2.478	2.279	8.0	16.8	52.3	13569	4.0
64.6	5.3	4.65	1.14	2.459	2.282	7.2	16.8	57.2	13038	3.9
64.5	5.3	4.8	1.10	2.442	2.305	5.6	16.1	65.4	14895	3.2
63.3	5.7	4.2	1.36	2.496	2.338	6.3	14.4	56.0	24556	4.8
63.3	5.7	4.35	1.31	2.477	2.348	5.2	14.1	63.4	21089	3.6
64.7	5.7	4.5	1.27	2.462	2.350	4.6	14.2	67.9	21262	3.7
62.9	5.7	4.65	1.23	2.448	2.352	3.9	14.3	72.7	23369	3.9
63.7	5.7	4.8	1.19	2.438	2.365	3.0	13.9	78.6	23224	3.4
64.6	6.1	4.2	1.45	2.485	2.319	6.7	15.1	55.7	20595	2.8
64.1	6.1	4.35	1.40	2.475	2.341	5.4	14.4	62.2	21103	3.3
64.0	6.1	4.5	1.36	2.470	2.346	5.0	14.4	65.0	21336	3.1
63.9	6.1	4.65	1.31	2.460	2.347	4.6	14.4	68.2	15094	2.3
64.7	6.1	4.8	1.27	2.458	2.361	4.0	14.1	71.8	13051	2.9
64.5	6.5	4.2	1.56	2.474	2.369	4.2	13.2	68.1	16570	3.5
64.5	6.5	4.35	1.49	2.469	2.375	3.8	13.2	71.1	16326	3.5
64.1	6.5	4.5	1.44	2.459	2.374	3.4	13.3	74.2	21249	3.2
62.4	6.5	4.65	1.40	2.447	2.375	3.0	13.4	78.0	19677	2.8
62.3	6.5	4.8	1.35	2.444	2.374	2.9	13.6	79.0	14686	3.3

4.7.1 Effect on Marshall Stability

The principle of Marshall stability is the resistance to plastic flow of cylindrical specimens of a bituminous mixture loaded on the lateral surface. The stability values achieved following the standard specification ASTM D 1559 (2004) for Marshall compacted specimens at a standard test temperature of 60^{o} C, represents the strength of the mixture. Literature disclosed that stability in most cases is affected significantly by the angle of internal friction of the aggregate and the viscosity of the bitumen at 60^{o} C (Berhe, 2007). Hence, one of the easiest ways to increase the stability of an asphalt mixture is to use a higher viscosity grade of bitumen. Literature found out that cubical particles exhibit interlock and internal friction, which results in higher mechanical stability than the flat, thin, and elongated particles (Ganapati & Adiseshu, 2013). Also, literature discovered that aggregate gradation has more influence in mix stability whereby, mixes made with middle gradation gives higher Marshall stability values than others (Lodhi & Yadav, 2016).

Comparing the literature and the materials used in the research, Marshall stability values for all test samples were above the minimum 9000 Newton specified for DBM mixes following MoWT General Specifications for Road and Bridge Works of Uganda. It was observed that the filler-to-binder ratio of 1.36 (i.e. 5.7/4.2) attained the maximum stability of the DBM mixture shown in Figure 4.4. In this research, angular crushed aggregates were used together with a higher viscosity bitumen to prepare DBM mixtures. Generally, mixtures with 5.7 percent filler content were observed to have the highest stability values ranging between 21089 N to 24556 N as shown in Figure 4.4. This is because, in these mixes, maximum aggregate particle interlock and internal friction caused by gradation are expected more since it is the optimum filler content chosen.

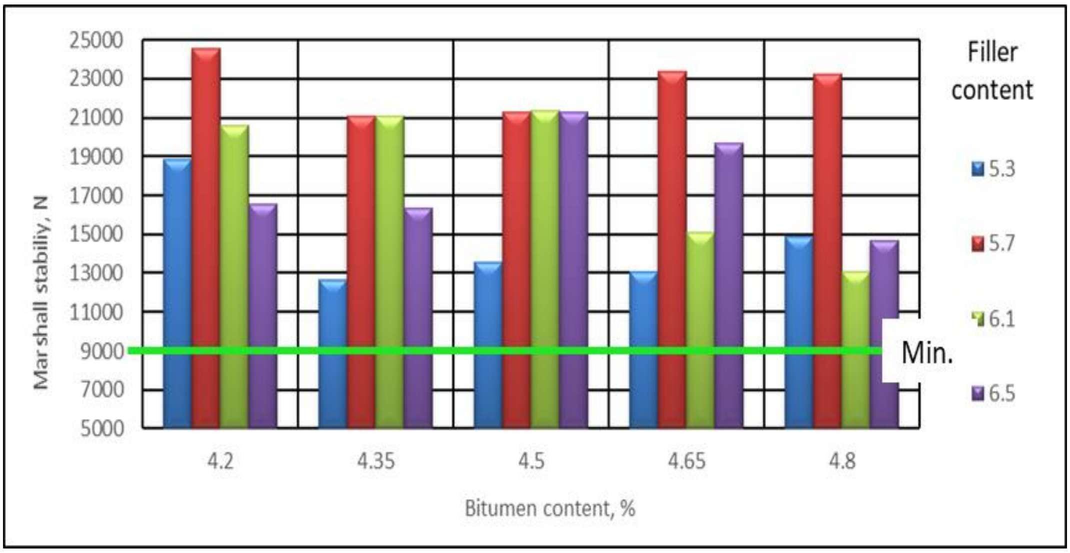


Figure 4.4: Variation of Marshall stability with bitumen contents

4.7.2 Effect on Marshall Flow

Flow values are measured as vertical deformation of specimens in hundreds of inches from the start of loading up to the maximum load attained by the compacted specimen during testing at 60^o C. Flow values are obtained at the same time as the Marshall stability test is conducted. High flow values indicate a plastic mix that is more prone to permanent deformation, whereas low flow values may indicate a mix with higher voids and insufficient binder for durability and could result in premature failure due to mixture brittleness (Berhe, 2007). In this research, all asphalt mixtures measured flow values above the minimum 2.0 mm required and only two mixtures measured flow values above the maximum 4.0 mm specified limit following MoWT General Specifications for Road and Bridge Works of Uganda. Asphalt mixtures prepared with 5.3 and 5.7 percent filler content were above the maximum flow values at low bitumen content of 4.2 percent as presented in Figure 4.5. This means that the bitumen content added to the mixture was less to induce plastic flow in specimens. The little filler added into the mix increased the surface area and hence increase internal friction between aggregate particles. Generally, 10 percent of the mixtures achieved flow values above the allowable maximum limit of 4.0 mm, while 90 percent of the flow values achieved lies within the required limits 2 to 4 mm recommended by the MoWT (2005) general specification for Uganda.

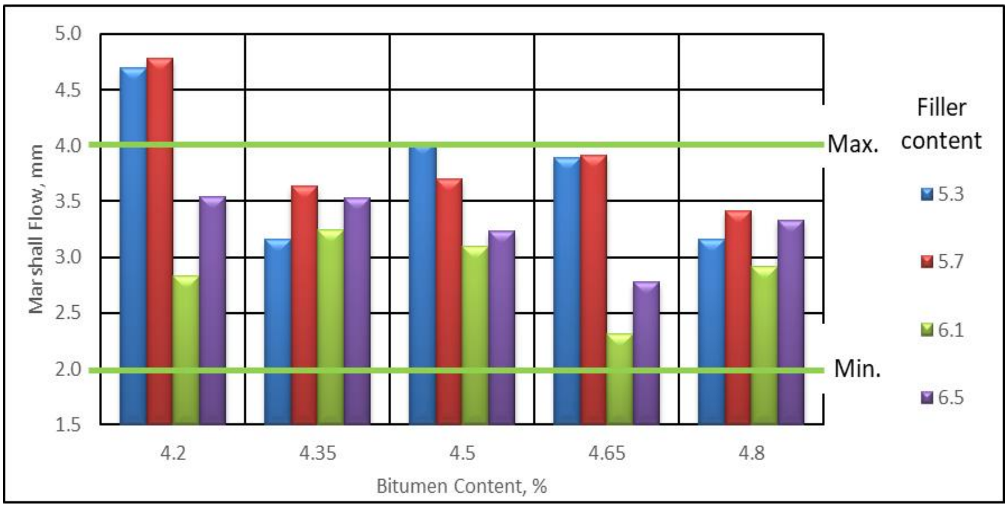


Figure 4.5: Variation of flow values with bitumen contents

4.7.3 Effect on Bulk Density

Bulk density of the compacted mix employing 75 blows on both sides, increases with increasing filler content up to a maximum then it decreases slightly, but with further addition of filler bulk densities increased higher following the same trend in all mixes. It is difficult to explain why this happened, but it may be due to a decrease in voids in the mineral aggregates as filler content increases but it does not reach its minimum value, hence increased bulk density presented in Figure 4.6. In the compacted mix, density is directly related to voids. The lowest bulk densities of the compacted specimens were observed in the mixtures containing 5.3 percent filler. This is because at lower content the mix becomes stiffer hence requiring greater compaction effort and consequently lower dense mixtures obtained. This phenomenon was not experienced for the mixtures prepared with much more amount of filler. While highest bulk densities were observed in mixtures with 6.5 percent filler as shown in Figure 4.6. Commonly, the more the filler quantity is added into the aggregate blend, the more the mixture can be easily compacted and hence higher compacted density. The reverse is true, the less the filler quantity is added, the less the mixture can be compacted and hence less compacted density is achieved. Filler reduces the air voids and increases the density of the compacted mixture. For each filler content, the higher the density of the mix, the lower the percentage of voids in the mix, and vice versa. This means that the densification of asphalt mixtures is influenced by filler content. The maximum bulk density achieved was 2.375g/cc for asphalt mixtures with a filler/asphalt ratio of 1.4 at a proportion of asphalt content 4.65 percent. Similarly, Sady (2013) reported the maximum bulk density of 2.353g/cc for the asphalt mixture that was achieved after using a filler/binder ratio of 1.5 at a proportion of asphalt content 4.95 percent.

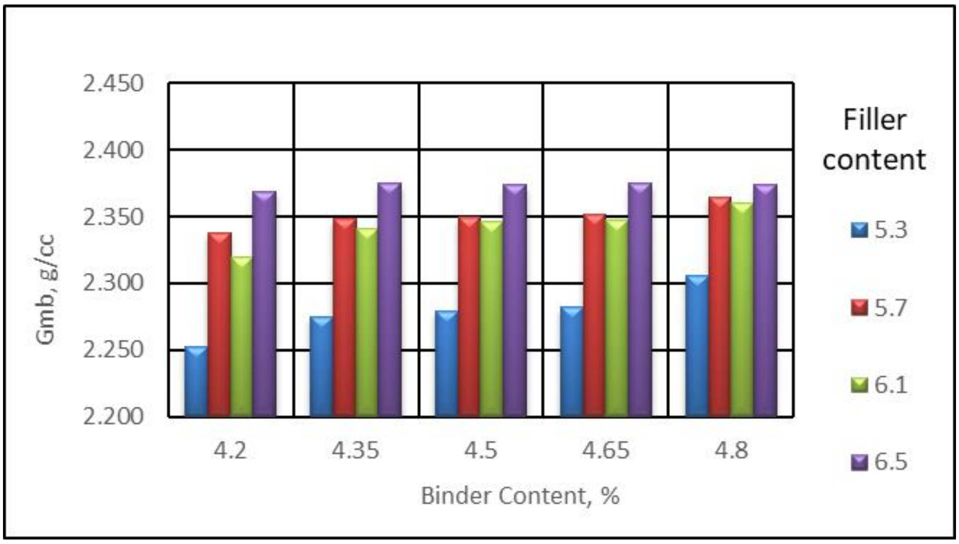


Figure 4.6: Bulk density of compacted mix vs. bitumen content

4.7.4 Effect on Air Voids (VA)

Air voids are small spaces of air that occur between the coated aggregate particles in the final compacted mix. A certain percentage of air voids is essential in all asphalt pavement mixtures to allow some secondary compaction under traffic. Also, air voids in the compacted mixture provide spaces into which some small amounts of bitumen can flow during subsequent compaction. The durability of an asphalt pavement mixture is a function of air-voids content. This is because the lower the air-voids content, the less permeable the mixture becomes. Too high an air-voids content above 8.0 percent, provides passageways through the asphalt mixture for the ingress of destructive air and moisture. Too low of an air void content less than 3.0 percent can lead to bleeding, a condition in which excess bitumen squeezes out of the mix to the surface. For all filler contents in this research, air voids decreased with increasing filler and binder content.

A higher amount of air voids (≥ 8.0 percent) was measured in mixtures with the lowest percentage of filler content (5.3 percent), such mixtures with insufficient binder and high air voids are prone to ingress of air and water hence oxidation. The least amount of air voids (< 3 percent) was measured in mixtures with the highest percentage of filler content (6.5 percent). Generally, it was evident that 5 percent of the mixes achieved air voids less than 3.0 percent, 10 percent of the mixes achieved air voids content above 8.0 percent, while 85 percent of the mixes attained air voids between 3.0 and 8.0 percent as indicated in Figure 4.7. This justifies that using inert filler in preparation of bituminous mixtures makes the bitumen more solid and stiffer hence affect the air voids. As well, beyond a certain range of filler-to-binder ratio (0.8-1.6

by mass) recommended by the Asphalt Institute in MS-2 for DBM mixtures, the values may not comply with the Ugandan specifications.

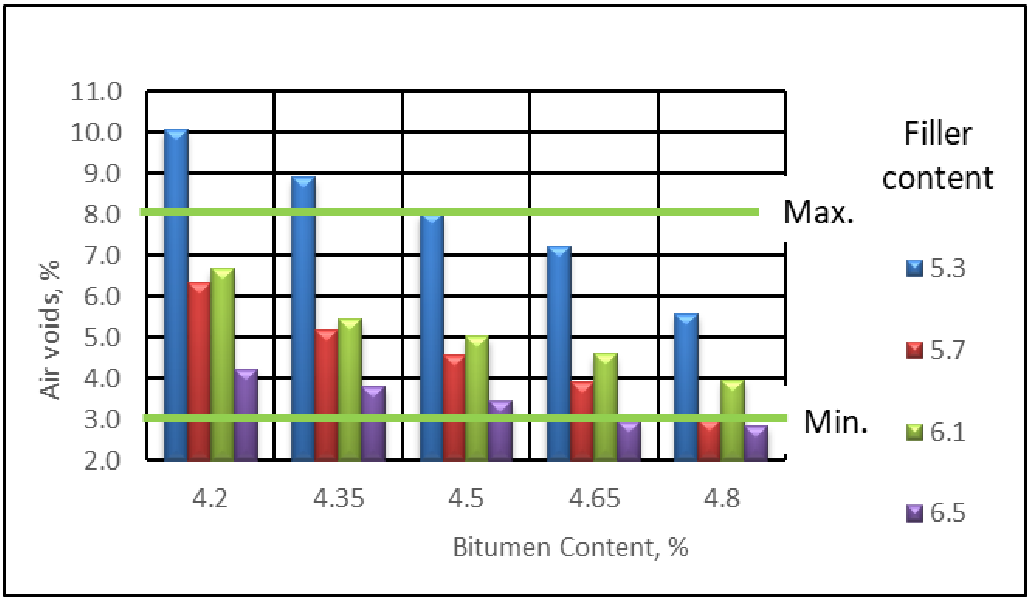


Figure 4.7: Relationship between bitumen content with air voids

4.7.5 Effect on Voids in Mineral Aggregate (VMA)

Voids in mineral aggregate (VMA) are the air-void spaces that exist between the aggregate particles in a compacted mixture, including spaces filled with bitumen. The space available to accommodate bitumen and the voids necessary in the mixture is represented by VMA. The primary purpose of VMA is to ensure reasonably high bitumen content to coat the aggregate particles in the mix. An increase in the filler proportion, generally decreases the VMA but further increase beyond the maximum required in a mix increases the VMA with increasing bitumen content as shown in Figure 4.8. This is due to the relationship between particle diameter and surface area. Increasing the amount of material passing the 0.075 mm sieve, result in a larger overall surface area of the aggregate blend. Bruce A. et .al (1999) in a report said that though there was increase in the fines of the asphalt after construction, a change in total surface area is not expected. Also, he reported that without particle diameter the contribution of the material passing 0.075 mm sieve, their surface area cannot be accurately estimated. It can be assumed that the larger this percentage is, the greater the actual surface area. All mixtures indicated satisfied the VMA minimum requirement of 12.5 percent following the Overseas Road Note 31 (TRL, 1993). VMA decreases with increasing bitumen content in the mixture. The more VMA in the dry aggregate, the more space is available for bitumen film on the aggregate particles, the more durable the paving mixture. Minimum VMA values should be achieved for a durable asphalt film thickness. When the aggregate gradation is made denser, VMA values obtained leads to thinner asphalt film and a dry looking mix and hence a low durability mix.

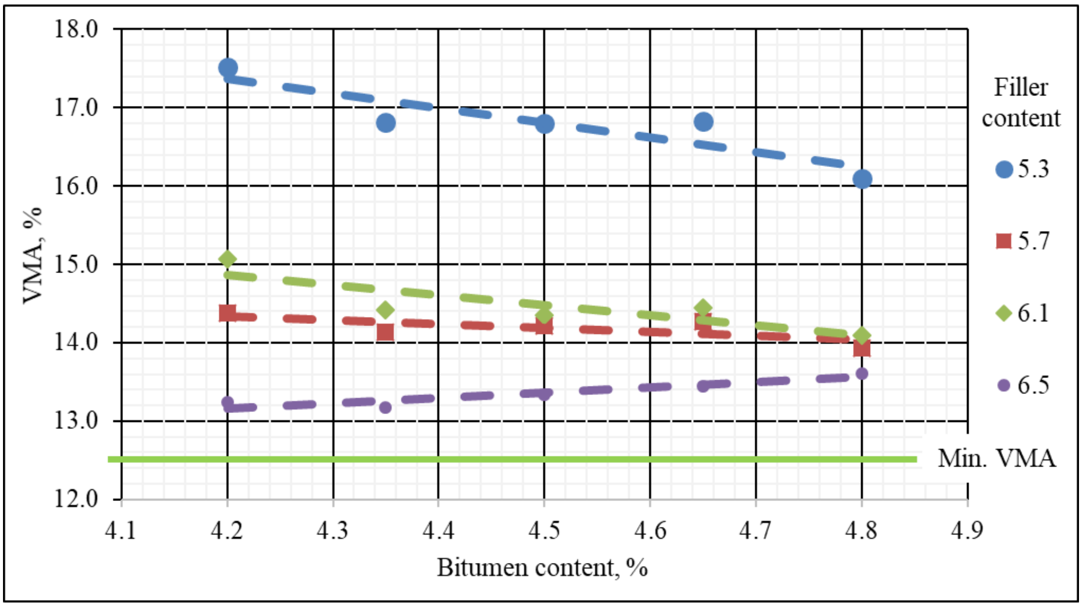


Figure 4.8: Relationship between bitumen content with VMA (%)

4.7.6 Effect on Voids Filled with Bitumen (VFB)

The effect of filler and binder contents on the voids filled with the bitumen property of the mixture is indicated in Figure 4.9. DBM mixes should maintain a reasonable amount of air voids between 65–75 percent expected to be filled with bitumen following the Marshall criteria. The criteria is important for the durability of mixes and is less related to the effective binder content in the mix. If the percentage of voids filled with a binder is lower than the limit indicated, there will be less binder film around the aggregate particles. Lower binder 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 binder than required for durability. This can be explained as the binder film around aggregate particles is thicker and lower voids than required are left. This increased amount of effective binder results in bleeding and lower stiffness of the mix. The VFB are very essential whereby its requirement helps to avoid those mixes that are susceptible to failures under substantial traffic loading. Mixtures prepared by 5.3 percent filler content for all binder contents, the voids filled with a binder is lower than the minimum limit set by Marshall criteria. This implied that the designed mixture had excessive voids to accommodate both filler and binder at the same time. The VFB provides an additional factor of safety during the design stage and actual construction in terms of performance.

In general, 40 percent of the mixes achieved VFB below the minimum 65 percent required, such mixes were observed to be drier and brittle. Then 45 percent of the mixes achieved VFB between 65 and 75 percent as required, while 15 percent of the mixes achieved VFB above the maximum 75 percent needed. Such mixtures having VFB above the maximum value 75 percent were tender and shiny and difficult to compact since they contained a higher percentage of bitumen and mineral filler.

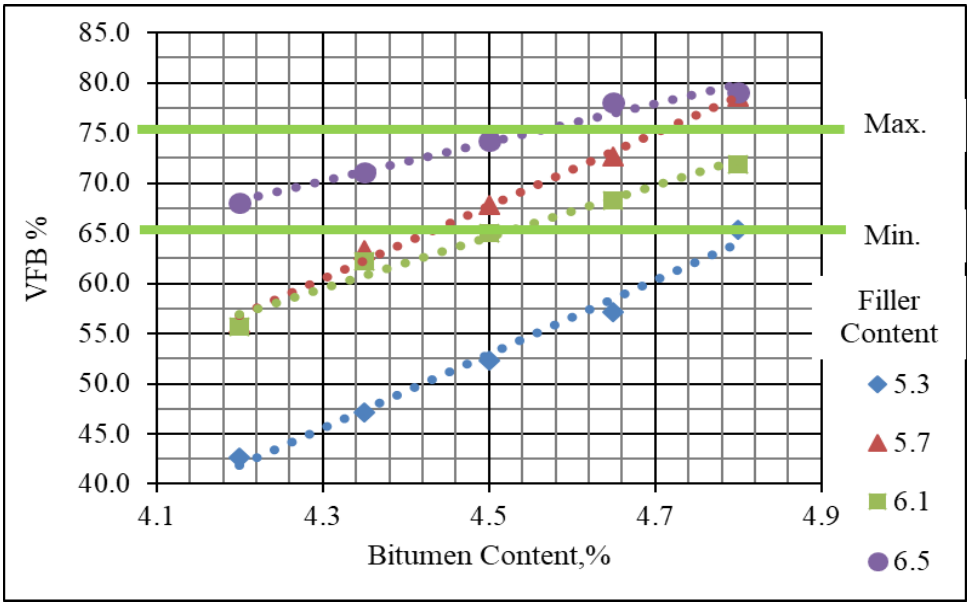


Figure 4.9: Relationship between bitumen content with VFB (%)

4.8 REFUSAL DENSITY COMPACTION

Refusal density compaction is used as an addition to the standard Marshall mix design procedure. The objective is to design asphalt mixtures that can retain the required minimum air voids content after secondary compaction by traffic. The refusal density design ensures that the compacted mix prepared following the DMF, can retain 3.0 percent void content (TRL, 1993). The Marshall compaction was continued until no further densification of the bituminous mix was obtained. The design was done on three duplicate specimens prepared to receive 300, 400, 450 and 500 blows respectively. A graph of air voids content against the number of blows was plotted as shown in Figure 4.10 and the number of blows corresponding to the 3.0 percent air-voids content was adopted. The 400 blows that satisfied the mix requirements by the minimum void content of 3.0 percent was achieved.

Preparation of specimens for the refusal density test on asphalt mixtures were categorically done using any of the three laboratory compaction tools: (i) an automatic Marshall impact hammer, (ii) an electrically operated vibrating hammer and (iii) a gyratory compactor.

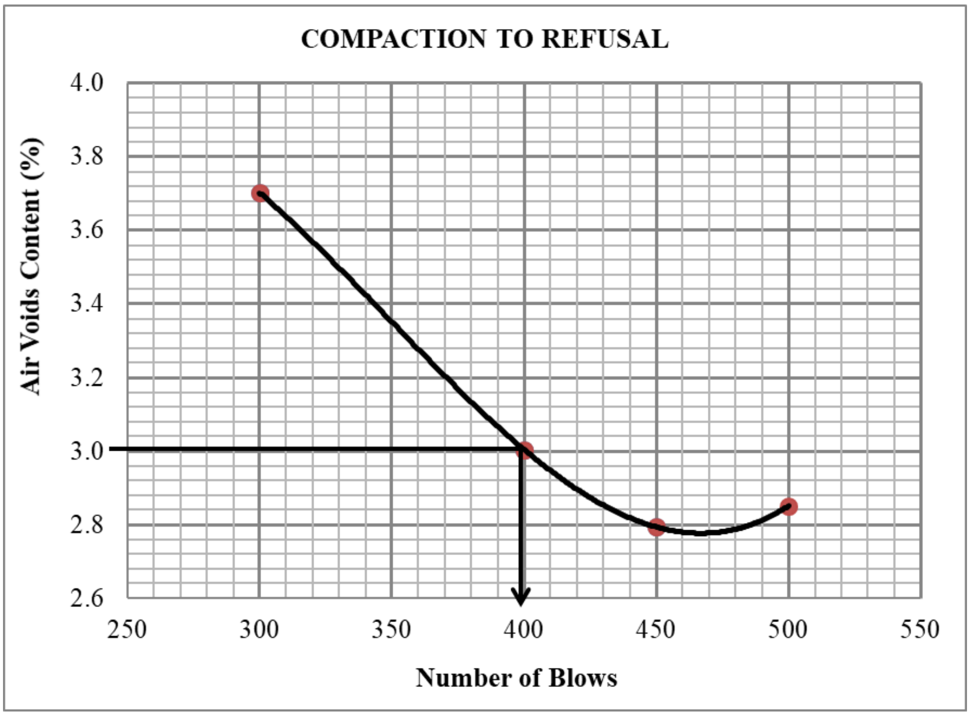


Figure 4.10: Void content at refusal density

4.8.1 Refusal Density Compaction by an Automatic Marshall Impact Hammer

This is a procedure of extended Marshall compaction to design asphalts mixtures that can retain the required minimum voids in the mix after secondary compaction by traffic as highlighted by the Overseas Road Note 31 (TRL, 1993). It is a continued Marshall compaction until no further densification of the mix is obtained.

Durable mixes require a high degree of compaction and this is best achieved by compacting specimens to refusal density. Air voids were determined in the compacted specimens and those retained 3.0 percent and above were considered satisfactory. Those specimens which failed to achieve the minimum 3.0 percent were regarded as unsuitable for road pavement construction. The measured results shown in Table 4.12 were obtained after testing mixtures that contained filler and bitumen content varied from the optimum as earlier determined.

Table 4.12: Retained air voids in the mixture after 400 blows on each face

AIR VOIDS IN SPECIMENS COMPACTED WITH 400 BLOWS EACH FACE BY AN AUTOMATIC MARSHALL IMPACT HAMMER							
Sample height	Filler Content of mix, $P_{0.075}$	Bitumen Content of mix, Pb	Dust to binder ratio $P_{0.075}/Pb$	Bitumen SG, Gb	Maximum SG, Gmm	Bulk Density of compacted mix, Gmb	Air voids, VA
mm	%	%				(g/cc)	%
64.5	5.3	4.20	1.26	1.028	2.504	2.299	8.2
64.3	5.3	4.35	1.22	1.028	2.497	2.289	8.3
64.6	5.3	4.50	1.18	1.028	2.478	2.321	6.3
64.5	5.3	4.65	1.14	1.028	2.459	2.347	4.6
63.7	5.3	4.80	1.10	1.028	2.442	2.340	4.2
62.3	5.7	4.20	1.36	1.028	2.496	2.394	4.1
64.2	5.7	4.35	1.31	1.028	2.477	2.387	3.6
64.0	5.7	4.50	1.27	1.028	2.462	2.382	3.3
61.3	5.7	4.65	1.23	1.028	2.448	2.373	3.1
61.7	5.7	4.80	1.19	1.028	2.438	2.367	2.9
61.7	6.1	4.20	1.45	1.028	2.485	2.378	4.3
63.0	6.1	4.35	1.40	1.028	2.475	2.379	3.9
60.3	6.1	4.50	1.36	1.028	2.470	2.391	3.2
61.0	6.1	4.65	1.31	1.028	2.460	2.384	3.1
61.0	6.1	4.80	1.27	1.028	2.458	2.395	2.6
62.4	6.5	4.20	1.55	1.028	2.474	2.405	2.8
62.3	6.5	4.35	1.49	1.028	2.469	2.408	2.4
61.6	6.5	4.50	1.44	1.028	2.459	2.419	1.6
61.3	6.5	4.65	1.40	1.028	2.447	2.420	1.1
61.3	6.5	4.80	1.35	1.028	2.444	2.423	0.9

In all categories of filler content, air voids decreased with increasing bitumen content as presented in Figure 4.11. Also, air voids decreased with increasing filler content for all mixtures. Only mixtures with filler content ± 0.4 percent from the optimum filler content which is 5.7 percent, retained the required 3.0 percent air voids up to bitumen content 4.65 percent. Mixtures with filler content + 0.8 percent from the optimum filler content could not retain the minimum required air voids when specimen were compacted with 400 blows using an automatic Marshall impact hammer for the Percentage Refusal Density (PRD) test. DBM mixtures prepared with fewer filler content retained more air voids compared to those with more filler. Generally, 65 percent of the total mixtures retained air voids above 3.0 percent minimum required, 15 percent of the mixes retained air void above 2.5 percent, while 20 percent of the total mixes retained air voids below 2.5 percent after compacting specimens with 400 blows on each face. Considering the analysis above, not all mixtures prepared within the specified range of filler and binder contents could retain the specified minimum air voids when compacted using an automatic Marshall impact hammer. This is because the incorporation of filler in the aggregate blend, slightly shifts the gradation curve to the finer side and this changes the volumetric properties of the mixture. Mixtures with a slightly more amount of filler content tend to fill all the air spaces left in the fine aggregate and hence reduced air voids. The more the filler is added into an asphalt mix, the less the air voids are retained in a compacted mix. Similarly, the more bitumen is added into an asphalt mix the less the retained air voids. The reverse is true the fewer the filler, the more the retained air voids in compacted specimens and the less the binder the more air voids left in a compacted specimen.

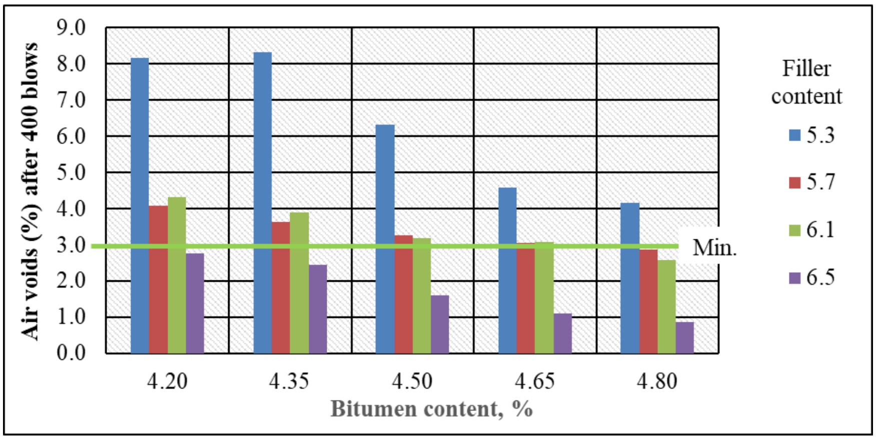


Figure 4.11: Relationship between bitumen content with air voids at refusal compaction 400 blows

4.8.2 Refusal Density Compaction by an Electrically Operated Vibrating Hammer

This is an alternative method, based on the extended Marshall compaction procedure used in the Percentage Refusal Density (PRD) test (BS 598 Part 104, 1989), which uses a vibrating hammer for compaction. Mixtures were prepared and subjected to a 2-minute vibration on each face, using a vibrating hammer as a means of refusal compaction to determine retained air voids. The specimens were compacted in a 153 mm diameter mould to an approximate thickness to be laid on the road (Overseas Road Note 31, 1993). Table 4.13 shows test results from compacted specimens using a vibrating hammer tool, for mixtures designed with different filler and binder contents and later checked for retained air voids.

Table 4.13: Retained air voids in the mixture after using a vibrating hammer

AIR VOIDS IN SPECIMENS COMPACTED USING ELECTRICALLY OPERATED VIBRATING HAMMER							
Sample height	Dust Content of mix, $P_{0.075}$	Bitumen Content of mix, Pb	Dust to binder ratio $P_{0.075}$/Pb	Bitumen SG, Gb	Maximum SG, Gmm	Bulk Density of compacted mix, Gmb	Air voids, Va
mm	%	%				(g/cc)	%
104.2	5.3	4.20	1.26	1.028	2.504	2.329	7.0
104.2	5.3	3.50	1.51	1.028	2.497	2.359	5.5
103.8	5.3	4.50	1.18	1.028	2.478	2.397	3.3
104.4	5.3	4.65	1.14	1.028	2.459	2.384	3.1
103.7	5.3	4.80	1.10	1.028	2.442	2.370	2.9
99.9	5.7	4.20	1.36	1.028	2.496	2.431	2.6
99.9	5.7	4.35	1.31	1.028	2.477	2.430	1.9
101.3	5.7	4.50	1.27	1.028	2.462	2.431	1.3
98.9	5.7	4.65	1.23	1.028	2.448	2.429	0.8
98.7	5.7	4.80	1.19	1.028	2.438	2.426	0.5
99.3	6.1	4.20	1.45	1.028	2.485	2.395	3.6
95.0	6.1	4.35	1.40	1.028	2.475	2.436	1.6
100.0	6.1	4.50	1.36	1.028	2.470	2.440	1.2
100.0	6.1	4.65	1.31	1.028	2.460	2.446	0.6
100.0	6.1	4.80	1.27	1.028	2.458	2.431	1.1
95.0	6.5	4.20	1.55	1.028	2.474	2.442	1.3
99.3	6.5	4.35	1.49	1.028	2.469	2.443	1.0
97.8	6.5	4.50	1.44	1.028	2.459	2.435	0.9
99.2	6.5	4.65	1.40	1.028	2.447	2.435	0.5
100.9	6.5	4.80	1.35	1.028	2.444	2.438	0.2

It was found out that only 25 percent of the mixtures could retain the required 3.0 percent air voids as the minimum recommended by the MoWT (2005) specification for Uganda. 10 percent of the mixtures had air voids above 2.5 percent which can be accepted when reported to one whole number, but it was less than 3.0 percent which is the minimum required and 65 percent retained air voids less than 2.5 percent. Almost all mixtures categorized with 5.3 percent filler content retained the required air voids except one with the highest binder content of 4.8 percent. One mixture under the grouped filler content of 6.1 percent measured air voids above 3.0 percent at a bitumen content of 4.2 percent which is less than the optimum binder content as shown in Figure 4.12. This indicates that air voids in an asphalt mixture are affected by both filler and bitumen contents. The more filler is added in an asphalt mixture, the less air voids retained and the reverse is true, the less filler added the more retained air voids. The same applies to binder content in the asphalt mixtures. Also, the delivered energy variables, the efficiency in energy transfer, and the difficulty to spot operation problems when using the vibrating hammer contribute much to further densification of mixtures, hence reduced air voids.

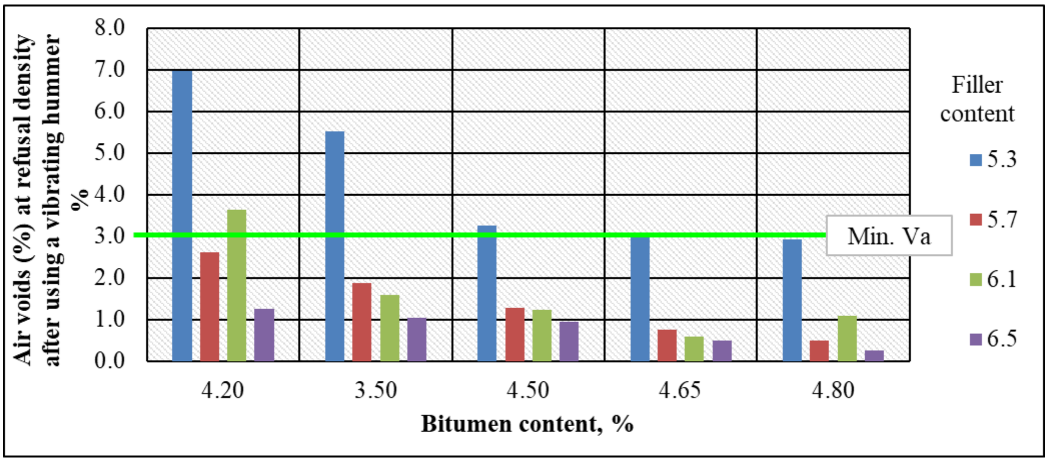


Figure 4.12: Relationship between bitumen content with air voids with a vibrating hammer

4.8.3 Refusal Density Compaction by a Gyratory Mechanism

Among many testing tools for analyzing compaction characteristics of asphalt mixtures, a Superpave gyratory compactor was also used to simulate the compaction process of DBM mixtures. The aim was to find out whether DBM mixtures designed using the Marshall method could retain the minimum air voids when compacted using 205 number of gyrations. This compaction device had been designed to compact HMA samples to a density similar to that obtained in the field under traffic (Brown et al, 2009). It also tends to orient the aggregate particles similar to that observed in the field. The gyratory compactor was used on DBM mixtures prepared in four major categories and test results are shown in Table 4.14.

Table 4.14: Retained air voids in the mix after using a gyratory compactor

AIR VOIDS IN SPECIMENS COMPACTED USING A GYRATORY COMPACTOR							
Sample height	Dust Content of mix, $P_{0.075}$	Bitumen Content of mix, Pb	Dust to binder ratio $P_{0.075}$/ Pb	Bitumen SG, Gb	Maximum SG, Gmm	Bulk Density of compacted mix, Gmb	Air voids, Va
mm	%	%				(g/cc)	%
89.7	5.3	4.20	1.26	1.028	2.504	2.416	3.5
110.7	5.3	3.50	1.51	1.028	2.497	2.433	2.6
109.2	5.3	4.50	1.18	1.028	2.478	2.436	1.7
111.0	5.3	4.65	1.14	1.028	2.459	2.437	0.9
110.0	5.3	4.80	1.10	1.028	2.442	2.450	0.0
110.0	5.7	4.20	1.36	1.028	2.496	2.430	2.6
112.0	5.7	4.35	1.31	1.028	2.477	2.416	2.4
109.2	5.7	4.50	1.27	1.028	2.462	2.445	0.7
110.2	5.7	4.65	1.23	1.028	2.448	2.436	0.5
108.4	5.7	4.80	1.19	1.028	2.438	2.447	0.0
110.7	6.1	4.20	1.45	1.028	2.485	2.422	2.5
111.0	6.1	4.35	1.40	1.028	2.475	2.415	2.4
110.2	6.1	4.50	1.36	1.028	2.470	2.420	2.0
110.0	6.1	4.65	1.31	1.028	2.460	2.437	1.0
110.5	6.1	4.80	1.27	1.028	2.458	2.434	1.0
111.0	6.5	4.20	1.55	1.028	2.474	2.417	2.3
110.2	6.5	4.35	1.49	1.028	2.469	2.434	1.4
111.7	6.5	4.50	1.44	1.028	2.459	2.437	0.9
110.2	6.5	4.65	1.40	1.028	2.447	2.432	0.6
109.9	6.5	4.80	1.35	1.028	2.444	2.437	0.3

For each filler category, bitumen increased with decreasing percentage of air voids retained in the mixtures as shown in Figure 4.13. Similarly, filler content increased with decreasing percentage of retained air voids. It was found out that only the drier mixes retained some reasonable amount of air voids content. The driest mixture comprised 5.3 percent filler and 4.2 percent binder content. This is an indication that it is hard to compact the dry mixture to its fullest. The bitumen quantity was not enough to fully coat the aggregate in the mixture that is why compaction was difficult. In general, only 5.0 percent of the total mixes compacted using the gyratory compactor with 205 number of gyrations, retained air voids content above 3.0 percent. 15 percent of the mixtures retained air voids between 2.5 and 3.0 percent. 40 percent of the mixtures retained air voids between 1.0 and 2.5 percent and the remaining 40 percent of the mixtures retained less than 1.0 percent air voids. Test results shown in Figure 4.13 indicate that mixtures designed using the Marshall method do not retain the minimum required air voids when compacted using a gyratory compactor. In general, Superpave Gyratory Compactor achieved less air voids content of the Marshall mixes; this prevents additional compaction a result of traffic loads.

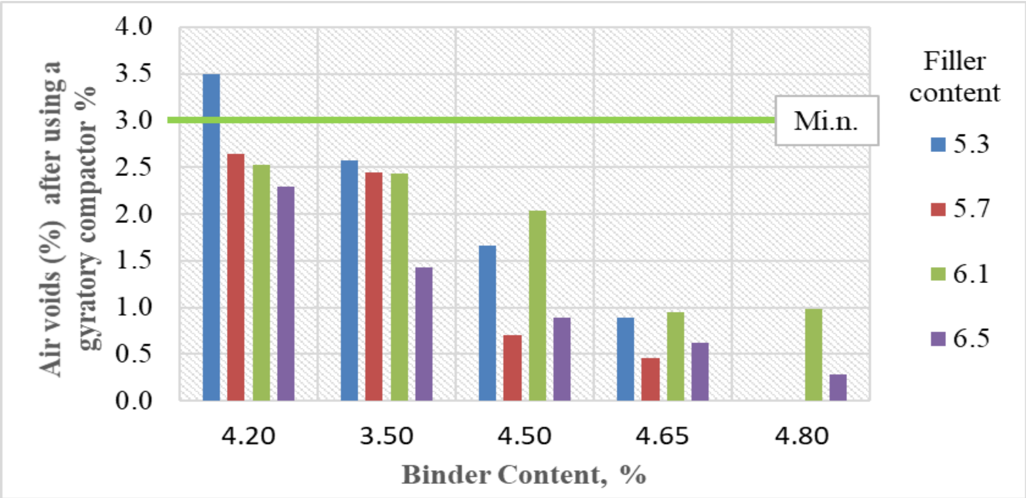


Figure 4.13: Relationship between bitumen content with Air voids after gyratory compaction

Additionally, choosing DBM mixtures prepared using the optimum filler content (5.7 percent) suggests that it takes less energy to compact mixtures with less bitumen to achieve the required air voids than those with more bitumen. The same trend was observed with the compaction effort using a vibrating hammer and a gyratory compactor. This is clearly shown in the strong correlation obtained between bitumen content and retained air voids R^2 = 0.9557, R^2 = 0.9736 and R^2 = 0.9034 in Figure 4.14, Figure 4.15 and Figure 4.16 respectively. Air voids in the compacted mixtures seem to be more sensitive to the change in the bitumen content. This is illustrated by the coefficient of determination, R^2.

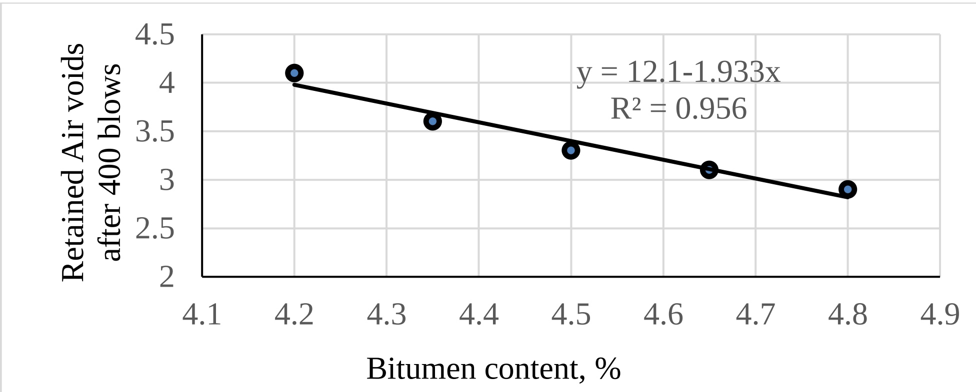


Figure 4.14: Impact hammer compaction at optimum filler content

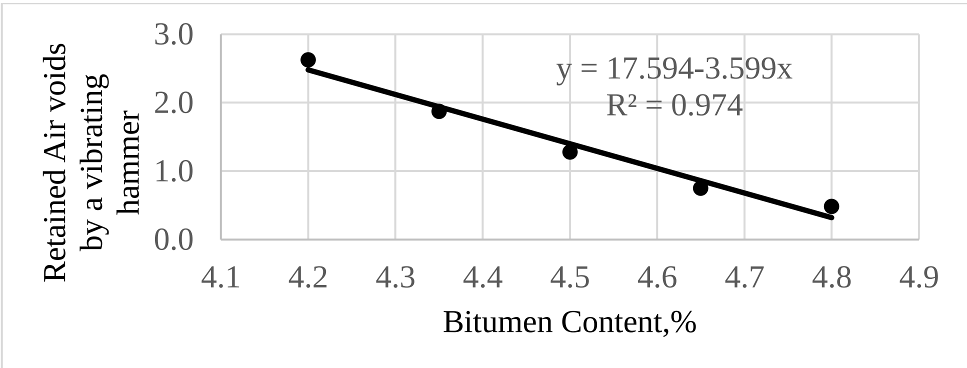


Figure 4.15: Vibrating hammer compaction at optimum filler content

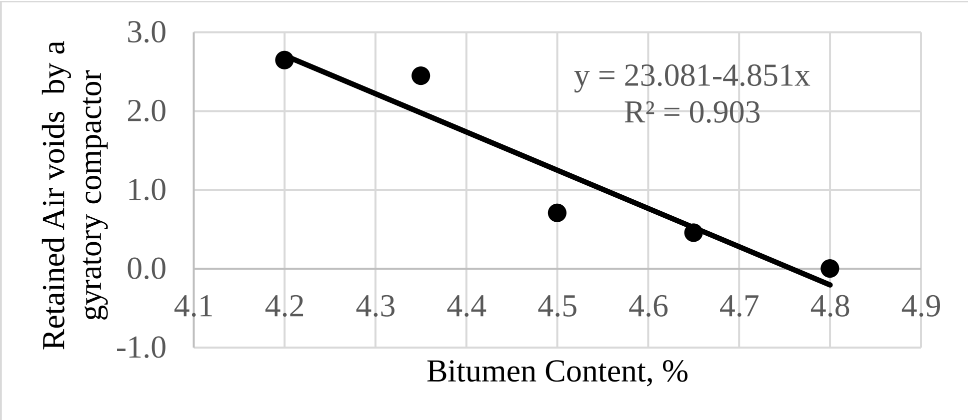


Figure 4.16: Gyratory compaction at optimum filler content

4.9 COMPARISON OF REFUSAL COMPACTION METHODS

It was observed that mixtures compacted using an automatic impact hammer, retained a reasonable amount of air voids as compared to those compacted using a vibrating hammer tool and a gyratory compactor. This is thought that once the asphalt mixture achieved the refusal density using the impact hammer, there was no further densification beyond the maximum attained. To a certain extent, there is a similarity in the operating mechanism between a vibrating hammer and a gyratory compactor. The vibrating compactor to a certain extent orients the aggregate particles in the mix similar to a gyratory compactor. That is why the results of the vibrating hammer and a gyratory compactor are close as shown in Table 4.15.

Since the vibrating hammer and gyratory compactor seem to compact more than an automatic compactor (Table 4.15), it would require designing asphalt mixtures with fewer concentration of fines than traditional mixtures. With fewer fines, the asphalt is somehow porous to allow the concentration of air voids. The asphalt mixtures should be designed with too much voids content if a vibrating hammer or a gyratory compactor is recommended to be used as tools to prepare specimens for the percentage refusal density test.

The gyratory compactor exerts pressure on the entire surface of the specimen when compacting specimens which are not the same like for the impact hammer and a vibrating hammer. The force applied by a gyratory compactor on specimens is continuous up to the end of the compaction process so, there is no loss in temperature during compaction. This is not true when an impact hammer or a vibrating hammer is used to compact specimens whereby temperature loss is higher. For that reason, the degree of compaction is expected to be higher in specimens when a gyratory compactor used.

Aggregates tend to break when an impact hammer was used and this contributed to higher air voids in the compacted specimens. The method of compaction exposes the mixture to a sudden impact which induces larger aggregate particle sizes to split into pieces. Breakage of aggregates in the mixture does not happen when a vibrating hammer or a gyratory compactor is used.

The sample sizes for all the specimens differ whereby the smaller sample loses temperature faster than the larger sizes. In this case, specimens prepared for the gyratory compactor tend not to lose temperature as compared to those prepared to be compacted using a vibrating hammer and impact hammer tools. The faster the temperature loss the less the specimens are compacted and hence higher retained air voids. The process of transferring the samples from the oven to the machine, and changing from one side to the other the temperature is lost. This procedure applies to both the impact hammer and the vibrating hammer samples.

Table 4.15: Retained air voids for the three compaction methods

EVALUATION OF RETAINED AIR VOIDS FOR THE THREE COMPACTION METHODS AND TOOLS					
Filler Content of mix, $P_{0.075}$	Bitumen Content of mix, Pb	Dust to binder ratio P0.075/Pb	Retained Air voids after 400 blows	Retained Air voids by a vibrating hammer	Retained Air voids by a gyratory compactor
%	%		%	%	%
5.3	4.20	1.26	8.2	7.0	3.5
5.3	4.35	1.22	8.3	5.5	2.6
5.3	4.50	1.18	6.3	3.3	1.7
5.3	4.65	1.14	4.6	3.1	0.9
5.3	4.80	1.10	4.2	2.9	0.0
5.7	4.20	1.36	4.1	2.6	2.6
5.7	4.35	1.31	3.6	1.9	2.4
5.7	4.50	1.27	3.3	1.3	0.7
5.7	4.65	1.23	3.1	0.8	0.5
5.7	4.80	1.19	2.9	0.5	0.0
6.1	4.20	1.45	4.3	3.6	2.5
6.1	4.35	1.40	3.9	1.6	2.4
6.1	4.50	1.36	3.2	1.2	2.0
6.1	4.65	1.31	3.1	0.6	1.0
6.1	4.80	1.27	2.6	1.1	1.0
6.5	4.20	1.55	2.8	1.3	2.3
6.5	4.35	1.49	2.4	1.0	1.4
6.5	4.50	1.44	1.6	0.9	0.9
6.5	4.65	1.40	1.1	0.5	0.6
6.5	4.80	1.35	0.9	0.2	0.3

The Marshall compaction method, the vibrating hammer compaction method and the gyratory compaction method were used to investigate their impact when used to compact DBM mixtures. The compacted specimen prepared using the three tools mentioned above, were checked for retained air voids. The values achieved by the gyratory compaction method measured the highest impact. The method allowed almost no air voids in most mixtures of varying contents of filler and binder. It was followed by the vibrating hammer method where the compacted specimens retained almost similar results of retained air voids achieved after using a gyratory compactor. Lastly, the Marshall impact compaction method measured the least impact where almost all mixtures, apart from the one recorded with the highest filler content (6.5 percent) shown in Figure 4.14 below. The specimens produced using the Marshall impact compaction method has the best test accuracy as opposed to the vibrating hammer method and gyratory compaction mechanism. When the filler content remains fixed, the average air voids in compacted specimens are reduced with increasing binder content by at least 35 percent when the Marshall compactor was used, those compacted using a vibrating hammer air voids reduced by 75 percent, and those compacted using a gyratory compactor air voids reduced by 95 percent. Comparing the three compaction methods used in this research, if the designer is to choose either a vibrating hammer or a gyratory compactor to test specimens in a way of simulating secondary compaction by traffic, one is to design a mix with a fewer add-ons or without filler for better results.

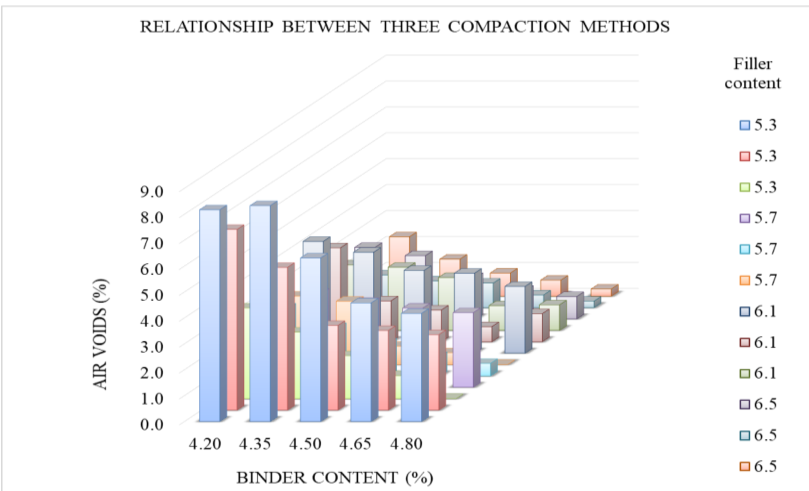


Figure 4.17: Relationship of three compaction methods

4.10 CHAPTER SUMMARY

A mix design is a laboratory undertaking process used to determine the appropriate proportionate quantities of aggregate and amount of bitumen binder for use in bitumen macadam. The mix design process manipulates three variables: (1) aggregates, (2) bitumen binder, and (3) the ratio of aggregates to bitumen binder content to obtain a mix resistant to deformation, resistant to fatigue, resistant to low temperature cracking, durable, resistant to moisture damage, resistant to skidding and workable. Mix design has many limitations but has proven to be the most cost-effective method in constructing roads to carry heavy traffic loads.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, a summary of the key issues discussed in each of the previous chapters is presented, with particular attention paid to the main conclusions obtained from the study. Some recommendations for future research are also suggested at the end of the chapter.

5.2 CONCLUSIONS

The major outcome of the research study was to appreciate DBM mixtures when different contents of filler and binder were used in relation to durability. The study also evaluated for the laboratory compaction efforts (an automatic Marshall impact hammer, an electrically operated vibrating hammer and a gyratory compactor) on retained air voids. The design of DBM mixtures with varied filler and binder contents was followed by the research. Based on experimental work covered by this report and within the limitations of the test procedures, materials and conditions used in this study, the following conclusions are warranted.

The proportion of filler and binder contents in a bituminous mixture is critical and must be precisely determined at design. Therefore, the design mix formula developed in the laboratory should be treated as a guide in the mix design only, primarily used to estimate the contents of filler and binder close to optimum. The finer the mix gradation, the larger the total surface area of the aggregate and the greater the amount of bitumen required to uniformly coat the particles. Conversely, coarser mixes have a less total aggregate surface area, they demand less bitumen. The relationship between aggregate surface area and optimum binder content is most pronounced where filler material is involved.

Small increases in the amount of filler in a gradation can absorb much of the bitumen binder, resulting in a dry, unstable mix. Small decreases have the opposite effect i.e. too little filler results in the too rich mix. Variations in filler content cause changes in mix properties, from dry to wet. The relative proportions of the materials determine the physical properties of the mix, and ultimately, how the mix will perform as a finished pavement. Minor deviations in filler and/or binder content can usually be tolerated if the required volumetric properties are met. Mixtures with insufficient binder will always have higher air voids and such mixtures are brittle and such mixtures are prone to ingress of air and water hence oxidation.

For a selected gradation for any aggregate type, the filler content should be relative to the chosen compaction effort to be applied to compact specimens for the percentage refusal density test. When the contents of the DBM mixture had more mineral filler, it was easy to compact so an appropriate amount of mineral filler improves the workability of mixtures and contribute to compaction. Adding mineral filler to an asphalt mixture with more filler content beyond the maximum amount will not do good to compaction any longer; this is because excessive mineral filler will make mixtures dry and hard and do harm to compaction. When the content of coarse aggregate is kept constant, the mixture having more mineral filler and bitumen has a smaller air voids and density increase is attained. The asphalt mixture having enough fine aggregate but lacking enough mineral filler is more difficult to compact and the final air voids is high.

It was observed that different laboratory asphalt compaction tools and methods produce samples with different retained air voids. The influence of the compaction method on the retained air voids of the mixes appeared to be mixture dependent. Even though the specimens prepared using an impact hammer yielded the best results, an electrically vibrating tool simulated more of the field compaction than the Marshall impact hammer tool and a gyratory compactor. Specimens prepared using an electrically operated vibrating tools for PRD test must have comparable thickness to that to be laid on the road. The element of impact and kneading was observed during the preparation of DBM specimens using the electrically operated vibrating hammer. This is almost what happens in the field when compacting laid DBM mixtures whereby the initial compaction of the paved asphalt mixture is done using a steel double drum roller without vibration (kneading) and followed by two double drum roller passes with vibration (impact) and lastly with the dynamic rollers (kneading). Therefore, the best compaction method is an electrically vibrating hammer for mixtures designed using the Marshall method.

5.3 RECOMMENDATIONS

i) Though in most cases, the optimum binder content is selected based on the compacted specimens having retained 4 percent air voids, selection requires more of the engineering judgment, depending on traffic, climate and experience with the local materials used.

ii) The results of this research work are thought to be used as the basis for further investigation on the effect of inert filler and binder contents to improve asphalt mixtures as well as find the best ranges.

iii) The desired properties of any DBM mix should be checked and verified using the plant produced, laboratory compacted DBM mixture. Tests should be run to determine the characteristics of the mix being manufactured.

iv) DBM mixtures designed following the Marshall criteria, will always be simulated for further densification by traffic using the extended Marshall method of compaction. The procedure helps the designer to closely compare the size of the specimens, visually tell the extent of coarse aggregate breakages if any. The sizes of the specimens prepared using an electrically vibrating hammer and a gyratory compactor, are not comparable. The specimens for both normal and extended Marshall test should be prepared at the same time to maintain similar conditions. Thus, the conditioning period and temperature regulation for DBM mixture to fabricate specimens should be similar in order to achieve comparable results. Since the specimens are small in size, the quartering of the DBM mixture should be carefully done to have specimens with balanced material.

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