PERFORMANCE PREDICTIVE MODEL FOR SISAL-PLASTIC MODIFIED ASPHALT CONCRETE FOR ROAD PAVEMENT

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Performance predictive model for sisal-plastic modified asphalt concrete for road pavement

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as University Supervisors.

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DEDICATION

I dedicate this thesis to God Almighty my creator, my strong pillar, my source of inspiration, wisdom, knowledge and understanding. I also dedicate this work to my family who have taught me that the best kind of knowledge to have is that which is learned for its own sake. They have taught me that even the largest task can be accomplished if it is done one step at a time.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Asphalt concrete
AIV	Aggregate impact value
COPF	Cellulose oil palm fibre
CRRI	Central Road Research Institute (India)
GGA	Gap graded asphalt
HDPE	High density polyethylene
HMA	Hot mix asphalt concrete
ITS	Indirect tensile strength
JKUAT	Jomo Kenyatta University of Agriculture and Technology
LDPE	Low density polyethylene
MAC	Modified asphaltic concrete
MC	Moisture content
MDD	Maximum dry density
MOGA	Modified open graded asphalt
MGGA	Modified gap graded asphalt
MQ	Marshall quotient
MSMA	Modified stone matrix asphalt
OBC	Optimum binder content
OFC	Optimum fire content
OGA	Open graded asphalt
OPC	Optimum plastic content
OSC	Optimum sisal content
PET	Polyethylene terephthalate

PMOGA	Plastic modified open graded asphalt
PMSMA	Plastic modified stone matrix asphalt
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
SBS	Styrene butadiene styrene
SF	Sisal fibre
SLDW	Sisal leaf decortications waste
SMA	Stone matrix asphalt
SMOGA	Sisal modified open graded asphalt
SMSMA	Sisal modified stone matrix asphalt
SPMAC	Sisal-plastic modified asphaltic concrete
SPMACM	Sisal-plastic modified asphalt concrete mixes
SPMOGA	Sisal plastic modified open graded asphalt
SPMSMA	Sisal plastic modified stone matrix asphalt
SPOGA	Sisal plastic open graded asphalt
TSR	Tensile strength ratio
VFB	Voids filled with bitumen
WMA	Warm mix asphalt
WP	Waste plastic

ABSTRACT

Preserving road network requires a coordinated approach for good performance and efficient movement of goods and services. The road construction materials and design have great influence on future road conditions and maintenance scenarios. Weather changes and increase in traffic loads have exposed pavements to major distresses such as rutting, potholes, fatigue cracking, and temperature cracking. These forms of pavement failure cause traffic congestion, loss of man hour, increase in wear and tear of the vehicle and increase in road accidents. There is loss of money in frequent road repairs, vehicle repairs and treatment to the injured persons. Therefore, there is need to increase the load-bearing capacities of road pavements. The aim of this study was to investigate the performance of sisal-plastic modified asphalt concrete for road pavements. The properties of modified gap graded asphalt concrete was evaluated through characterization of asphalt concrete mixes modified using sisal fibre and waste plastics. Sisal fibre and plastic wastes were used as asphalt concrete stabilizers and modifiers respectively to enhance stability against bitumen drain down, bleeding and cracking. Clean waste plastics were cut into small sizes so as to pass through 2-3 mm sieve using shredding machine. The aggregate used in preparation of gap graded asphalt (GGA) were sizes 20-6mm for stone matrix asphalt (SMA) concrete and 12-6mm for open graded asphalt (OGA) concrete. The respective aggregate mix was heated and the waste plastics effectively coated over the aggregate. Sisal fibre was cut into 5 mm long threads, treated using sodium hydroxide solution and mixed with hot bitumen. The waste plastic coated aggregate was mixed with the mixture of treated sisal fibre and bitumen. Sisal fibre treated in 0.5N solution of sodium hydroxide makes sisal fibre become less porous with high density thus making more rigid asphalt concrete mix. The treatment improves the adhesion due to increase in surface tension and surface roughness. The asphalt concrete mix samples were analyzed for various engineering properties to assess their suitability for road pavement construction. The samples were subjected to different performance tests, namely, Marshall Test, drain down test and indirect tensile strength test. Using the Marshall procedure, the optimum additive contents were determined as 0.3% for sisal fibre and 5% for waste plastics in asphalt concrete mixes respectively. The Optimum Binder Content (OBC) values determined were 5.5% and 6.5% for open graded asphalt (OGA) and stone matrix asphalt (SMA) respectively. The stability test result values for both gap graded asphalt (GGA) concrete were 11.8kN and 12.8kN when modified with sisal fibre and waste plastics respectively. However, when sisal and plastics were both used, the stability values recorded were 13.6kN and 12.9kN for sisal-plastic modified OGA and sisal-plastic modified SMA respectively. The tensile strength test value determined was 1.23MPa for both sisal-plastic modified gap graded asphalt concrete. The tensile strength ratio was 99.9% while bitumen drain down value determined was 0% for both sisal-plastic modified gap graded asphalt concrete. A mathematical model was developed to predict the tensile strength of sisal-plastic modified asphalt concrete. The model was found to be adequate with 97.5% confidence level. A model road pavement consisting of control section and sisal-plastic modified were constructed. There was no bleeding, rutting, cracking or aggregate loss observed on modified section. However, the control section had 2mm settlement and loss of aggregate was observed. In conclusion, the use of this innovative technology in the usage of sisal

and waste plastics will strengthen the road pavements by 99%, reduce loss of bitumen by 100%, increase the roads' service life by 99% and help in the improvement of the environment through utilization of waste plastics. Hence, sisal-plastic modified OGA and SMA mixture provide better resistance against permanent deformations due to their high stability and high MQ. This technology contributes to recirculation of plastic wastes to protect the environment. The effective utilization of the sisal fibre and waste plastics will result in substantial increase in the scrap value for sisal and waste plastics. This will also lead to an ecofriendly sustainable construction method. It is recommended that sisal-plastic modified road section can be constructed on a busy road and monitored for longer period exceeding five years so as to evaluate its performance characteristics under prolonged heavy traffic loads.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

There are two types of road pavements, namely, rigid road pavement and flexible road pavement. Rigid road pavements are constructed using concrete while bitumen is used for construction of flexible road pavements. In Kenya, flexible road pavements are the most used road infrastructure. The classified road network in Kenya has increased from 41,800 km to 63,575km since the year 1963 to 2019. The roads that are in good condition and are maintainable are 44,100 km while 18,900 km requires rehabilitation or reconstruction. This represents 70 and 30% of road network, respectively (KeNHA, 2019).

Increase in axle load and traffic intensity weakens the bituminous binders and damages the road pavements (Swami et al., 2012). Weakening of bituminous binder causes bleeding in hot climate, cracking in cold climate, hence development of ruts and potholes. The road pavement is rendered impassable because of the deplorable condition (Dixit & Rastogi, 2013). The increase in traffic intensity, especially with regard to commercial vehicles coupled with variations in daily and seasonal temperature requires improved road characteristics by modifying the asphalt concrete. Road pavement failure causes a lot of inconvenience to users. Impassable roads results into loss of time, increases chances of accident occurrence, loss of revenue and damage to vehicle which impacts negatively on the country's economy. Pavement failure phenomena can be reduced by strengthening load bearing capacity by modifying asphalt concrete to meet the increasing traffic loads by use of stabilizers and modifiers such as sisal fibre and waste plastics. In this regard new road construction techniques and better road construction materials can be of great help in Kenya's road construction industry. Improvements are specifically needed in the property of the asphalt concrete used so as to enhance its load bearing capacity.

Increase in population and rapid industrial growth has resulted in increase in generation of various types of waste materials such as waste plastics. There is rising use of plastics as packaging materials for food and other essentials commensurate with rise in the amount of waste plastics being generated daily. Plastic in different forms is found to be almost 20% in municipal solid waste, which is toxic in nature (Kasozi and Harro, 2010). Waste plastics are user-friendly but not eco-friendly. These wastes consist of carry bags, cups, plastic bag wrappers and plastic bottles. These waste plastics are non-biodegradable material and are therefore not environmentally friendly (Bhardwaj & Dhriyan, 2015). In Nairobi alone, the consumption of plastics has increased to 2,400 tons per day of solid wastes, of which 20% comprises of waste plastics. 50 to 60% of the total plastic generated is light polythene carrier bags for packaging (Wachira, 2014) while the rest are high and low-density polyethylene. In the year 2017, use of plastic carrier bags was banned in Kenya. This reduced the generation of light polythene carrier bags (NEMA, 2018). However, the ban did not include high-density polyethylene (HDPE) and low-density polyethylene (LDPE) type of waste plastics (NEMA, 2018). When waste plastics are disposed of, they do not undergo bio-decomposition. They are either land-filled or incinerated. These two methods of waste plastic disposal are not ecofriendly. They pollute both the air and the land (Rajasekaran *et al*., 2013). Waste plastics are made of different chemical elements. They are highly pestilent materials which do not decompose in the natural environment. Therefore, the disposal of waste plastic is a serious challenge and if burnt, they cause environmental pollution.

Experiments have been carried out to determine whether waste plastic can be reused in road construction. Analysis done have found out that waste plastics can be used as modifier in the production of asphaltic concrete to improve its engineering characteristics (Dixit & Rastogi, 2013). When waste plastics are added to hot aggregate, they form a fine coat of plastic over the aggregate. The coated aggregate, when mixed with the binder is found to give higher strength, higher resistance to water and better performance over a period of time (Bindu & Beena, 2014). Use of waste plastics in road construction increases its life span, makes it economically sound and environment friendly (Prasad, 2012). Roads constructed using plastic waste can perform better compared to those constructed with conventional bitumen and are not subjected to stripping when in contact with water (Poweth *et al.*, 2013).

Waste plastics increases the strength and performance of the road (Vasudevan *et al*., 2007). Incorporating plastic materials in road construction reduces shrinkage and road surface cracking. It improves the abrasion and slip resistance of flexible pavement (Rajasekaran *et al*., 2013). However, stabilizing additives such as coil, glass and sisal fibres are needed to prevent bitumen drain down from the asphalt concrete mix. Fibre tend to perform better than polymers in reducing the drain down (Gawande *et al*., 2013). Addition of sisal fibre to asphalt mix enhances material strength and fatigue characteristics while increasing ductility. It also prevents bitumen drain down during transportation and laying of concrete mix (Raju *et al*., 2015). Therefore, a combination of waste plastics as modifiers and sisal fibre as stabilizers can produce strong asphalt concrete. Waste plastics binds aggregate particles together while sisal fibre prevents bitumen drain down. This would solve the problem of bitumen drain down and improve the strength of gap graded asphalt concrete.

This research has assessed the performance of sisal-plastic road pavement with ultimate aim of obtaining material for use in preparation of asphalt concrete mix which is adequately strong, durable, resistive to fatigue and permanent deformation, environment-friendly and economical. These road pavements would be useful for hot and humid climate such as Kenya.

1.2 Problem Statement

Bitumen used as a binder in the construction of flexible roads has various weaknesses. These include bitumen drain down and bleeding at high temperatures during storage, transportation, placement and compaction of asphalt concrete (Mazumder *et al.*, 2016). Further, oxidation of bitumen causes cracking and crazing phenomenon in asphalt while water absorption causes bitumen which is hydrophilic to strip off aggregates. This causes asphalt fatigue, rutting, cracking and the ultimate pothole formation when exposed to heavy traffic loading (Soni *et al*., 2013). Over the years, road failure in Kenya has been largely due to the hardening of bitumen and increased traffic loading (Mulei *et al*., 2002). Premature road pavement failure causes increased occurrence of road accidents leading to injuries and loss of lives.

Many families in the process lose their bread winners or spend a lot of money to offset medicals bills. The family's savings are utilized in medical care, money which could have been utilized in income generating projects. By extension, the country's economy is adversely affected due to productive persons no longer being able to work and contribute to economic development. When a road is in deplorable condition, there is increased tear and wear on vehicles and reduced traffic. Vehicles also have to move at low speeds, causing congestion and loss of valuable man-hours resulting into loss of revenue to government and income to individual persons. Frequent road repair, results into huge loss of money and denies other sectors of economy the much-needed resources such as healthcare, security and food.

On the other hand, disposal of waste plastics by burning or burying causes environmental pollution. Gases that emanates from burning plastics causes air and water pollution. Air pollution causes respiratory diseases while water pollution causes damage to animal and human health. The pollutants destroy the environment by affecting vegetation and living organisms. As a result, a lot of resources is utilized in treating and managing sicknesses. Emission of gases from burning waste plastics contribute to ozone layer depletion, causing climate change which results into crop failure and extreme weather conditions such as floods and drought. Ultimately, there is destruction of lives by landslides, floods and luck of food.

Lack of existing model to predict the performance of modified asphalt concrete for road pavement has resulted into expressive and tedious laboratory trial tests. This causes waste of money and time in sourcing testing the samples which could have been utilized in actual construction of the road pavement.

1.3 Objectives

1.3.1 Main Objective

The main objective of this study was to assess the performance predictive model for sisal-plastic modified asphalt concrete for road pavement.

1.3.2 Specific Objectives

The specific objectives of the study were:

i. To assess the properties of the aggregates, bitumen and waste plastics used in the formation of modified asphalt concrete.
ii. To assess the properties of open graded and stone matrix asphalt concrete modified with sisal fibre and waste plastics.
iii. To develop and validate a mathematical model for predicting the performance of asphalt concrete modified with sisal fibre and waste plastics.
iv. To evaluate the performance of a model-section of a road constructed using sisal-plastic modified asphalt concrete.

1.4 Justification and Significance of the study

Utilizing wastes plastics and sisal fibre increases road pavement strength. Sisal-plastic modified road pavements have high load bearing capacity resulting from increased traffic loads. They are more resistance to failure by cracking or rutting. As a result, frequent road repair and reconstruction of pavement are eliminated. Deaths, injuries and diseases resulting from road accidents, environmental pollution and crop failure are reduced. Therefore, money that could be spent in treatment, medication and food is channeled into other projects and economic activities. This spur economic growth of a country. Use of waste plastics in pavement construction offers a better solution for disposal. Utilization of sisal fibre as bitumen stabilizer offer good market for it locally. Sisal-plastic modified asphaltic concrete pavement is strong, resistance to cracking and rutting. The waste plastics binds aggregate particles together as sisal fibre prevents loss of bitumen through drain down. The construction of sisal-plastic road pavements, will help reduce costs resulting from frequent road repairs, loss of man-hours and lives, and vehicle maintenance.

The use of predictive mathematical model developed will reduce the tedious and costly process of determining the effect of varying quantities of sisal fibre and waste plastics on the performance of modified asphalt concrete. The model would ensure appropriate number of modifiers and stabilizers are used to design a strong pavement that resist cracking and rutting when under heavy traffic loads. This research work is useful to road agencies like Kenya Urban Roads Authority (KURA), Kenya National Highways Authority (KeNHA), Kenya Rural Roads Authority (KeRRA), road engineering consultants and contractors.

1.5 Research hypothesis

i. Aggregates, sisal fibre and waste plastics used in preparation of gap graded asphalt concrete meet the standard specifications when tested under specified conditions
ii. Open graded and stone matrix asphalt concrete modified using sisal-plastics perform better on Marshal properties, bitumen retention and tensile strength than when modified with sisal fibre or waste plastics separately.
iii. The mathematical model for use in the prediction of tensile strength of modified asphalt concrete is accurate.
iv. Model-section of a road constructed using sisal-plastic modified asphaltic concrete (SPMAC) performs better than control section.

1.6 Scope of the study and limitations

1.6.1 Scope of the study

- Bitumen class 80/100 was used as the binder in preparation of the mixes in sample preparations. Aggregates, sisal fibre and waste plastics were sourced from local quarries in Mulolongo, Kitui and Dandora dumpsite respectively.

- Model road sections were constructed near fundilima offices, road leading to JKUAT primary school, JKUAT, Juja campus, Kenya. The construction was done in accordance WITH road design manual part III (RDM III) and evaluation of the road performance was done after g accelerated traffic loading. The modified open graded asphalt was laid on existing road base stabilized with 4% cement and compacted using a seven-tone roller at 95% maximum dry density (MDD).

- The control section and modified section of the model section were evaluation for a period of six months to check for rutting, cracking, patching, bleeding and deformation. Accelerated traffic loading was done by passing 7-20 Tons commercial vehicle, at least 50passes a day over the model sections to conform to traffic class T_5.

1.6.2 Limitations of the study

i. The model road pavement sections evaluation period was 6 months. Longer period in conformity to 15 years design life of the pavement could be used for better assessment of durability of asphalt concrete modified with waste plastics and sisal fibre. However accelerated traffic loading where at least 50 passes of commercial vehicle were done daily on each section produced traffic that conform to class T_5.

ii. The section requires exposure to high traffic loads which could be found on busy roads exposed to commercial vehicles. This was mitigated by passing seven to twenty tons Lorries which have high damaging effect to pavements.

iii. Laying of asphalt concrete was done manually instead of paving machine. However, spreading was done evenly and regulated using a rake while taking levels to ensure uniformity.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This thesis research evaluates the use of waste plastics and sisal fibre in asphalt concrete for road construction. Herein, materials such as aggregates, plastics, sisal fibre and bitumen have been discussed as useful materials in flexible road pavements. Flexible road pavement consists of surface course, binder course, base course, and subbase course and subgrade layer. Wearing course and binder course are composed of asphalt concrete. Sisal fibre and waste plastics are used as stabilizer and modifier for asphalt concrete respectively to modify both open graded asphalt concrete and stone matrix asphalt concrete. The modified open graded asphalt is used in the construction of wearing course while stone matrix asphalt is used in the construction of binder course. The literature review covers both theoretical and empirical literature on asphalt concrete composition, pavements, pavement failure and review of past researches on asphalt concrete additives and stabilizers.

2.2 Properties of materials used in formation of asphalt concrete

2.2.1 Aggregates

Aggregates are inert materials like sand, gravel, crushed stone and rock dust. They mixed with bitumen as binding medium to make asphalt concrete (AASHTO M 147, 2017). Aggregates are extracted from large rocks by crushing them to usable sizes by means of mechanical crushing (Alam *et al*., 2015). Clean and graded aggregates are mixed with the bitumen to make wearing course and binder course for flexible pavements. They are the major load-bearing component of an asphalt concrete pavement. The aggregates physical properties such as size, toughness and abrasion resistance have the greatest effect on the quality of asphalt concrete. These physical properties determine the load bearing capacity of road pavements and resistance to failure. The open graded aggregates sizes are 12/6mm while stone matrix aggregate sizes are 20/6mm. Both aggregate sizes should have crushing and abrasion values of less than 30% (Mazumder *et al.*, 2016).

Particle size distribution characteristics of aggregates determines how they perform as a pavement material. Gradation determine asphalt concrete properties such as stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and moisture susceptibility. Therefore, gap graded aggregates with large aggregate sizes contributing up to 70% produce asphalt concrete with higher stiffness, stability, fatigue and frictional resistance (Roberts *et al*., 1996). This is possible as a result of stone to stone contact that enhances cohesion due to interlocking of the particles.

Aggregates undergo wear and tear; hence, they should be hard and tough enough to resist crushing, degradation and disintegration during manufacturing, stockpiling, production, placing and compaction (Mazumder *et al.*, 2016). They should be able to adequately transmit loads from the pavement surface to the underlying layers and eventually to the subgrade. Aggregates that are not adequately resistant to abrasion and polishing will cause premature structural failure and loss of skid resistance (Zhang *et al*., 2001). Toughness or hardness is the ability of the aggregate to resist crushing or disintegration during mixing, placing, and compacting; or under traffic loading. Although similar to toughness, soundness is the aggregate's ability to resist deterioration caused by natural elements such as the weather (Wang, 2011). The shapes of aggregate particles influence the asphalt mixture's overall strength and workability as well as the density achieved during compaction. When compacted, irregular particles such as crushed stone tend to 'lock' together and resist displacement. Workability and pavement strength are influenced by surface texture. A rough texture results in a higher strength than a smooth texture. Smooth aggregates are easy coated with bitumen but form weak asphalt concrete compared with rough interlocking aggregates because reduced 'grip' on the smooth surface aggregates. The porosity of an aggregate permits the aggregate to absorb asphalt and form a bond between the particle and the asphalt. Soil particles, foreign or deleterious substances make aggregates unsuitable for making asphalt concrete for road pavement (Speight, 2014).

2.2.2 Waste Plastic

Plastics are materials that contain one or more organic polymers of large molecular weight and describe a wide variety of resins or polymers with different characteristics and uses (Jawaid *et al.*, 2018). Polymer can be used as a synonym for plastic although other types of molecules such biological and inorganic are also polymeric. Plastics are durable and degrade very slowly because their chemical bonds are very strong, making the materials resistant to natural processes of degradation. Plastics are grouped into two categories such as thermosets and thermoplastics (Horath, 2017).

Thermosets undergo a chemical change when they are heated and solidify irreversibly. Since they are durable and strong, they are used in automobiles and construction works. Examples of thermoset plastics are polyethylene, polypropylene, polyamide, polyoxymethylene, polytetrafluorethylenes and polyethylene terephthalate (Horath, 2019; Jawaid, 2018).

Thermoplastics soften when exposed to heat, and return to original condition at room temperature. Thermoplastic polymers can be heated and formed, then heated and formed again and again. The shape of the polymer molecules is generally linear or slightly branched. This means that the molecules can flow under pressure when heated above their melting point. Thermoplastics can easily be shaped and molded into products such as milk jugs, floor coverings, credit cards, and carpet fibre. These plastic types are known as phenolic, melamine, unsaturated polyester, epoxy resin, silicone, and polyurethane (Horath, 2019; Jawid, 2018).

In Kenya, plastic waste forms the largest proportion of solid waste. The convenience and cost-effectiveness associated with plastics has translated to massive increase in use of plastics. Added to this is increased urbanization that has triggered increased plastic bag waste generation (Wachira *et al*., 2014). Over 24 million plastic bags are used monthly in Kenya, half of which end up in the solid waste mainstream. Waste plastics constitute the biggest challenge to solid waste management in Kenya. Waste plastics of various sizes and colours are available. The expansion of plastic production and consumption is having a significant impact, both visibly and invisibly on the socio-physical environment in Kenya (Ikiara *et al*., 2004). A study reveals that most people around the 26.5-hectare Dandora dumpsite breathe in the smoky air and many complain of respiratory, abdominal and intestinal complications, and even malaria, (UNEP, 2007). Many of Nairobi's poor engage in collection of waste as a means of income generation. Scavengers are estimated to collect 20 tonnes of the approximately 800 to 1000 tonnes generated daily in Nairobi (Wachira *et al*., 2014).

Waste plastics are classified on the basis of the polymer from which they are made. They are mainly divided into these 7 types; namely polyethylene Terephthalate (PET), High Density Polyethylene (HDPE), Polyvinyl Chloride, Low Density Polyethylene, Polypropylene and Polystyrene. Terephthalate (PET) are used in the manufacture of plastic soft drink and water bottles, beer bottles, mouthwash bottles, salad dressing containers, boil-in food pouches, processed meat packages. High Density Polyethylene (HDPE) make Milk bottles, detergent bottles, oil bottles, toys and plastic bags, while PVC (Polyvinyl Chloride) make food wrap, vegetable oil bottles, blister packaging. The Low-Density Polyethylene (LDPE) are materials such as bread bags, frozen food bags, squeezable bottles, fibre, tote bags, bottles, clothing, furniture, carpet, shrink-wraps and garment bags. PP (Polypropylene) make margarine and yoghurt containers, caps for containers, wrapping to replace cellophane while PS (Polystyrene) are materials that make egg cartons, fast food trays and disposable plastic silverware (Jawaid *et al*., 2018).

Waste plastics suitable for modification of asphalt concrete should be compatible with bitumen in binding and bonding of aggregates. This leads in reduction of pores in aggregate thereby reducing rutting and aggregate raveling. They should be capable to resist degradation at asphalt mix temperatures during processing and laying. The waste plastics should give rise to coating viscosity at 105^0C and maintain their premium properties during storage, transportation application of asphalt concrete. Waste plastics are meant to improve the moisture susceptibility of asphalt concrete to enhance the strength (Abiola *et al*., 2014). Both low density polyethylene (LDPE) and high-density polyethylene (HDPE) meet these requirements and therefore qualify as suitable polymer for bitumen blending (Bindu *et al*. 2010). Manufacturing, sale and distribution of plastic carrier bags made from low density polyethylene was banned in Kenya in the year 2017. However, waste plastics such as milk bottles, detergent bottles, and oil bottles, toys vegetable oil bottles, bread bags, frozen food bags, squeezable bottles and water bottles are still in use and are available in large quantities. These waste plastics were used in the modification of asphalt concrete samples.

2.2.3 Sisal fibre

Sisal fibre is naturally available material which is produced from sisal plant and is extracted by a process known as decortication. This is a process through which the leaves are crushed and beaten by a rotating wheel set with blunt knives, so that only fibres remain (Figure 2.1). Sisal fibre has been used as a stabilizing additive for improving the engineering properties of gab graded bituminous mix because it is durable, anti-static and recyclable (Dash *et al*., 2016). When coated with bitumen, it becomes exceptionally durable and non-biodegradable (Moghaddam *et al*., 2014; Kamil, 2012). It can be used as an additive in asphaltic concrete as an effective stabilizing agent. The role of a stabilizer is to stiffen the mastic, thereby reducing drainage of the mixture at high temperatures during storage, transportation, placement and compaction of asphalt concrete (Naveen *et al*., 2019).

Figure 2.1 : Sisal fibre from Kitui

The quality of sisal fibre depends on moisture content, hence proper drying is important (Ziska *et al*., 2014). Sisal fibre has a density of 1.45 g/cm^3, tensile strength of 468-640 MPa and elongation at break of 3-7%. They are recyclable, anti-static and do not absorb moisture or water easily. They also exhibit good sound and impact absorbing properties (Badshah *et al*., 2015). Sisal fibres are preferred in the modification of asphalt concrete because of their strength, durability, ability to stretch and resistance to deterioration (Kar, 2012). Based on these qualities, sisal fibre can be used to strengthen asphalt concrete and act as a modifier to reduce bitumen drain down.

2.2.4 Bitumen

Bitumen is used as a binder that holds aggregates together firmly for pavement constructions. This is possible because of its adhesive properties and ability to be in liquid state when heated and solid when cool. It is derived from the residue left by the refinery from naturally occurring asphalt. Bitumen found in natural state known as asphalt contains large quantities of solid mineral matter (Vasudevan *et al*., 2007). When petroleum crude is refined, the various components are separated through fractional distillation in the order of decreasing volatility. The distillation of the residual bituminous residue produces straight-run bitumen which is known as penetration grade bitumen or steam-refined petroleum bitumen. The grade of straight run bitumen is chosen depending on the climatic conditions of the region in which surface dressing is to be constructed (Dixit *et al*., 2013). Viscosity of bitumen is made adequate by heating at the time of mixing and compaction. Bitumen suitable for road pavement construction, should be durable in all seasons. It should not become too soft during summer or develop cracks during winter (Rokade, 2012).

The common bitumen products used in road construction are cutback and emulsion. Cut back is often mixed with comparatively volatile solvents to improve workability of the material. The solvent gets evaporated, leaving behind the particles together. The cutback bitumen is classified into slow, medium and rapid curing, depending upon the type of solvent used. Emulsion is a mixture of two normally immiscible liquids. Asphalt gets broken up into minute globules in water in the presence of the emulsifiers. It improves the workability of bitumen or asphalt. As a result of emulsification, asphalt is available at normal temperature in the liquid form. The bitumen particle charge can be positive (cationic), negative (anionic), or uncharged (non-ionic), depending on the emulsifier employed. The binder can be either a bitumen, cutback, or modified bitumen. Bitumen emulsions are used largely in road surfacing applications, such as surface dressing, cold mixtures and slurry seals (Sandhya *et al*., 2013). Bitumen are grouped according to their penetration values. These are bitumen grade 60/70, bitumen grade 80/100, bitumen grade 85/100, bitumen grade 30/40, bitumen grade 40/50, bitumen grade 85/25, bitumen grade 90/15 and bitumen grade 115/05. Bitumen grade 80/100 is most suitable for asphalt pavements with superior properties to resist rutting and cracking under heavy traffic loads. This bitumen grade is used in the manufacture of hot mix asphalt for bases and wearing courses (Kishchynskyi1 *et al*., 2016). Bitumen has the following weaknesses such as bleeding, pavement cracking, crazing and stripping off of aggregates. Bitumen bleeding at high temperature is caused by bitumen softening thereby causing draining from aggregates. This weakens the asphalt concrete which leads to stripping of aggregates when exposed to water, creating potholes on roads. This is because bitumen is water repellent. Bitumen oxidation during asphalt concrete manufacture at high temperatures weakens the binding properties of bitumen. This may cause the pavement to develop cracks when under traffic loading (Rokade, 2012).

Bitumen’s thermoplastic and low strength makes it most sensitive to the effects of traffic loads and climatic factors when compared to aggregates component of asphalt concrete. Softening of bitumen during hot seasons causes rutting on pavements while cold weather causes low-temperature cracking (Kishchynskyi1 *et al*., 2016). To improve bitumen properties and increase asphalt concrete durability, bitumen has been modified by use of additives such as plastics, latex and terpolymers. These additives increase bitumen cohesive strength and heat resistance. They enhance elasticity and improve bitumen behavior at low temperatures (Kishchynskyi1 *et al*., 2016).

2.3 Types and properties of Asphalt concrete

Asphalt concrete is a mixture of a bituminous binder with mineral aggregate (stone), sand and filler. The properties of asphalt concrete are dependent on the type, size and amount of aggregate used in the mixture which are adjusted to provide the required road construction qualities (Haseeb, 2017). There are three major types of asphalt concrete based on their methods of preparation, namely; hot mix asphalt concrete, warm mix asphalt concrete and cold mix asphalt concrete.

2.3.1 Hot mix asphalt concrete

Hot mix asphalt concrete (HMA) is produced by mixing heated aggregates, fillers and bitumen. Dried aggregates are heated at 150°C for virgin asphalt concrete or 166°C for plastic modified asphalt concrete. Bitumen is heated at 95°C to decrease its viscosity before mixing with aggregates (Espersson, 2014). Paving and compaction is done while asphalt concrete is sufficiently hot during hot weather because in cold seasons, the compacted base cool asphalt concrete before compacting to the required density. HMA is used on high traffic pavements like major highways, racetracks and airfields (Maria, 2014). Hot mix asphalt concrete is resistant to all types of weather during rainy and dry seasons. It cools down quickly, thus allowing for minimal road closure times during construction. Hot mix asphalt concrete is durable for high traffic roads and highways. Its flexibility and malleability allow it to shrink and expand during different temperatures without cracking or rutting, thus makes it widely used in hot and cold areas (Hsu *et al*., 2017). These properties were considered in the use of HMA in carrying out this research which required heating and mixing aggregates with waste plastics at high temperature for effective coating. HMA is grouped into two major categories, namely; dense graded asphalt (DGA) and gap graded asphalt (GGA). Dense graded mix is an impermeable well-graded HMA mix which defined by nominal maximum aggregate size which range from 37mm to 10mm. Gap graded asphalt is HMA mixtures have less fines compared to dense graded asphalt concrete. Hence, they have high bitumen loss due to large pore spaces between the aggregate particles. The two main categories of gap graded asphalt are open graded asphalt and stone matrix asphalt.

Open graded asphalt (OGA) is used as wearing course in pavement construction so as to provide more safety in wet weather conditions, through reduced surface water and spray during rain. It also reduces traffic noise levels on a road pavement when there is traffic movement (Hamedi *et al*., 2017. Open graded asphalt is a porous gap graded asphalt mix whose aggregate sizes are 12/6mm and designed to provide large voids to allow surface water to drain away thereby improving the safety of the motorist. Potential associated with OGA mixtures are bitumen loss and bleeding due to large internal voids (Kar, 2012).

Stone matrix asphalt (SMA) is another type of gap-graded asphalt. It is designed to optimize resistance to deformation like rutting and increase durability. This is achieved through structural basis of stone-on-stone contacts of aggregates size 20/6mm. Since the aggregates are all in contact, rut resistance relies on aggregate properties rather than asphalt binder properties (Kumar *et al*. 2005).

2.3.2 Warm mix asphalt concrete

Warm Mix Asphalt (WMA) concrete is produced at lower temperatures by adding either zeolites, waxes, emulsions or water to bitumen before mixing with aggregates. WMA mixing is done at temperatures 30 to 120 degrees Fahrenheit lower than traditional hot-mix asphalt concrete. This allows lower mixing and laying temperatures and results in lower consumption of fossil fuels, thus releasing less carbon dioxide, aerosols and vapors (Hsu *et al*., 2017). Lower laying temperatures improves the working conditions and leads to more rapid availability of the surface for use, which is important for construction sites with critical time schedules (Jason *et al*., 2019). However, at low temperatures, modification of asphalt concrete cannot be effectively done since waste plastics should be heated at high temperatures for effective coating, laying and compaction (Chavan, 2013).

2.3.3 Cold mix asphalt concrete

Cold mix asphalt (CMA) concrete is made of water emulsified bitumen mixed with aggregate. When asphalt is emulsified it is less viscous and the mixture is easy to work and compact. Cold mix asphalt concrete is weak and only used to do small scale pavement repairs like temporary cracks and patches. (Federal Highway Administration, 2011). Due to areas of application, CMA cannot me modified using waste plastics since they require heating and mixing at high temperatures to effectively coat the aggregates (Chavan, 2013).

2.4 Road pavement failure

Pavements get weak due to bitumen drain down and get damaged by traffic overloading or extreme weather conditions such as rain runoff. Damages that are visible at the surface of the pavement are often called 'surface distress' (Sutter *et al*. 2016). Some of the notable pavement failures are bitumen loss, bleeding, cracking, shoving, potholes, raveling rutting and stripping.

2.4.1 Bitumen drain down

Drain down is that portion of the asphalt concrete mix of fines and bitumen that separates itself from the sample as a whole and flows downward through the mixture. Drain down test is very important for gap graded asphalt such as open graded and stone matrix asphalt mixtures than for conventional dense-graded mixtures. It is used to determine whether the amount of bitumen loss measured for a given bituminous mixture is within the specified acceptable levels. The test is mainly used for mixtures with high coarse aggregate content. The internal voids of the uncompacted mix are larger, resulting in high bitumen loss in gap graded asphalt concrete (Shukla *et al., 2014*). Storage and placement temperatures cannot be lowered to control bleeding and bitumen loss due to the difficulties in obtaining the required pavement compaction. Hence, stabilizing additives can be added to stiffen the mastic. This would increase bitumen retention of the mixture at high temperatures and obtain higher binder contents for increased durability (Aderson *et al*., 2001).

2.4.2 Pavement Cracking

These are series of interconnected cracks caused by fatigue failure of the surface under repeated traffic loading. When traffic loads are significantly high, longitudinal cracks begin to form usually in the wheel paths. After repeated loading, these longitudinal cracks connect forming many-sided sharp-angled pieces that develop into a pattern that resemble the back of an alligator or crocodile as seen in Figure 2.2 (Sutter, 2016).

Figure 2.2: Pavement cracking (Muriri-Isiolo road)

Increase in traffic loading, road surface shrinkage surface due to low temperatures or asphalt binder hardening result into development of cracks on road pavement (Sutter, 2016). Cracks allow water infiltration into the base and subgrade which ultimately result in potholes development and pavement disintegration. This pavement failure is caused by inadequate structural strength to support given traffic loading. Loss of adequate strength can result from a decrease in pavement load supporting characteristics. Due to poor drainage, there is loss of base, subbase or subgrade. Water under pavement causes the underlying materials to become weak. Stripping on the bottom of the pavement layer further weakens road pavement by decreasing the pavement thickness.

2.4.3 Bleeding

This is a film of asphalt binder on the pavement surface as shown in Figure 2.3. Bleeding creates a shiny, glass-like reflecting surface which becomes sticky when dry and slippery when wet. It occurs when bitumen expands onto the pavement surface after it fills the aggregate voids during hot weather or upon traffic compaction (Mahler *et al*., 2012). As a result of bleeding phenomenon, the pavement losses skid resistance when wet.

Figure 2.3: Pavement bleeding (Meru-Maua road)

Bitumen accumulate on the pavement surface over time during cold weather or periods of low loading, thus causing bleeding. Bleeding is caused by excessive bitumen binder in the pavement due to a poor mix design or manufacturing problems. It can also be caused by excessive application of bitumen binder and low air void content. Low air voids are lack of enough void space for the bitumen to occupy due to poor mix design (Sutter, 2016).

2.4.4 Shoving

Shoving is a form of distortion perpendicular to the traffic direction, appearing inform of ripples (corrugation) or waves (shoving) forming across the pavement surface (Mahler *et al*., 2012). Figure 2.4 shows pavement surface shoving on a busy intersection in Isiolo town. This type of pavement failure mostly occurs at points where traffic movement starts and ends or in areas where pavement is next to a rigid object. Shoving causes roughness on the pavement surface as seen in Figure 2.4 (Watts et l., 2010).

Figure 2.4: Pavement shoving (Isiolo town)

Shoving of pavement is caused by traffic action such as starting and stopping coupled with low stiffness asphalt concrete and excessive moisture in the subgrade. Low stiffness asphalt concrete mix is caused by mix contamination, poor mix design, poor HMA manufacturing, or lack of aeration of liquid asphalt emulsions (USDOT, 2000).

2.4.5 Depression

Pavement depressions are localized pavement surface areas with slightly lower elevations than the surrounding pavement (Van Metre *et al*., 2009). Depression result in surface roughness and depressions as shown in Figure 2.5. They are noticeable when they get filled with water after it has rained. This type of pavement failure is caused by subgrade settlement if compaction was not adequately done during construction (FHWA, 2010).

Figure 2.5: Pavement depression (Muriri-Isiolo road)

2.4.6 Patching

Patching is an area of pavement that has been replaced with new material to repair the existing pavement. A patch is considered a defect no matter how well it performs (McNichol, 2005). Major causes of pavement patching are as a result of utility cuts and localized pavement deterioration that has been removed and patched as shown in Figure 2.6 (FHWA, 2010).

Figure 2.6: Utility patch on pavement (Kirinyaga road in Nairobi)

2.4.7 Potholes

Pothole is a bowl-shaped depression on the pavement surface that penetrates down to the base course through the pavement layer. These depressions are generally with sharp edges and vertical sides at the top as shown in Figure 2.7. Potholes mostly occur on roads with thin pavement surfaces of less than 50mm than pavements with deeper surfaces (Mazumder, Kim, & Lee, 2016).

Figure 2.7: Pothole on wheel path area (Kamiti road)

Potholes are remaining holes after the pavement chunk is dislodged as a result of fatigue cracking. When fatigue cracking becomes severe, the interconnected cracks create small chunks of pavement, which get dislodged as traffic move over them. Potholes on pavement cause roughness and moisture infiltration. This pavement failure causes serious vehicular damage which results from driving across potholes at high speeds (USDOT, 2000).

2.4.8 Raveling

Raveling is a progressive disintegration of asphalt concrete layer from the surface due to dislodgement of aggregate particles as shown in Figure 8. Asphalt raveling results in loose debris on the surface, roughness and water collecting in the raveled sections. This type of failure causes vehicle hydroplaning and loss of skid resistance on road surface (Van *et al*., 2009). Major cause of Asphalt raveling is loss of bond between aggregate particles and the asphalt binder. This phenomenon may be as a result of asphalt binder aging, inadequate compaction, aggregates dust coating and segregation (Van *et al*., 2009): Asphalt binder aging is attributable to asphalt binder oxidation as it gets older. As bitumen ages, oxygen reacts with its constituent molecules thus resulting into stiffer and viscous material that likely to lose aggregates on the pavement surface as they get pulled away by traffic. Dust coating on the aggregate particles makes the asphalt bitumen to form a bond with the dust rather than the aggregate. This weakens the asphalt concrete bonds which makes aggregates chip off upon traffic loading. When fine particles are missing from the aggregate matrix as gap graded asphalt as a result of aggregate separation, forms weak bonds between binder and aggregates. Adequate compaction is required to develop sufficient cohesion within the asphalt concrete. Inadequate compaction results in rutting because the pavement continues to compact in the wheel paths under traffic loading.

Figure 2.8: Raveling (Kamiti road)

2.4.9 Rutting

Rutting is a surface depression on the wheel path as shown in Figure 2.9. It is a permanent deformation in any of a pavement's layers or subgrade which is caused by consolidation or lateral movement of the materials due to traffic loading (Mahler *et al*., 2012). There are two types of rutting; mix rutting and subgrade rutting. Mix rutting is type of failure which occurs when the subgrade does not rut though the pavement surface shows wheel path depressions as a result of compaction or mix design problems. However, subgrade rutting occurs when the subgrade exhibits wheel path depressions due to traffic loading. As a result, shearing of pavement occur along the sides of the rut which are particularly evident, when they are filled with water after rainfall (McNichol, 2005).

Figure 2.9: Shallow pavement rutting (Meru-Maua road)

In shallow pavement rutting, the pavement settles the subgrade ruts, causing surface depressions in the wheel path. This result in ruts getting filled with water which causes vehicle hydroplaning. This is hazardous because ruts tend to pull vehicle towards the rut path as it is steered across the same (FHWA, 2010). Pavement rutting is caused by high bitumen content, inadequate compaction and inadequate pavement structure. Poor mix design such as excessively high asphalt content, excessive mineral filler or insufficient amount of angular aggregate particles. This results into week asphalt mix with low strength which cannot support traffic loading. When asphalt concrete is not adequately compacted initially, pavement continue to densify when under traffic loads and inadequate pavement structure causes settlement of subgrade along wheel loading paths (USDOT., 2000).

2.4.10 Stripping

Stripping is the displacement of asphalt on the aggregate particle surface by water. It is as a result of loss of bond between aggregates and asphalt binder that typically begins at the bottom of asphalt concrete layer and progresses upward (Figure 2.10). However, when stripping begins at the surface and progresses downward, it is referred to as raveling. Stripping may be as a result of mineralogy and chemical composition of the aggregates (Roberts *et al*., 1996). Aggregates which have an affinity for water over asphalt (hydrophilic) tend to be acidic and suffer from stripping after exposure to water. However, aggregates which have an affinity for asphalt over water (hydrophobic), tend to be basic and do not suffer from stripping problems. In addition, aggregates when in contact with water will affect its adhesion to asphalt concrete thus causing moisture damage. Hence, aggregate surface chemistry seems to be an important factor in stripping. However, specific cause-effect relationships are still being established. Stripping leads to decreased structural support, rutting, shoving/corrugations, raveling, or fatigue and longitudinal cracking (Van Metre *et al*., 2009).

Figure 2.10: Stripping (Muriri-Isiolo road)

2.4.11 Water Bleeding and Pumping

Water bleeding takes place when water seeps out of joints or cracks, or through excessively porous layers as shown in Figure 2.11. Pumping happens when water and fines are ejected from underlying layers through cracks or on the sides of the pavement layer when under moving loads. Bleeding and pumping results into decreased skid resistance due to high pavement porosity (water bleeding) and decreased structural support (pumping). Possible causes of water bleeding and pumping are high water table, poor drainage and porous pavement as a result of inadequate compaction during construction or poor mix design (USDOT, 2000).

Figure 2.11: Water bleeding (Kamiti road)

In conclusion, these road failures discussed here in, have caused loss of man hours in traffic congestions, loss of life as a result of frequent accidents, loss of money utilized in treating the injured or in road repairs. To eliminate these pavement failures, asphalt concrete has been modified using various additives and stabilizers as discussed in Sections 2.5 and 2.6.

2.5 Properties of open graded asphalt concrete modified with sisal fibre and waste plastics.

2.5.1 Open graded asphalt concrete modified with plastics

Experimental observations have shown that plastics can be used to increase the Marshall stability, flow and permeability of asphaltic concrete when used as modifiers. However, they showed poor performance on bitumen drain down, bleeding and ductility (Haggam *et al*., 2014). Characterization tests performed on plastic modified asphalt concrete mixes showed that there was increase in toughness, hardness and stability. The samples performed significantly well on compressive strength and permeability (Nikhil *et al*., 2016). A research experiment carried out by Sulyman *et al*., (2014) on effective utilization of waste plastics in construction of flexible pavement showed that plastics increase the melting point of the bitumen. Asphalt concrete modified with waste plastics forms better material for pavement construction. These modified mixes have high Marshall Stability value increase by 60% compared non-modified samples (Sulyman *et al*., 2014). Bindu *et al*., (2010) used shredded waste plastic as stabilizing agent in modification of asphalt concrete. Marshall Test, compressive strength test and tensile strength tests were performed with varying percentage of bitumen from 6 to 8% and percentages of waste plastics ranging from 6 to 12% by weight of mix. It was found that stability, tensile and hardness properties increased by 64, 18 and 75%, respectively compared to the conventional mix samples. Test done on samples for plastic modified asphalt concrete mixes show low bitumen retention value of 20% and low tensile strength value of 21% (Sulyman *et al*., 2014, Bale, 2011). Therefore, a stabilizing agent is required to improve on bitumen retention of the modified asphalt.

2.5.2 Open graded asphalt concrete modified with fibre

Fibre acts as a reinforcing material to provide additional tensile strength in the asphalt concrete mix. Reinforcement is achieved when fibre increases the amount of strain energy that is absorbed during the fatigue and fracture process of the mix and consequentially increasing pavement serviceable life. Chen *et al*., (2009) and Wu *et al*., (2006) in a research study showed that polyester fibre can be used as reinforcement of bitumen-fibre mastics to increase tensile strength and reduce drain down at high temperatures. Use of fibre in the stabilization of asphalt concrete showed improvement on the performance of asphalt mixtures against drain down, permanent deformation and fatigue cracking (Huaxin *et al*., 2009; Abiola *et al*., 2014). Experimental results have shown that fibre have better performance than waste plastics in reducing drain down by up to 20% and therefore, fibre are largely being used in open-graded friction course (Hassan *et al*., 2005). Asphalt concrete mixes stabilized with fibre shows increase in the optimum asphalt binder content compared to pure asphalt mixture since fibre behaves like fine aggregates in the mix. Hence, fibre stabilize asphalt to prevent leakage of bitumen due to its adsorption nature (Tapkin *et al*., 2010; Wu *et al*., 2015). It has been established that sisal fibre can be used to improve bitumen retention of open graded asphalt when 0.3% fibre is added to the mix (Kar, 2012) by 80%. Further research reports have concluded that fibre modified asphalt mixes have rutting resistance, low-temperature anti cracking properties and durability (Tapkin *et al*., 2010). The impact of fibre in the performance of asphalt concrete is profound, however the mechanism of how fibre modify asphalt is complicated (Hassan *et al*., 2005). From the literature review of past research works, it can be concluded that, sisal fibre can be used to increase bitumen retention of asphalt concrete as well as improve on rutting and cracking resistance of pavement surfacing layer.

2.6 Properties of stone matrix asphalt concrete modified with sisal fibre and waste plastics

2.6.1 Stone matrix asphalt concrete modified with waste plastics

A study done to evaluate the properties of bitumen modified with waste plastics showed that penetration and softening point improved with addition of the waste plastics (Dixit & Rastogi, 2013). Decrease in penetration values for modified samples indicated the improvement in their temperature susceptibility resistance characteristics. Waste plastics makes bitumen become increasingly viscous thus increases the softening point with increase in percentage of plastics (Abiola *et al*., 2014). Ductility of waste plastic modified bitumen decreases with increase in percentage of plastics up to 0.5% (Bueno *et al*., 2003). From the Marshall test results, stability value was higher by 12% for modified mix as compared to an unmodified one (Soni *et al*., 2013).

Luiz *et al*. (2016) researched on performance characterization of plastics modified asphalt binders and mixes. From this research work, it was established that Marshall stability was higher for sample mixtures prepared with plastic modified bitumen and lower moisture susceptibility as compared to conventional mixes. Montanell (2013) did a research to evaluate the use of plastics in modification of bitumen. It was established that plastic modified hot mix asphalt had higher Marshall stability, stiffness modulus, indirect tensile strength and fracture toughness of asphalt mixtures at 25°C and 60°C. This means that the modified mixes have increased resistance to fatigue cracking and rutting.

Rokade (2012) investigated the utilization of shredded waste rubber tyres and waste plastics in the modification of asphalt concrete for construction of flexible pavement. The results for Marshall Stability was 12kN and indirect tensile strength was 1.15MPa. It was concluded that the utilization of these waste materials improved the engineering properties of asphalt concrete. It also provided avenue for the collection of these wastes at lower cost while providing a solution to the ecological menace imposed by the increase in disposal of waste tyres and plastics. Research by Shankar *et al*. (2009) used crumb rubber to modify bitumen. Marshall's mix design was carried out by changing the modified bitumen content at constant optimum rubber content. The tests performed to determine the effect of crumb rubber on conventional bitumen (60/70) showed increased stability of 16.1kN compared with straight run bitumen with 12kN.

A research study done by Lee *et al*. (2008) on the use of tyre rubber in asphalt mixtures in the modification of asphalt concrete showed improvement in the results. The pavement showed improved skid resistance by 20%, reduced fatigue cracking by 23% and improved tensile strength by 28% compared to non-modified one. This means longer pavement life and reduced maintenance costs compared with conventional mixtures. Justo *et al*. (2002) at the Centre for Transportation Engineering of Bangalore University carried out a study on the possible use of the processed plastic bags as an additive in bituminous concrete mixes. The properties of the modified bitumen were compared with ordinary bitumen. It was observed that the penetration and ductility values of the modified bitumen decreased by 34% with increase in proportion of the plastic additive up to 12 % by weight.

In a study by Chavan (2013) to investigate the potential prospects of enhancing asphalt concrete properties, polyethylene was used. Two types of polyethylene added to coat the aggregates were high-density polyethylene (HDPE) and low-density polyethylene (LDPE). The results indicated that HDPE polyethylene modifier provides better engineering properties, with the recommended proportion of the modifier being 12% by the weight of bitumen content. Both polyethylene was found to increase stability by 22%, reduce density and increase air voids by 16%.

2.6.2 Stone matrix asphalt concrete modified with fibre

The most common fibres used in the modification of asphalt concrete are synthetic (polypropylene and polyester), mineral and cellulose fibres. They are used as stabilizers to prevent bitumen drain down during transportation and placement of hot bituminous mixture (Kamil *et al*., 2012). They also act as reinforcement in asphalt mixes to increase tensile strength of the asphalt concrete (Abiola *et al*., 2014). Fibres increase strain energy absorption of the asphalt mix in order to inhibit the formation and propagation of cracks which can decrease the structural integrity of the flexible pavement (Chen *et al*., 2009). They improve the service properties of the mixture by forming micromesh in the asphalt mixture to prevent the drain down of the asphalt so as to increase the stability and durability of the mixture (Ibrahim, 2006; Kumar *et al*., 2005). Research work done to determine the use of fibre in the modification of asphalt concrete, it was reported that fibre modifiers had a better effect on drain down reduction than polymer modifiers (Kumar *et al*., 2005).

Montanell (2013) used fibre compound for high modulus polymer. Experimental evidence showed increase in rigidity and resistance to fatigue and rutting by 28%. The modified mixes test results showed high workability and stability of 12kN.

Fibres reduce tensional engagement and the consequent rutting of the lower layers such as sub-base and subgrade. Ahmed and Mahmood (2015) investigated performance characteristics of glass and polyester fibre in the modification of asphalt concrete mixes. It was established that there was significant improvement with regard to flexure fatigue test, cracking, permanent deformation, indirect tensile strength by 30% compared to non-modified mixes.

Raju *et al*. (2015) used sisal fibre in asphalt modification. The test results showed good performance for Marshall Stability with 12kN, drain down was 4% while indirect tensile strength was 1.1MPa. However, moisture sensitivity test result was 52%, which is below the recommended value of 70% set by AASHTO T283. Thulasirajan *et al*. (2011) used coir fibre in bituminous concrete and found that it showed improved Marshall Stability. In the study, 60/70 penetration grade bitumen with fibre proportions of 0.3%, 0.5% and 0.7% by weight of aggregate and varying length of 10 mm, 15 mm and 20 mm were used. The results showed increase in bitumen retention, tensile strength and ductility up to fibre content of 0.5%. Muniandy *et al*. (2006) used cellulose oil palm fibre in proportions of 0, 0.2, 0.4, 0.6 and 0.8% to evaluate the fatigue life of flexible pavements. The fatigue life, tensile strength and stiffness increased as fibre content was increased up to 0.6%. Melting point of oil palm fibre modified asphaltic concrete was 80^{o}C. This low melting point means that pavements constructed with oil palm fibre are subject to bleeding at high temperatures.

Kar, (2012) carried out a laboratory study of bituminous mixes using sisal fibre in the modification of asphalt concrete. Sisal fibre was used in varying proportions from 0 to 0.5% by weight of the mix. At optimum fibre content of 0.3%, the asphalt mix samples showed increased bitumen retention by 22% and indirect tensile strength was 1.0 MPa. However, this study recommended that some of the properties of the modified asphalt concrete such as, moisture susceptibility characteristics and resistance to rutting needed to be further investigated. He further recommended that using sisal fibre modified asphalt concrete, experimental road sections can be constructed and periodic performances monitored. Other fibres such as polypropylene and aramid when used to modify asphalt concrete showed test results for tensile strength increased by 25-50% in comparison to control samples (Shukla *et al*., 2014). Lee *et al*., (2005) evaluated the influence of recycled carpet fibre on the fatigue cracking resistance of asphalt concrete. The results indicated that the increase in fracture energy by 25% represents a potential for improving asphalt fatigue life. Bangalore, Karnataka province, India, used the plastic blend in at least 25% of the road-laying works and a project to upgrade about 45 roads in the city. The plastic modified asphalt concrete was successfully used on major roads in Bangalore, including Shankar Mutt Road, K H Road, M G Road, J C Nagar Road, Miller's Road and Cunningham Road. The road showed superior, uniformity and less rutting as compared to a plastic-free road laid at the same time, which began to develop 'crocodile cracks' (Justo *et al*., 2002).

2.6.3 Drain down characteristics of modified gap graded asphalt

Drain down is partial separation of mixture of fines and bitumen from the asphalt concrete as a whole and flows downward the mixture (NAPA, 1999). The test for drain down is important for gap graded asphalt (OGA and SMA) than for dense-graded asphalt concrete because the former loses bitumen during transportation and laying of asphalt concrete. Gap graded asphalt concrete has high coarse aggregate content where the internal voids of the uncompacted mix are larger, resulting in more drain down (Huang *et al*., 2007). The main disadvantages of gap graded asphalt concrete are bitumen drain down and bleeding at high temperatures. Asphalt concrete temperatures are maintained high at 160^{o}C during storage, transportation and placement (This is the time bitumen drain down and bleeding takes place). However, temperatures cannot be made low during Storage and placement because it is difficult to obtain the required compaction (Bindu and Beena, 2009). Hence, stabilizing additives such as sisal fibre are added to stiffen the asphalt concrete mix thereby improve the bitumen retention at high temperatures. This ensures that we retain higher bitumen contents for increased strength and durability (FHA, 1992). Gap graded concrete mixes have higher bitumen binder content of between 5-7% by weight of mix compared with dense graded asphalt. High bitumen content and fillers results into high bitumen drain down. This makes the aggregate lose the bitumen binder that binds the aggregates together in the mix (Huang *et al*., 2007). The loss of bitumen and uneven distribution of bitumen as a result of drain down results into top sections of asphalt concrete mix have less bitumen content. This too result into mix with less of permeability in sections with higher concentrations of binder content (Bindu and Beena, 2014; Mallick *et al*.,2000).

2.7 Mathematical model to predict the tensile strength of asphalt concrete modified with sisal fibre and waste plastics.

Mix design is done to formulate a mix of aggregates and binder that is economical and with sufficient binder to ensure adequate strength and durability. Proper asphalt mix design enhances workability to permit laying the mix without the risk of segregation and provides the pavement with sufficient strength over the service life of the pavement (Robert *et al*., 1996, Sulyman *et al*., 2014, Bindu *et al*., 2012). For this reason, indirect tensile Strength is used to determine the tensile strength of asphalt concrete which indicates the ability of road pavement to resist cracking, fatigue, and rutting which is caused by repeated traffic wheel loads on flexible pavements. However, the higher the tensile strength of pavement, the higher the ability of the pavement to resist cracking and fatigue (Oba, 2019). Most researchers have developed mathematical models on Portland cement concrete mixtures based on Scheffe's simplex theory (Gamil *et al*., 2015). Scheffe's model is based on the simplex lattice and simplex theory or approach (Scheffe, 1958). Scheffe's simplex theory considers several components, *q*, and a degree of polynomial, *m*, such that the sum of all the i^{th} components is not more than 1 as shown in Equation 2.1.

$$\sum_{i=1}^{q} x_i = 1 \quad (2.1)$$

Equation 2.1 can be expanded to generate Equation 2.2, such that

$$x_1+x_2+x_3 \ldots\ldots +x_q=1 \quad (2.2)$$

for $0 \leq x \leq 1$, the factor space is S_{q-1}. The $\{q, m\}$ simplex lattice design is a symmetrical arrangement of points in polynomial Equation which represents the response surface (Scheffe, 1958).

The number of points,

$$N = C_m^{q+m-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

Equation 2.3 can be re-written as

$$N = \frac{(q+m-1)!}{(q-1)!(m)!} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.4)}$$

Where

N is the design points

q is the number of components

m or n is the degree of polynomial

The number of points, N have (m+1) equally spaced values of x_i = 0, $^1/_m$, $^2/_m$........., $^m/_m$. Therefore, for a 4-component asphalt concrete mix with degree of polynomial 2, ({4,2} simplex), there are 10 points with equally spaced values of x_i = 0, 1/2, and 1

$$N = C_m^{q+m-1} = C_2^{4+2-1} = N = \frac{(4+2-1)!}{(4-1)!(2)!} = \frac{(5*4*3!)}{(3!)!(2*1)} = 10$$

The ten (10) design points are (1,0,0,0), (0,1,0,0), (0,0,1,0), (0,0,0,1), (1/2,1/2,0,0), (1/2,0,1/2,0), (1/2,0,0,1/2), (0,1/2,1/2,0), (0,1/2,0,1/2), (0,0,1/2,1/2).

A polynomial of degree, m with component variables q, the general scheffe's equation is given by Equation 2.5

$$Y = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_{ij} + \sum b_{ijk} x_i x_i x_k + \sum b_{i1i2\ldots in} x_{i1} x_{i2} x_{in} \ldots\ldots\ldots \text{(2.5)}$$

Where

$1 \leq i \leq q$, $1 \leq i \leq j \leq q$, $1 \leq i \leq j \leq k \leq q$

Y=Variable to be predicted

b_0 is the constant coefficient

b is constant for constituents i, j and k

x is Pseudo component for constituents i, j and k

Therefore, Equation (2.2) becomes

$x_1+x_2+x_3+x_4=1$ ……………………………………...…………...…………… (2.6)

Multiplying Equation 2.6 by b_0 results into Equation 2.7 below

$b_0x_1 + b_0x_2 + b_0x_3 + b_0x_4 = b_0$………………………………………………………… (2.7)

Further Equation 2.6 can be multiplied by x_1, x_2, x_3 and x_4 and make x_1, x_2, x_3, and x_4 the subject of the respective formulas to generate Equation 2.8 below

$x_1^2 = x_1 - x_1x_2 - x_1x_3 - x_1x_4$, $x_2^2 = x_2 - x_1x_2 - x_2x_3 - x_2x_4$,

$x_3^2 = x_3 - x_1x_4 - x_2x_4 - x_3x_4$, $x_4^2 = x_1 - x_1x_4 - x_2x_4 - x_3x_4$……………….…………… (2.8)

Substituting Equation 2.7 and Equation 2.8 into Equation 2.5, Equation 2.9 is generated.

$Y = b_0x_1 + b_0x_2 + b_0x_3 + b_0x_4 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 + b_{11}(x_1 - x_1x_2 - x_1x_3 - x_1x_4 + b_{22}(x_2 - x_1x_2 - x_2x_3 - x_2x_4 + b_{33}(x_3 - x_1x_3 - x_2x_3 - x_3x_4 + b_{44}(x_4 - x_1x_4 - x_2x_4 - x_3x_4$
……………………………………………………………………………….………… (2.9)

Bringing the constants together, Equation 2.10 can be generated from Equation 2.9, such that

$$Y = (b_0 + b_1 + b_{11})x_1 + (b_0 + b_2 + b_{22})x_2 + (b_0 + b_3 + b_{33})x_3 + (b_0 + b_4 + b_{44})x_4 + (b_{12} - b_{11} - b_{22})x_1x_2 + (b_{13} - b_{11} - b_{33})x_1x_3 + (b_{14} - b_{11} - b_{44})x_1x_4 + (b_{23} - b_{22} - b_{33})x_2x_3 + (b_{24} - b_{22} - b_{44})x_2x_4 + (b_{34} - b_{33} - b_{44})x_3x_4 \qquad (2.10)$$

Let

$\square_1=b_o+b_1+b_{11}$
$\square_2=b_o+b_2+b_{22}$
$\square_3=b_o+b_3+b_{33}$
$\square_4=b_o+b4+b_{44}$
$\square_{12}=b_{12}+b_{11}+b_{22}$
$\square_{13}=b_{13}+b1_1+b_{33}$
$\square_{14}=b_{14}+b_{11}+b_{44}$
$\square_{23}=b_{23}+b_{22}+b_{33}$
$\square_{24}=b_{24}+b_{22}+b_{44}$
$\square_{34}=b_{34}+b_{33}+b_{44}$

Equation 2.10 is then simplified to generate Equation 2.11 below

$$Y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 \qquad (2.11)$$

Equation 2.11 can be summarized to generate Equation 2.12.

$$Y = \sum_{i=1}^{4} \beta_i x_i + \sum_{1 \le i \le j \le 4} \beta_{ij} x_i x_j \qquad (2.12)$$

Where

Y is a dependent variable (Indirect Tensile strength of concrete).

Equation 2.12 is the general equation for any polynomial, while Equation 2.11 is the general equation for a {*4,2*} polynomial with 10 terms. This conforms Scheffe's theory in Equation 2.5 with 10 terms. Equation 2.11 becomes the equation which was used to predict the strength of asphalt concrete modified using sisal fibre and waste plastics.

2.8 Literature review summary and research gap

A number of research work from empirical and theoretical literature review, have exposed weakness of different modifiers and stabilizers used in modification of open graded asphalt. While waste plastics and other polymer are good in improving the compressive strength, permeability and melting point, they do not significantly improve bitumen retention of gap graded asphaltic concrete. Bitumen retention of asphalt concrete modified with plastics was low with average values below 90%. Gap graded asphalt concrete modified using fibres such as glass fibre, sisal fibre and coir fibre showed high bitumen retention of up to 98% but low Marshall stability and tensile strength of 1.05MPa. Average tensile strength ratio was 80% indicating high moisture susceptibility compared to plastic modified asphalt concrete whose tensile strength ratio is above 95% (Luiz *et al*., 2016; Lee *et al*., 2005; Bueno *et al*.,2003; Kar, 2012; Muniandy *et al*., 2016; Raju *et al*., 2015; Sheelan *et al*., 2015; Ibrahim, 2006; Kumar *et al*., 2015, Huaxin *et al*.,2009; Abiola *et al*., 2014; Soni *et al*., 2013; Bueno *et al*., 2003; Sandhya *et al*., 2013; Hassan *et al*., 2005, Moghaddam *et al*., 2014). Therefore, this research combined waste plastics and sisal fibre to evaluate their effect on the asphalt concrete to come up with a mix that reduces moisture susceptibility, increases bitumen retention, tensile strength and Marshall stability.

Previous research works have revealed that open graded asphalt (OGA), which is used as a wearing course to provide increased safety in wet weather have not been investigated when modified with sisal fibre and waste plastics (Huaxin *et al*.,2009; Abiola *et al*., 2014; Soni *et al*., 2013; Bueno *et al*., 2003; Sandhya *et al*., 2013; Hamzah et al., 2010). Hence, this research investigated performance of OGA when modified with sisal fibre and waste plastics.

Scheffe's mathematical model has been used to predict the strength of concrete. However, it has not been used to predict the tensile strength of gap graded asphalt concrete when modified with sisal fibre and waste plastics. Therefore, this research, developed and evaluated Scheffe's predictive mathematical model to use in determination of tensile strength of asphalt concrete, when modified with varying proportion percentage components of sisal fibre and waste platics.

2.9 Conceptual framework

The research was modeled to focus on mix design of gap graded asphalt modified using sisal fibre and waste plastics. Varying proportion percentages of sisal fibre and waste plastics were used to modify OGA and SMA. The modified samples were analyzed for Marshall stability, tensile strength, moisture susceptibility and bitumen retention. Predict mathematical model was developed using Scheffe's theory to predict the tensile strength of asphalt concrete modified using sisal fibre and waste plastics. Tensile strength was the independent variable Y, while sisal fibre, waste plastics, bitumen and aggregates were the dependent variables with pseudo components X_1, X_2, X_3 and X_4.

Using the optimum percentages of sisal fibre and waste plastics that gave the maximum strength and highest bitumen retention, sisal-plastic modified asphalt concreate was used to construct a road pavement section. This section together with control section was monitored and assessed to determine its performance using Raters' Guideline for Visual Assessment of Road Pavements: Part B. The road pavement sections were constructed using modified open graded asphalt concrete for wearing course and modified stone matrix asphalt concrete for base course. The conceptual frame work to determine the effect of sisal fibre and waste plastics on properties and performance of gap graded asphalt in the study are depicted in Figure 2.12.

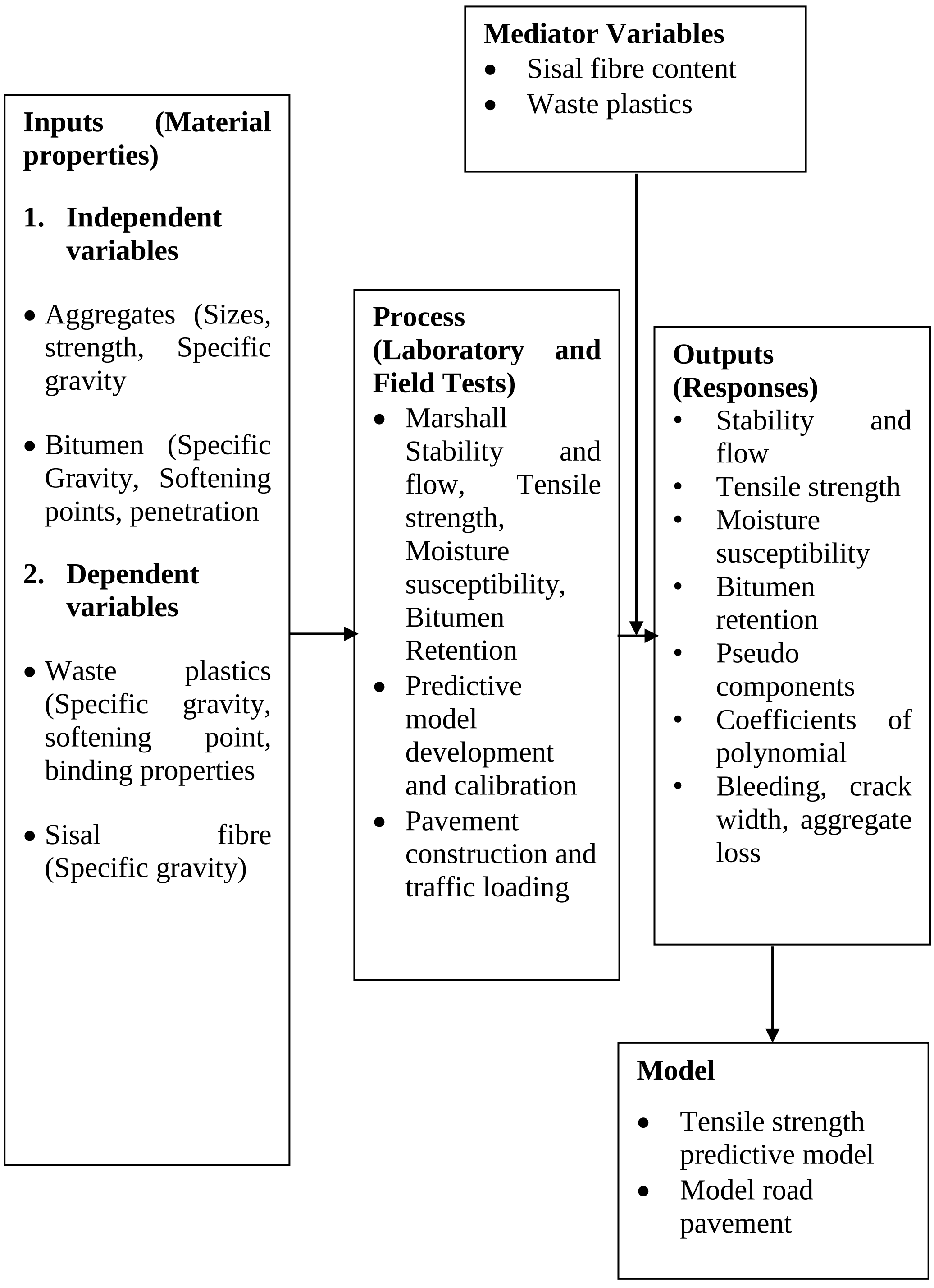

Mediator Variables
Sisal fibre content
Waste plastics
Inputs (Material properties)
1. Independent variables
Aggregates (Sizes, strength, Specific gravity
Bitumen (Specific Gravity, Softening points, penetration
2. Dependent variables
Waste plastics (Specific gravity, softening point, binding properties
Sisal fibre (Specific gravity)
Process (Laboratory and Field Tests)
Marshall Stability and flow, Tensile strength, Moisture susceptibility, Bitumen Retention
Predictive model development and calibration
Pavement construction and traffic loading
Outputs (Responses)
Stability and flow
Tensile strength
Moisture susceptibility
Bitumen retention
Pseudo components
Coefficients of polynomial
Bleeding, crack width, aggregate loss
Model
Tensile strength predictive model
Model road pavement

Figure 2.12: Conceptual framework

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter discusses the methods that were used to test for material characteristics and modified asphalt concrete samples. The research methodology adopted were standard test methods to determine the characteristics of aggregates, waste plastics, sisal fibre and bitumen. Using Marshall Design method, dosage of sisal fibers and waste plastics was determined and optimum contents were used in the preparation of sisal-plastic modified asphaltic concrete.

3.2 Material acquisition and preparation

The aggregates of the required sizes were sourced from Mlolongo quarries in Athi River, Machakos County, Kenya. The aggregates were air dried to remove moisture before grading. Waste plastics were sourced from dumping site in Embakasi, Nairobi-Kenya, shredded into 2-3mm sizes, cleaned and air dried. Sisal fibre were sourced from Kitui market and cut into 5mm long threads. The sisal fibre were put into oven at 105^{C} for 24 hours to ensure moisture-free fibre. Bitumen class 80/100 was supplied by colas East Africa Ltd.

3.3 Assessing the properties of aggregates, bitumen and waste plastics

3.4 Properties of aggregates

The coarse aggregates used were sampled in accordance with standard specification ASTM C136 for varying sizes of stone matrix (20-6 mm) and open graded (12-6 mm). The properties of aggregates were determined as per standards given in Table 3.1.

Table 3.1: Tests on aggregates

S/No.	Tests	Standard
1	Sieve analysis	**ASTM C136/C136M – 14**
2	Impact value (%)	**BS EN 1097-2:2010**
3	Crushing value (%)	**BS EN 1097-2:2010**
4	Abrasion value (%)	**BS EN 1097-8:2009**
5	Specific gravity and water absorption value (%)	**BS EN 1097-6:2013**

3.4.1 Aggregates gradation

The test procedure was as per ASTM C136/C136M – 14. The samples were dried to constant mass at a temperature of 110 ± 5ºC, and the weight recorded. Sieves were selected with suitable openings as required by specifications for the material to be tested and nested in order of decreasing size. The samples were placed on the top sieve and agitated by a mechanical apparatus for 5 minutes. Then, mass of each size increment was determined on balance and recorded to the nearest 0.1% of the total original dry sample mass. Total mass of material after sieving, which did not deviate by more than 0.3% of the original dry sample after completion of sieving procedures was recorded as acceptable data. The results calculated and recorded were percentage (%) passing, total percentage (%) retained and percentage (%) passing rage.

3.4.2 Aggregates impact value

The test procedure used in determining the impact value was as per BS EN 1097-2:2010. The Aggregates were dried by heating at 100-110° C for a period of 4 hours and cooled, then sieved to correct sizes between 14 mm and 10 mm. After drying, they were filled to about 1/3 depth of measuring cylinder and compacted by giving 25 gentle blows with the rounded end of the tamping rod. Two layers were added in similar manner, to make the cylinder full and any surplus aggregates were removed. The net mass of the aggregates to the nearest gram was determined and recorded as **A**. Impact machine was brought to rest without wedging or packing up on the level plate, block or floor, so that it was rigid and the hammer guide columns are vertical. The cup was fixed firmly in position on the base of machine and whole of the test sample placed in it and compacted by giving 25 gentle strokes with tamping rod. The hammer was raised until its lower face was 380 mm above the surface of aggregate sample in the cup and allowed it to fall freely on the aggregate sample. 15 such blows were given at an interval of not less than one second between successive falls. The crushed aggregates were removed from the cup and sieved through 2.36 mm sieves until no further significant amount passes in one minute. Fraction passing the sieve was weighed to an accuracy of 1 gram and recorded as **B**. Also, mass of the fraction retained in the sieve was recorded as **C**. If the weight **(B+C)** was less than the initial weight (**A**) by more than one gram, the result was discarded and a fresh test done.

Aggregate impact value = (B/A) x 100% ……………………………………… (3.1)

Three such tests were carried out and the mean of the results was reported as the impact value.

3.4.3 Aggregate crushing value

Aggregate crushing value was determined per BS EN 1097-2:2010. The aggregates were oven-dried at a temperature of 100 to 110^{o}C for 3 to 4 hours. The cylinder of the apparatus was filled in 3 layers, each layer tamped with 25 strokes of a tamping rod. Mass of aggregates was measured and recorded as **A**. The surface of the aggregates was leveled and the plunger inserted. Then the sample was placed in the compression testing machine and loaded at a uniform rate so as to achieve 40-ton load in 10 minutes. After this, the load was released. Crushed sample was sieved through a 2.36 mm sieve and the fraction passing through the sieve was weighed and recorded as **B**.

Aggregate crushing value = (B/A) x 100% ……….……………………… (3.2)

Three such tests were carried out and the mean of the results was reported as Aggregate crushing value.

3.4.4 Aggregates abrasion value

Aggregates abrasion value was determined per BS EN 1097-8:2009. Aggregates and steel balls were placed on the cylinder and the cover fixed. The abrasion machine was set to rotate at 30-33 revolutions/minute, for 1000 revolutions. After the revolutions, the resultant aggregate materials were discharged to a tray and sieve analysis done. Material coarser than 1.70 mm size was weighed correct to one gram and abrasion value was calculated as follows;

Original mass of aggregate sample = $\mathbf{W_1}$

Mass of aggregate sample retained = $\mathbf{W_2}$

Mass passing 1.70 mm IS sieve = $\mathbf{W_1 - W_2}$

Abrasion value = $\frac{W1 - W2}{W1 \times 100}$ ……………………………………......…………… (3.3)

Three such tests were carried out and the mean of the results reported as aggregate abrasion value.

3.4.5 Specific gravity and water absorption value of aggregates

Specific gravity and water absorption value was determined as per determined per BS EN 1097-6:2013. 2000g of aggregates were thoroughly washed to remove finer particles and dust, drained and then placed in the wire basket and immersed in distilled water at a temperature of 22-32^oC. The entrapped air was removed by lifting the basket and allowing it to drop 25 times in 25 seconds. The basket and aggregate sample remained immersed for a period of 24 hours thereafter. The aggregates were weighed (mass **C**). They were then removed from the water, allowed to drain for a few minutes, after which the aggregates were gently emptied from the basket on to one of the dry clothes and gently surface-dried with the cloth, transferring it to a second dry cloth when the first would remove no further moisture. The aggregates were spread on the second cloth and exposed to the atmosphere away from direct sunlight till it appears to be completely surface-dry. The aggregates were weighed (mass **B**) and then placed in an oven at a temperature of 100 to 110^oC for 24 hours. It was then removed from the oven, cooled and weighed (mass **A**). The bulk specific gravity and the percentage of absorption was calculated using the following formulae:

$$\text{Bulk specific gravity of the aggregate, } G_{sb} = \frac{B}{B - C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

$$\%\ \text{Absorption} = \left[\frac{B - A}{A}\right] x100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

Where:

A – mass of oven-dried sample in air (grams)

B – mass of surface dry sample in air (grams)

C - immersed mass of saturated sample (grams)

3.5 Properties of waste plastics

Samples of shredded waste plastics were tested for various properties as indicated in Table 3.2.

Table 3.2: Tests to determine properties of waste plastics

Properties of waste plastics tested	Standard test method	Permissible values
Specific gravity	ASTM D1505 - 18	**1.3-1.4**
Softening point		**100-120 No gas release**
Binding properties		**More than 10 N/mm^2**

3.5.1 Waste plastics specific gravity and softening point.

Five samples of shredded waste plastics, passing sieve 4.75 and retained on sieve 2.36 were first weighed in air, then immersed in distilled water at 23°C using a sinker and wire.

Specific gravity was calculated as follows:

$$\text{Specific gravity} = \frac{A}{(C-B)} \quad \text{(3.6)}$$

Where
A = Mass of oven dry sample in air.
B = Mass of sample in water.
C = Mass of saturated surface dry sample.

Average results of three samples was recorded as the specific gravity.

Thereafter, the five samples were placed in the oven and temperature raised to 100-120^{0}C and release of gas monitored in accordance with standard specification ASTM D 1505-18. The softening point of the waste plastics is recorded when no gas is released at 100-120^{0}C.

3.5.2 Waste plastics binding properties

Eight cubes made of waste plastics, measuring 150x150x150mm were tested for binding properties using compression testing machine. Aggregate size 12/6 mm were mixed with shredded waste plastics at varying percentages of 5%, 10%, 15% and 20%. The samples with the required percentage of waste plastics and aggregates were placed on a water tight non-absorbent platform until the mixes were thoroughly blended and uniform. The materials were then heated at 150^{0}C until the waste plastics melted. The hot mix was put in the cleaned and oiled molds in layers of approximately 5 cm thick upon each other. Each layer was compacted with not less than 35 strokes per layer using a tamping rod (steel bar 16 mm diameter and 60cm long, bullet pointed at lower end). The top surface was levelled and smoothened with a trowel. The test specimens were stored in moist air for 24 hours and thereafter marked and removed from the molds and kept submerged in clear fresh water.

After 3 days, the samples were removed from water and excess water wiped out from the surface. The dimensions were taken to the nearest 0.2 m. The bearing surface of the compression machine was cleaned and sample aligned centrally on the base plate. The movable portion was rotated gently by hand so that it touched the top surface of the sample, load was applied gradually without shock and continuously at the rate of 140 kg/cm^2/minute until the specimen failed. The maximum load at the point of failure was recorded and compressive strength calculated using Equation below.

$$\text{Compressive strength } = \frac{\text{maximum load}}{\text{area in mm}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

Where

Maximum load is load at the point of failure.

Area is the cross-section area of the top surface in contact with base plate.

3.6 Specific gravity of sisal fibre

Sisal fibre cut into 5mm long, were first weighed in air, then immersed in distilled water at 23°C using a sinker and wire. Specific gravity of three sisal fibre samples was calculated as follows:

$$\text{Specific gravity } = A/(C-B) \quad \text{...} \quad (3.8)$$

A = Mass of oven dry sample in air.
B = Mass of sample in water.
C = Mass of saturated surface dry sample.

3.7 Properties of bitumen

In this research, 80/100 penetration grade bitumen was used as binder for preparation of mixes. The properties of the bitumen that were determined by standard tests are given in Table 3.3.

Table 3.3: Tests to determine the properties of bitumen

S/No.	Tests	Standard
1	Penetration in mm at 25^{o}C	BS EN 1426:2015
2	Softening point (^{o}C)	BS EN 1427:2000
3	Ductility	ASTM D113-17
4	Specific gravity	ASTM D70-97

3.7.1 Bitumen penetration test

The standard test methods used was in accordance with standard BS EN 1426:2015. Apparatus used in the determination of the penetration of bitumen were penetrometer, water bath and bath thermometer of range 0-44^oC, graduation 0.2^oC. Bitumen which is sufficient to fill the container to a depth of at least 15 mm in excess of the expected penetration was sampled.

The bitumen was softened above the softening point (between 85 and 120^oC). It was stirred thoroughly to remove air bubbles and water. Bitumen was then poured into a container to a depth of at least 100 mm. It was cooled at an atmospheric temperature of 15-30^oC for $1\frac{1}{2}$ hours, then placed in a transfer dish in the water bath at 25.0 ± 0.1^oC for 1 hour. The container was kept on the stand of the penetration apparatus. The needle was adjusted to make contact with the surface of the sample. The dial reading was adjusted to zero. With the help of the timer, the needle was released for exactly 5 seconds and the dial reading was recorded as penetration in mm. The value of penetration reported was the mean of three determinations expressed in tenths of a mm.

3.7.2 Bitumen softening point test

The determination of bitumen softening point was carried out as per BS EN 1427:2000. The apparatus was assembled with the rings, thermometer and ball guides in position. The beaker was filled with boiled distilled water at a temperature 5.0 ± 0.5^oC per minute. With the help of a stirrer, the liquid was stirred and heat applied to the beaker at a temperature of 5.0 ± 0.5^oC per minute. Heat was applied until the bitumen softens and the ball was allowed to pass through the ring. The temperature at which the ball touched the bottom was recorded. The mean of three temperatures at which the ball touched the bottom, was recorded as the softening point of bitumen.

3.7.3 Bitumen ductility test

Ductility test was done as per standard specification ASTM D 113-17. Apparatus used are briquette mould, water bath, testing machine and thermometer with range 0-44°C and readable up to 0.2°C.

The bitumen 80/100 was completely melted by heating it to a temperature of 75-100°C until it became completely fluid. The mould was assembled on a brass plate and in order to prevent the material under test from sticking, the surface of the plate and the interior surfaces of the sides of the mould was coated with a mixture of equal parts of glycerine and dextrin. The heated bitumen was poured in a thin stream, back and forth from end to end of the mould until it was more than level full. It was left to cool at room temperature for 30 to 40 minutes, then placed in a water bath maintained at 25°C for 30 minutes. The excess bitumen was cut off by means of a hot, straight-edged putty knife, so that the mould was just level full. The brass plate and mould with briquette specimen were placed in the water bath for about 80 to 90 minutes. The briquettes were removed from the plate and the side pieces. The clips were hooked carefully on the machine without causing any initial strain and the pointer was adjusted to zero. The machine was started and clips pulled horizontally at a uniform speed of 50 mm per minute until the briquette ruptured. The distance was measured in centimeters through which the clips had been pulled to produce rupture. While the test was being done, it was ensured that the water in the tank of the testing machine covered the specimen both above and below by at least 25 mm. The distance in centimeters through which the clips were pulled to produce rupture was measured. The average of three normal tests which were within $\pm 5\%$ of their mean value was reported as ductility of the sample.

3.7.4 Bitumen specific gravity test

Specific gravity test was done as per standard specification ASTM D70/D70M-21. The apparatus used in the determination of specific gravity of bitumen were pycnometer, stopper, glass beaker, water bath, thermometer and distilled water. The bitumen sample was carefully heated and stirred to prevent local overheating until it had become sufficiently fluid to pour. While heating, the temperature was monitored not to exceed 111°C. The pycnometer was cleaned, dried, and weighed to the nearest 1 milligram (mg), recorded as **A**. The glass beaker was filled with freshly boiled distilled water, placing the stopper loosely in the Pycnometer. The Pycnometer was placed in the beaker and the stopper pressed firmly in place. The beaker was returned to the water bath and allowed the Pycnometer to remain in the water bath for a period of not less than 30 minutes. The pycnometer was removed and immediately the top of the stopper dried with one stroke of a dry towel, followed by outside area of the pycnometer. It was then weighed to the nearest 1 mg. The mass of the pycnometer plus water was recorded as **B**. Enough sample was poured into the clean, dry, warmed Pycnometer to fill it about three-fourths of its capacity. Precautions was taken to keep the material from touching the sides of the Pycnometer above the final level, and also prevent the inclusion of air bubbles. The Pycnometer and its contents were allowed to cool to ambient temperature for a period of not less than 40 minutes, and weighed with the stopper to the nearest 1 mg. Designate the mass of the Pycnometer plus sample as **C**. The beaker was removed from the water bath. The Pycnometer containing the bitumen was filled with freshly boiled distilled water, placing the stopper loosely in the Pycnometer. No air bubbles allowed to remain in the Pycnometer. The Pycnometer was placed in the beaker and the stopper firmly pressed in place. The beaker was returned to the water bath. The Pycnometer was allowed to remain in the water bath for a period of not less than 30 minutes. The Pycnometer was removed from the bath, dried and weighed using the same technique and timing discussed above. The mass of Pycnometer plus sample plus water was recorded and noted as **D**.

Hence,

$$\text{Specific Gravity} = \frac{(C - A)}{\left((B - A) - (D - C)\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

Where,

A = mass of pycnometer plus stopper

B = mass of pycnometer filled with water

C = mass of pycnometer partially filled with bitumen

D = mass of pycnometer + asphalt + water

3.8 Determining properties of open graded and stone matrix asphalt concrete modified using sisal fibre and waste plastics

To determine the effect of sisal fibre and waste plastics in the modification of stone matrix and open graded asphalt concrete, the following mixes were done and various performance tests were carried out.

(i) Control specimen where only bitumen was used to prepare asphalt concrete (AC).
(ii) Stone matrix and open graded asphalt concrete modified using sisal fibre
(iii) Stone matrix and open graded asphalt concrete modified using waste plastics
(iv) Stone matrix and open graded asphalt concrete modified using both sisal fibre and waste plastics.

In the preparation of the above samples, the following procedure was used,

(i) Sisal fibres were used to prepare samples for modified stone matrix and open graded asphalt concrete. The percentage proportion of sisal fibre dosage of 0, 0.1, 0.2, 0.3 and 0.4% were used in each respective mix. Their performance of each mix was assessed by subjecting them to the tests indicated in Table 3.4 to determine the optimal mix proportions.
(ii) Waste plastics were used to prepare samples for modified stone matrix and open graded asphalt concrete. The plastic dosage of 0, 1, 3, 5 and 7% was used in each

respective mix. The performance of each mix was assessed by subjecting them to the tests indicated in Table 3.4 to determine the optimal mix proportions.

(iii) The optimum contents of sisal fibre and waste plastics were then used to prepare samples of sisal-plastic modified asphalt concrete. The performance of the samples was assessed using the tests indicated in Table 3.4.

Table 3.4: Performance evaluation tests for the modified asphaltic concrete mixes

S/No.	Tests Done	Standard Test methods
1.	Marshall durability and flow	**AASHTO T 245-15**
2.	Tensile strength and moisture susceptibility	**AASHTO T 283-14**
3.	Drain down	**AASHTO T 305**

3.8.1 Asphalt concrete Marshall flow and stability test

To determine the flow and stability of asphalt concrete, the following apparatus were used

(i) Marshall Stability apparatus.
(ii) Dial gauge.
(iii) Balance and water bath.

In the preparation of Marshall Stability test samples, required proportions of coarse aggregates, fine aggregates, filler and modifiers for modified samples were selected in such a way as to fulfill the required specification. The total weight of the aggregate in the mix was 1200 g. The test procedure used to determine 0arshall stability and flow of bituminous mixtures was as per the AASHTO T 245-15.

The weighed aggregates and the bitumen were heated separately up to 170^{o}C and 163^{o}C respectively. For modified samples, plastics were heated together with aggregates. Sisal fibre was treated using 0.5N solution of sodium hydroxide solution (NaOH) at a temperature of 15-18°C. The fibre was immersed in a bucket of the solution for 12 hours, then removed and air-dried. The materials were mixed thoroughly and transferred to the compaction mould arranged on the compaction pedestal. For sisal modified samples, heated bitumen and aggregates were mixed together with treated sisal fibre. For sisal-plastic modified samples, plastics heated together with aggregates were mixed with bitumen as treated sisal was being added. 75 blows were done on the top side of the respective mix sample with a standard hammer (45cm, 4.86 kg). The specimen was reversed and done 75 blows again. The mould with the specimen was taken and cooled for a few minutes. The specimen was removed from the mold by gentle pushing. The respective specimens were marked and cured at room temperature, overnight. Before testing the samples, they were kept in the water bath at 60^{o}C for half an hour. The stability and flow of the samples were checked on the Marshall apparatus by loading to attain maximum load. The dial gauge was read for flow test result. Graph plot of percentage of bitumen content on the x-axis and stability on the y-axis was done to get maximum Marshall Stability of the bituminous mix. Dial gauge reading at the attained maximum load was taken for flow test result. The average of three tests were calculated as the mean value for the flow.

3.8.2 Asphalt concrete tensile strength and moisture susceptibility resistance test

The procedure used to determine the tensile strength and moisture susceptibility of asphalt concrete was as per AASHTO T 283-14. Six cylindrical samples of each modified bituminous concrete mixes were prepared and divided into two groups to determine the tensile strength values. The first group was preconditioned by vacuum saturation, that is, 55–80% of the air voids were filled with water. Samples showing above 80% saturation after the vacuum soaking were discarded since they were viewed to be severely saturated. This process was repeated with a new sample. If saturation had not reached 55% in a conditioned sample after the initial vacuum soaking, then the specimen was returned for additional vacuum soaking until a minimum saturation level of 55% was reached. The samples were wrapped in plastic bags and put in a freezer for 16 hours at -18°C. After 16 hours in the freezer, the samples were put into a water bath for 24 hours at 60°C and finally placed into another water bath for 2 hours at 25°C. Each cylindrical modified bituminous concrete mix sample was loaded with vertical compressive loads to failure. The test was performed at 25°C in indirect tension at 50.8 mm/min deformation rate. Failure occurred by splitting along the loaded plane. This generates a relatively uniform tensile stress along the vertical diametrical plane. The average of three normal tests was reported. Indirect tensile strength and tensile strength ratio were calculated using Equations below;

$$ITS = \frac{2P_{max}}{\pi td} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.10)}$$

Where

ITS is Indirect tensile strength

P_{max} is peak load (N),

t is the average height of specimen (mm)

d is the diameter of specimen (mm).

Tensile strength ratio (TSR), $TSR = \frac{ITS_{Con}}{ITS_{uncon}} x100$ .... (3.11)

The average of three tests was determined as the moisture susceptibility of the modifier.

3.8.3 Asphalt concrete bitumen drain down test

The test procedure used in the determination of bitumen drain down was done as per ASTM D 6390-11. The uncompacted asphalt concrete mix was placed in a wire basket which was positioned on a pre-weighed dry paper plate. The entire apparatus was placed in a forced draft oven for one hour at 177°C. After 60 minutes, the basket containing the concrete sample was removed from the oven along with paper plate. The paper plate was weighed to determine the amount of bitumen drain down that occurred. Drain down was calculated as percentage of binder which drained out of the basket compared to the original weight of the sample. The average of three normal tests was reported as the drain down of the modifier.

3.9 Developing and validating mathematical model for predicting performance of asphalt concrete modified with sisal fibre and waste plastics.

To develop a tensile strength predictive model of modified asphalt concrete, asphalt concrete samples were modified with varying mix percentages of sisal fibre and waste plastics to form sample sets of 0.1% sisal fibre plus1% waste plastics, 0.2% sisal fibre plus 3% waste plastics, 0.3% sisal fibre plus 5% waste plastics and 0.4% sisal fibre plus 7% waste plastics. These set of modifiers were mixed with bitumen grade 80/100 and gap graded aggregates for open graded asphalt mix, to produce the modified asphalt concrete. Two replicates were made for the compacted specimen with cylindrical diameter of 10.16cm with height of 6.35cm. The weight in grams for various proportions of sisal fibre and waste plastics were measured and mixed with 5.5% bitumen to prepare asphalt concrete samples as given in Table 3.5.

Table 3.5: Mix design in grams of modified asphalt concrete samples

Modifier Mix percentage portions	SF (gm)	WP (gm)	Bitumen (gm)	Aggregates (gm)
0.1%SF plus 1% wp	1.189	11.893	65.409	1123.841
0.2%SF plus 3% wp	2.377	35.660	65.376	1123.274
0.3%SF plus 5% wp	3.470	57.842	63.626	1093.204
0.4%SF plus 7% wp	4.555	79.720	62.637	1076.223

The first four mix ratios were derived from Table 3.5 by dividing every respective mix design row by the respective weight of bitumen. The resultant rations were recorded in Table 3.6.

Table 3.6: Mix design ratios of modified asphalt concrete samples

Modifier portions	SF ratio	WP ratio	Bitumen ratio	Aggregates ratio
0.1%SF plus 1% wp	0.018	0.182	1.000	17.182
0.2%SF plus 3% wp	0.036	0.545	1.000	17.182
0.3%SF plus 5% wp	0.055	0.909	1.000	17.182
0.4%SF plus 7% wp	0.073	1.273	1.000	17.182

These can be put in matrix form in Equation 3.12.

$$S = \begin{vmatrix} 0.018 & 0.036 & 0.055 & 0.073 \\ 0.182 & 0.545 & 0.909 & 1.273 \\ 1.000 & 1.000 & 1.000 & 1.000 \\ 17.182 & 17.182 & 17.182 & 17.182 \end{vmatrix} \quad (3.12)$$

Their corresponding pseudo components are given in Equation 3.13.

$$X = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (3.13)$$

With centre points

X12 = (0.5 0.5 0 0)

X13 = (0.5 0 0.5 0)

X14 = (0.5 0 0 0.5)

X23 = (0 0.5 0.5 0)

X24 = (0 0.5 0 0.5)

X34 = (0 0 0.5 0.5)

According to Scheffe, (1958), $S_{ij}=XS_i$

Substituting the matrix in Equation 3.12 and corresponding pseudo components in Equation 3.10 with centre points, matrix Equation 3.14 is generated

$$\begin{bmatrix} S_{12} \\ S_{13} \\ S_{14} \\ S_{23} \\ S_{24} \\ S_{34} \end{bmatrix} = \begin{vmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0 & 0.5 & 0 \\ 0.5 & 0 & 0 & 0.5 \\ 0 & 0.5 & 0.5 & 0 \\ 0 & 0.5 & 0 & 0.5 \\ 0 & 0 & 0.5 & 0. \end{vmatrix} * \begin{vmatrix} 0.0003 \\ 0.0364 \\ 0.0455 \\ 0.0455 \\ 0.0545 \\ 0.0636 \end{vmatrix} \quad \text{……………………………………..…. (3.14)}$$

Similarly, this process was repeated for an additional ten (10) control points that was used for the verification of the formulated model in the second round of tensile strength experiments as shown in Appendix XIX and XX. Three samples for each set was prepared using 5.5% bitumen and aggregates that conform to OGA grading requirements and the test were carried out for tensile strength as discussed in section 3.7.2.

3.10 Construction of model sections of road pavement using modified asphalt concrete

Model sections of a pavement was constructed on the road leading to JKUAT Academy, within Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya. Two sections were constructed such that there was a lane for control section and modified section for comparison purposes. Control section (C-S) was constructed using open graded asphalt (OGA) as wearing course and stone matrix asphalt (SMA) as the base course. The modified section was constructed using sisal-plastic modified open graded asphalt (SPMOGA) as wearing course and sisal-plastic modified stone matrix asphalt (SPMSMA) as the binder course. The procedure used in the construction of the road section was as per RDM part III;

The section was selected and marked in dimensions of 6 m by 10 m. One lane was used as control section constructed using hot mix asphalt, and the other constructed using sisal-plastic modified asphalt concrete. Removal of existing tarmac layer of 50 mm thick was done together with base layer made of hardcore to a depth of 150 mm. Total depth attained was 200 mm thick. Sub-base layer was hacked to enable good binding with base layer. 50mm base layer was constructed using murram which was stabilized with 5 bags of cement to attain 4% cement stabilization.

The section was well compacted using a roller of 3.5 tones and samples taken for analysis of moisture content and maximum dry density. Intended bituminous layers was 150 mm for sisal-plastic stone matrix asphalt concrete as binder course and 50 mm for sisal-plastic modified open graded asphalt concrete as wearing course. The construction section area was divided into two lanes and labeled as MS (modified section) and CS (control section). Priming of the base surface was done using cutback bitumen, MC-30 at high temperature. After three days, bitumen emulsion, K160 was applied and 100mm binder course was constructed using hot stone matrix asphalt (SMA) and sisal plastic modified stone matrix asphalt (SPMSMA) for CS and MS, respectively. The sections were compacted by passing 3.5 tone roller equally over the CS and MS sections.

After seven days of traffic using the section, they were swept clean and bitumen emulsion K 160 spayed on the surface of the sections. The control lane wearing course was constructed using hot open graded asphalt (OGA) and the modified lane was constructed using hot sisal plastic modified asphalt (SPMOGA). 50mm thick surface layer sections were compacted using 3.5 tone roller. Accelerated loading was done by passing 20 passes of seven tone tracks daily to attain T5 traffic loading of 0.25-1MSA in the six months of monitoring. During this monitoring period, visual assessment was done to assess the pavement distress. The visual assessment was done using Raters' Guideline for Visual Assessment of Road Pavements (Part B: Flexible Pavements). The engineering assessments done were surfacing structural failures such as patching, cracks width, aggregate loss, bleeding deformation, rutting and settlement while the functional assessment done were roughness, skid resistance, surface drainage, and edge brakes.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

Test results for aggregates, bitumen, waste plastics plus asphalt concrete modified with sisal fibre and waste plastics are discussed in this chapter. It was observed that the effect of sisal fibre and waste plastics in the modification of open graded asphalt and stone matrix asphalt resulted in high Marshal stability of 13.5kN.

4.2 Properties of the aggregates, bitumen and waste plastics

4.2.1 Gradation of aggregates

The coarse aggregate used were normal weight aggregates with varying sizes for open graded and stone matrix asphalt concrete. Gradation of aggregates is one of the most important factors for the design of asphalt mixture. Results of the sieve analysis for blending aggregates for the use in the preparation of open graded and stone matrix asphalt concrete samples are given in Appendices I and II respectively.

It can be deduced that fine particles were 30% while grain sizes 12/6 mm was 70% of the total mix (Appendix I). The grading results were found to be within the OGA percentage grading range as shown in Figure 4.1. From the results, it is expected to have grain-to-grain contact, high void content and high permeability.

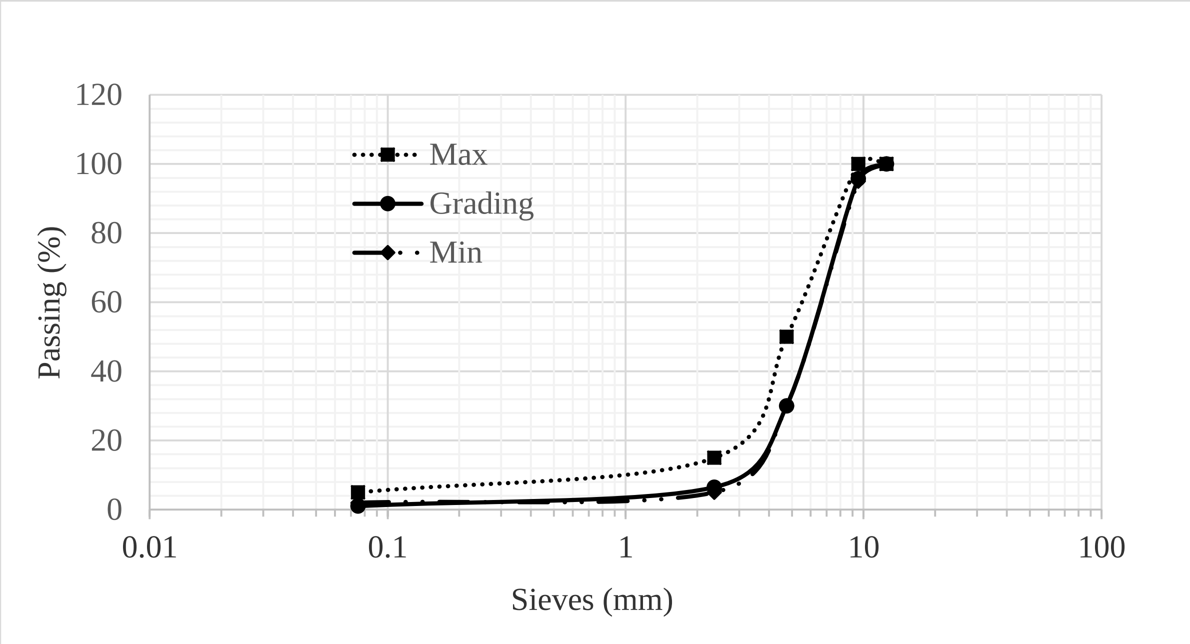


Figure 4.1: Grading curve for 12/6 mm aggregate for open graded asphalt concrete mix.

The results show that gap graded aggregates provide a strong bond of asphalt concrete due to grain to grain contact AASHTO M 147. Less fillers make the open graded asphalt concrete able to reduce noise generated by traffic on road surface as well as provide the required roughness to reduce skidding (Gwande et al., 2013. The grading curve lies between the limits for aggregates to be used in preparation of open graded asphalt mix. The grading data and results for aggregates used in the preparation of stone matrix asphalt concrete were recorded in Appendix II and presented in Figure 4.2. The results were found to be within the percentage grading range as per AASHTO M 147. The coarse aggregates that range between sieve sizes 19 and 13.2 mm were found to be 50% of the total aggregate. The aggregates between sieve 9.5 and 4.752 were found to be 30% of total aggregate, while the fines were 20%.

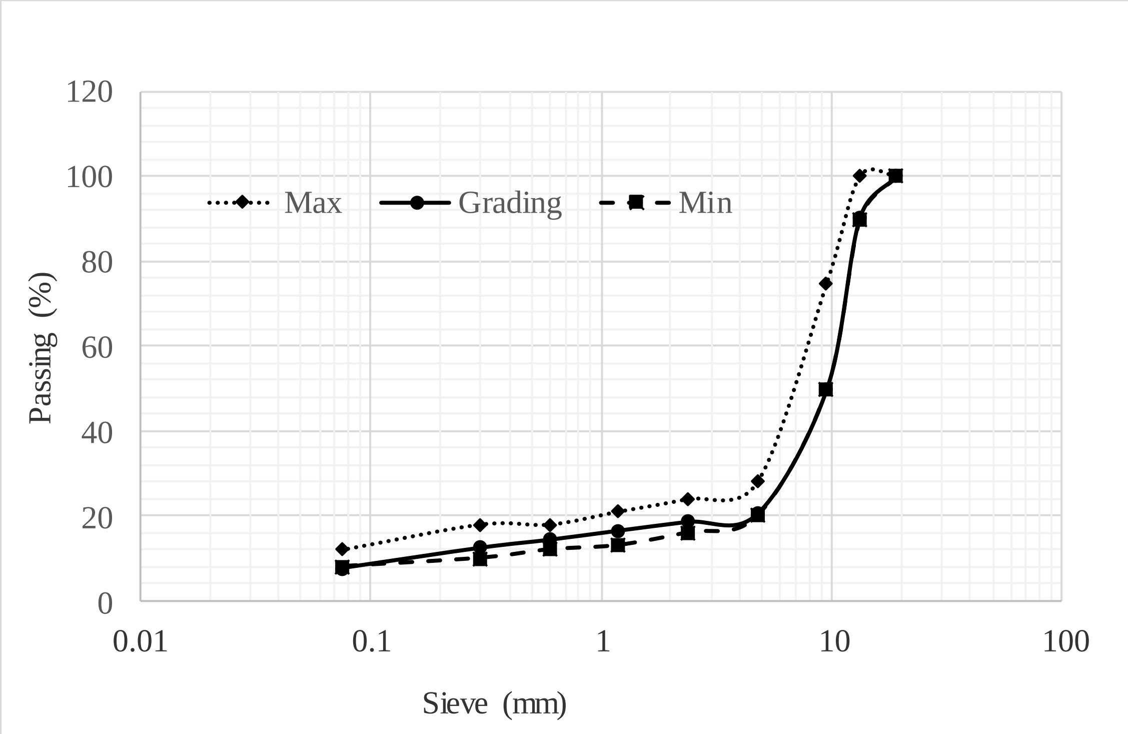


Figure 4.2: Grading curve of 20/6 mm aggregate for stone matrix asphalt concrete

The aggregates size 20/6 mm had composition ratio for coarse aggregates size 20-14 mm, coarse aggregates size 12-6 mm and fines as 50:30:20 (Appendix II). The grading curve lies between the limits for aggregates used in preparation of stone matrix asphalt. These aggregate sizes provide a stone to stone contact when used as a binder course in road construction. It makes road surface more resistant to cracking and rutting.

4.2.2 Impact Value of aggregates

The aggregate impact value (AIV), gives a relative measure of the resistance of aggregates to sudden shock or impact. This is a measure of aggregates toughness. Three sample tests were done and the results given in Table 4.1.

Table 4.1: Impact value test results

Coarse aggregates 14-10	Weight in grams		
	Sample No.1	Sample No.2	Sample No.3
Weight of oven dry aggregate in air (A) grams	2643.1	2639.4	2640.6
Weight of fines passing sieve 2.36mm (B) grams	702.3	712.2	703.3
Impact value (AIV), B/A %	26.57	26.98	26.63
Average impact value (AIV)	26.73		

From the results in Table 4.1, it can be seen that the aggregates' average impact value (AIV) was 26.73%. This meets the standard (BS EN 1097-2:2010) requirement of less than 30%. It means that the aggregates have sufficient toughness to resist their disintegration due to impact. The property of a material to resist impact is known as toughness. Due to movement of vehicles on the road the aggregates are subjected to impact resulting in their breaking down into smaller pieces.

4.2.3 Crushing Value of aggregates

Three sample tests were done and results are as shown in Table 4.2 below.

Table 4.2: Crushing value test results.

Coarse Aggregates 14-10 samples	Masses		
	Sample No.1	Sample No.2	Sample No.3
Mass of Oven dry aggregate in air (A) grams	2645.2	2642.8	2646.3
Mass of fines passing sieve 2.36 mm (B) grams	702.3	695.2	693.8
Crushing value (ACV) % (B/A)	26.55	26.31	26.22
Average crushing value (ACV) %	26.36		

The average crushing value (ACV) was 26.36 % which is within the BS EN 1097-2:2010 standard requirements of less than 30% for bituminous mix. This means that the aggregates are resistant to crushing under a gradually applied compressive load caused by traffic loads. It is therefore suitable for road construction.

4.2.4 Aggregates Abrasion Value

The tests were done on three samples and the average results recorded as shown in Table 4.3.

Table 4.3 Abrasion value test results

Mass of Samples Before Test					Mass After Test		
Passing (mm)	Retained on (mm)	A (W_1) g	B (W_1) g	C (W_1) g	A (W_2) g	B (W_2) g	C (W_2) g
20	12.5	2500					
12.5	10	2500					
10	6.3		2500				
6.3	4.75		2500				
4.75	2.36			5000			
1.7					3606	3592	3598
Total mass		5000	5000	5000	3606	3592	3598
Los Angeles abrasion value %					27.88	28.16	28.04
Los Angeles abrasion value %					28.03		

The results showed that the aggregates had abrasion value of 28.03%. This fulfills the standard BS EN 1097-8:2009 requirements of less than 30% for bituminous mix. Abrasion test was carried out to test the hardness property of aggregates, and to decide whether they were suitable for different pavement construction works. The aggregates were found to be hard and therefore resistance to further disintegration as a result of traffic loads. The aggregates were found suitable for use in the preparation of bitumen mixes.

4.2.5 Specific gravity and water Absorption of aggregates

The samples were tested and average results were recorded as shown in Appendices III, IV and V. The aggregate sizes 20/14 mm and 12/6mm had specific gravity of 2.72. Water absorption was 1.16% and 0.85%, respectively. The fines had specific gravity of 2.48 and water absorption of 0.33%. This means that the aggregates meet the requirements of the standard BS EN 1097-6:2013 which specifies specific gravity range of 2.5-3 and water absorption value of less than 2%. This means that the aggregates are not porous, which is indicative of less bitumen absorption. When less bitumen is absorbed, more of it is utilized in binding the aggregate particles together forming a strong bond.

4.2.6 Waste plastics specific gravity test results

Three samples of shredded waste plastics, passing sieve 4.75 and retained on sieve 2.36, were tested for specific gravity and results obtained are recorded in Table 4.4.

Table 4.4: Waste plastics specific gravity

Sample Description	Sample No.1	Sample No.2	Sample No.3
Weight of oven dry sample in air (A) grams	1852.5	1835.6	1781.7
Weight of sample in water (B) grams	545.3	535.8	530.5
Weight of saturated surface dry sample (C) grams	1865.6	1844.1	1795.8
Specific gravity (A/C-B)	1.40	1.40	1.41
Average specific gravity	1.40		

The average specific gravity test results for waste plastics was 1.40. This value is within the permissible range of 1.3-1.4 (Soni and Punjabi, 2013). This means, the waste plastics have the ability to adequately coat the aggregates particles (Sultana *et al*., 2012). Hence waste plastics have the required specific gravity for use in the modification of asphalt concrete (AC). The specific gravity is an indirect measure of density. It is the most important parameter of quality of waste plastics which results in higher strength of the modified asphalt concrete.

4.2.7 Waste plastics softening point

Softening point of waste plastics was determined for five samples of waste plastics and the results are presented in Table 4.5.

Table 4.5: Waste plastics softening point

Samples	**A**	**B**	**C**	**D**	**E**	**Permissible Value**
Temperature (^{0}C)	115	108	122	118	120	**100-120**
Gas release	No gas	No gas	No gas	No gas	No gas	**No gas release within the range**

The test results showed that no gas released for temperature range of up to 120^{0}C as shown in Table 4.5. The results were within the permissible range of 100-120^{o}C as stipulated in standard ASM D1505-18. This means that the plastics can be melted at high temperatures of between 100-120^{0}C without emission of gases which could be hazardous to the environment by causing air pollution (Soni and Punjabi, 2013). Melting the plastic wastes at high temperatures enables the molten plastics to penetrate the aggregate pores and adequately coat the aggregates. This results into higher strength of asphalt concrete. Hence, waste plastics are found to be suitable for use as modifier of asphalt concrete to enhance the strength.

4.2.8 Waste Plastics Binding Properties

Samples of cubes made of aggregates coated with waste plastics were tested for compressive strength to determine the binding properties of waste plastics. The binding property is an indicator of waste plastics ability to hold the aggregates together. The test data was recorded in Appendix VI and results shown in Figure 4.3. The compressive strength increased with increase in percentage of waste plastics up to maximum value as shown in Figure 4.3.

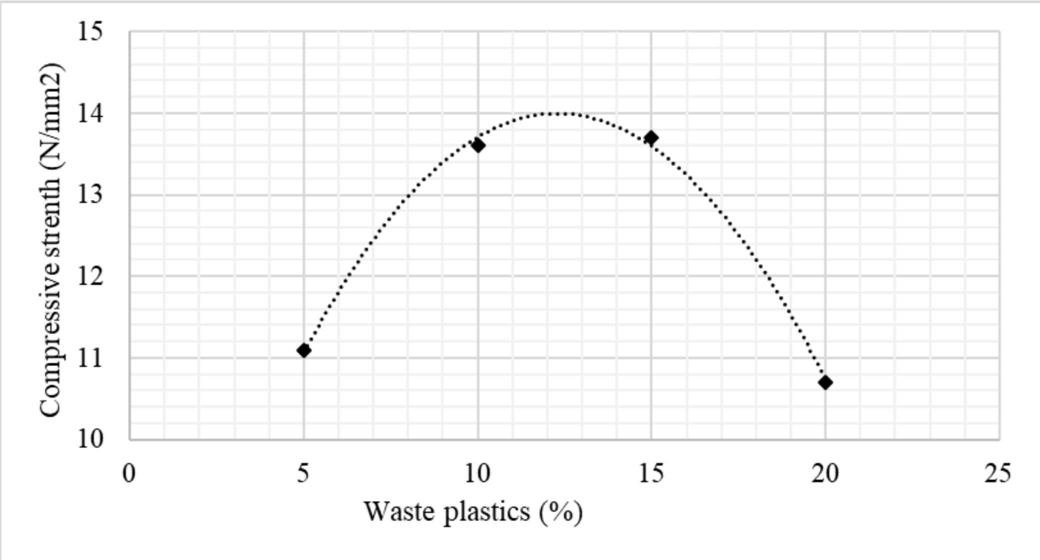


Figure 4.3: Binding properties of waste plastics

Compressive strength of cubes made of aggregates coated with waste plastics increased with percentage increase in percentage increase in waste plastics up to 12.5% when the compressive strength was 14 N/mm^2. Waste plastics, when in molten state binds the aggregates together by forming a strong bond with increase in waste plastics. Beyond 12.5% of waste plastic content, the strength reduced with increase in waste plastic content. This is as a result of weakening of friction and cohesion between the aggregate particles. Waste plastics are expected to make the modified asphalt concrete stronger to withstand high traffic loads.

4.2.9 Properties of sisal fibre

The test results for properties of sisal fibre are recorded in Table 4.6. The sisal fibre diameter and density test results recorded were 0.14mm and 1.33 g/cm^3, respectively. This implies that sisal fibre can be used as a stabilizing additive in preparation of asphalt concrete to hold aggregates and bitumen into a firm matrix.

Table 4.6: Properties of sisal fibre

Properties of Sisal Fibre Tested	Values
Diameter (mm)	0.14
Density (g/cm3)	1.33
Natural moisture content (%)	11.6
Water absorption (%)	98

Matrix formed will increase the strength of the asphalt concrete and reduce bitumen drain down during transportation and placement of hot asphalt concrete (Bindu C.S and Beena K.S. 2014). Reduction in loss of bitumen results in stronger pavements which can hold higher traffic loads compared to pavements constructed from non-modified asphalt concrete.

4.2.10 Bitumen penetration test results

Samples of bitumen grade 80/100 penetration test results obtained are recorded in Table 4.7. The average penetration test result obtained was 89mm, at 25^{o}C.

Table 4.7: Bitumen penetration test results

	Samples					Average	Permissible
	A	B	C	D	E	Value	Value
Penetration (mm)	92	87	86	90	89	89	80-100

The test result of 89mm which is within the standard specification limits of bitumen grade 80/100 as stipulated by standard BS EN 1426:2015. This implies that this bitumen can bind and coat the aggregate particles to form a strong asphalt concrete that can withstand high traffic loads. Hence, it can be used as a binder material to coat and bind aggregate particles (Justo *et al*., 2002).

4.2.11 Bitumen softening point test results

The softening point is the temperature at which bitumen attains a particular degree of softening under specified condition as stipulated in the standard BS EN 1427:2000. The results obtained are given in Table 4.8.

Table 4.8: Bitumen softening point test results

	Samples					Average value	Permissible value
	A	B	C	D	E		
Temperature (^{0}C)	48	46	45	48	46	47	42-50

The average results for the five samples was 47^{o}C. This was within the range of permissible value of 42-50^{0}C (BS EN 1427:2000). It also implies that road pavement made of asphalt concrete manufactured using this bitumen class 80/100 can withstand high tropical temperatures without rutting when under traffic load (Ibrahim M.A., 2006).

4.2.12 Bitumen ductility test results

The ductility values at 25^{o}C, in centimeters (cm) were determined for five samples of bitumen grade 80/100. The results are given in Table 4.9.

Table 4.9: Bitumen ductility test results

	Samples					Average value	Permissible value
	A	B	C	D	E		
Distance in cm	102	110	106	102	104	105	Min 75

The average value of ductility for five samples was 105 cm against the standard requirement of a minimum of 75cm. Hence bitumen class 80/100 met the standard requirements ASTM D113-17. The ductility test gives a measure of adhesive property of bituminous material and its ability to stretch. In flexible pavement design, it is necessary that binder should form a thin ductile film around aggregates so that physical interlocking of the aggregates is improved to prevent formation of pervious pavement surface. Asphalt concrete which has insufficient ductility gets cracked when subjected to repeated high traffic load.

4.2.13 Bitumen specific gravity test results

The specific gravity is the ratio of mass of given volume of bitumen to the mass of equal volume of water at 27^0C. The results obtained for five samples of bitumen class 80/100 are recorded in Table 4.10.

Table 4.10: Bitumen specific gravity test results

Samples					Average value	Permissible value
A	B	C	D	E		
1.01	1.02	1.04	1.01	1.03	1.02	1.01-1.05

The results indicate that the mean specific gravity was 1.02, which is within the standard (ASTM D70-97) requirements range of 1.01-10.5. Specific gravity of bitumen binder is a fundamental property necessary in classifying binders for use in pavement construction. Specific gravity is used when Bitumen weights are converted into volumes for asphalt concrete mix design calculations. It is essential in the design of asphalt concrete using Marshall volumetric model. Bitumen with higher values of specific gravity implies that bitumen contains mineral impurities which leads to wrong asphalt concrete design parameters such as strength and bitumen content. Poorly designed pavement as a result of specific gravity will result into week pavement that can easily crack or rut when under high traffic load (Mazumder *et al.*, 2016).

4.3 Evaluation on Marshall properties of modified asphalt concrete

4.3.1 Determination of bitumen content in asphalt concrete

Three samples each of open graded asphalt and stone matrix asphalt concretes were prepared for each bitumen content. The bitumen content was varied from 4.5 to 6% for open graded asphalt and 4.5 to 7% for stone matrix asphalt of total weight of corresponding sample. The test data was recorded in Appendices VII and VIII and results presented in Figure 4.4 to Figure 4.6. It was observed that the strength of the asphalt concrete samples increases to a maximum value of 7.314kN and 7.416kN with increase in bitumen content up to 5.5 and 6.5% for OGA and SMA respectively. Beyond 5.5 and 6.5% BC, there was a reduction in strength. This means that as bitumen content increased, the binder held the aggregate particles firmly together.

The bond between the aggregates became firm as bitumen content increased up to optimum bitumen content of 5.5 and 6.5% for open graded and stone matrix asphalt concrete, respectively, where further increases resulted into loose bonds. The excess bitumen increased wetting condition around the aggregate particles causing weak bonds by reducing cohesion between the particles. Flow increased with increase in binder content. This means that as bitumen content was increased, bitumen coated the aggregates, which reduced the friction between the aggregates. The volume of the sample increased as bitumen was further added since it had filled all the spaces between the aggregates. Thus, the voids decreased with increase in bitumen content which results into pavement bleeding and rutting when excess bitumen is used.

4.3.2 Bulk specific gravity for asphalt concrete mixes

The bulk specific gravity of control mixes of OGA and SMA were determined with increasing proportion of bitumen. The data are given in Appendices VII and VIII respectively and results presented in Figure 4.4.

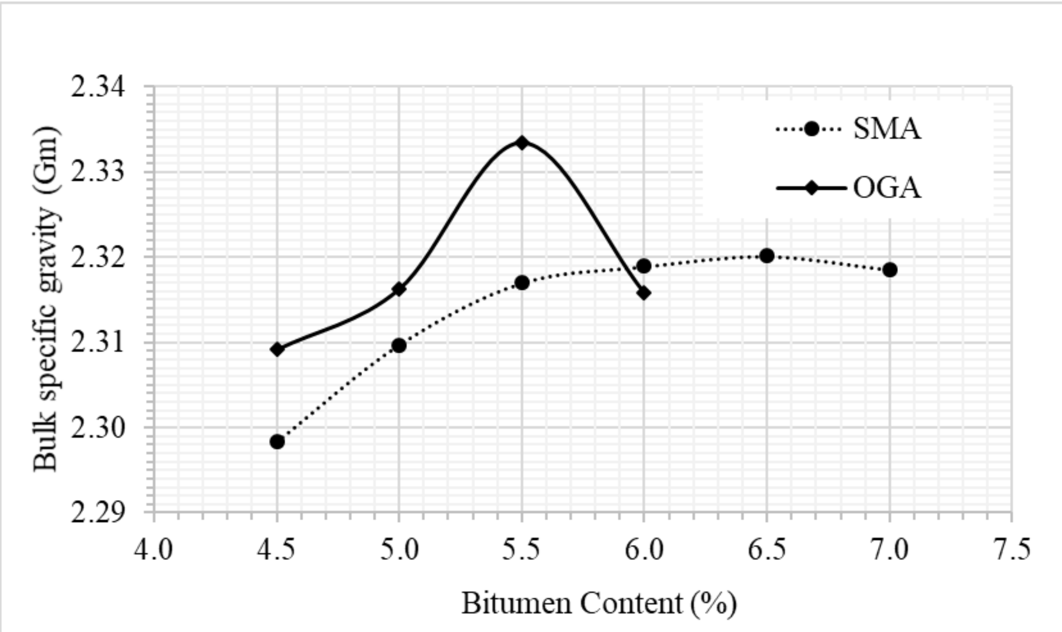


Figure 4.4: Specific gravity for control asphalt concrete

The variation in bulk specific gravity of the open graded and stone matrix asphalt mixes at varying bitumen contents given in Figure 4.4 shows that maximum density of 2.333 for open graded asphalt mix and 2.32 for stone matrix asphalt were achieved at 5.5 and 6.5% of bitumen content, respectively. As binder content increased, it coated the aggregates and formed a strong bond. This caused increased weight with little change in volume. This resulted in increase in specific gravity until the bitumen maximum content was achieved. Thereafter, the excess bitumen increased the volume by wetting the aggregates with little change in weight. Since bitumen is less dense than aggregates, bulk specific gravity decreased when bitumen content was increased beyond the optimum value. Accurate bitumen content in important is design of asphalt concrete for road pavement. Excess bitumen result in pavement bleeding thus reducing the surface roughness while less bitumen content result in weak bond between aggregate particles. This results into weak pavements that fail by cracking, aggregate loss and pothole development.

4.3.3 Stability of asphalt concrete mixes

The stability test results for asphalt control mixes of OGA and SMA were done by varying the bitumen content from 4.5% to 7.0%. The data were recorded in Appendices VII and VIII and results presented in Figure 4.5.

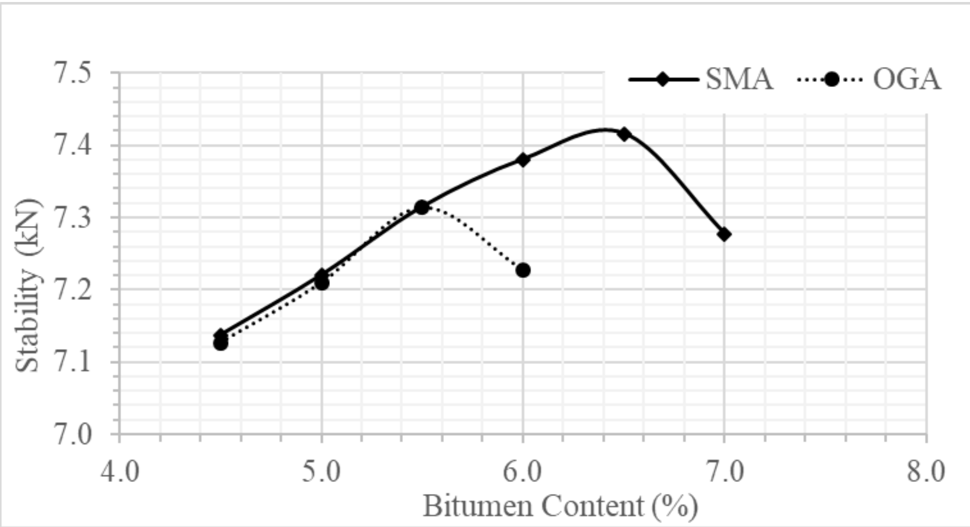


Figure 4.5: Stability of control asphalt concrete

The maximum stability of 7.314 and 7.42kN for open graded and stone matrix asphalt control asphalt concrete samples were achieved at 5.5 and 6.4% bitumen content, respectively. Bitumen added to aggregate mix binds the aggregate particles together as its content is increased up to the optimal content point. However, when optimum bitumen content is exceeded, bitumen wetting of aggregates sets in and dispersion takes place as a result of high bitumen content. This causes reduction of aggregate to aggregate particle contact which in turn causes reduction in cohesion, hence reduction in stability or strength. At optimum content, the pavement can withstand traffic loads without rutting or cracking. Beyond this binder content, the ability of the pavement to resist failure such as cracking and rutting reduces.

4.3.4 Air voids of asphalt concrete mixes

The percentage air voids of control OGA and SMA samples at various mix proportions of bitumen contents were determined. The data are given in Appendices VII and VIII respectively and the results given as shown in Figure 4.6. The air voids decreased with increase in bitumen mix proportions content.

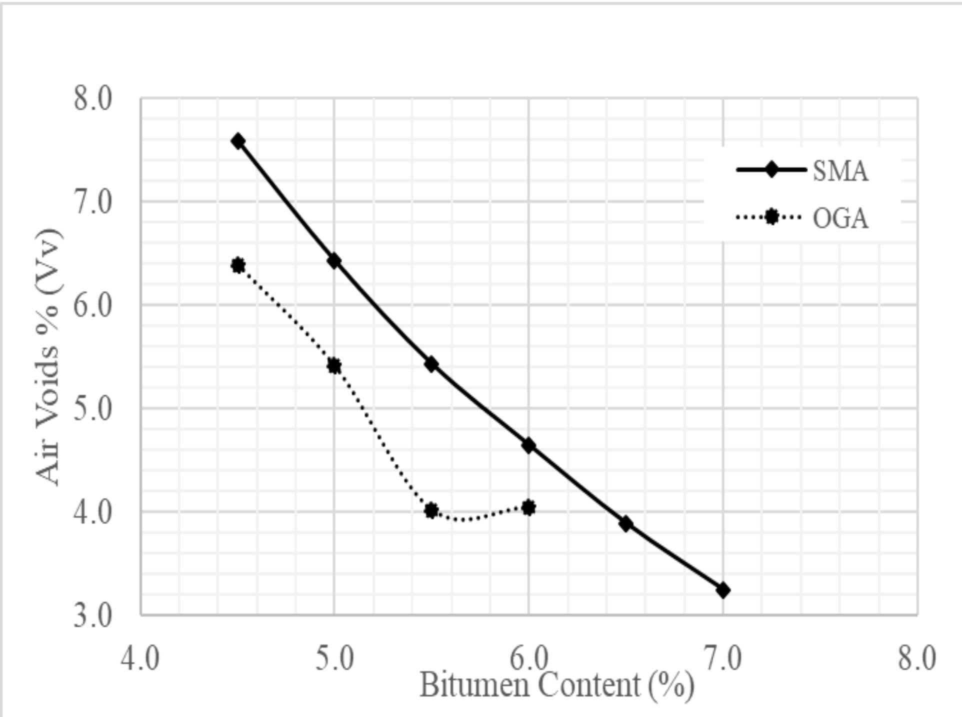


Figure 4.6: Air voids test results for control asphalt concrete

Air voids of OGA concrete mixes reduces up to 4.02% at 5.5% bitumen content while reduction of air voids of SMA concrete mixes is continuous. This means that the compacted OGA mixes had fewer air spaces compared to SMA. This is attributed to smaller aggregate sizes of OGA as compared to larger aggregate sizes of SMA. Air voids is the total volume of the small spaces of air between the coated aggregate particles in a compacted asphalt concrete mix, which are expressed as a percentage of the bulk volume of the compacted sample. Air voids in asphalt concrete affects the pavement strength, durability and permeability (Bruce *et al*., 1999).

4.3.5 Determination of optimum bitumen content of asphalt concrete mixes

Optimum bitumen content for asphalt concrete mixes was calculated using Equation 4.1, by Tom (2012).

$$B_o = \frac{B_1 + B_2 + B_3}{3} \quad \text{...} \quad (4.1)$$

Where

B_0 is the optimum bitumen content.

B_1 are 5.5 and 6.5% bitumen content at optimum bulk specific gravity of open graded and stone matrix asphalt concrete (Figure 4.4).

B_2 are 5.5 and 6.4% bitumen content at maximum stability (kN) of open graded and stone matrix asphalt concrete (Figure 4.5).

B_3 are 5.5 and 6.5% bitumen content at 4% air voids (Vv) of open graded and stone matrix asphalt concrete (Figure 4.6).

For OGA samples optimum bitumen content was calculated as shown below.

$$\boldsymbol{B_0} = \frac{\mathbf{5.5 + 5.5 + 5.5}}{\mathbf{3}} = \mathbf{5.5\%} \quad \text{...} \quad (4.2)$$

While SMA samples optimum bitumen content was determined as shown below,

$$B_0 = \frac{6.5 + 6.4 + 6.5}{3} = 6.5\% \quad \text{…………………….…………………………….. (4.3)}$$

Optimum bitumen contents 5.5% and 6.5% of OGA and SMA concrete mixes respectively were used in the subsequent studies to determine the effects of sisal fibre and waste plastics on OGA and SMA samples.

4.4 Sisal fibre modified asphalt concrete test results

4.4.1 Marshall stability and flow for sisal fibre modified asphalt concrete

The test results showing the effect of addition of various proportions of sisal fibre in OGA and SMA concrete samples are given in Appendices IX and X. The sisal fibres increased the stability with increasing sisal fibre proportion in the modified asphalt concrete (MAC) both for OGA and SMA concrete as shown in Figure 4.7. This is indicative of improvement of mix toughness and hardness thus increase in Marshall stability with increase in sisal fibre proportions. Control asphalt concrete samples had lowest stability of 7.314kN and 7.42kN for OGA and SMA while the highest achieved stability result was 9.68kN and 9.76kN for sisal fibre modified OGA and SMA concretes respectively.

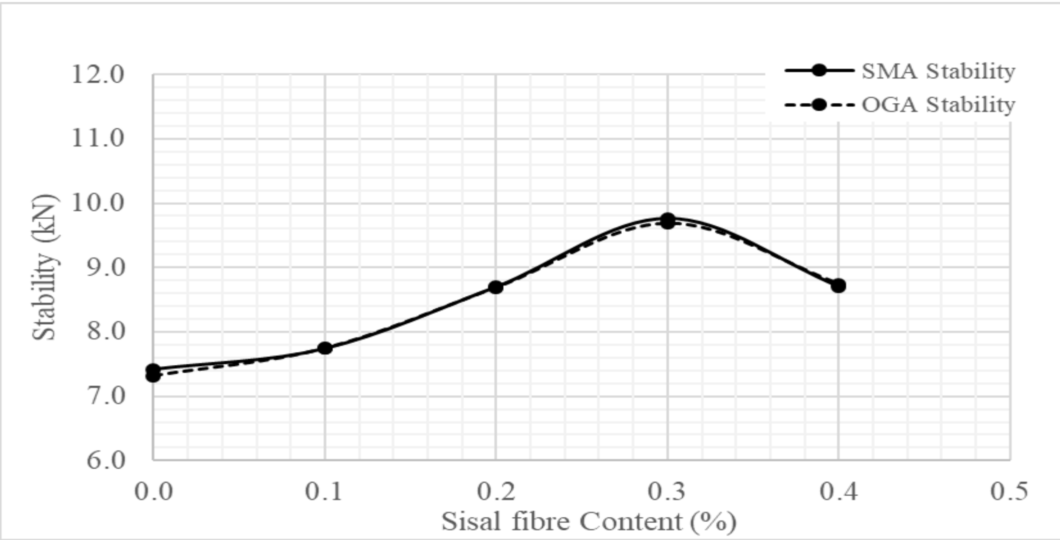


Figure 4.7: Stability of sisal fibre modified asphalt concrete

Asphalt concrete mix is an inconsistent, non-uniform, multi-phased composite material consisting of aggregates and sticky bitumen (Bindu and Beena, 2014). Hence, sisal fibres' proportion higher than the optimum value may not uniformly mix with asphalt concrete. They coagulate together and form weak points inside the mix. This causes the stability to decrease as the sisal fibre proportion increases beyond the optimal point. At 0.3% sisal fibre content, the samples had the highest stability of 9.68 and 9.76kN for sisal fibre modified open graded and stone matrix asphalt concrete, respectively. This means that sisal fibre modified asphalt concrete has higher rutting resistance and better performance at this optimal mix proportions. The change in stability for sisal fibre modified samples compared to the control mixture was about 32% increase in strength. This is attributed to adhesion and networking effects of sisal fibre which contributed to sisal fibre's reinforcement ability (Chen & Lin, 2005). Sisal fibre has bridging effect when cracking of asphalt mix appears by resisting the continuation of crack development (Behbahani *et al*., 2009). Additionally, fibre generally improves the stiffness and viscosity of bituminous mix (Huang & White, 2001), as a result of bitumen absorption (de Mello, de Farias, Kaloush, 2016) thereby increasing the strength of the sisal modified asphalt concrete. High strength values imply that sisal fibre modified asphalt concrete can be used to construct road pavements with higher strength to resist damage caused by traffic loads. The flow value of sisal fibre modified asphalt concrete samples decreased on adding fibres in increasing proportions as shown in Figure 4.8.

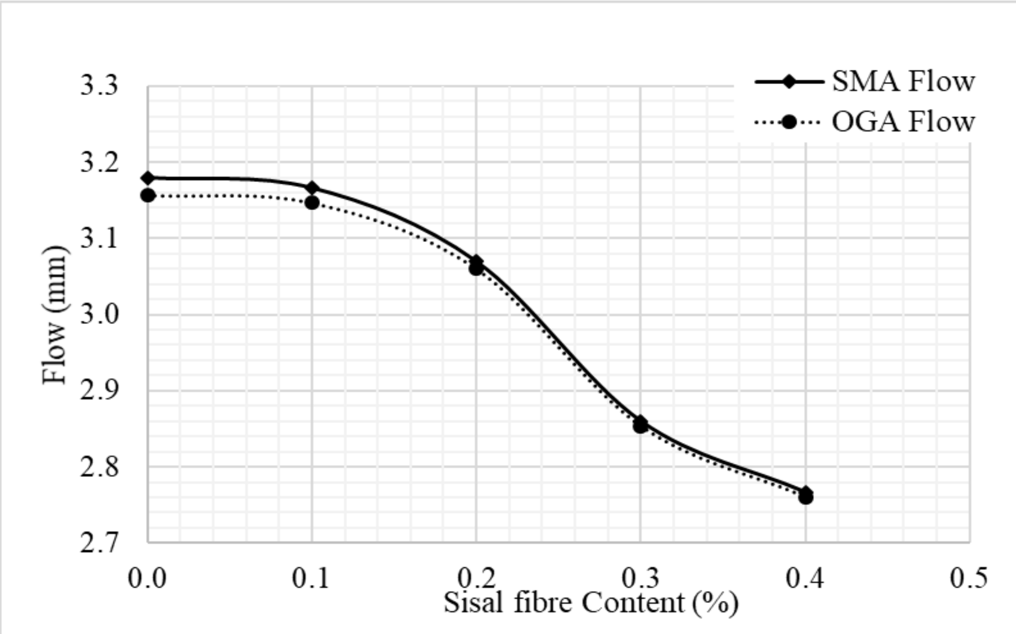


Figure 4.8: Flow test results for sisal fibre modified asphalt concrete at various mix proportions of sisal fibre

Due to the stiffness of sisal fibres modified asphalt concrete mix samples were less flexible and resistant deformation due to the stiffness of sisal fibres. This resulted into decrease in flow value for the samples with proportion increase in sisal fibre. At optimum fibre content of 0.3% when the stability for the sisal modified asphalt concrete samples was highest, the flow values were 2.85mm and 2.86mm for sisal fibre modified OGA and SMA respectively which are within the required specification range of 2-4 mm (AASHTO T 245). At 0.3% sisal fibre, the modified asphalt concretes samples acquired optimum strength and acceptable flow values which lies within the limits specified by the standard. The flow values imply that the sisal fibre forms a stiff matrix when mixed with aggregates and bitumen to modify asphalt concrete that can resist deformation by rutting or crack development in pavements.

4.4.2 Marshall Quotient values for sisal fibre modified asphalt concrete

Sisal modified asphalt concrete samples were tested for Marshall quotients (MQ) and values are as shown in Appendices VIII and IX. The values were calculated by dividing the stability with the flow and results presented in Figure 4.9. MQ also known as the rigidity ratio, is the ratio of stability to flow value of the sisal fibre modified asphalt concrete mix.

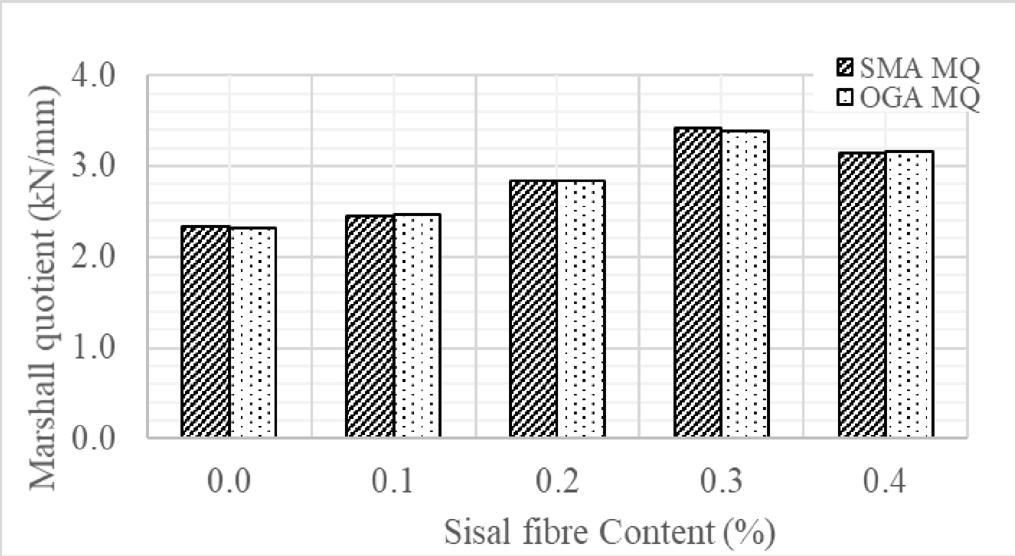


Figure 4.9: Marshall Quotient for sisal fibre modified asphalt concrete

The MQ increased with increase in the proportion increase in sisal fibre percentage up to optimum content of 0.3% as shown in Figure 4.9. MQ increased from 2.33kN/mm to a maximum value of 3.4kN/mm as sisal fibre proportion increased from 0% to 0.3%. The sisal fibre modified asphalt concrete give a high resistance against permanent deformations due to high MQ. Higher values of MQ shows that the modified asphalt concrete produce stiff bituminous mix which should be used to construct road pavement that resist rutting and crack development under high traffic loads.

4.4.3 Bulk specific gravity of sisal fibre modified asphalt concrete

The bulk specific gravity was assessed for modified OGA and SMA using various sisal fibre mix proportions. The data for tests is given in Appendices IX and X and the results presented in Figure 4.10. It was observed that the bulk specific gravity of modified asphalt mixtures decreased with increasing sisal fibre mix proportion.

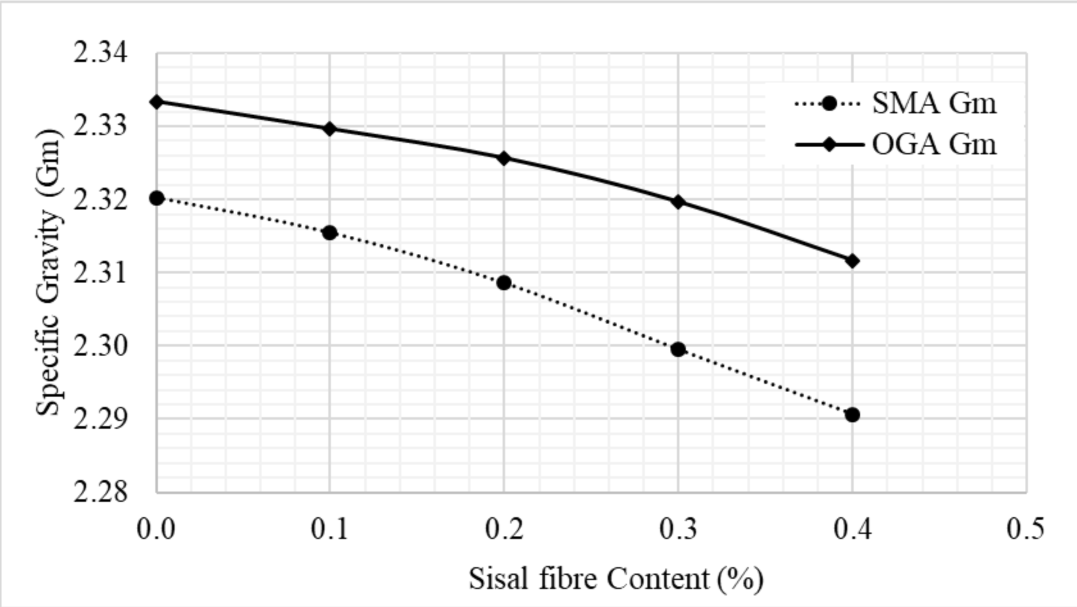


Figure 4.10: Bulk specific gravity of asphalt concrete mix with increasing sisal fibre mix proportion.

This trend in results is attributed to lower specific gravity of fibre compared to that of aggregates (Swami et al., 2012; Sultana and Prasad, 2012). The elastic properties of sisal fibre modified asphalt concrete mix increases with increase in sisal fibre proportion content. This is attributable to the elastic behavior of sisal fibres and therefore, additional sisal fibre content decreases the bulk specific gravity of the modified asphalt concrete mix. Increasing the percentage proportion of sisal fibre beyond 0.3% weakens the asphalt concrete due to reduction in specific gravity as a result of elastic behavior of sisal fibre. This can cause rutting in pavement when more than 0.3% sisal fibre content is used in modification of asphalt concrete.

4.4.4 Air Void, Voids in mineral aggregates and Voids filled with bitumen

The tests were done on samples of sisal fibre modified asphalt concrete for air voids (Vv), Voids in the mineral aggregates (VMA) and Voids filled with bitumen (VFB). The data for the tests is given in Appendices IX and X while the results given in Figures 4.11, 4.12 and 4.13. The percentage air voids increased as higher proportion of sisal sisal fibre was added into asphalt mixes. At 0.3% sisal fibre content, when the asphalt concrete attained the maximum strength, the air voids are 4.35% and 4.61% for sisal fibre modified open graded and stone matrix asphalt, respectively.

The behavior is influenced by the networking effect of sisal fibre within the asphalt mix.

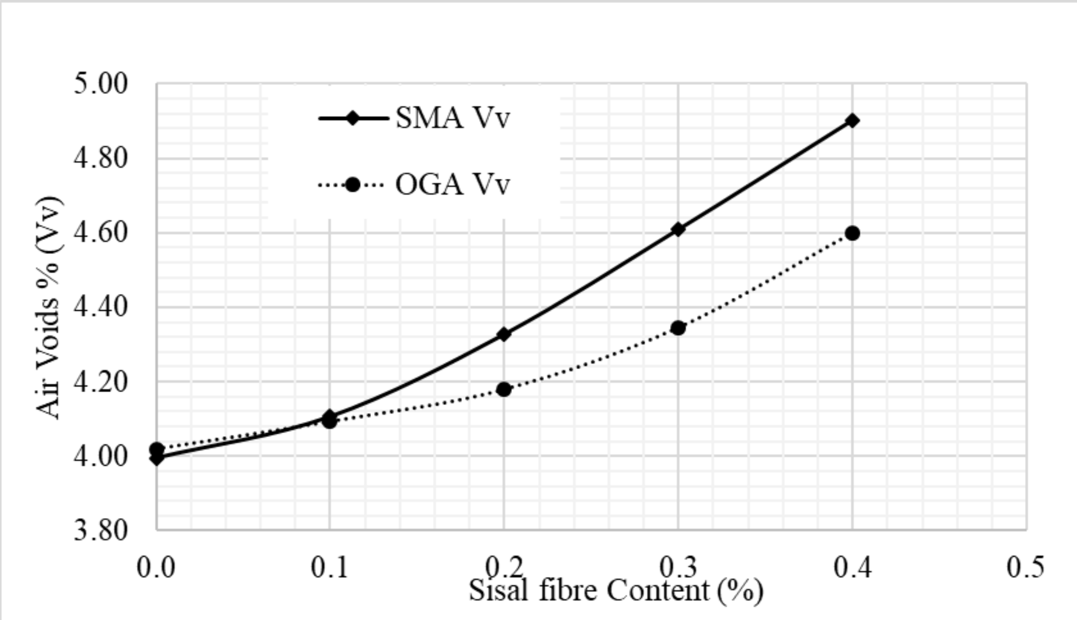


Figure 4.11: Air void of asphalt concrete mix with sisal fibre

These air voids result values are within AASHTO T 312 standard range of 3-5%. Pavements constructed with asphalt concrete with air voids greater than 5%, develop cracks which result into road failure. Sisal fibre absorbs bitumen which results into insufficient bitumen binder to coat the aggregates. This make the asphalt concrete have weak bonds between aggregates which results into cracking of pavements when under traffic loads. Air void below 3% is as result of excess of bitumen binder in the asphalt concrete mix samples. This causes pavement rutting due to plastic flow and bleeding of excess bitumen in asphalt concrete. Voids in the mineral aggregates (VMA) of sisal fibre modified asphalt concrete mix samples increased as higher proportion of sisal fibre contents were added in the mix as seen in Figure 4.12. At 0.3% sisal fibre content, when the asphalt concrete attained the maximum strength and the air voids are within the standard range of 3-5%, VMA values are 16.85% and 19.13% for sisal fibre modified open graded and stone matrix asphalt concrete, respectively.

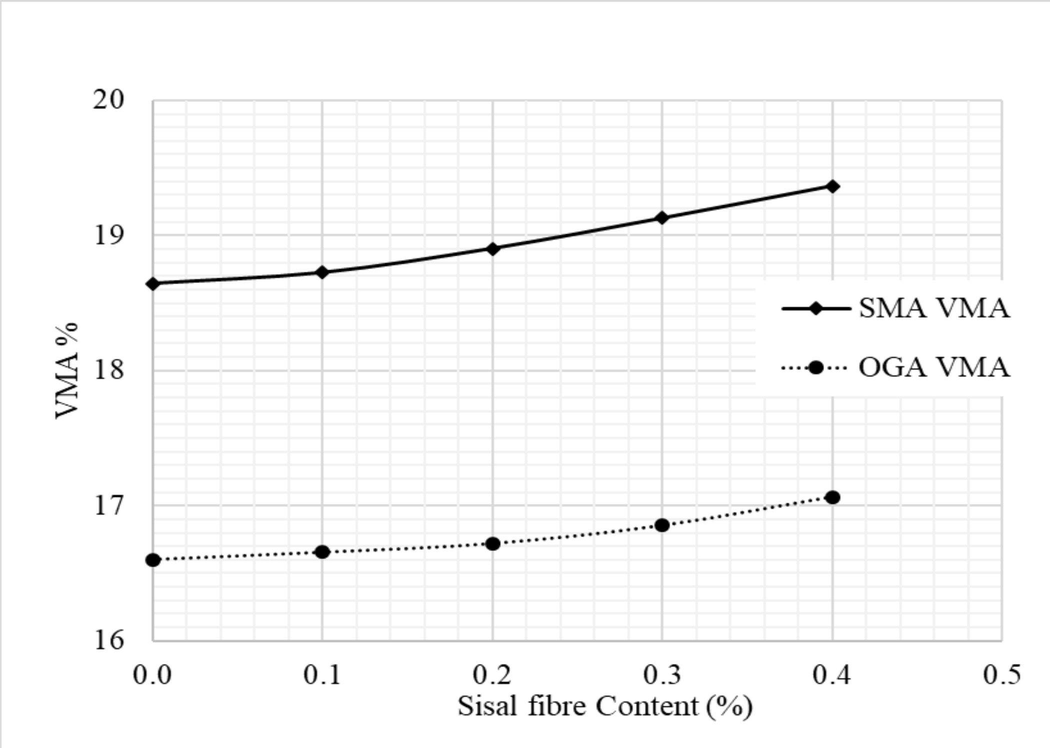


Figure 4.12: VMA of asphalt concrete mix modified with proportion sisal fibre content

Increase in VMA with increasing proportion percentage of sisal fibre content indicates voids available for bitumen binder to coat aggregate particles. VMA is a percentage of compacted asphalt concrete mixture comprising bitumen not absorbed into the aggregate and air voids. Voids in the mineral aggregates are the air-void spaces that exist between the aggregate particles in a compacted paving mixture together with spaces filled with asphalt. VMA values determine stability of asphalt concrete mix and strength of pavement (Chadbourn et al., 1999). The test result values of VMA for OGA and SMA obtained when stability is maximum and air voids between 3-5% represents the modified asphalt concrete that produce a strong pavement to with stand traffic loads. Low VMA causes bitumen bleeding due to excess bitumen when air voids are below 3%. This ultimately leads to pavement rutting when umder high traffic load. High values of VMA arising from high air voids results into weak asphalt concrete due to less bitumen that bids the aggregate particles. This phenomenon results into weak pavement which develops cracks when under traffic load. Voids filled with bitumen (VFB) reduced with increase in proportion of sisal fibre content in asphalt concrete samples as seen in Figures 4.13. When maximum stability of asphalt concrete samples modified with 0.3% sisal fibre content, VFB test values were 74.25% and 75.9% for OGA and SMA mixes respectively.

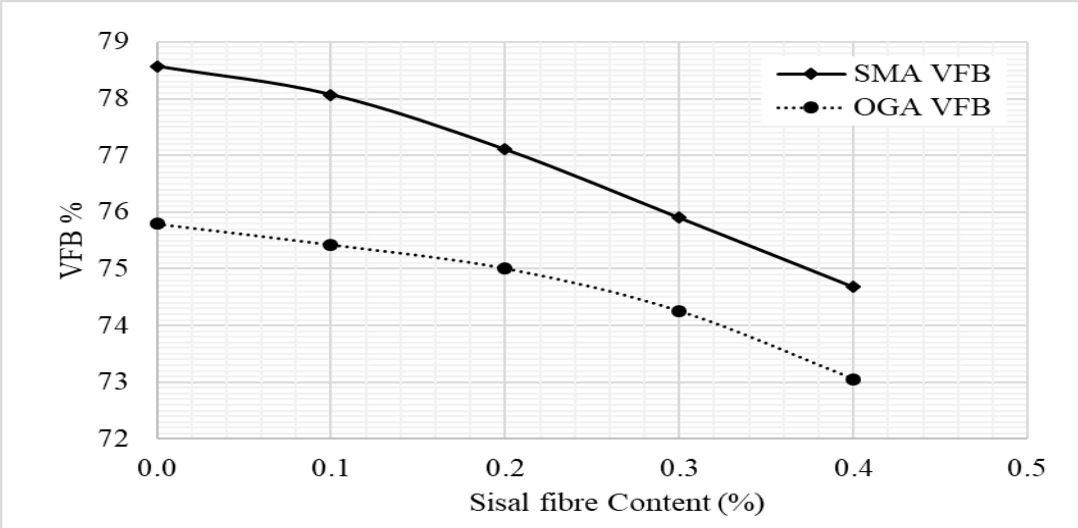


Figure 4.13: VFB of asphalt concrete mix with sisal fibre

The VFA test results are within the AASHTO T 312 standard specification range of 70-80%. VFA is a measure of relative durability of the pavement. Low VFA of less than 70% indicates low strength asphalt concrete mix which leads to development of potholes in road pavements when they crack. Higher values of VFA, beyond 80% indicates more bitumen binder in the asphalt concrete. This leads to bitumen bleeding and rutting of pavement when under traffic load.

4.5 Waste plastics modified Asphalt Concrete

4.5.1 Marshall stability and flow value

The Marshall Stability test data for OGA and SMA samples modified using waste plastics at varying content were recorded in Appendices XI and XII while the results presented in Figure 4.14. It was observed that as percentage proportion of waste plastics was increased, the stability values of the samples increased up to maximum value of 12.8kN at 5% waste plastics content for both OGA and SMA. Addition of 5% waste plastics (WP) to modified asphalt concrete raises the Marshall stability of control mix with 0% waste plastics OGA and SMA from 7.3kN and 7.4kN to 12.8KN, respectively. This represents a percentage increase in strength of 75.6% and 72.5% for waste plastic modified OGA and SMA samples respectively. This behavior can be attributed to the low specific gravity of the waste plastics. This enables the heated waste plastics to penetrate between aggregate particles, bind and coat them. As a result, aggregates particles interlock firmly, which increases the stability and decreases the flow value.

The decrease in stability when more than 5% of WP was added is related to the decrease in interlocking bond. The excess WP occupies the space which could be occupied by the bitumen. Therefore, the stone to stone interlocking bond offered by bitumen binder and waste plastic coated aggregate particles reduces tremendously. Stability test values of 12.8 kN for MOGA and MSMA indicate higher resistance to rutting. Asphalt concrete mix failure mostly occur within the binder or at the aggregate-binder interface. Failure within the binder is called cohesive failure while failure at the aggregate-binder interface is referred to as adhesive failure. The adhesive bond strength of asphalt mix affects the failure behavior in the Marshall Stability test (Bindu & Beena, 2012). Therefore, when WP is used in the modification of bituminous mixtures, there is increased adhesive bond strength. This ultimately leads to increased stability values of the waste plastic modified asphalt concrete mixes.

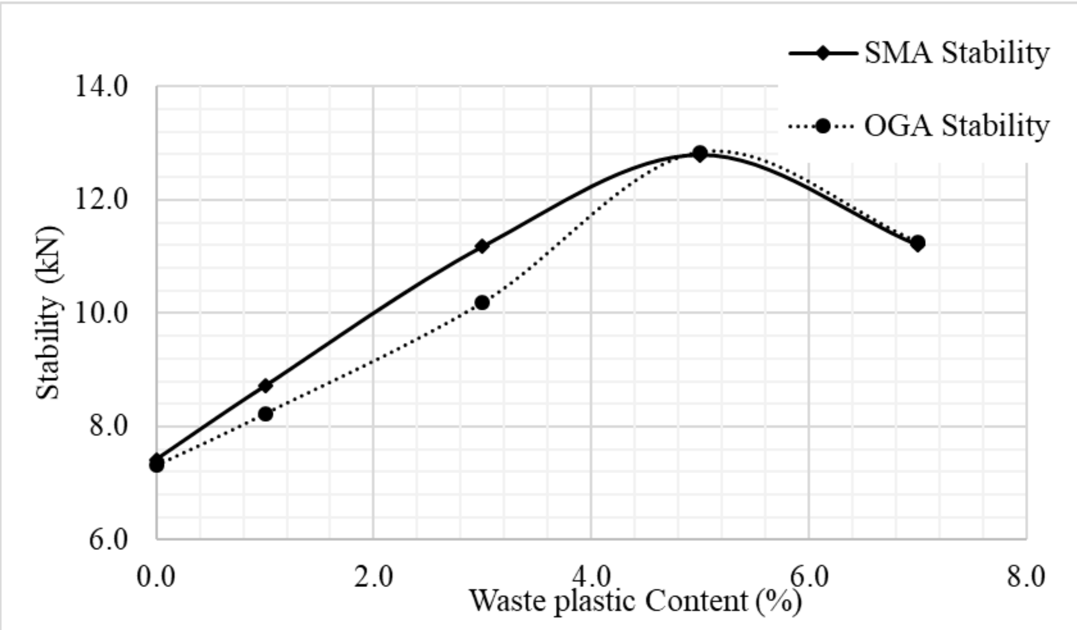


Figure 4.14: Stability of waste plastic modified asphalt concrete

The test data for flow were recorded in Appendices XI and XII while the results were as shown in Figure 4.15. The flow values of the waste plastic modified asphalt concrete mixes decreased as mix proportion of waste plastic (WP) content increased up to 5%, and thereafter increased. Flow value obtained when 5% WP was used to modify the asphalt concrete are 2.81 and 2.82mm for OGA and SMA sample mixes. These flow values obtained at 5% WP content when maximum stability was also achieved are within the required AASHTO T 245-15 specifications, 2-4 mm. Flow values less than 2mm implies that the asphalt concrete is rigid and less flexible, which make the pavement develop cracks. Flow values more than 4mm indicates that more WP has been used in the modification of the asphalt concrete. This would reduce cohesion and adhesion properties of the asphalt concrete mix due to the decrease in the stone to stone contact. The WP modified asphalt concrete becomes weak, thus reducing its strength and increasing its flow. As a result, the pavement fails by rutting when under heavy traffic load. However, when flow values are between 2-4 mm, the pavement does not fail by cracking or rutting when under traffic load (FHWA, 2019).

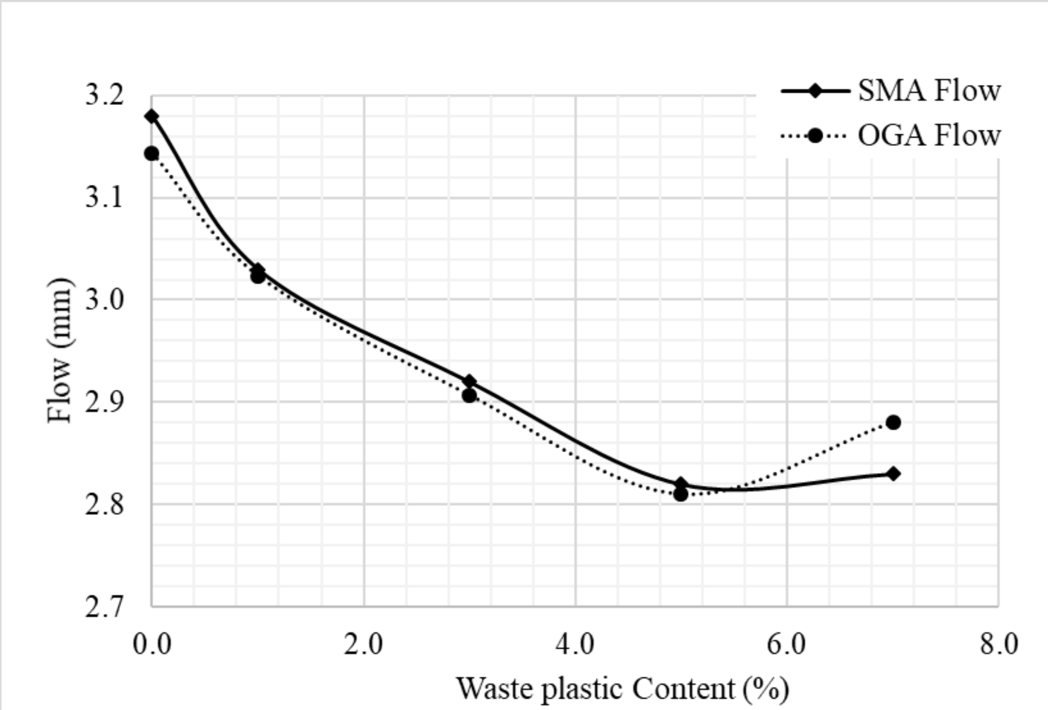


Figure 4.15: Flow values of waste plastic modified asphalt concrete

The Marshall quotient (MQ) test data for waste plastic modified asphalt concrete were recorded in Appendices XI and XII while results are shown in Figure 4.16. Marshall quotient of the plastic modified samples increased with increase in proportion percentage of waste plastics up to 5%. The MQ obtained at 5% when the highest stability was also achieved were 4.57kN/mm and 4.54kN/mm for OGA and SMA, respectively. WP enhances the bonding between bitumen and aggregates by coating the aggregates. This increases the bond strength as a result of improved cohesion and adhesion. This means, the stability increases and flow reduces until the maximum waste plastic content. Beyond the maximum WP content, the bonds become weak due to excess WP taking up the place of binder. The flow increases as stability reduces. It can be concluded that WP modified OGA and SMA, provide pavements with greater resistance against permanent deformations compared to control samples at optimal mix when 5% waste plastics are used to modify asphalt concrete.

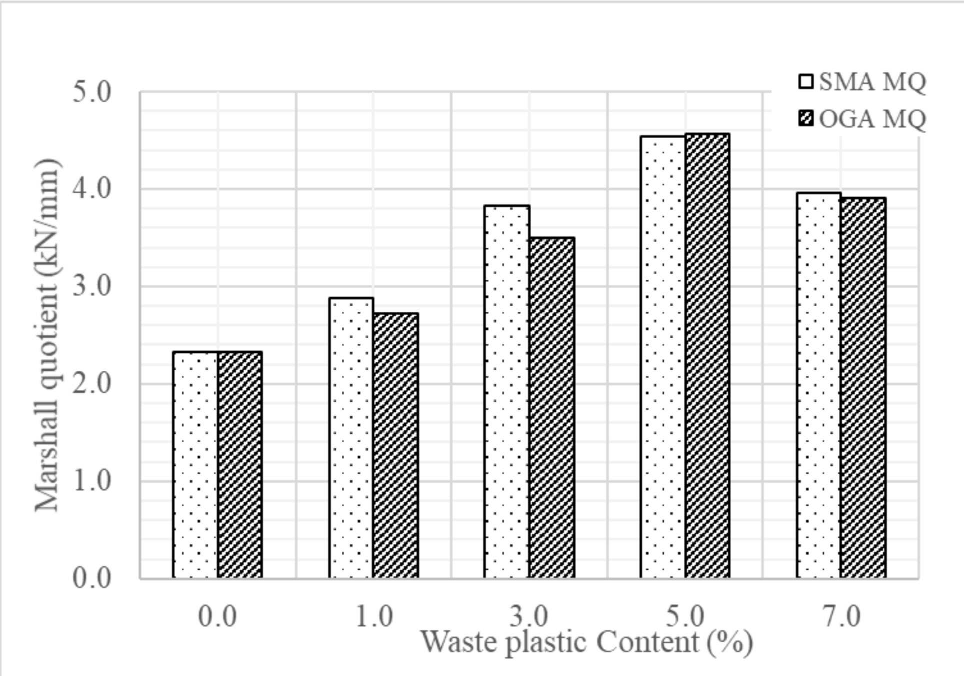


Figure 4.16: Marshall quotient of waste plastic modified asphalt concrete

4.5.2 Air Void and bulk specific Gravity

The Air voids and bulk specific gravity was tested for waste plastic modified asphalt concrete samples and data recorded in Appendices XI and XII. The results obtained for air voids are as shown in Figure 4.17. It was observed that air voids decreased as proportion content of waste plastics increased. At 5% maximum WP content, when WP modified asphalt concrete samples had maximum stability, the air voids achieved are 3.76% and 3.11% for OGA and SMA respectively. These air voids result values are within AASHTO T 312 standard range of 3-5%. When waste plastics (WP) are heated up, they penetrate into the aggregates and also form a coating over the particles. This is attributed to the fact that the density of waste plastics is much less than that of aggregates. Due to the waste plastics' filling effect, the WP modified samples of OGA and SMA, have less air voids compared to the control mix, thus, as the WP content increased in the asphalt concrete mix, the air voids decreased (Figure 4.17). These WP modified asphalt concrete produces pavements that do not undergo further compaction when under traffic load. The pavement does not easily rut or bleed due to waste plastics coating and reduced air voids (Tayfur et al., 2007).

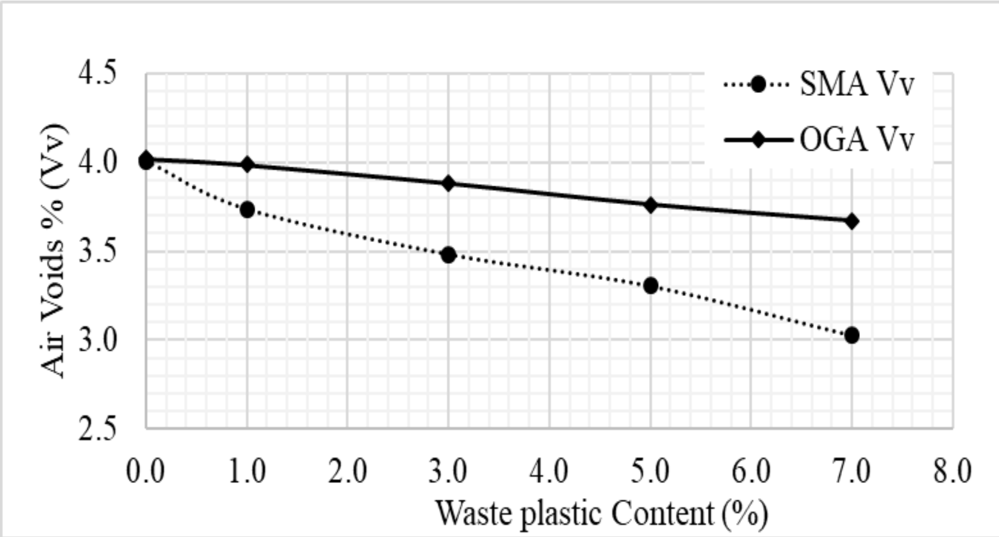


Figure 4.17: Air void waste plastic modified GGA

Bulk specific gravity of PMOGA and PMSMA values obtained with varying WP mix proportion in the asphalt concrete are shown in Figure 4.18. The specific gravity of WP modified OGA samples decreases as the proportion WP content increased (Figure 4.18). However, there was a noted increase in specific gravity of WP modified SMA samples with increase in proportion WP content in the mix. At 5% WP content, when the modified samples attained the maximum stability values, the specific gravity for WP modified OGA and SMA are 2.26 and 2.35 respectively. Specific gravity depends on the air voids which means that less air voids results into reduction in bulk volume. Waste plastics coats the aggregate particles of SMA and in the process occupies the large air spaces thus reducing the air voids. This makes PMSMA dense with little or no change in volume as weight increases, unlike in PMOGA whose aggregates of 12/6mm have less air voids compared to SMA of sizes 20/6. Waste plastic coats the OGA particles thus increasing the volume but with little change in weight. The pavement made of WP modified asphalt concrete is strong to resist rutting or cracking due to traffic loads

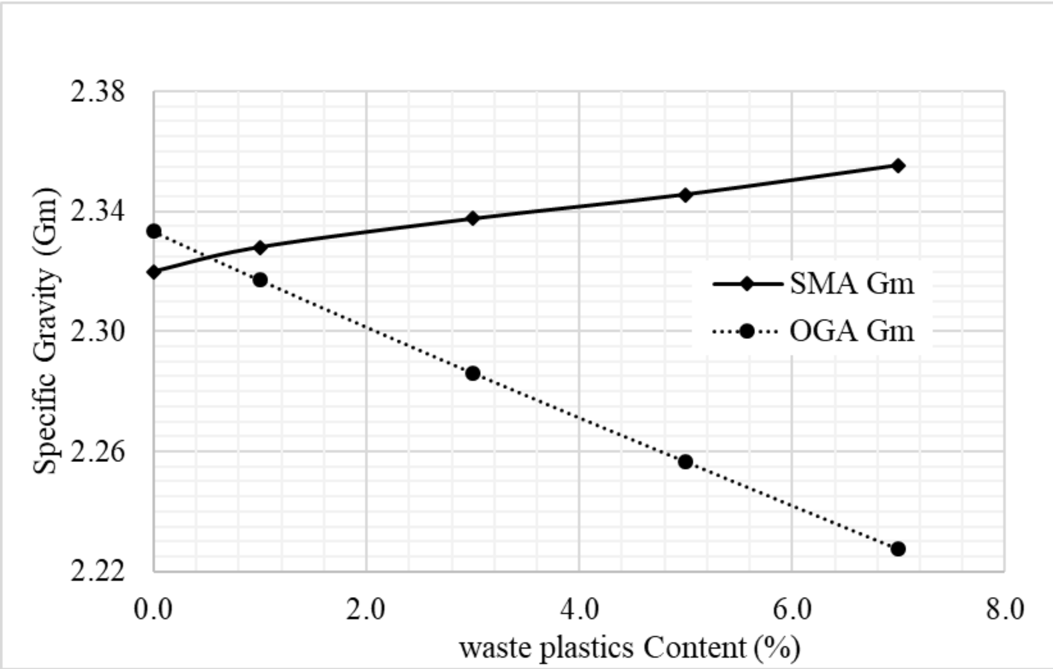


Figure 4.18: Specific gravity of waste plastic modified asphalt concrete

4.5.3 Voids in the mineral aggregates and Voids fill with bitumen

Waste plastics modified asphalt concrete samples were evaluated for Voids in the mineral aggregates (VMA) and voids filled with bitumen (VFB). Test data was as recorded in Appendices XI and XII while the results are as shown in Figures 4.19 and 4.20. VMA decreased with proportion increase of WP in OGA and SMA mixtures (Figures 4.19). At 5% WP content, when the stability of asphalt concrete was maximum, the VMA for OGA and SMA was 15.93 and 17.39%, respectively. This is as a result of the decrease of bulk specific gravity as WP content increased thus reducing voids occupied by bitumen. This makes the waste plastics modified asphalt concrete resist permanent deformation by rutting when under heavy traffic load.

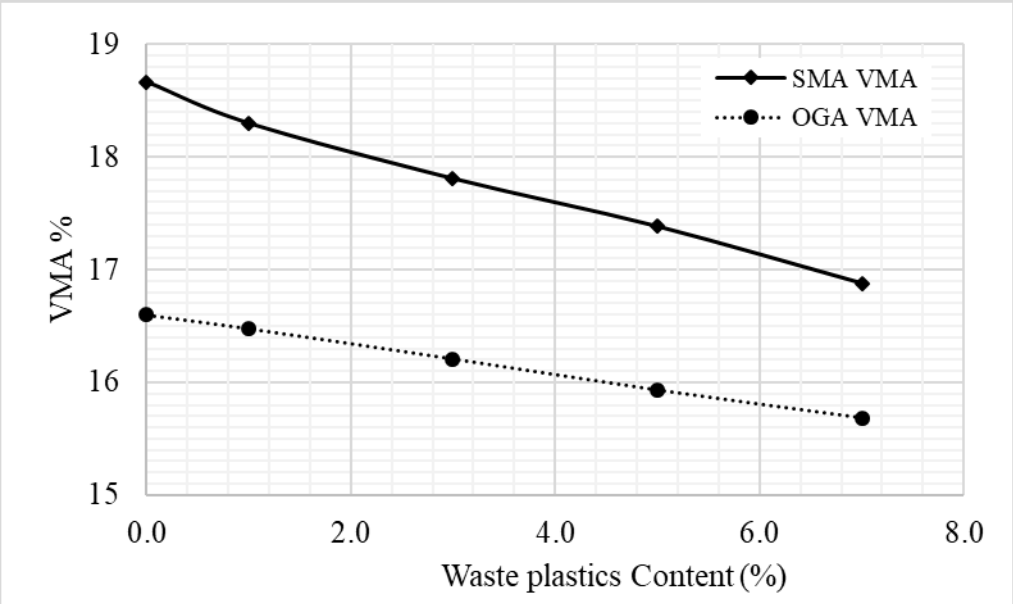


Figure 4.19: VMA of waste plastic modified asphalt concrete

Voids filled with bitumen (VFB) test results for waste plastic modified asphalt concrete are presented as shown in Figure 4.20. VFB increased with increase in proportion content of WP in the asphalt concrete mix. At 5% WP content, when the stability value was optimum, the VFB of the WP modified asphalt concrete are 76.4% and 81% for OGA and SMA, respectively. VFB is inversely related to air voids. Therefore, as air voids decreases, the VFB increases. Since VFB represents the volume of the effective bitumen content in the sample, increase in waste plastic content coated the aggregates as bitumen was made available to bind the aggregates. This makes pavements constructed using these modified asphalt mixes, strong enough to resist rutting and cracking when subjected to heavy traffic load.

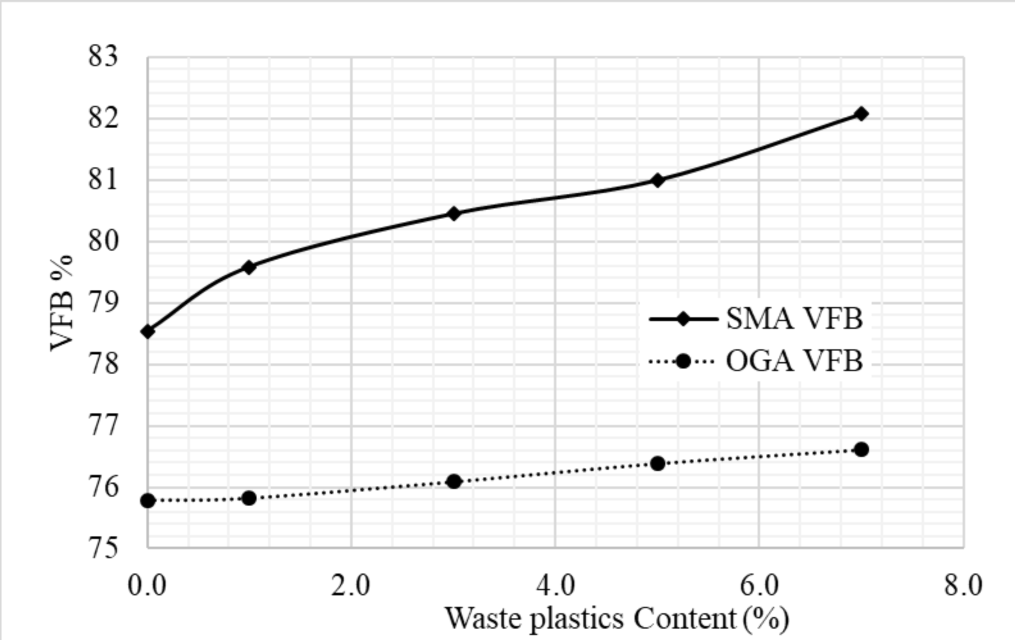


Figure 4.20: VFB of waste plastic modified asphalt concrete

4.6 Sisal-Plastics stabilized asphalt concrete

4.6.1 Marshall stability and flow value of sisal plastic modified asphalt concrete

The optimum mix proportions determined, 0.3% of sisal fibre (SF) and 5% of waste plastics (WP) contents by weight were combined to modify gap graded asphalt concrete ((open graded asphalt (OGA) and stone matrix asphalt (SMA)). The variation in Marshall stability and flow properties assessed for sisal-plastic modified OGA and SMA were data recorded in Appendices XIII and XIV. The Marshall stability determined are 7.31 and 7.42kN (Figure 4.21) for control OGA and SMA samples, respectively. The test result for sisal fibre modified asphalt concrete are 9.68kN and 9.78kN for OGA and SMA respectively. The test result for waste plastic modified asphalt concrete are 12.84 and 12.80kN for OGA and SMA, respectively. The sisal-plastic modified asphalt concrete (SPMAC) showed higher stability of 13.57 and 12.94kN for OGA and SMA, respectively in comparison to sisal fibre and waste plastic modified asphalt concrete. When sisal fibre is added to this mix, they reinforce it and form a strong matrix with higher resistance to failures. The sisal fibre prevents bitumen from drain down or settling to lower sections, thus ensuring even distribution. This evenly distributed bitumen combined with waste plastics rigidly hold aggregates together. This in turn makes strong bonds thus increasing the strength of the modified asphalt concrete. This implies that the pavements constructed using SPMAC, with high Marshall stability of 13.57 and 12.94kN, is more resistant to rutting and cracking due to heavy traffic loads (Huang et al., 2007).

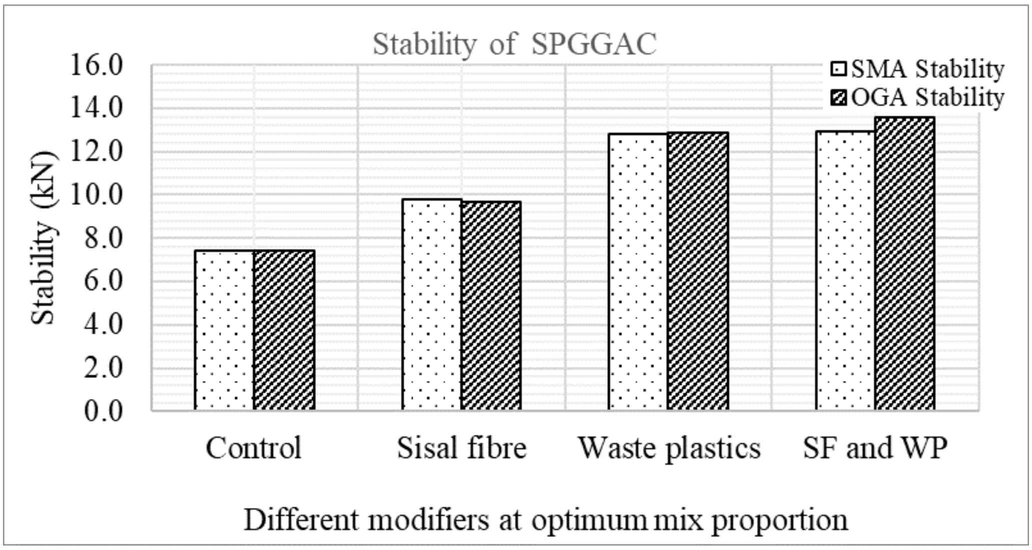


Figure 4.21: Stability performance of modified asphalt concrete

Flow values of the asphalt concrete modified using different modifiers at optimum mix proportions, decreases when modifiers were used as represented in Figure 4.22. This may be due to the decrease in the stone to stone contact of OGA mixtures. The flow value for control asphalt concrete samples are 3.14 and 3.18mm for OGA and SMA. When sisal fibre, waste plastics and Sisal-fibre were used to modify the asphalt concrete, the flow reduced to 2.5, 2.81 and 2.82mm, respectively. The modifiers reduced the grain to grain contact of the aggregates. The waste plastics coated the aggregates while sisal fibres formed a stiff matrix with asphalt concrete, which ultimately reduced the flow of the mix. With flow values within the required standard specification range of 2-4 mm, the asphalt concrete modified with a combination of sisal fibre and waste plastics, can produce pavement that resist rutting and bitumen bleeding.

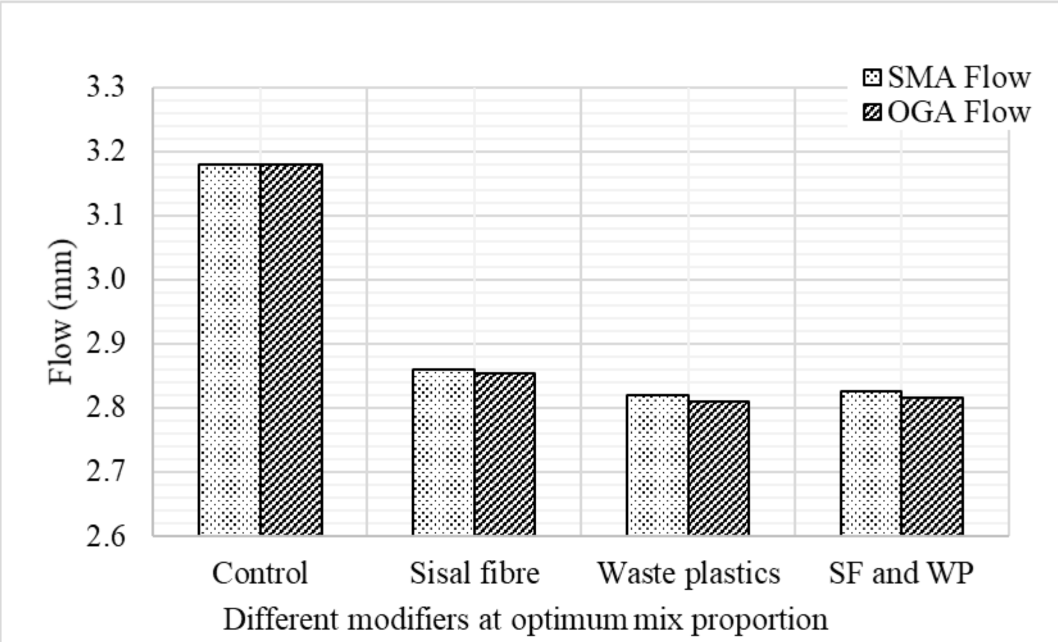


Figure 4.22: Flow performance of modified gap graded asphalt concrete

4.6.2 Air void and Bulk specific gravity

The test data for air voids and specific gravity for modified asphalt concrete were recorded in Appendices XIII and XIV while the results are presented in Figures 4.23 and 4.24. The air voids for control asphalt concrete samples are 4.02 and 4.01% for OGA and SMA, respectively. The air voids increased to 4.41 and 4.61% for sisal fibre modified OGA and SMA, respectively. This is associated with bulk nature of sisal fibre which forms a bulk matrix thus increasing air voids. When the asphalt concrete was modified using waste plastics, the air voids were 3.74 and 3.64% for OGA and SMA, respectively. However, when both sisal fibre and waste plastics were used to modify the asphalt concrete mixes, the air voids increased to 4.14 and 3.81% for OGA and SMA, respectively. Since the density of waste plastic is lower than that of aggregates, they penetrate into the aggregates and also form a coat over them. The filling effect of waste plastics resulted in less air voids in waste plastic modified samples compared to the control mixture and sisal fibre modified asphalt concrete samples. Sisal fibre, when used to modify gap graded asphalt, the fibres occupy the spaces between the aggregate particles. They stiffen and reinforce the asphalt concrete mix. However, their presence makes the samples have more air voids due to increase in air space between the aggregate particles. The air voids within the standard specified limit of 3-5% produces pavement that does not fail by rutting when under traffic load (Taj et al., 2007).

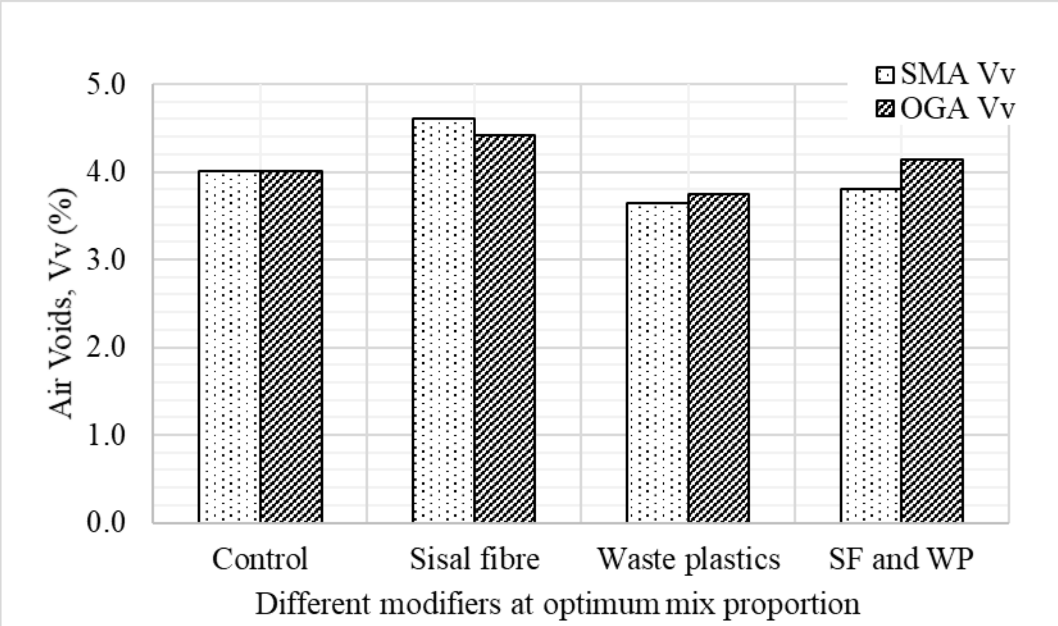


Figure 4.23: Air voids of asphalt concrete modified with different additives

The specific gravity test results for modified asphalt concrete is presented in Figure 4.24. Air voids of gap graded asphalt (GGA) determines bulk specific gravity of the mix. The specific gravity for OGA modified with sisal fibre and waste plastics were 2.32 and 2.26, respectively, but increased to 2.37 when both sisal fibre and waste plastics were used to modify OGA. The specific gravity for SMA modified with sisal fibre and waste plastics were 2.30 and 2.25, respectively, but reduced to 2.24 when both sisal fibre and waste plastics were used to modify SMA. This means that the air voids are linearly related to specific gravity. Higher air voids correspond to higher specific gravity as shown in Figures 4.23 and 4.24. Specific gravity of waste plastic modified gap graded asphalt was the lowest compared to control and sisal fibre modified samples. This is attributed to penetration and coating effect of the aggregates by waste plastics. Open graded asphalt concrete samples modified with both sisal fibre and waste plastics resulted into increase in air voids and specific gravity but reduced for SMA. Sisal occupies the spaces in between the large spaces between the large aggregate sizes in SMA. The waste plastics coat and penetrate into the aggregate particles. These processes reduce or increase the air voids (Figure 4.23) and bulk volume which in turn resulted into low or high specific gravity (Figures 4.24). The specific gravity affects bitumen bleeding and therefore use of sisal fibre produce asphalt concrete that made road pavements that resist aggregate segregation and bitumen bleeding.

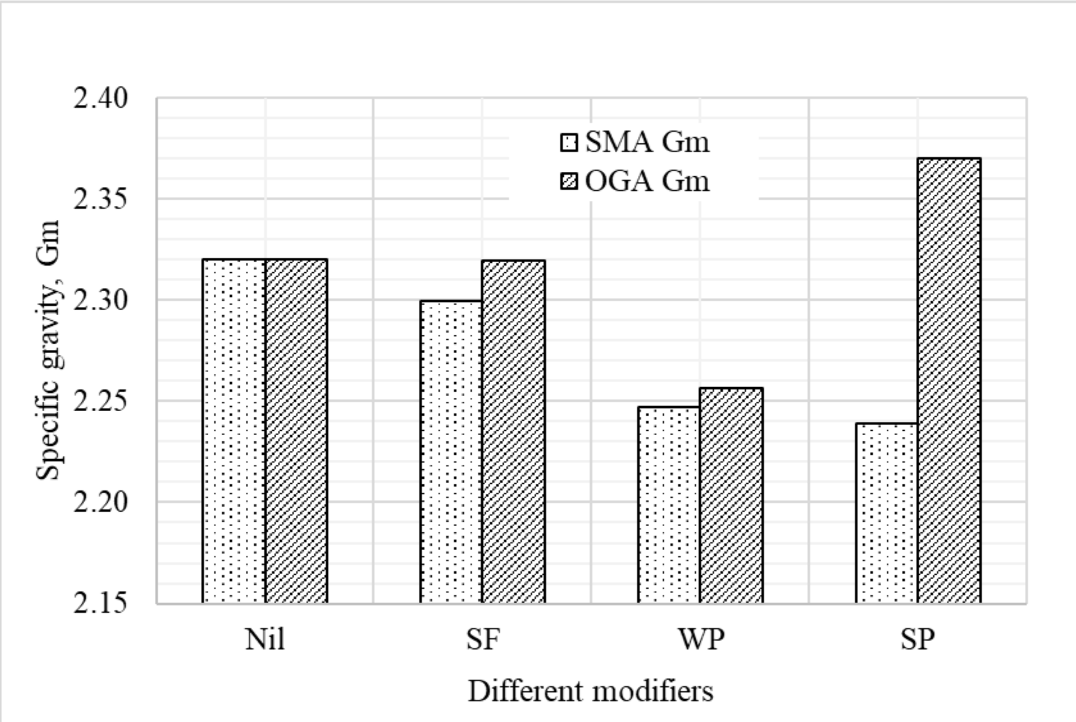


Figure 4.24: Specific gravity of asphalt concrete modified with different additives

4.6.3 Voids in the mineral aggregates and voids filled with bitumen for modified asphalt concrete

Test data for voids in the mineral aggregates (VMA) and voids filled with bitumen (VFB) for modified asphalt concrete were recorded in Appendices XIII and XIV. VMA for the control samples were 16.602 and 18.644% for OGA and SMA, respectively. When sisal fibre was used to modify OGA and SMA, the VMA increased to 16.85 and 19.128%, respectively. However, when waste plastics were used as the modifier, VMA decreased to 15.931 and 17.382%, respectively. The VMA for asphalt concrete samples modified using both sisal fibre and waste plastics were 16.922 and 17.219% for OGA and SMA, respectively as shown in Figure 4.25. This is due to the variations of bulk specific gravity which is dependent on modifiers used. Decrease in bulk specific gravity at optimum content of SF and WP reduced voids occupied by bitumen. This makes the sisal-plastic modified asphalt concrete resist permanent deformation by rutting when under heavy traffic load or bleeding at high temperatures.

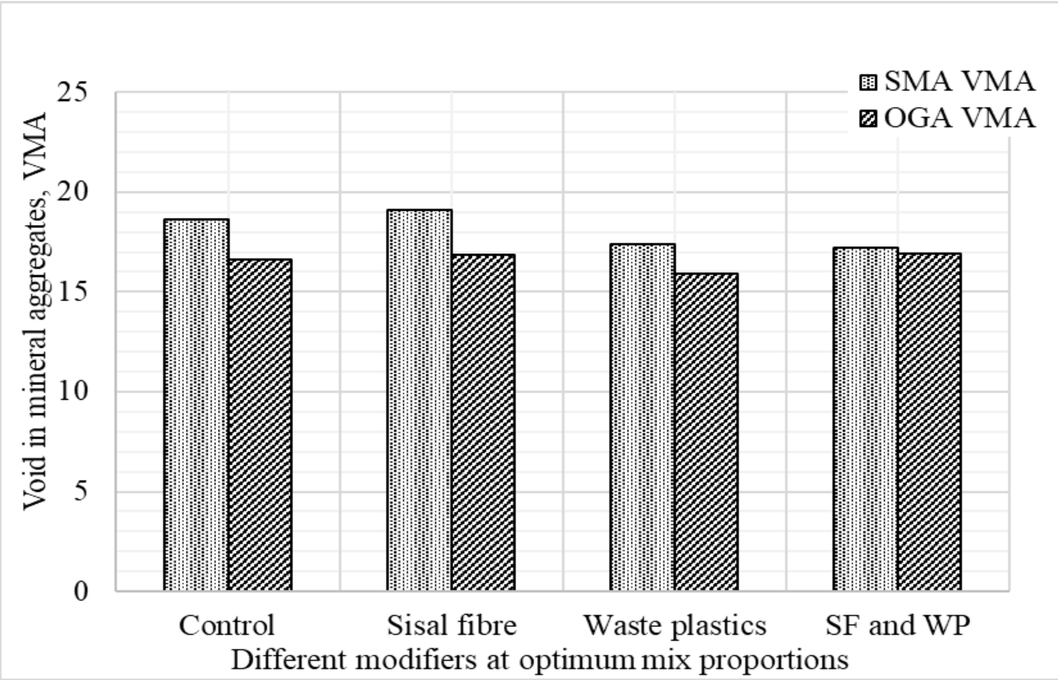


Figure 4.25: Variation asphalt concrete VMA with different additive

Voids filled with bitumen (VFB) test results for MOGA and MSMA are as shown in Figure 4.26. VFB for control asphalt concrete samples are 75.78 and 78.60% for OGA and SMA, respectively. When SMA modified using sisal fibre and waste plastics, the VFB test results recorded are 75.90 and 80.46%, respectively. In the case of OGA, the VFB were 74.26 and 76.48% when sisal fibre and waste plastics were used as modifiers, respectively. The VFB values for asphalt concrete modified with waste plastics was high as compared to sisal fibre modified samples. This means that the waste plastics penetrated and coated the aggregate particles making bitumen available to bind the aggregates. As the air voids decreases, the VFB increases since they are inversely related The VFB of asphalt concrete modified with sisal fibre and waste plastics were 77.89 and 75.52% gives values that represent the volume of the effective bitumen content (Swami et al., 2012). This available effective bitumen content produces asphalt concrete which can be used to construct road pavement strong enough to resist failure by cracking or rutting.

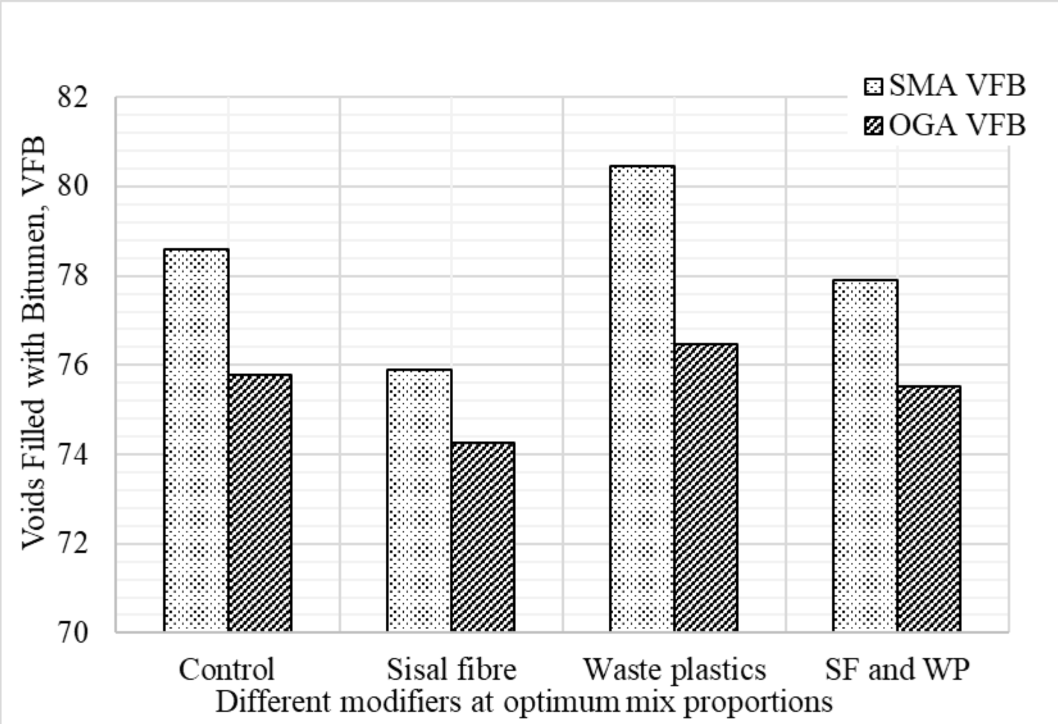


Figure 4.26: VFB of asphalt concrete modified with different additives

4.6.4 Summary of Marshall properties of sisal plastic modified asphalt concrete.

The type of modifiers and their contents have a significant role in the volumetric and mechanical properties of gap graded asphalt concrete. The determined optimum sisal fibre and waste plastic content were 0.3, and 5%, respectively. At these optimum modifier contents, the asphalt concrete samples have the highest stability and Marshall Quotient. The stability achieved are 13.6kN and 12.94kN against the minimum standard requirement of 6kN (AASHTO T 245-15). Marshall quotient were 4.81 and 4.58 for OGA and SMA respectively. These test results showed that sisal fibres have reinforcing effects while waste plastics have binding effects. The strength of sisal-plastic modified asphalt concrete increased by 85.43% and 74.42% for OGA and SMA respectively. The flow values achieved was 2.8mm against the standard requirement of 2-4mm (AASHTO T 245-15) while the voids filled with bitumen were 75.5% and 77.89% for modified OGA and SMA respectively. This means that adding sisal fibre and waste plastic to gap graded asphalt concrete mix produce pavement material with improved mechanical properties that can resist cracking or rutting under heavy traffic load.

4.7 Tensile strength characteristics for modified gap graded asphalt concrete

The indirect tensile strength tests were done for asphalt concrete mixes modified using varying proportions of sisal and waste plastics to determine their tensile strength characteristics. The test data for the modified gap graded asphalt concrete samples are recorded in Appendices XV and XVI while the results are presented in Figures 4.27 and 4.28. The samples modified with sisal fibre and waste plastics showed higher tensile strength of 1.23 and 1.21MPa compared to asphalt control samples with 0.83 and 0.81MPa for OGA and SMA, respectively. This could be associated with enhanced stiffness of sisal fibre and waste plastic modified OGA and SMA samples compared to the control asphalt concrete samples. Waste plastics enhances the bonding between the aggregate particles and bitumen while sisal fibre reinforces the asphalt concrete mix forming a stiffened matrix. The tensile strength ratio increased from 52.19 to 97.33% and 97.78 for OGA modified sisal fibre and waste plastics, respectively. This could be attributed to balling effect of sisal fibre and overcoating of waste plastics. When the samples were conditioned by putting then in a water bath, the tensile strength decreased compared to unconditioned samples. This is associated with wetting of the samples which weakened the bond that held the particles together (Jawaid et al. 2018). Strength reduction as a result of conditioning were average of 48 % for control sample, 3% for waste plastics and 2% for sisal plastics at optimum contents. However, the decrease in strength for modified samples using combination of sisal fibre and plastics at optimum contents was 0%. This means that road pavements constructed using sisal-plastic modified asphalt concrete withstand higher traffic loads compared to non-modified asphalt concrete, without cracking or rutting.

4.7.1 Tensile strength of sisal modified asphalt

Asphalt concrete was modified using varying proportion percentages of sisal fibre. The samples were tested for tensile strength before and after conditioning the samples by putting them in water bath. The indirect tensile strength test result for sisal fibre modified asphalt mix are presented in Figure 4.27. The tensile strength results for unconditioned modified asphalt concrete mix samples increases with proportion increase in sisal fibre content up to optimum value of 1.10 and 1.11MPa for OGA and SMA, respectively. When the asphalt concrete samples were conditioned, tensile strength results reduced to 1.07 and 1.08MPa, respectively. This is associated with weakened bond by wetting as a result of conditioning. Weak bonds are as a result of reduced cohesion when friction between particles reduces. The tensile strength of sisal fibre modified OGA increased from 0.83 to 1.10MPa and from 0.43 to 1.07 MPa for unconditioned and conditioned samples, respectively. Further, the tensile strength of sisal fibre modified SMA increased from 0.81 to 1.11MPa and from 0.43 to 1.08 MPa for unconditioned and conditioned samples, respectively. The aggregates particles are held together by bitumen as a binder and sisal fibre acts as reinforcing agent in stiffening the mix thus increasing tensile strength. When sisal fibre reinforces the bond formed by bitumen and aggregates, a stiff matrix is formed. However, addition of sisal fibre beyond 0.3% content, the sisal fibre weakens the sample as a result of bitumen absorption, which would coat and bind the aggregates and reduction of grain to grain contact of the aggregates. This results into weakened bond and adhesion between the aggregates thus having weakened bond (Anderson et al., 2001). At optimum sisal fibre content of 0.3%, the modified asphalt concrete has tensile strength that produce road pavements that resist low temperature cracking, fatigue and rutting.

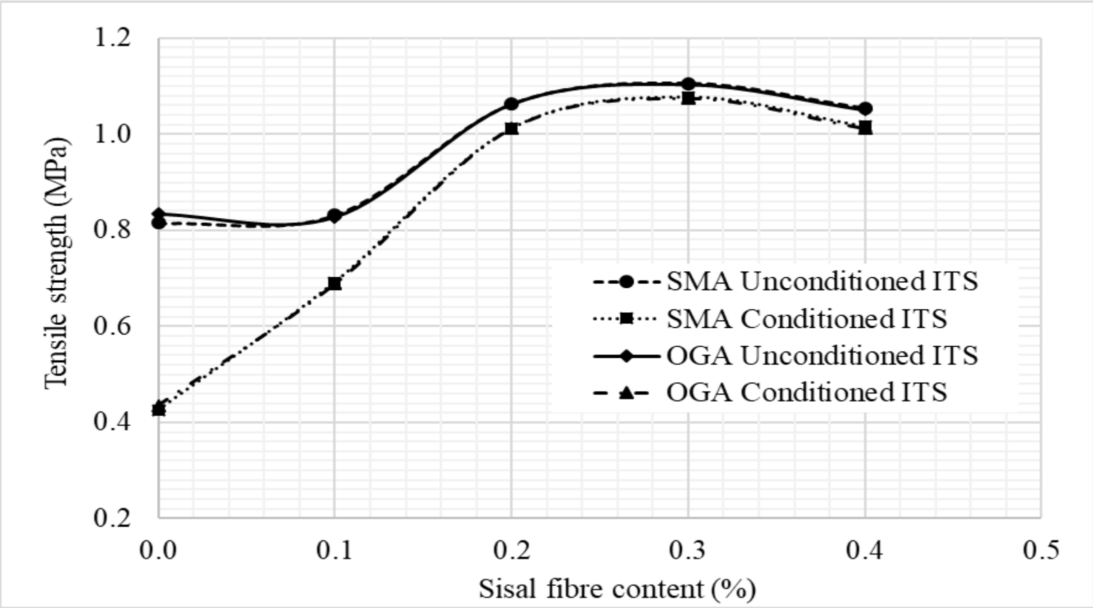


Figure 4.27: Tensile strength of sisal fibre modified asphalt concrete

4.7.2 Tensile strength of waste plastic modified asphalt

The tensile strength results for unconditioned and conditioned waste plastic modified mix samples are presented in Figure 4.28. Tensile strength increased with increase in proportion increase in waste plastic content. The tensile strength (TS) values increased from 0.83 to 1.20MPa and from 0.43 to 1.17MPa for unconditioned and conditioned modified OGA, respectively. The modified SMA tensile strength values increased from 0.81 to 1.21MPa and from 0.43 to 1.18MPa for unconditioned and conditioned modified OGA, respectively. This is as a result of weakened bond by wetting when conditioning took place. Wetting reduced the friction between particles and thus reducing cohesion. For both conditioned and unconditioned samples, the strength increased as waste plastic content increased up to maximum content of 5%, when optimum stability was achieved. Waste plastics increases the adhesion between aggregate and bitumen by coating and binding the aggregates together with bitumen. This ultimately leads to a decrease in the stripping of particles, thus resulting in increased tensile strength. The addition of waste plastics improves the cracking résistance of pavements since it can withstand higher tensile strains.

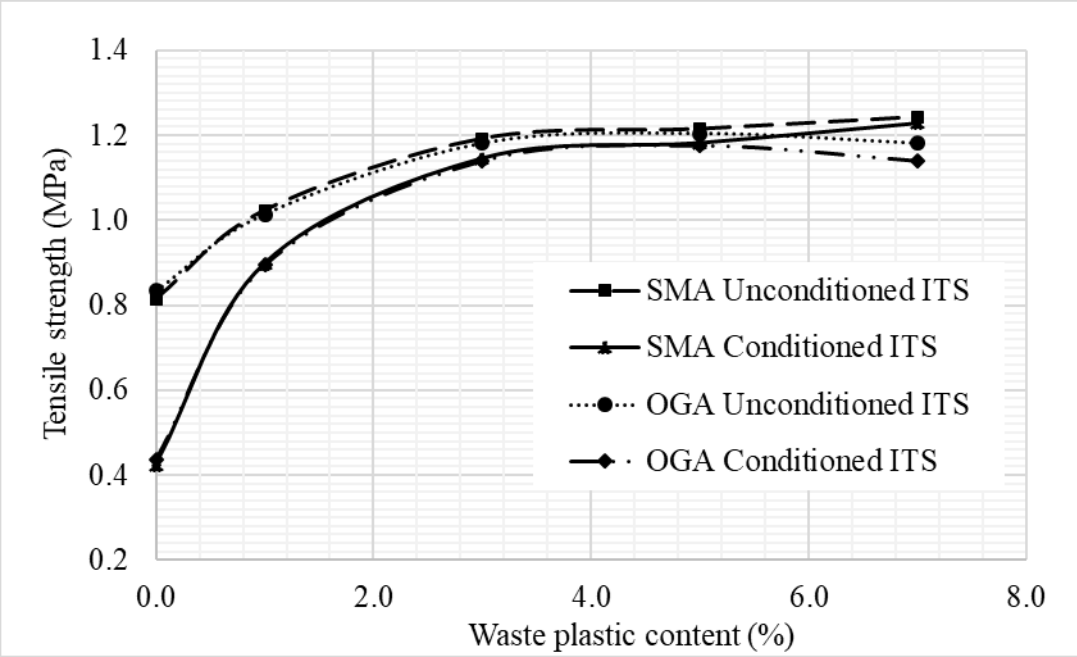


Figure 4.28: Tensile strength of waste plastic modified asphalt concrete

4.7.3 Tensile strength for Sisal-Plastic modified asphalt concrete

Tensile strength results for open graded asphalt and stone matrix asphalt when modified with both 0.3% sisal fibre content and 5% waste plastics are presented in Figures 4.29 and 4.30. Tensile strength for unconditioned OGA are 0.83MPa for control samples but increases to 1.1, 1.2 and 1.23MPa for Sisal fibre, waste plastics and sisal-plastic modified asphalt concrete, respectively. This represent 32, 44 and 47% increase when sisal fibre, waste plastics and sisal-plastic were used to modify OGA, respectively. Similarly, the tensile strength for unconditioned SMA are 0.81MPa for control samples but increases to 1.1, 1.2 and 1.21MPa for Sisal fibre, waste plastics and sisal-plastic modified asphalt concrete, respectively. This represent 36, 48 and 52% increase when sisal fibre, waste plastics and sisal-plastic were used to modify SMA, respectively. High tensile strength values show that the road pavement made from sisal-plastic modified asphalt concrete has sufficient strength to accommodate heavy traffic load without cracking as compared with asphalt concrete modified using sisal fibre or waste plastics only (Tayfur et al., 2007 and Swami et al., 2012).

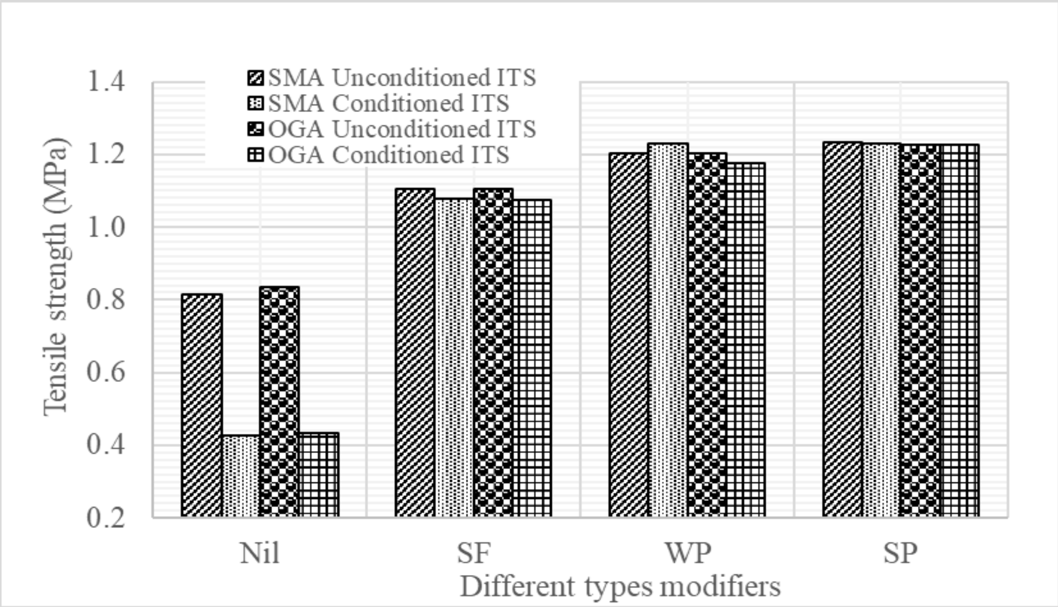


Figure 4.29: Tensile strength of modified asphalt concrete

Sisal-plastic modified asphalt concrete (SPMAC) samples had the highest percentage increase in strength of 47 and 52% for unconditioned OGA and SMA samples as compared to sisal fibre or waste plastics stabilized samples. This is associated with the fact that the samples with sisal-plastic are more firm and stronger due to fibre reinforcement and waste plastic coating that form stiffer matrix samples compared to use of plastic or sisal fibre alone (Wu et al., 2006). It can be concluded that sisal-plastic additive demonstrates better cracking resistance as compared to sisal fibre and waste plastics modifiers only.

4.8 Moisture Susceptibility of modified gap graded asphalt concrete

Moisture susceptibility is measured by tensile strength ratio (TSR) by dividing tensile strength of unconditioned and conditioned asphalt concrete samples. Test results for moisture susceptibility of modified OGA and SMA samples were as shown in Figure 4.30. The tensile strength ratio (TSR) for the control samples is 52.2 %. However, TSR increased to 97.3, 97.7 and 99.9% when OGA was modified using sisal fibre, waste plastics and sisal-fibre, respectively. Similarly, when SMA was modified using sisal fibre, waste plastics and sisal-fibre, TSR increased to 97.4, 98.9 and 99.0%, respectively. This means that the control mix has more moisture susceptibility, which would result into pavement damage by water. However, the tensile strength ratios for the samples with sisal fibre, waste plastics and sisal-plastic modifiers have TSR greater than the specification limit, AASHTO T283 of 70%. The sisal-plastic modified asphalt has the highest TSR of 99.9 and 99.0% for OGA and SMA, respectively.

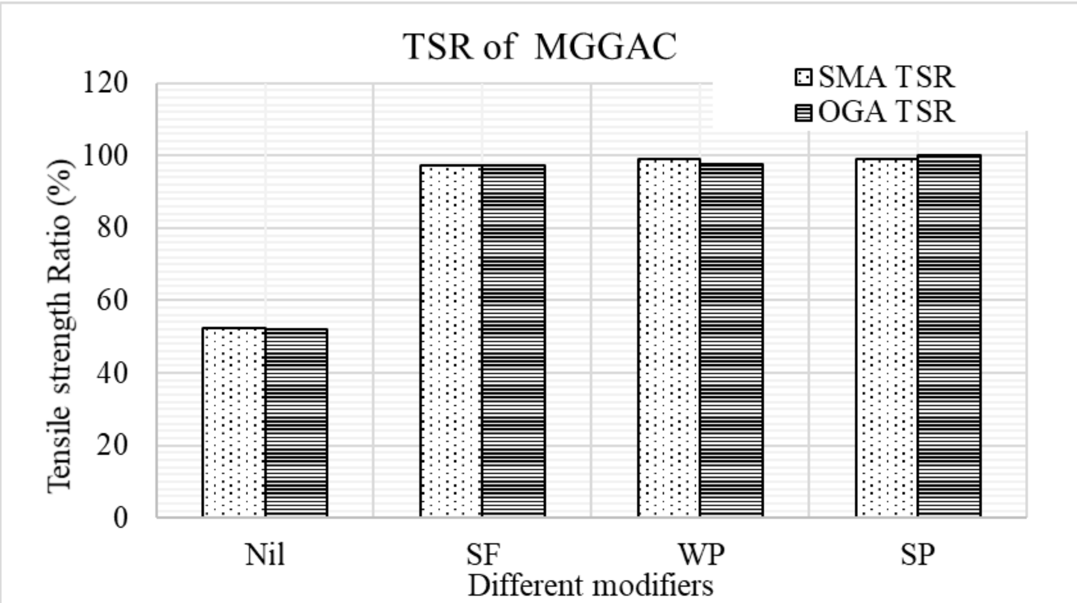


Figure 4.30: Tensile strength ratios for asphalt concrete with different additives

Asphalt concrete samples modified using sisal fibre and waste plastics are more firm and stronger due to fibre reinforcement and waste plastics coating that form stiffer matrix. This reduces water-induced damage to the pavements thus preventing the development of cracks.

4.9 Drain down characteristics of modified gap graded asphalt concrete

4.9.1 Drain down test results for modified gap graded asphalt concrete

Bitumen drain down test data at various proportion percentages of sisal fibre and waste plastics in OGA and SMA samples were recorded in Appendices XVII and XVIII while the results are presented in Figures 4.31 and 4.32. It is observed that bitumen drain down reduced from 6.5 to 0% as the proportion increase in percentage sisal fibre content increased from 0 to 3% for both OGA and SMA samples. When waste plastics were used to modify the asphalt concrete, bitumen drain down reduced from 6.5 at 0% waste plastic content to 0.8 at 5% waste plastic content. The additives provide higher stabilization to the modified asphalt concrete mix in comparison to the control mix without modifiers. Drain down of the control mixture is 6.5% which is beyond the specified limits 0.3% as per AASHTO T 305. However, at 0.3% of sisal fibre modified asphalt concrete sample, bitumen retention was 0% compared to waste plastics modified asphalt concrete whose bitumen retention is 0.8%. Sisal fibres stiffen and hold bitumen around the aggregates in the mix thus prevents the bleeding phenomenon of the asphalt concrete mix and bitumen drain down. The coating of aggregates using plastics reduces the bleeding phenomena by holding the bitumen in the mixture. This produces a strong road pavement which resist rutting, cracking and bitumen blending.

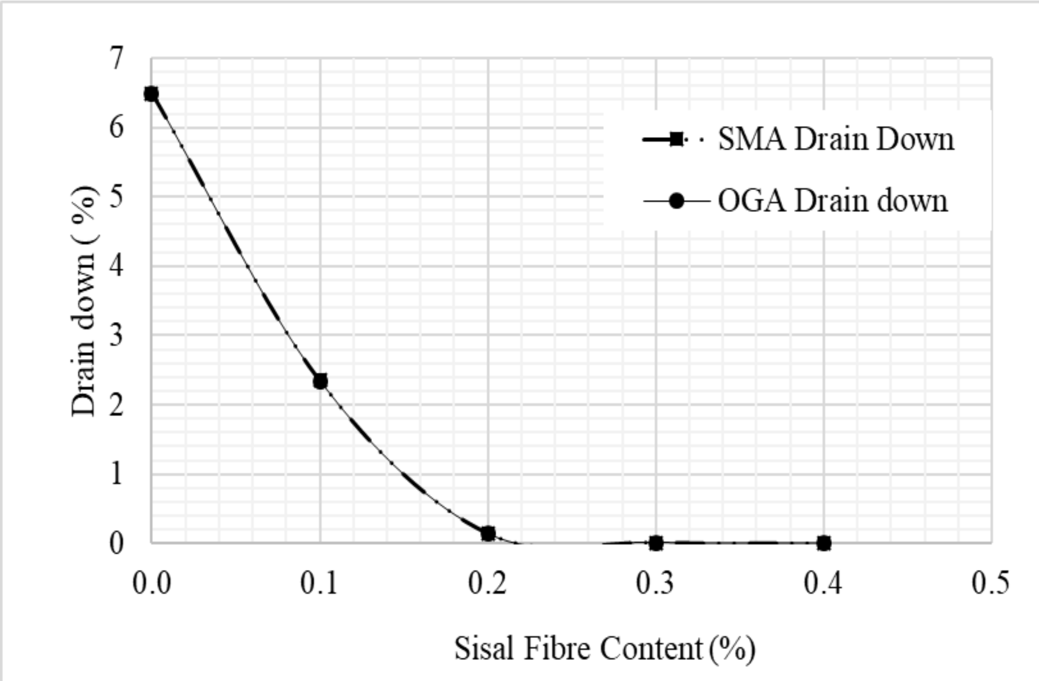


Figure 4.31: Drain down characteristics of sisal modified gap graded asphalt

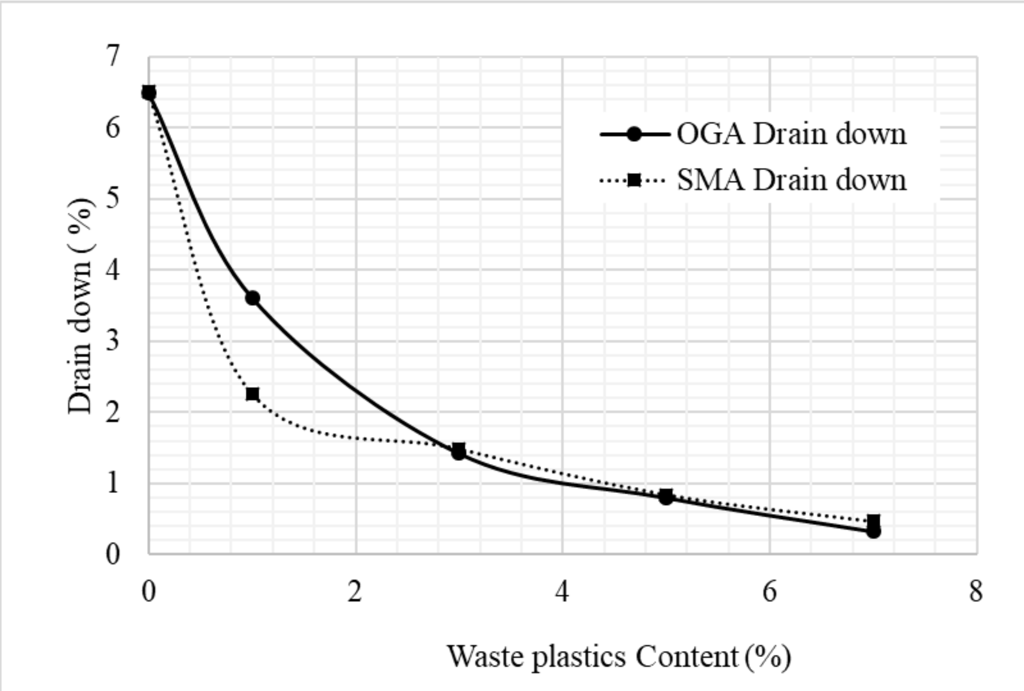


Figure 4.32: Drain down characteristics of plastic modified asphalt concrete

4.9.2 Bitumen retention of sisal-plastic modified gap graded asphalt

To evaluate the effect of combination of sisal fibre and waste plastics on asphalt concrete, 0.3% sisal fibre and 5% waste plastics were both used to modify gap graded asphalt concrete. These percentages of modifiers were selected since they are optimum contents when asphalt concrete had highest strength. Bitumen drain down test results for sisal-plastic modified gap graded asphalt concrete are presented in Figure 4.33. The bitumen drain down for non-modified asphalt concrete mix was 6.5%. When 0.3% of sisal fibre was used to modify the asphalt concrete, bitumen loss was 0%. However, when 5% waste plastics were used to modify the asphalt concrete, the bitumen loss was 0.80 and 0.84% for OGA and SMA, respectively. Further when 0.3% sisal fibre and 5% of waste plastics were both used to modify the asphalt concrete, the bitumen loss was 0%. This means that sisal fibres have strong stabilizing ability as compared to waste plastics due to the absorption ability of sisal fibres. Sisal fibres and waste plastics bind the aggregates to make a firm and stiff mix (Shukla et al., 2014). This enhances bitumen retention and reduces bleeding. When both sisal and plastics are used, the reinforced and coated asphalt concrete mix form a rigid and stiffened mass which ultimately reduce bitumen drain down to 0% for both OGA and SMA. This makes road pavements that are constructed using these sisal-plastic modified asphalt concrete mixes have sufficient strength to withstand traffic load without cracking and rutting as well as resist bitumen blending at high temperatures.

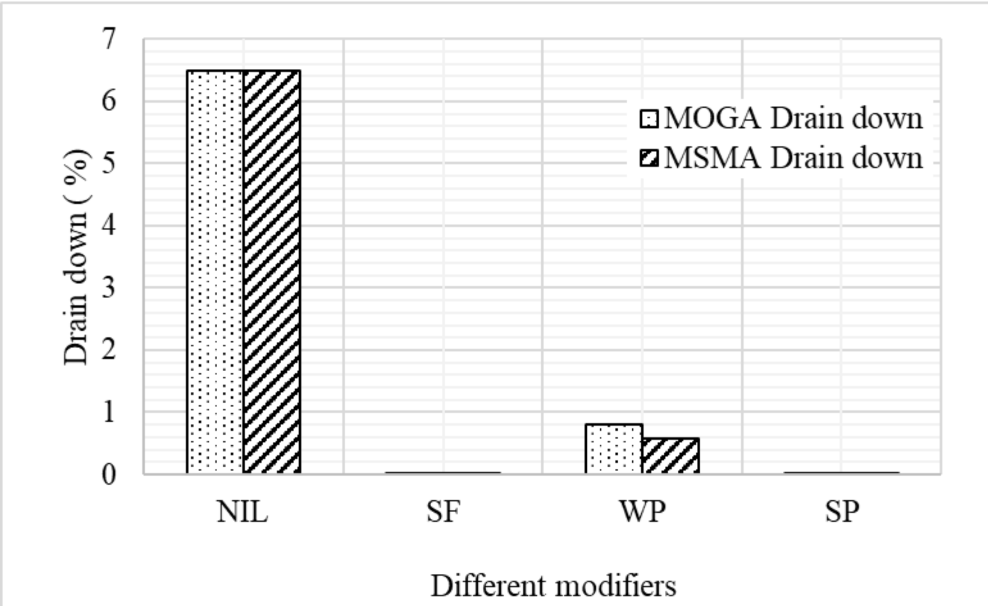


Figure 4.33: Drain down results for modified asphalt Concrete

4.10 Mathematical model to predict the tensile strength of asphalt concrete modified using sisal fibre and waste plastics.

4.10.1 Development of the mathematical model

The indirect tensile strength was used to determine the tensile strength of a modified asphalt concrete specimen using the split tensile test. Thereafter a mathematical model was derived using Scheffe's simplex theory. This theory was applied for four mix ratios of sisal fibre, waste plastics, bitumen and aggregate in the preparation of modified asphalt concrete samples. Two replicate samples were prepared using actual and control mix ratios of sisal fibre, waste plastic, bitumen and aggregates as shown in Appendices XIX and XX. The tensile strength tests data for the sisal-plastic modifies asphalt concrete were recorded in Appendix XXI. The coefficients of polynomial in Scheffe's predictive model for indirect tensile strength Equation 4.4 were determined using data in in Appendix XXI.

$$Y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 \quad \text{.......} (4.4)$$

Where

Y is a dependent variable (Indirect Tensile strength of concrete).

X_1 is Pseudo component ratio of sisal fibre

X_2 is Pseudo component ratio of waste plastics

X_3 is Pseudo component ratio of bitumen

X_4 is Pseudo component ratio of aggregates

Data in Appendix XXI was used to determine the coefficients in the polynomial in equation 2.11. The values obtained are β_1=1.034, β_2=1.127, β_3=1.228, β_4=1.124,

$\beta_{12}=4Y_{12}-2Y_1-2Y_2=4*1.085-2*1.034-2*1.127=0.018$, $\beta_{13}=4Y_{13}-2Y_1-2Y_3=4*1.127-2*1.034-2*1.228=-0.015$, $\beta_{14}=4Y_{14}-2Y_1-2Y_4=4*1.191-2*1.034-2*1.124=0.44955$, $\beta_{23}=4Y_{23}-2Y_2-2Y_3=4*1.188-2*1.127-2*1.228=0.4155$, $\beta_{24}=4Y_{24}-2Y_2-2Y_4=4*1.221-2*1.127-2*1.124=0.383$, $\beta_{34}=4Y_{34}-2Y_3-2Y_4=4*1.169-2*1.288-2*1.124=-0.026$

Substituting these coefficients in Equation 4.4 generates Equation 4.5.

$$Y = 1.034x_1 + 1.127x_2 + 1.139x_3 + 1.201x_4 + 0.018x_1x_2 - 0.015x_1x_3 + 0.450x_1x_4 + 0.4155x_2x_3 + 0.383x_2x_4 - 0.026x_3x_4 \quad \text{......} (4.5)$$

Where

Y is a dependent variable (Indirect Tensile strength of concrete).

X_1 is Pseudo component ratio of sisal fibre

X_2 is Pseudo component ratio of waste plastics

X_3 is Pseudo component ratio of bitumen

X_4 is Pseudo component ratio of aggregates

Equation 4.5 is the mathematical model which can be used to predict the tensile strength of asphalt concrete modified using sisal fibre and waste plastics.

4.10.2 Mathematical model performance assessment

To assess the performance of the predictive mathematical model, the tensile strength data from control samples tested in the laboratory and data predicted by the model were recorded in Appendix XXII while the results were represented in Figures 4.34 and 4.35.

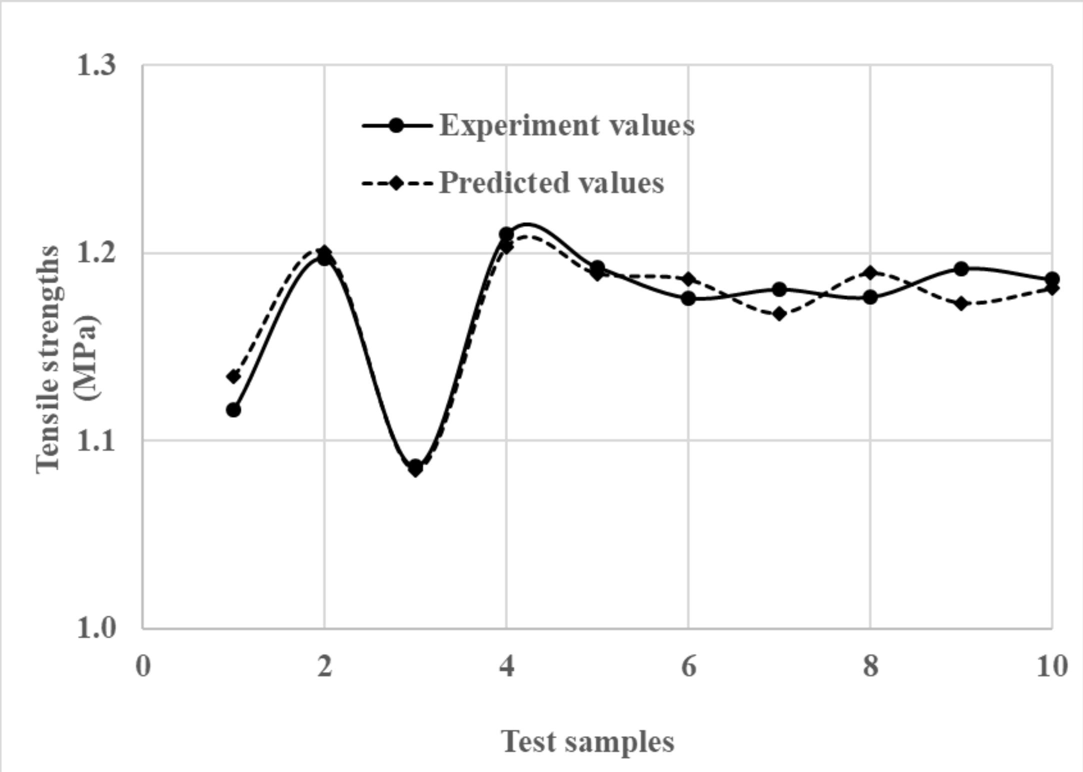


Figure 4.34: Comparison between experimental and predicted tensile strengths of modified asphalt concrete

The results from the laboratory test and those predicted by the model were presented in Figures 4.34. The results obtained from experiments and those predicted using the model were very similar with a difference of less than ±0.01MPa.

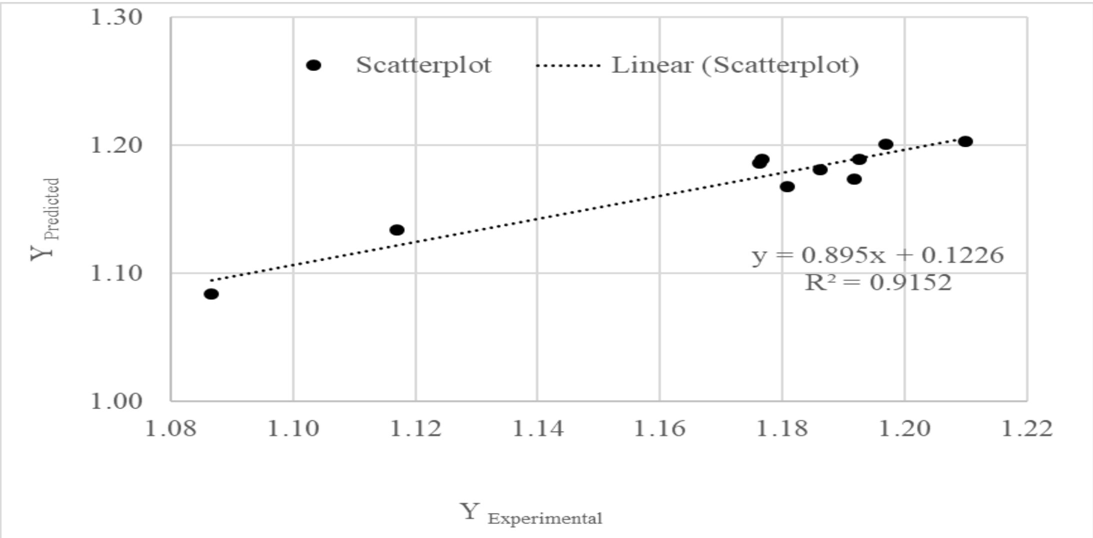


Figure 4.35: Scatterplot of predicted vs. experimental tensile strengths of modified asphalt concrete

When the scatterplot was done as shown in Figure 4.35, the correlation coefficient obtained R^2=0.9152 with best fitting line whose equation is y = 0.895x + 0.1226. This means that the tensile strengths of asphalt concrete modified using sisal fibre and waste plastics can be predicted using mathematical model Equation 4.1 with confidence level of 91.52%.

4.10.3 Test of adequacy of the mathematical model

A two-tailed t-test at 95% confidence level was carried out. This implies a 5% significance given by 100 – 95 = 5%. However, since it is a two-tailed test, the level of significance = 5/2 = 2.5%. Hence, the corresponding confidence level = 100 – 2.5 = 97.5%.

The difference between the experimental and predicted tensile strength test results can be taken as D, while the mean of D taken as D_a, which can be calculated from Equation 4.6.

$$D_a = \frac{1}{n}\sum_{i=1}^{n} D_i \quad (4.6)$$

Where

D_a is the mean of the experimental and predicted tensile strength test results, D.

n is the number of test result observation done.

D_i is the experimental and predicted tensile strength test results at any given observation.

The t-test tensile strength data for sisal-plastic modified asphalt concrete samples were recorded in Table 4.11. Column 4 shows the values of D with a total sum of 0.0042. That is $\sum_{i=1}^{n} D_i = 0.0042$. The mean of the experimental and predicted tensile strength test results given by Equation 4.2, $D_a = \frac{0.0042}{10} = 0.0004$

The variance of the mean of the experimental and predicted tensile strength test results is given by Equation 4.7.

$$S^2 = \left(\frac{1}{n-1}\right) \sum_{i=1}^{n} (D - D_a)_i^2 \text{...} (4.7)$$

Where

S is the variance of the mean of the experimental and predicted tensile strength test results

D the mean of the experimental and predicted tensile strength test results

D_a is the mean of the experimental and predicted tensile strength test results, D.

n is the number of test result observation done

n-1 is the degree of freedom

The square of the sum of D-D_a was calculated and found to be 0.0012 as given in Table 4.11, column 6. Therefore $S^2 = \left(\frac{0.0012}{9}\right) = 0.00012798$

$$S = \sqrt{0.00012798} = 0.011312843$$

The calculated t-test, $t_{calculated}$ is given by Equation 4.8 as

$$t_{calculated} = \frac{D_a\sqrt{n}}{S} \text{..} (4.8)$$

Where

$t_{calculated}$ is the calculated t-test

S is the variance of the mean of the experimental and predicted tensile strength test results

D_a is the mean of the experimental and predicted tensile strength test results.

n is the number of sample test done

Hence, using D_a and number of sample test in Table 4.11, the calculated t-test, $t_{calculated}$ was calculated using Equation 4.4 as shown below.

$$t_{calculated} = \frac{0.0004\sqrt{10}}{0.011312843} = 0.117$$

The two tailed t-test carried out had confidence level of 97.5% and 2.5% significance level. From the t-table, Table 4.11, $t_{(\beta,v)}$ can be determined. Where v = 10 – 1 = 9, and β = significance level 0.975 (97.5%). $t_{(0.975,9)}$ =2.5 significance level while $t_{calculated}$=0.117. Since $t_{calculated} < t_{(0.975,9)}$ and lies between -2.5 and 2.5, there is no significant difference between the experimental and predicted tensile test results. The model is therefore confirmed to be adequate to use as a predictive model for tensile strength of asphalt concrete modified using sisal fibre and waste plastics.

Table 4.11: t-test for tensile strength of modified asphalt concrete

Sample No.	Tensile strength (N/mm^2)		t-test		
	$Y_{experimental}$	$Y_{predicted}$	$Y_{exp}-Y_{pred}$	D_a-D	$(D_a-D)^2$
C1	1.1170	1.1343	-0.0173	0.0178	3.153E-04
C2	1.1970	1.2010	-0.0040	0.0044	1.912E-05
C3	1.0867	1.0844	0.0023	-0.0019	3.518E-06
C4	1.2100	1.2035	0.0065	-0.0061	3.698E-05
C5	1.1926	1.1892	0.0034	-0.0030	8.796E-06
C6	1.1763	1.1861	-0.0098	0.0103	1.055E-04
C7	1.1809	1.1680	0.0129	-0.0124	1.547E-04
C8	1.1767	1.1895	-0.0128	0.0132	1.740E-04
C9	1.1918	1.1736	0.0181	-0.0177	3.135E-04
C10	1.1861	1.1812	0.0049	-0.0045	2.047E-05
Total			0.0042		0.0012
Average, D_a			0.0004		

4.11 Performance of model-sections of road pavement

To evaluate the performance of road pavement constructed using asphalt concrete modified using sisal fibre and waste plastic, two model road sections comprising a control section and modified section were constructed. The control section (C-S) was constructed using SMA as binder course and OGA as wearing course while the modified section (M-S) was constructed using SPSMA as base course and SPOGA as wearing course. The control and modified sections of the model road section were as shown in Appendices XXIII and XXIV. The sections' engineering and functional assessment were done for six months using Raters' Guideline for Visual Assessment of Road Pavements: Part B as shown in Appendices XXV and XXVI. Monitoring was done daily during the first week, weekly for next three weeks and thereafter monthly for five months, in accordance with standard specification ASTM D 6433-20 and data recorded in Appendices XXVII and XXVIII. It was observed during laying of asphalt concrete that the modified section attained compaction with fewer number of rollers of 10 passes, compared to control section that had 13 passes. The modified section was able to compact more firmly and faster because of the bonding of waste plastics with aggregates and the effect of waste plastics cooling faster than the bitumen. This made the modified section not to undergo any further compaction when traffic loads were applied it. Smoothness of the surface of the modified section is also associated with coating of waste plastics on aggregates and retention of bitumen.

Aggregate loss of $10g/m^2$ and $12g/m^2$ during the first and second week respectively was measured in the control section while no aggregate loss was noted in the modified section as shown in Figure 4.36.

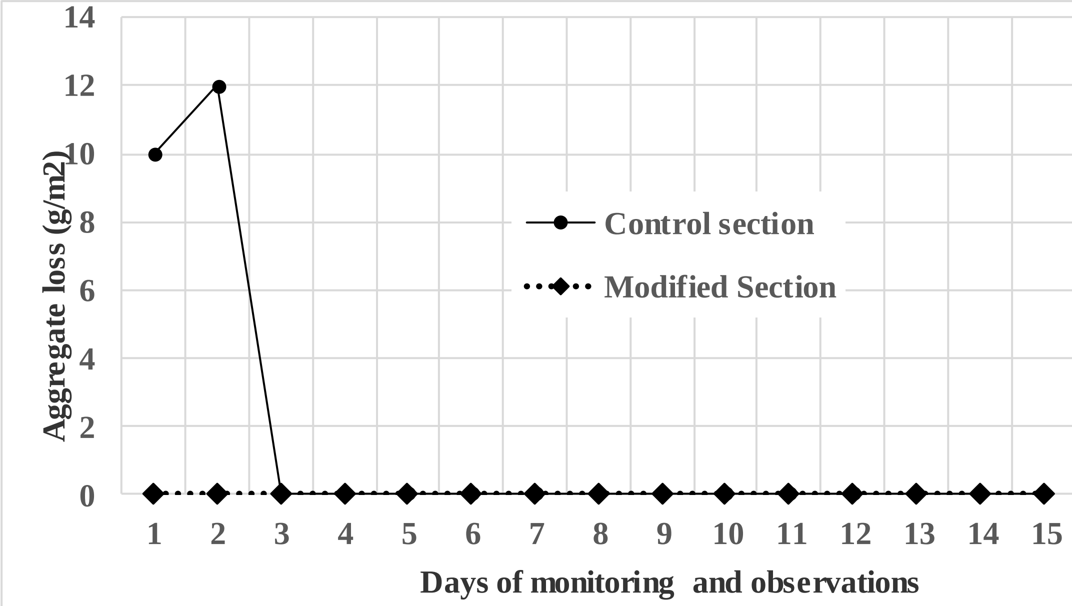


Figure 4.36: Aggregate loss observations on the control and modified road pavement sections

Waste plastics bonded firmly with aggregates and sisal fibre to stiffen the asphalt concrete. This reduces loss of aggregates and increases the strength of pavement and roads ability to support heavy traffic load without the danger of developing cracks or rutting.

During the monitoring period, there was 15mm and 20mm depression measured in the 1st and 2nd week respectively in the control section as opposed to the modified section as illustrated in Figure 4.37.

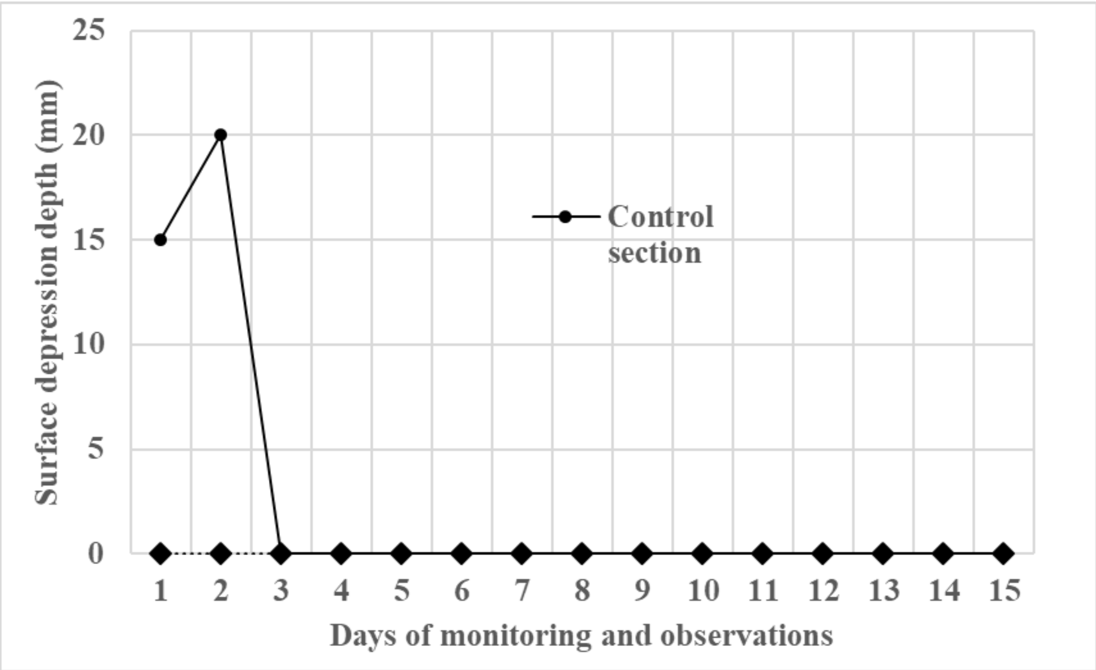


Figure 4.37: Surface depression observations on the control and modified road pavement sections

Waste plastics coated aggregates and formed a firm matrix with sisal fibre to produce strong asphalt concrete mix. This sisal-plastic modified asphalt concrete produces strong road pavements that support heavy traffic load without developing surface depression as observed on the control section of the pavement.

Bleeding was also noticeable in the 1st day while no bleeding in the modified section. This is associated with fast cooling and compatibility of sisal-plastic modified asphalt concrete compared to control asphalt concrete. Therefore, it can be concluded that road pavements constructed using asphalt concrete modified with sisal fibre and waste plastics are strong to resist deformation, bitumen bleeding and rutting due to traffic loads.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

- Modified OGA and SMA provide better resistance against permanent deformations (rutting) and also indicate that these mixtures can be used in pavements where stiff bituminous mixture is required. SPMOGA gives the best result, with a percentage increase in stability value of about 85% and Marshall Quotient of 90% with respect to the control OGA. The retained stability value is 99%. Use of sisal fibre and waste plastics in the modification of open graded asphalt (OGA) concrete improves the strength, flow and drain down. At 0.3% Sisal Fibre and 5% Waste plastics, Stability was highest at 13.565kN as compared to sisal fibre and waste plastics when used separately. Sisal-plastic modified OGA had highest TSR of 99.94%. This shows that the SPMOGA is less susceptible to water. Further, the sample results showed 0% bitumen drain down. Therefore, SPMOGA is suitable for construction of wearing course.

- Sisal fibre and waste plastics used in the modification of stone matrix asphalt (SMA) concrete for use as a binder course material, improves the strength, flow and drain down. At 0.3% sisal fibre and 5% waste plastics, stability was highest at 12.942 kN as compared to sisal fibre and waste plastics when used separately. Sisal-plastic modified SMA had highest TSR % of 98.95. This shows that the SPMSMA is less susceptible to water. Further, the sample results showed 0% bitumen drain down. Therefore, SPMSMA is suitable for construction of base course of a road pavement.

- Mathematical model to predict the tensile strength was confirmed to be adequate to use as a predictive model for tensile strength of asphalt concrete modified using sisal fibre and waste plastics. The model has significance level of 0.975 (97.5%). Since $t_{(0.975,9)}$ =2.5 and $t_{calculated}$=0.117 which lies between -2.5 and 2.5,it means that tensile strength results predicted by this mathematical model are accurate without any significant difference between the experimental and predicted tensile test results.

- The performance evaluation of a model-section of a road constructed using sisal-plastic modified asphaltic concrete (SPMAC) showed no signs of settlement, cracking, depression, patching, pothole development or rutting. The control section showed initial further compaction by traffic of 15-20mm settlement as compared to modified section. Modified section showed ability for fast compaction, and no further settlement. This means the section is more rigid, stronger and likely to serve longer period before failure.

5.2 Recommendations

- Asphalt concrete modified using sisal fibre and waste plastic is recommended for road construction where heavy traffic is expected.

- Modified OGA and SMA are suitable for construction of wearing course and base course respectively.

- Mathematical model is recommended for use to predict the tensile strength of asphalt concrete modified using sisal fibre and waste plastics since it is accurate and precise.

5.3 Areas for further studies

There are different areas which were considered vital for further investigation.

(i) To evaluate the effect of variation of bitumen content, further study can be done where bitumen content is varied as quantity of modifiers are held constant, to ascertain the effect on overall quality of modified OGA and SMA.

(ii) A trial section, using modified material can be constructed on a busy road and monitored for longer period exceeding five years so as to evaluate any changes in performance characteristics.

REFERENCES

AASHTO T 305 (2000). AASHTO T 305: Determination of Drain down Characteristics in Uncompacted Asphalt Mixtures, Washington DC: American Association of State Highway and Transportation Officials.

AASHTO T 283 (2007). AASHTO T 283: Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. Washington DC.: American Association of State Highway and Transportation Officials.

AASHTO T 245 (2013). AASHTO T 245: Method of Test for Resistance to Plastic Flow of Bituminous mixtures Using Marshall Apparatus from SAI Global. Washington DC: American Association of State Highway and Transportation Officials1

AASHTO M 147 (2017). AASHTO M 147: Standard Specification for Materials for Aggregate and Soil–Aggregate Subbase, Base, and Surface Courses. Washington DC: American Association of State Highway and Transportation Officials.

AASHTO T 283-14 (2018). AASHTO T 283-14: Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage

AASHTO T 312 (2015). AASHTO T 312: Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor. Washington DC: American Association of State Highway and Transportation Officials.

AASHTO SRPD (1976). AASHTO SRPD: Guidelines for Skid Resistant Pavement Design. Washington DC: American Association of State Highway and Transportation Officials.

Abiola, O. S., Kupolati, W. K., Sadiku, E. R. & Ndambuki, J. M. (2014). Utilization of natural fibre as modifier in bituminous mixes: *A review. Construction and Building Materials, 54*(5), 305-312.

Ahmed, S. A., & Mahmood, O. T. (2015). Influence of Mineral Fibre Properties on the Performance of Hot Mix Asphalt for the Surface Layer of Pavement. *Department of Civil Engineering, Faculty of Engineering, Koya University, Erbil, Iraq, International Journal of Engineering Trends and Technology (IJETT)– Volume*, *26*(3), 14-11.

Alam, S. Y., & Hammoum, F. (2015). Viscoelastic properties of asphalt concrete using micromechanical self-consistent model. *Archives of Civil and Mechanical Engineering*, *15*(1), 272-285.

Anderson, D. A., Lapalu, L., Marasteanu, M. O., Le Hir, Y. M., Planche, J. P., & Martin, D. (2001). Low-temperature thermal cracking of asphalt binders as ranked by strength and fracture properties. *Transportation Research Record*, *1766*(1), 1-6.

ASTM D6390-11 (2017). ASTM D6390-11: Standard Test Method for Determination of Drain down Characteristics in Uncompacted Asphalt Mixtures.

ASTM D 1505 – 18 (2017). ASTM D 1505 – 18: Standard Test Method for Density of Plastics by the Density-Gradient Technique

ASTM D113 – 17 (2017). ASTM D113 – 17: Standard Test Method for Ductility of Asphalt Materials

ASTM D70 / D70M - 21 (2017). ASTM D70 / D70M - 21 Standard Test Method for Specific Gravity and Density of Semi-Solid Asphalt Binder (Pycnometer Method)

ASTM D6433 - 20 (2017). ASTM D6433 – 20: Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys

Badshah C., Arun K., & Eswaraiah B., (2015). Fabrication and testing of natural (sisal) fibre reinforced polymer composites material. *International Journal of Emerging Trends in Engineering Research. 3*(5). 17-21.

Bale, A. S. (2011). Potential reuse of plastic waste in road construction: a review. *International Journal of Advances in Engineering & Technology (IJAET), 2*, 233-236.

Behbahani, H., Nowbakht, S., Fazaeli, H., & Rahmani, J. (2009). Effects of Fibre Type and Content on the Rutting Performance of Stone Matrix Asphalt. *Journal of Applied Sciences*, *9*(10), 1980-1984.

Bhardwaj A. & Dhriyan S.S. (2015). Application of Waste Plastic in Modifying Bitumen Properties. *International Journal of Science and Research, 6*(8), 2319-7064.

Bindu C.S & Beena K.S. (2014). Influence of additives on the drain down characteristics of stone matrix asphalt mixtures. *International Journal of Research in Engineering and Technology, 3* (7), 2321-7308.

Bindu C.S., & Beena K.S. (2012). Waste plastic as a stabilizing additive in Stone Mastic Asphalt. *International Journal of Engineering and Technology, 2* (6), 379-387.

Bindu, C. S. & Beena, K.S. (2010). Use of waste plastic in road construction. *Journal of Technology World, V* (1), 91-100.

Bisanda E. T. N. (2000). The Effect of Alkali Treatment on the Adhesion Characteristics of Sisal Fibres, *Applied Composite Materials.* Kluwer Academic Publishers.331.

Bueno, B. D. S., Silva, W. R. D., Lima, D. C. D., & Minete, E. (2003). Engineering properties of fibre reinforced cold asphalt mixes. *Journal of environmental engineering*, *129*(10), 952-5.

Chadbourn, B. A., Skok Jr, E. L., Newcomb, D. E., Crow, B. L., & Spindle, S. (1999). The effect of voids in mineral aggregate (VMA) on hot-mix asphalt pavements. University of Minnesota Department of Civil Engineering retrieved from *ttps://conservancy.umn.edu/handle/11299/198800.*

Chavan, M. A. J. (2013). Use of plastic waste in flexible pavements. *International Journal of Application or Innovation in Engineering and Management*, *2*(4), 540-552.

Chen, H., Xu, Q., Chen, S., & Zhang, Z. (2009). Evaluation and design of fibre-reinforced asphalt mixtures. *Materials & Design*, *30*(7), 2595-2603.

Chen, J. S., & Lin, K. Y. (2005). Mechanism and behavior of bitumen strength reinforcement using fibre. *Journal of materials science*, *40*(1), 87-95.

Dash, S. B., & Panda, M. (2016). A Study on Use of Natural Fibre for Improvement in Engineering Properties of Dense Graded Bituminous Mixes with Coal Ash. *Transportation in Developing Economies*, *1*(2), 1-10.

De Mello, L. G. R., de Farias, M. M., & Kaloush, K. E. (2018). Effect of temperature on fatigue tests parameters for conventional and asphalt rubber mixes. *Road Materials and Pavement Design*, *19*(2), 417-430.

Dixit, S., & Rastogi, D. (2013). Studies on the improvement of characteristics of bitumen with use of waste plastic. *International Journal of Emerging Technology and Advanced Engineering*, *3*(3), 895-900.

Espersson, M. (2014). Effect in the high modulus asphalt concrete with the temperature. *Construction and Building Materials*, *71*, 638-643.

Federal Highway Administration (FHWA). (2009). *Highway Statistics 2009. Office of Highway Policy Information, Federal Highway Administration*. Washington, D.C.: Federal Highway Administration. Retrieved from http://www.fhwa.dot.gov/policyinformation/statistics.cfm.

Federal Highway Administration, (2011). *Pavement Management Primer*. Washington, D.C. U.S Department of Transportation.

Gamil, Y. M. R., & Bakar, I. H. (2016, July). The Development of Mathematical Prediction Model to Predict Resilient Modulus for Natural Soil Stabilized by Pofa-OPC Additive for the Use in Unpaved Road Design. In *IOP Conference Series: Materials Science and Engineering*, *136*(1), 0120071.

Gawande A., Zamre G., Renge V. C., Tayde S., & Bharsakale G. R. (2013). An overview on waste plastic utilization in asphalting of roads. *International Journal of Innovative Research in Science, Engineering and Technology*, *2*(3), 1943-1948.

Haggam, R. A., Ibrahim, I. M., Abdelatif, M. E. S., Abd El Latief, M., & El-Kholy, S. A. (2014). Improvement of Asphalt Properties Using Polymethyl Methacrylate. *Open Journal of Organic Polymer Materials*, *4*(2), 43-54.

Hamedi, G. H., & Esmaeeli, M. R. (2017). Mechanical Properties of Open Graded Asphalt Mixtures with Pumice Aggregate. *AUT Journal of Civil Engineering*, *1*(2), 189-194.

Hamzah, M. O., Hassan, M. R. M., Ismail, M. R., & Shahadan, Z. (2010). Effect of temperature on abrasion loss of porous and dense asphalt mixes. *Eur. J. Sci. Res*, *40*(4), 589-597.

Haseeb J., (2017). Types of Bitumen and Importance of Bituminous Materials. Retrieved from *www.aboutcivil.org/importance-types-of-bituminous-materials.html.*

Highway Research Board, (1972). Friction and Surface Texture Characterization of 14 Pavement Test Sections in Greenville, North Carolina. *Transportation Research Record 1639.* Washington, D.C. Transportation Research Board, National Research Council.

Horath, L. (2019). Fundamentals of materials science for technologists: properties, testing, and laboratory exercises. *Long Grove, Illinois: Waveland Press*.

Hsu, C. S., & Robinson, P. R. (Eds.). (2017). Springer handbook of petroleum technology. *New York: Springer*.

Huang, H., & White, T. D. (1996). Dynamic properties of fibre-modified overlay mixture. *Transportation Research Record*, *1545*(1), 98-104.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, conservation and recycling*, *52*(1), 58-73.

Huaxin C., Qinwu X.B., Shuanfa C.A., & Zhengqi Z. (2009). Evaluation and design of fibre reinforced asphalt mixtures. *Mat PP Design, 30*, 2595–2603.

Ibrahim M. A. (2006). "Laboratory comparison study for the use of stone matrix asphalt in hot weather climates". *Construction and Building Materials, 20*(10), 982-989.

Jason J., & Bryant P. (2019). High Modulus Asphalt (EME2) Pavement Design (Technical Note 142) (PDF*). Fortitude Valley,* Queensland, Australia: State of Queensland (Australia) Department of Transport and Main Roads.

Jawaid, M., Thariq, M., & Saba, N. (Eds.). (2018). Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites. *Woodhead Publishing.*

Justo, C.E.G., Veeraragavan A. (2002). Utilization of Waste Plastic Bags in Bituminous Mix for Improved Performance of Roads. *Banglore University, Bengaluru*.

Kamil, E. K., Waleed A. Z., Krishna P. B., & Maria C. R. (2012). Evaluation of Fibre-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests. *Arizaona: Arizona State University* Department of Civil and Environmental Engineering.

Kandhal, P. S. (2002). Designing and constructing Stone Matrix Asphalt Mixtures- State-of-the Practice, *National Pavement Association Quality Improvement Publication QIP*.

Kar D. (2012). A laboratory study of bituminous mixes using a natural fibre. Department of civil engineering. National institute of technology rourkela-769008.

Karthik K., Rohit M., & Sandeep T., (2015). Carbon fibre modified bitumen in bituminious macadam. *International Journal of Advance Engineering and Research Development, 2* (12).

Kasozi I., & Harro V.B. (2010). Solid Waste Management in Nairobi: A Situation Analysis: For the City Council of Nairobi on contract for the United Nations Environment Programme Environmental & Process Systems Engineering Group, Cape town:

University of Cape Town. Retrieved from *http://www.ecopost.co.ke/assets/pdf/nairobi_solid_waste*.

KeNHA. (2019). Kenya Road Classified Network. Retrieved from *http://www.kenha.co.ke/index.php/road-network*

Kök, B. V., Yilmaz, M., Kuloğlu, N., & Turgu, P. (2010). "Laboratory investigation of syrian natural asphalt in asphalt concrete". *Proceeding of 9th International Congress on Advances in Civil Engineering*, 27-30.

Kumar P., Chandra S., Bose, S. (2005). Comparative study on stone matrix asphalt mixes with different stabilizers, *TRB Annual Meeting*.

Lee S.J, Akisetty C.K, & Amirkhanian S.N. (2008). "The effect of Crumb Rubber Modifier (CRM) on the performance properties of rubberized binders in HMA pavements, *Construction and Building Materials Journal, 22, 1368 –* 1376.

Lee, S. J., Rust, J. P., Hamouda, H., Kim, Y. R., & Borden, R. H. (2005). Fatigue Cracking Resistance of Fibre-Reinforced Asphalt Concrete. *Textile Research Journal, 75*(2), 123-128.

Luiz G. R. M.O, Marcio M. F., & Kamil E. K., (2016). Effect of Temperature on Fatigue Tests Parameters for Conventional and Asphalt Rubber Mix, Road Materials and Pavement Design". Elsavier publications, 108, 110-121.

Mahalakshmi S. Priyankaprakash T. & Shalini R., (2014). Bitumen *International Journal of Engineering Research & Technology (IJERT). 3(*2), 2720-2727.

Mallick, R.B., Kandhal, P., Cooley, L.A. & Watson, D.E. (2000). Design construction, and performance of new generation open-graded friction courses. *Paper prepared for presentation at the annual meeting of the Association of Asphalt Paving Technologists to be held in Reno,* Nevada (March 13-15, 2000). Auburn university: National Center for Asphalt Technology.

Mazumder, M., Kim, H., & Lee, S. J. (2016). Performance properties of polymer modified asphalt binders containing wax additives. *International Journal of Pavement Research and Technology*, *9*(2), 128-139.

McNichol, D. (2005). *Paving the way: asphalt in America*. Lanham, MD: Asphalt in America. National Asphalt Pavement Association, http://store.asphaltpavement.org/index.php?productID=144.

Moghaddam, A. M., Ziaee, S. A., Mollashahi, H. F., & Qazizadeh, M. J. (2014). Effects of waste fibre stabilizers on the drain down and moisture damage sensitivity properties of SMA mixtures. *International Journal of Transportation Engineering*, *2*(2), 155-165.

Montanelli, E. F. (2013). Fibre/polymeric compound for high modulus polymer modified asphalt (PMA). *Procedia-Social and Behavioral Sciences*, *104*, 39-48.

Mulei S.M, Mwatelah J.K.Z & Asano E. (2002). Investigation of causes of failures of flexible pavements: a case study of Nairobi-Thika highway. *Journal of Civil Engineering, JKUAT, 7*, 13-26.

Muniandy R., & Huat B.K. (2006). Laboratory Diameteral Fatigue Performance of Stone Matrix Asphalt with Cellulose Oil Palm Fibre. *American Journal of Applied Sciences 3* (9), 2005-2010.

National Asphalt Pavement Association (NAPA) (1999). *Designing and constructing SMA mixtures". State-of-the-Practice. Quality Improvement Series, 122, Information Series 110*. Lanham, Boulevard: National Asphalt Pavement Association Retrieved from https://www.il-asphalt.org/index.php/download_file/view/276/339/.

National Cooperative Highway Research Program Synthesis of Highway Practic (2000). *NCHRP synthesis 291; Evaluation of Pavement Friction characteristics: A Synthesis of Highway Practice*. Washington, D.C.: National Academy Press.

Naveen J., Jawaid M., P. Amuthakkannan P., & Chandrasekar M., (2019). Mechanical and physical properties of sisal and hybrid sisal fibre-reinforced polymer composites. New York: Elsevier.

NEMA, 2018. National environmental management authority. https://www.nema.go.ke/index.php?option = com content & view article & id =102 & Item id=121

Oba, K. M. (2019). A mathematical model to predict the tensile strength of asphalt concrete using quarry dust filler. *International Journal for Science Engineering Research*, *10*(2), 1491-1498.

Phologolo, T., Yu, C.W., Mwasiagi, J.I., Muya, N. & Fan, L. Z.F. (2012). Production and Characterization of Kenyan Sisal. *Asian Journal of textile; 2*(2), 17-25.

Poweth, M. J., George, S., & Paul, J. (2013). Study on use of plastic waste in road construction. *International Journal of Innovative Research in Science, Engineering and Technology*, *2*(3), 633-638.

Prasad, S. K., Manjunath, K. R., & Prasad, K. V. R. (2012). Study on Marshall Stability properties of BC mix used in road construction by adding waste plastic bottles. *IOSR J Mech Civil Eng*, *2*(2), 1-12.

Rajasekaran, S., Vasudevan, R., & Paulraj, S. (2013). Reuse of Waste Plastics Coated Aggregates-Bitumen Mix Composite for Road Application—Green Method. *American Journal of Engineering and Research*, *2*, 1-13.

Raju G.R, Naga k, Rao S. (2015). Characterization of Fibre Reinforced Bituminous Mixes. *International Journal of Science and Research (IJSR)*, 4 (12), 802-806.

Roberts, F. L. (1996). *Hot mix asphalt materials, mixture design, and construction*. Lanham, MD. United States: NAPA Education Foundation.

Rokade, S. (2012). Use of waste plastic and waste rubber tyres in flexible highway pavements. In *International conference on future environment and energy, IPCBEE* (Vol. 28).

Saboo, N., & Kumar, P. (2016). Performance Characterization of Polymer Modified Asphalt Binders and Mixes. *Advances in Civil Engineering*, *2016*, 239-250.

Scheffé, H. (1958). Experiments with mixtures. *Journal of the Royal Statistical Society: Series B (Methodological)*, *20*(2), 344-360.

Kishchynskyi, S., Nagaychuk, V., & Bezuglyi, A. (2016). Improving quality and durability of bitumen and asphalt concrete by modification using recycled polyethylene-based polymer composition. *Procedia engineering*, *143*, 119-127.

Shah, S. M. R., Zainuddin, N. I., Min, Y. H., Nasaruddin, N. A. I., & Sian, T. L. (2018). Reduction of Optimum Bitumen Content in Polyethylene Modified Bituminous Mixes. *American Journal of Civil Engineering*, *6*(3), 93-98.

Shukla, M., Tiwari, D., & Sitaramanjaneyulu, K. (2014). Performance characteristics of fibre modified asphalt concrete mixes. *International Journal on Pavement Engineering & Asphalt Technology*, *15*(1), 38-50.

Soni, K., & Punjabi, K. K. (2014). Improving the Performance of Bituminous Concrete Mix by Waste Plastic. *Int. Journal of Engineering Research and Applications*, *3*(5), 863-8.

Speight, J. G. (2014). *The chemistry and technology of petroleum*. Boca Raton, Florida : CRC press.

Stuart, K. D. (1992). *Stone mastic asphalt (SMA) mixture design.* McLean Virginia: Federal Highway Administration (FHWA.

Sultana, A. S., & Prasad, K. S. B. (2012). Utilization of waste plastic as a strength modifier in surface course of flexible and rigid pavements. *International Journal of Engineering Research Application*, *2*(4), 185-91.

Sulyman, M., Sienkiewicz, M., & Haponiuk, J. (2014). Asphalt pavement material improvement: a review. *International Journal of Environmental Science and Development*, *5*(5), 444-4.

Swami, V., Jirge, A., Patil, K., Patil, S., Patil, S., & Salokhe, K. (2012). Use of waste plastic in construction of bituminous road. *International Journal of Engineering Science and Technology*, *4*(5), 2351-2355.

Taj, S., Khan, S., & Munawar, M. A. (2007). Natural fibre-reinforced polymer composites. *Proceedings of the Pakistan Academy of Sciences*, *44*(2), 129-144.

Tayfur, S., Ozen, H., & Aksoy, A. (2007). Investigation of rutting performance of asphalt mixtures containing polymer modifiers. *Construction and Building Materials*, *21*(2), 328-337.

Thulasirajan, K., & Narasimha, V. L. (2011). Studies on coir fibre reinforced bituminous concrete International *Journal of Engineering Research and Applications (IJERA*) *4*(6), 835-838.

United States Department of Transportation (USDOT). (2000). *Comprehensive Truck Size and Weight Study*. United States Department of Transportation. Washington, D.C. http://www.fhwa.dot.gov/reports/tswstudy/index.htm

Van Metre, P. C., Mahler, B. J., & Wilson, J. T. (2009). PAHs underfoot: Contaminated dust from coal-tar sealcoated pavement is widespread in the United States. *Environmental Science & Technology*, *43*(1), 20-25.

Vasudevan, R. N. S. K., Velkennedy, R., Sekar, A. R. C., & Sundarakannan, B. (2010). Utilization of waste polymers for flexible pavement and easy disposal of waste polymers. *International Journal of Pavement Research and Technology*, *3*(1), 34-42.

Wachira, T. D., Wairire, G. G., & Mwangi, S. W. (2014). Socio-economic hazards of plastic paper bags litter in peri-urban centres of Kenya; a case study conducted at Ongata Rongai Township of Kajiado County. *International journal of scientific research and innovative technology*, *1*(5), 24.

Wambold, J. C., Meyer, W. E., & Henry, J. J. (1990). New-Generation Skid Testers for the 1990s. In Surface Characteristics of Roadways: International Research and Technologies. ASTM International.

Wang, L. B. (2012). Mechanics of asphalt: microstructure and micromechanics. *International Journal of Pavement Research and Technology*, *5*(1).

Wu, M. M., Li, R., Zhang, Y. Z., Fan, L., Lv, Y. C., & Wei, J. M. (2015). Stabilizing and reinforcing effects of different fibre on asphalt mortar performance. *Petroleum Science*, *12*(1), 189-196.

WU, S. P., Gang, L. I. U., MO, L. T., Zheng, C. H. E. N., & YE, Q. S. (2006). Effect of fibre types on relevant properties of porous asphalt. *Transactions of Nonferrous Metals Society of China*, *16*, s791-s795.

Zhang, Z., Roque, R., Birgisson, B., & Sangpetngam, B. (2001). Identification and verification of a suitable crack growth law. In *Association of Asphalt Paving Technologists Technical Sessions, 2001, Clearwater Beach, Florida, USA* (Vol. 70).

Ziska, L. H., & Dukes, J. S. (Eds.). (2014). *Invasive species and global climate change* (Vol. 4). CABI.

APPENDICES

Appendix I: Gradation of aggregates and their blends for OGA mix

Sieve Size (mm)	Percentage Passing (%) $N_n= C_n-P_n$	OGA % passing Range	12/6mm (70%) (A)	Fines (30%) (B)	Standard Adopted Grading A:B, 70:30	Min (%)
12.5	100.0	100	70		100.0	100
9.5	95.8	100-95			95.8	95
4.75	30.0	50-30			30.0	30
2.36	6.5	15-5		30	6.5	5
0.075	1.0	5-2			1.0	2

Appendix II: Gradation of aggregates and their blends for SMA mix.

Sieve Size (mm)	Percentage Passing (%) $N_n = C_n - P_n$	SMA % passing Range	20 mm (50%) (A)	10 mm (30%) (B)	Fines (20%) (C)	Adopted Grading A:B:C 50:30:20	Min (%)
19	100.0	100	50			100.0	100
13.2	90.4	90-100				90.4	90
9.5	50.0	50-75		30		50.0	50
4.75	20.5	20-28			20	20.5	20
2.36	18.6	16-24				18.6	16
1.18	16.5	13-21				16.5	13
0.6	14.4	12-18				14.4	
0.3	12.5	10-18				12.5	
0.075	7.7	8-12				7.7	

Appendix III: Specific gravity and water absorption of aggregate size 20/14 mm

Sample Description: 20/14 mm	Sample Masses		
	Sample No.1	Sample No.2	Sample No.3
Mass of oven dry sample in air (A) grams	2451.2	2455.1	2451.2
Mass of sample in water (B) grams	1579.3	1583.6	1578.3
Mass of saturated surface dry sample (C) grams	2479.6	2484.6	2478.6
Specific gravity (A/C-B)	2.723	2.721	2.723
Water absorption % 100(C-A)/A	1.16	1.20	1.12
Average specific gravity	2.72		
Average water absorption %	1.16		

Appendix IV: Specific gravity and water absorption of aggregate size 12/6 mm

Sample Description: 12/6mm	Sample weights		
	Sample No.1	Sample No.2	Sample No.3
Weight of oven dry sample in air (A) grams	2249.2	2251.5	2248.8
Weight of sample in water (B) grams	1440.5	1443.8	1442.3
Weight of saturated surface dry sample (C) grams	2268.5	2270.7	2267.9
Specific gravity (A/C-B)	2.716	2.721	2.723
Water absorption % 100(C-A)/A	0.858	0.853	0.849
Average specific gravity	2.72		
Average water absorption	0.85		

Appendix V: Specific gravity and water absorption of fines/fillers

Sample Description: Fines/Fillers	Sample weights		
	Sample No.1	Sample No.2	Sample No.3
Weight of oven dry sample in air (A) grams	2491.2	2485.5	2488
Weight of sample in water (B) grams	1494.5	1491.8	1492.9
Weight of saturated surface dry sample (C) grams	2499.5	2493.8	2496.4
Specific gravity (A/C-B)	2.478	2.480	2.479
Water absorption % 100(C-A)/A	0.333	0.331	0.337
Average specific gravity	2.5		
Average water absorption	0.33		

Appendix V1: Waste plastics binding properties

% of Waste Plastics	5%		10%		15%		20%	
Samples	A	B	C	D	E	F	G	H
Compressive strength (N/mm^2)	11.4	10.8	13.6	13.6	13.6	13.8	10.8	10.6
Av. strength (N/mm^2)	11.1		13.6		13.7		10.7	

Appendix VII: Performance of open graded asphalt (OGA) with varying percentages of bitumen

Bitumen Content (%)	Specific Gravity (G_m)	Stability (kN)	Flow (mm)	V_v (%)	V_b (%)	VMA (%)	VFB (%)
4.5	2.309	7.126	2.983	6.40	10.19	16.58	61.44
5	2.316	7.209	3.027	5.41	11.35	16.77	67.71
5.5	2.333	7.314	3.143	4.02	12.58	16.60	75.79
6	2.316	7.228	3.210	4.05	13.62	17.67	77.09

Appendix VIII: Performance of stone matrix asphalt (SMA) with varying percentages of bitumen.

Bitumen Content (%)	Specific Gravity (G_m)	Stability (kN)	Flow (mm)	V_v (%)	V_b (%)	VMA (%)	VFB (%)
4.5	2.298	7.137	2.95	7.60	10.14	17.74	57.17
5	2.310	7.220	2.94	6.44	11.32	17.76	63.76
5.5	2.317	7.314	2.97	5.44	12.49	17.93	69.68
6	2.319	7.380	3.01	4.65	13.64	18.29	74.57
6.5	2.320	7.416	3.18	3.89	14.79	18.68	79.15
7	2.319	7.277	3.35	3.25	15.91	19.16	83.03

Appendix XIV: Marshall properties of MOGA with sisal fibre

Sisal Fibre %Content	Stability kN	Flow	Marshall Quotient (kN/mm)	Air Voids V_v %	Bulk Specific Gravity G_m	% Vb	% VMA	% VFB
Nil	7.314	3.16	2.332	4.02	2.333	12.58	16.60	75.79
0.1	7.742	3.15	2.458	4.09	2.330	12.56	16.66	75.43
0.2	8.690	3.06	2.840	4.26	2.324	12.53	16.79	74.64
0.3	11.843	2.85	4.155	4.35	2.320	12.51	16.85	74.25
0.4	8.742	2.76	3.167	4.60	2.312	12.46	17.06	73.05

Appendix X: Marshall properties of MSMA with sisal fibre

Sisal Fibre Content (%)	Stability kN	Flow (mm)	Marshall Quotient (kN/mm)	Air Voids V_v (%)	Bulk Specific Gravity G_m	V_b (%)	VMA (%)	VFB (%)
Nil	7.420	3.18	2.333	4.00	2.320	14.65	18.64	78.57
0.1	7.743	3.17	2.445	4.11	2.315	14.62	18.73	78.07
0.2	8.701	3.07	2.834	4.33	2.309	14.58	18.90	77.11
0.3	11.862	2.86	4.148	4.61	2.299	14.52	19.13	75.90
0.4	8.705	2.77	3.147	4.90	2.291	14.46	19.37	74.68

Appendix XI: Marshall properties of OGA modified with waste plastics

WP Additive % Content	Stability (kN)	Flow (mm)	Marshall Quotient (kN/mm)	Air Voids V_v (%)	Bulk Specific Gravity G_m	% Vb	% VMA	% VFB
Nil	7.314	3.14	2.327	4.02	2.333	12.58	16.60	75.78
1.0	8.229	3.02	2.722	3.99	2.317	12.49	16.48	75.82
3.0	10.188	2.91	3.505	3.88	2.286	12.33	16.21	76.09
5.0	12.841	2.81	4.570	3.76	2.257	12.17	15.93	76.39
7.0	11.252	2.88	4.047	3.67	2.228	12.01	15.68	76.61

Appendix XII: Marshall properties of SMA modified with waste plastics

WP Content (%)	Stability kN	Flow (mm)	Marshall Quotient (kN/mm)	Air Voids V_v (%)	Bulk Specific Gravity G_m	V_b (%)	VMA (%)	VFB (%)
Nil	7.420	3.180	2.333	4.01	2.320	14.66	18.66	78.53
1.0	8.717	3.030	2.877	3.74	2.328	14.56	18.30	79.58
3.0	11.180	2.920	3.829	3.48	2.338	14.33	17.81	80.45
5.0	12.798	2.820	4.538	3.30	2.346	14.08	17.39	81.00
7.0	11.200	2.830	3.957	3.03	2.355	13.86	16.88	82.07

Appendix XIII: Properties of modified open graded asphalt

WP Additive % Content	Stability (kN)	Flow (mm)	Marshall Quotient (kN/mm)	Air Voids V_v (%)	Bulk Specific Gravity G_m	% Vb	% VMA	% VFB
Nil	7.314	3.14	2.327	4.02	2.333	12.58	16.60	75.78
SF	11.843	2.85	4.155	4.41	2.320	12.51	16.85	74.26
WP	12.841	2.81	4.570	3.74	2.257	12.17	15.93	76.48
SP	13.565	2.82	4.810	4.14	2.370	12.78	16.92	75.52

Appendix XIV: Properties of modified stone matrix asphalt

WP Additive % Content	Stability (kN)	Flow (mm)	Marshall Quotient (kN/mm)	Air Voids V_v (%)	Bulk Specific Gravity G_m	% Vb	% VMA	% VFB
Nil	7.420	3.18	2.333	4.01	2.320	14.72	18.62	78.60
SF	11.862	2.86	4.148	4.61	2.299	14.52	19.12	75.90
WP	12.798	2.820	4.538	3.30	2.346	14.08	17.38	80.46
SP	12.942	2.83	4.579	3.81	2.239	13.41	17.22	77.89

Appendix XV: Indirect tensile strength test results for modified open graded asphalt

Additives	%	ITS Unconditioned (MPa)	ITS Conditioned (MPa)	% TSR (MPa)
Nil	0	0.83	0.44	52.19
Sisal fibre (SF)	0.1	0.83	0.69	83.12
	0.2	1.06	1.01	95.18
	0.3	1.10	1.07	97.33
	0.4	1.05	1.01	96.29
Waste plastics (WP)	1	1.01	0.90	88.27
	3	1.18	1.14	96.61
	5	1.20	1.18	97.78
	7	1.18	1.14	96.62
Sisal fibre and waste plastics (SP)	0.3% SF 5% WP	1.23	1.23	99.94

Appendix XVI: Indirect tensile strength results for modified stone matrix asphalt

Additives	%	ITS Unconditioned (MPa)	ITS Conditioned (MPa)	% TSR (MPa)
Nil	0	0.81	0.43	52.25
Sisal Fibre (SF)	0.1	0.83	0.69	83.21
	0.2	1.06	1.01	95.28
	0.3	1.11	1.08	97.42
	0.4	1.05	1.02	96.39
Waste Plastics (WP)	1	1.02	0.90	87.92
	3	1.19	1.15	96.22
	5	1.21	1.18	97.39
	7	1.24	1.23	98.93
Sisal Fibre and Waste Plastics (SP)	Sisal Fibre 0.3% Waste Plastics 5%	1.23	1.23	98.95

Appendix XVII: Drain down data for sisal fibre modified asphalt concrete

Sisal Fibre (%)	OGA Drain down (%)	SMA Drain down (%)
0	6.489	6.497
0.1	2.340	2.347
0.2	0.136	0.144
0.3	0.008	0.012
0.4	0.000	0.000

Appendix XVIII: Drain down data for waste plastic modified asphalt concrete

Waste Plastics (%)	OGA Drain down (%)	SMA Drain down (%)
0	6.489	6.497
1	3.610	2.261
3	1.426	1.489
5	0.804	0.844
7	0.330	0.470

Appendix XIX: Actual Mix Ratios of asphalt concrete

Sample Points	Actual Components				Response	Pseudo Components			
	SF	WP	Bitumen	Aggregates	Yexp	SF	WP	Bitumen	Aggregates
	S1	S2	S3	S4		X1	X2	X3	X4
0.1S1WP	0.0182	0.1818	1.0000	17.1818	Y1	1	0	0	0
0.2S3WP	0.0364	0.5455	1.0000	17.1818	Y2	0	1	0	0
0.3S5WP	0.0545	0.9091	1.0000	17.1818	Y3	0	0	1	0
0.4S7WP	0.0727	1.2727	1.0000	17.1818	Y4	0	0	0	1
N1	0.0003	0.3636	1.0000	17.1818	Y12	0.5	0.5	0	0
N2	0.0364	0.5455	1.0000	17.1818	Y13	0.5	0	0.5	0
N3	0.0455	0.7273	1.0000	17.1818	Y14	0.5	0	0	0.5
N4	0.0455	0.7273	1.0000	17.1818	Y23	0	0.5	0.5	0
N5	0.0545	0.9091	1.0000	17.1818	Y24	0	0.5	0	0.5
N6	0.0636	1.0909	1.0000	17.1818	Y23	0	0	0.5	0.5

Appendix XX: Control mix ratios of asphalt concrete

Sample Points	Actual Components				Response	Pseudo Components			
	SF	WP	Bitumen	Aggregates		SF	WP	Bitumen	Aggregates
	S1	S2	S3	S4	Yexp	X1	X2	X3	X4
C1	0.0364	0.5454	1.0000	17.1801	Yc1	0.3333	0.3333	0.3333	0.0000
C2	0.0477	0.7727	1.0000	17.1818	Yc2	0.0000	0.6250	0.1250	0.2500
C3	0.0273	0.3636	1.0000	17.1818	Yc3	0.6250	0.2500	0.1250	0.0000
C4	0.0545	0.9088	1.0000	17.1749	Yc4	0.0000	0.3330	0.3333	0.3333
C5	0.0274	0.5454	1.0000	17.1801	Yc5	0.3333	0.3333	0.0000	0.3333
C6	0.0330	0.6136	1.0000	17.1818	Yc6	0.2500	0.1250	0.2500	0.3750
C7	0.0330	0.6136	1.0000	17.1818	Yc7	0.2500	0.1250	0.6250	0.0000
C8	0.0387	0.6591	1.0000	17.1818	Yc8	0.1250	0.1250	0.1250	0.6250
C9	0.0485	0.7878	1.0000	17.1801	Yc9	0.3333	0.0000	0.3333	0.3333
C10	0.0455	0.7273	1.0000	17.1818	Yc10	0.2500	0.2500	0.2500	0.2500

Appendix XXI: Indirect tensile strength of modified asphalt concrete

Sample	Load (kN)		L(m)	d (m)	(2P/3.14ld)	Indirect tensile strength (N/mm^2)		
	A	B				A	B	Average
0.1S1WP	9.96	10.97	101.5	63.5	0.000984	0.984	1.084	1.034
0.2S3WP	11.41	11.39	101.6	63.4	0.001128	1.128	1.126	1.127
0.3S5WP	12.40	12.41	101.4	63.5	0.001227	1.227	1.228	1.228
0.4S7WP	11.30	11.41	101.7	63.3	0.001118	1.118	1.129	1.124
N1	10.91	11.05	101.5	63.5	0.001078	1.078	1.092	1.085
N2	11.45	11.43	101.7	63.6	0.001128	1.128	1.126	1.127
N3	12.08	11.95	101.5	63.3	0.001197	1.197	1.185	1.191
N4	12.03	12.03	101.6	63.5	0.001187	1.187	1.188	1.188
N5	12.30	12.38	101.4	63.5	0.001217	1.217	1.225	1.221
N6	11.88	11.80	101.4	63.6	0.001173	1.173	1.165	1.169
C1	11.29	11.32	101.7	63.4	0.001115	1.115	1.118	1.117
C2	12.19	12.09	101.6	63.6	0.001202	1.202	1.192	1.197
C3	10.96	11.07	101.7	63.5	0.001081	1.081	1.092	1.087
C4	12.27	12.24	101.4	63.6	0.001212	1.212	1.208	1.210
C5	12.12	12.02	101.5	63.5	0.001198	1.198	1.188	1.193
C6	11.98	11.81	101.6	63.4	0.001185	1.185	1.168	1.176
C7	12.06	11.89	101.7	63.5	0.001189	1.189	1.173	1.181
C8	12.00	11.87	101.6	63.6	0.001183	1.183	1.170	1.177

C9	12.04	12.05	101.5	63.4	0.001191	1.191	1.192	1.192
C10	12.01	11.99	101.5	63.5	0.001187	1.187	1.185	1.186

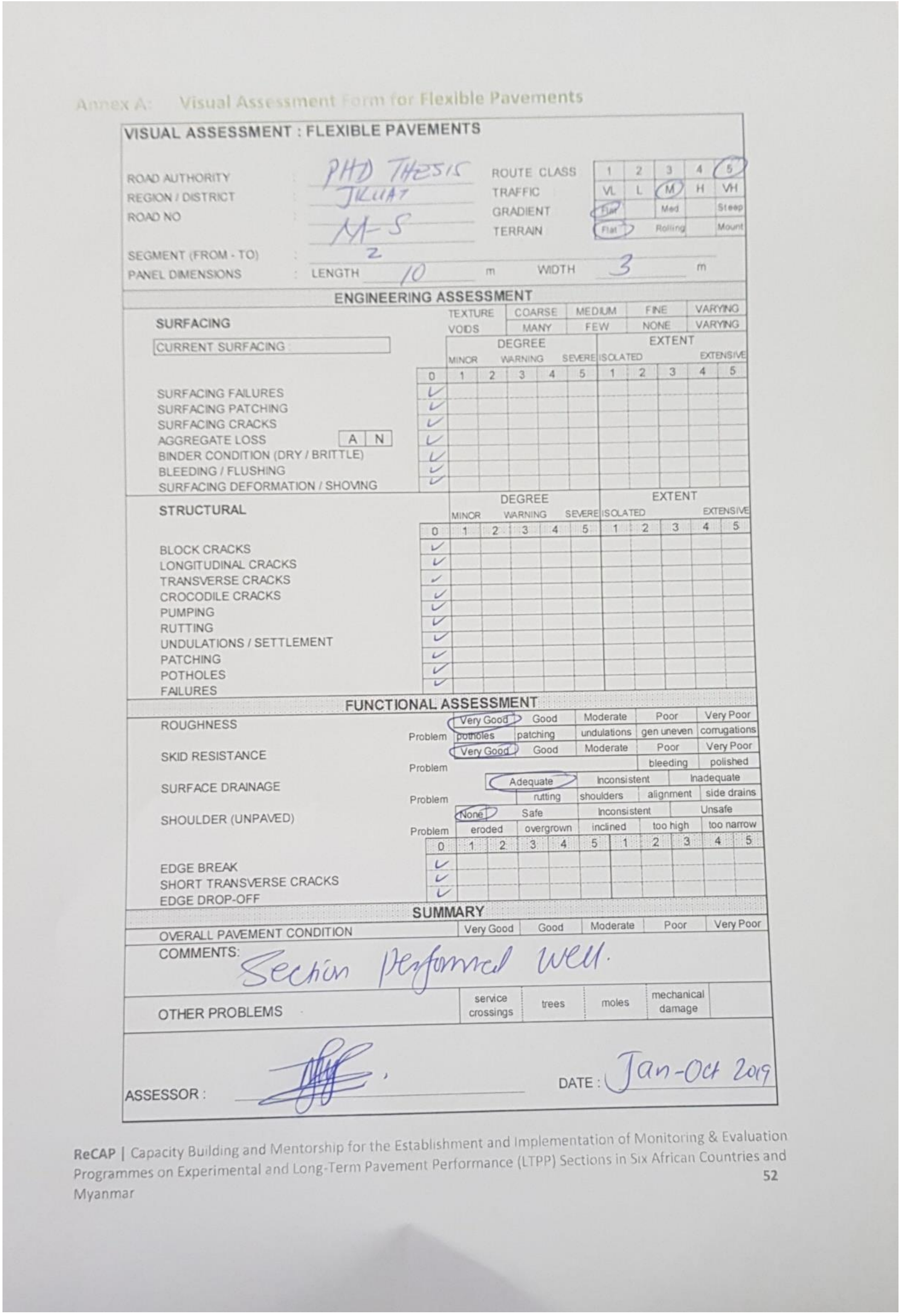
Appendix XXII: Experimental and predicted data of tensile strength of asphalt concrete modified with sisal fibre and waste plastics

Sample points	Test sample Y_{exp}	Pseudo Components				Tensile strength Y (Mpa)	
		SF	WP	Bitumen	Aggregates		
		X1	X2	X3	X4	$Y_{experimental}$	$Y_{predicted}$
C_1	1	0.3333	0.3333	0.3333	0.0000	1.1170	1.1343
C_2	2	0.0000	0.6250	0.1250	0.2500	1.1970	1.2010
C_3	3	0.6250	0.2500	0.1250	0.0000	1.0867	1.0844
C_4	4	0.0000	0.3330	0.3333	0.3333	1.2100	1.2035
C_5	5	0.3333	0.3333	0.0000	0.3333	1.1926	1.1892
C_6	6	0.2500	0.1250	0.2500	0.3750	1.1763	1.1861
C_7	7	0.2500	0.1250	0.6250	0.0000	1.1809	1.1680
C_8	8	0.1250	0.1250	0.1250	0.6250	1.1767	1.1895
C_9	9	0.3333	0.0000	0.3333	0.3333	1.1918	1.1736
C_{10}	10	0.2500	0.2500	0.2500	0.2500	1.1861	1.1812

Appendix XXIII: Model section of the road

Appendix XXIV: Model section performance monitoring

Appendix XXV: Visual assessment form for modified section.



Annex A: Visual Assessment Form for Flexible Pavements

VISUAL ASSESSMENT : FLEXIBLE PAVEMENTS

ROAD AUTHORITY : PHD THESIS
REGION / DISTRICT : JKUAT
ROAD NO : M-S

ROUTE CLASS	1	2	3	4	(5)
TRAFFIC	VL	L	(M)	H	VH
GRADIENT	(Flat)		Med		Steep
TERRAIN	(Flat)		Rolling		Mount

SEGMENT (FROM - TO) : 2
PANEL DIMENSIONS : LENGTH 10 m WIDTH 3 m

ENGINEERING ASSESSMENT

SURFACING

TEXTURE	COARSE	MEDIUM	FINE	VARYING
VOIDS	MANY	FEW	NONE	VARYING

CURRENT SURFACING

	0	DEGREE: MINOR 1	2	WARNING 3	4	SEVERE 5	EXTENT: ISOLATED 1	2	3	4	EXTENSIVE 5
SURFACING FAILURES	✓										
SURFACING PATCHING	✓										
SURFACING CRACKS	✓										
AGGREGATE LOSS (A / N)	✓										
BINDER CONDITION (DRY / BRITTLE)	✓										
BLEEDING / FLUSHING	✓										
SURFACING DEFORMATION / SHOVING	✓										

STRUCTURAL

	0	DEGREE: MINOR 1	2	WARNING 3	4	SEVERE 5	EXTENT: ISOLATED 1	2	3	4	EXTENSIVE 5
BLOCK CRACKS	✓										
LONGITUDINAL CRACKS	✓										
TRANSVERSE CRACKS	✓										
CROCODILE CRACKS	✓										
PUMPING	✓										
RUTTING	✓										
UNDULATIONS / SETTLEMENT	✓										
PATCHING	✓										
POTHOLES	✓										
FAILURES	✓										

FUNCTIONAL ASSESSMENT

ROUGHNESS		(Very Good)	Good	Moderate	Poor	Very Poor
	Problem	potholes	patching	undulations	gen uneven	corrugations
SKID RESISTANCE		(Very Good)	Good	Moderate	Poor	Very Poor
	Problem				bleeding	polished
SURFACE DRAINAGE		(Adequate)		Inconsistent		Inadequate
	Problem		rutting	shoulders	alignment	side drains
SHOULDER (UNPAVED)		(None)	Safe	Inconsistent		Unsafe
	Problem	eroded	overgrown	inclined	too high	too narrow

	0	1	2	3	4	5	1	2	3	4	5
EDGE BREAK	✓										
SHORT TRANSVERSE CRACKS	✓										
EDGE DROP-OFF	✓										

SUMMARY

OVERALL PAVEMENT CONDITION	Very Good	Good	Moderate	Poor	Very Poor

COMMENTS: Section Performed well.

OTHER PROBLEMS	service crossings	trees	moles	mechanical damage

ASSESSOR : [signature] DATE : Jan-Oct 2019

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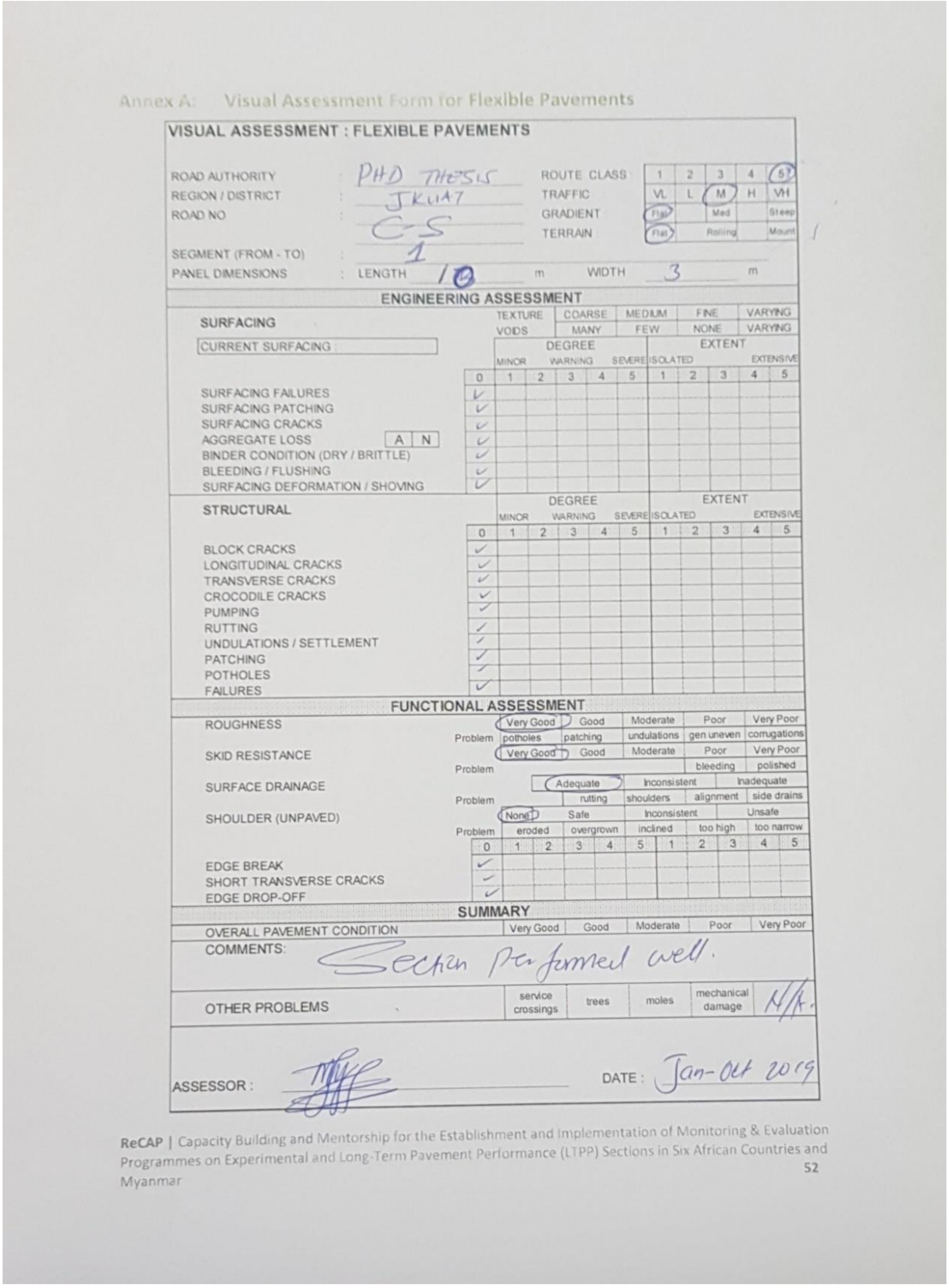
Appendix XXVI: Visual assessment form for non-modified section



Annex A: Visual Assessment Form for Flexible Pavements

VISUAL ASSESSMENT : FLEXIBLE PAVEMENTS

ROAD AUTHORITY : PHD THESIS
REGION / DISTRICT : JKUAT
ROAD NO : C-S
SEGMENT (FROM - TO) : 1
PANEL DIMENSIONS : LENGTH 10 m WIDTH 3 m

ROUTE CLASS	1	2	3	4	(5)
TRAFFIC	VL	L	(M)	H	VH
GRADIENT	(Flat)		Med		Steep
TERRAIN	(Flat)		Rolling		Mount

ENGINEERING ASSESSMENT

SURFACING

TEXTURE	COARSE	MEDIUM	FINE	VARYING
VOIDS	MANY	FEW	NONE	VARYING

CURRENT SURFACING :

		DEGREE (MINOR – WARNING – SEVERE)					EXTENT (ISOLATED – EXTENSIVE)				
	0	1	2	3	4	5	1	2	3	4	5
SURFACING FAILURES	✓										
SURFACING PATCHING	✓										
SURFACING CRACKS	✓										
AGGREGATE LOSS (A / N)	✓										
BINDER CONDITION (DRY / BRITTLE)	✓										
BLEEDING / FLUSHING	✓										
SURFACING DEFORMATION / SHOVING	✓										

STRUCTURAL

		DEGREE (MINOR – WARNING – SEVERE)					EXTENT (ISOLATED – EXTENSIVE)				
	0	1	2	3	4	5	1	2	3	4	5
BLOCK CRACKS	✓										
LONGITUDINAL CRACKS	✓										
TRANSVERSE CRACKS	✓										
CROCODILE CRACKS	✓										
PUMPING	✓										
RUTTING	✓										
UNDULATIONS / SETTLEMENT	✓										
PATCHING	✓										
POTHOLES	✓										
FAILURES	✓										

FUNCTIONAL ASSESSMENT

ROUGHNESS	(Very Good)	Good	Moderate	Poor	Very Poor
Problem	potholes	patching	undulations	gen uneven	corrugations
SKID RESISTANCE	(Very Good)	Good	Moderate	Poor	Very Poor
Problem				bleeding	polished
SURFACE DRAINAGE	(Adequate)		Inconsistent		Inadequate
Problem		rutting	shoulders	alignment	side drains
SHOULDER (UNPAVED)	(None)	Safe	Inconsistent		Unsafe
Problem	eroded	overgrown	inclined	too high	too narrow

	0	1	2	3	4	5	1	2	3	4	5
EDGE BREAK	✓										
SHORT TRANSVERSE CRACKS	✓										
EDGE DROP-OFF	✓										

SUMMARY

OVERALL PAVEMENT CONDITION	Very Good	Good	Moderate	Poor	Very Poor

COMMENTS: Section Performed well.

OTHER PROBLEMS	service crossings	trees	moles	mechanical damage	N/A.

ASSESSOR : [signature] DATE : Jan-Oct 2019

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Appendix XXVII: Monitoring data of Control section

Monitoring observations	Parameters assessed				
	Aggregate loss in grams/m^2	Surface Depression Depth in mm	Bleeding	Cracks Depth in mm	Rutting depth in mm
Day 1	10	15	Shoe stuck	0	0
Day 2	12	20	0	0	0
Day 3	0	0	0	0	0
Day 4	0	0	0	0	0
Day 5	0	0	0	0	0
Day 6	0	0	0	0	0
Day 7	0	0	0	0	0
Week 2	0	0	0	0	0
Week 3	0	0	0	0	0
Week 4	0	0	0	0	0
Month 2	0	0	0	0	0
Month 3	0	0	0	0	0
Month 4	0	0	0	0	0
Month 5	0	0	0	0	0
Month 6	0	0	0	0	0

Appendix XXVIII: Monitoring data of modified section

Monitoring observations	Parameters assessed				
	Aggregate loss in grams/m^2	Surface Depression Depth in mm	Bleeding	Cracks Depth in mm	Rutting depth in mm
Day 1	0	0	0	0	0
Day 2	0	0	0	0	0
Day 3	0	0	0	0	0
Day 4	0	0	0	0	0
Day 5	0	0	0	0	0
Day 6	0	0	0	0	0
Day 7	0	0	0	0	0
Week 2	0	0	0	0	0
Week 3	0	0	0	0	0
Week 4	0	0	0	0	0
Month 2	0	0	0	0	0
Month 3	0	0	0	0	0
Month 4	0	0	0	0	0
Month 5	0	0	0	0	0
Month 6	0	0	0	0	0