# UNIVERSITY OF NAIROBI

## FACULTY OF ENGINEERING

### DEPARTMENT OF CIVIL & CONSTRUCTION ENGINEERING


# PERFORMANCE OF PLASTIC WASTE AND WASTE ENGINE OIL AS PARTIAL REPLACEMENT OF BITUMINOUS ASPHALT CONCRETE IN FLEXIBLE PAVEMENTS


**By**

## JOYCE SUSAN LIAVULI OGADA

## F56/34580/2019


**A Thesis submitted in partial fulfilment of the requirements for the award of the Degree of Master of Science in Civil Engineering (Transportation Engineering) of the University of Nairobi**

## SEPTEMBER 2023

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**This thesis is submitted with our approval as university supervisors:**

**<u>SUPERVISORS:</u>**

Prof Sixtus. Kinyua Mwea

SIGNATURE: DATE: 7$^{th}$ September 2023

Eng. George Matheri

SIGNATURE: DATE: 7th September 2023

# ACKNOWLEDGEMENT

I give thanks to God for giving me a sound mind to enable me to do my MSc. Thesis. I do appreciate my supervisors, Prof. S. K. Mwea and Eng. George P.K. Matheri, for their relentless support and for imparting ideas and knowledge, which improved my thesis. Special thanks to everyone who encouraged and supported me in whichever way.

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Name of student: Joyce Susan Liavuli Ogada

Registration: F56/34580/2019

Faculty/School/Institute: Faculty of Engineering

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# ABSTRACT

Plastic waste is an emerging issue posing serious pollution problems to the environment. Waste Engine Oil has also become an environmental nuisance causing water pollution and soil degradation. In addition to the emerging environmental issues, the sources of bitumen for road construction are continuously being depleted hence the need for innovative ways of sustaining road construction through use of plastic waste and waste engine oil. This research project reviewed available literature on the concept of using HDPE waste plastic and waste engine oil as partial replacements of bitumen in road construction together while also carrying out the Marshall Stability test in both neat and bituminous mixes modified with plastic waste and waste engine oil. The optimum bitumen content was determined as 6% from the neat samples. Samples of the modified mix were then prepared with the percentage plastic content varying as 10%, 20%, 30%, and 40% of the mass of bitumen. The optimum plastic content was determined at 18% with a stability value of 8580N (an increase from 8337.4N for the neat samples). Samples with both plastic waste and waste engine oil replacements were prepared with 18% plastic waste being replaced with 10%, 20%, 30%, and 40% waste engine oil while bitumen content remained constant at 6%. The optimum replacement was determined at 19% giving the highest stability of 8820N (an increase of 2.8% from the plastic only modified mix and an increase of 5.8% from the neat sample). The use of polymer modified bituminous mix in the construction of flexible pavements, the problems of pollution and improper waste disposal would be mitigated. Implementation of such innovative technology in highway construction not only improves the environment but also increases its road life. Results from the Marshall Stability test showed that an optimum plastic content of 18% gave the highest stability. Both the values of stability (8820N) and flow (2.9mm) fell within the AASHTO specified recommendations of 7000N minimum for stability and 2-4mm for flow. Volumetric properties of bulk density, voids in mineral aggregates, voids in mix and voids filled with bitumen also fell within acceptable ranges.

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# LIST OF ABBREVIATIONS

AC Asphalt Cement

ASTM American Society for Testing and Materials

Gmb Bulk Density of Compacted Specimen

Gmm Theoretical Maximum Specific Gravity

Gsb Bulk Specific Gravity

HDPE High-Density Polyethylene

Pb Bitumen content

Pba Absorbed bitumen.

Ps Aggregate content percent by total weight of mix.

VFB Voids Filled with Bitumen

VIM Percent Air Voids in Compacted Mix

VMA Voids in Mineral Aggregate

SPI Society of Plastics Industry

WEO Waste Engine Oil

# CHAPTER ONE

## 1.0 Introduction

### 1.1 Background Information

The transportation infrastructure assets are heavily dependent on functional and structural performance of pavement networks such as ports, airports, and highways for their efficiency and productivity. Construction of new pavement requires advanced technologies and high-quality materials. However, there is a significant burden on non-renewable natural resources such as carbon-based energy carriers (bituminous binder and industrial fuel) and quarried aggregate sources as a result of pavement construction. Year after year, the demands for roads continue to rise. Commercial vehicles with increased axle loads are always increasing in number and the trend is expected to continue in the future. It is therefore crucial to increase the use of sustainable materials and construction technologies in road paving. This sustainability would cut down on the environmental impact of pavement design and construction. Highway engineers have been tasked with coming up with alternative solutions to this growing challenge.

All over the globe, there is currently a growing call to conserve or minimize using natural resources such as crude oil which produces bitumen used in road paving. There is also growing calls by environmentalists to reuse waste materials. Several studies have been conducted to discuss reusing waste materials in road paving to minimize the use of bitumen (Costa et al., 2013, Anastasiou et al., 2015, Costa et al., 2017). Studies that investigate the performance of new asphalt binders which incorporate wastes are vital in reducing the use of bitumen directly obtained from oil sources, which is essential for the sustainable development of road paving construction. Some of the studies have referred to non-petroleum binders (Metwally and Williams, 2010) and synthetic binders consisting of polymers, resins, and used oils (Fuentes-Auden et al., 2007).

Plastics are an example of waste materials that can be reused as they occur in numerous forms as post-consumer products. Plastics form a large percentage of solid wastes in most towns across the world. Due to the rising human population, it is expected the consumption of plastic products will continue to rise globally hence continue to pose a threat to the environment. Various governments have put in place legal frameworks with the aim of controlling the usage of plastic products. For example, in 2017, the Kenyan government banned the importation, use, and manufacture of plastic carrier bags (Kenya Ministry of Environment, 2017). However, people continue to use plastic products hence the need to manage plastic wastes.

Waste Engine Oil (WEO) is also another waste material that can be reused as a partial replacement for bitumen due to its viscosity. Engine oil is a product of fractional distillation of crude oil. The demand for oil is still expected to increase (Deffeyes, 2006). Limited oil resources should therefore be carefully utilized. In addition to finding substitutes for oil products, used oil products can be reused.

The current study discusses the performance of bitumen modified with plastic waste and WEO. In incorporating plastic wastes and WEO in asphalt concrete, aggregate is coated with recycled plastic waste before being mixed with bitumen and WEO then laying on the road surface. Binder modified with HDPE and WEO has shown to improve characteristics of conventional bitumen with slightly higher penetration and high softening point temperatures. Experimental results have also shown that modified binder improves the mechanical properties of the pavement and provides better binding properties, density and better in waterproofing. In the long run, using modified asphalt mixes in paving roads reduces the quantity of bitumen used hence cutting down the expenses of road construction. The new binder can be considered as a sustainable solution for road paving since it meets both environmental and economic considerations (Moretti et al., 2013, Moretti et al., 2017). Using reduced quantities of bitumen in the mixes, and replacing them with waste materials, would reduce the costs of the asphalt mixes. The key challenge in using asphalt modified with waste materials is identifying the type of plastic and quantity of WEO and plastic for partial replacement which are most suitable for use in the process.

## 1.2 Problem Statement

Due to ongoing environmental concerns and limited resources, there have been increased calls by environmentalists and policymakers to reuse waste materials in road paving. Numerous studies have been conducted to investigate alternatives to bitumen. Construction industries, specifically road paving industries, use high quantities of limited natural resources such as bitumen and aggregates. Bitumen plants are responsible for environmental pollution due to high amounts of greenhouse gases they emit. The process of producing bitumen is not eco-friendly. Bitumen is also non-renewable hence the need to use it carefully.

The continued increased demand for transport networks to be created in previously remote areas so as to spur economic growth in the country has necessitated the need for more construction materials for roads. With increasing cost of investing in road projects, coupled with the increasing pollution of the environment caused by plastic wastes lying around, there are calls for appropriate solutions to manage the plastic waste which will greatly reduce the cost of road construction while at the same time help mitigate the effects of plastics on the environment.

In construction of flexible pavements, bitumen is extensively used because of its properties of being cohesive in nature and being waterproof enabling it to be used as a sealant in road pavements (Transport Research Laboratory, 2002). However, the prices of bitumen in the world market keep increasing as the sources of the product become depleted as it is not renewable. The author visited Quality Bitumen Products Limited, a local provider of bitumen in the country, and was advised a 200-liter drum of K365 cutback retails at $175.60 while that of A4-60 cutback goes for $171.42. The use of polymer-modified bituminous mixes could offer a solution to this problem by reducing the expenditure of pavement construction`.

With increasing cost of investing in road projects, coupled with the increasing pollution of the environment caused by plastic wastes lying around and poorly disposed WEO, calls for appropriate solutions to manage such wastes which will greatly reduce the cost of road construction while at the same time help mitigate the effects of plastics and used oil on the environment. WEO is a waste product from generators in petrol stations and garages. High rates of discharges of WEO have negative impacts on the environments, it leads to soil degradation, negatively affects flora and fauna hence a concern for public health and a concern for the country's image across the globe. Kenya produces an estimated 30 million litres of WEO each year (Takouleu, 2019). The disposal of waste engine oil has been poor in Kenya over the years. It has led to contamination. There is no legal framework which has been put in place to ensure the proper disposal of WEO hence address the issue of environmental pollution by WEO. Therefore, there is need to develop a sustainable management of WEO and plastic waste. Reusing these waste materials in road paving would reduce environmental pollution while also providing an economical and sustainable solution to challenges facing highway engineers.

## 1.3 Objectives of Study

The main objective of the study was to investigate the performance of plastic waste and waste engine oil as partial replacement of bitumen in bituminous asphalt concrete in flexible pavements. To achieve the main objective, the study was guided by the following specific objectives:

i. To evaluate the Optimum Bitumen Content (OBC) of the bituminous concrete mix by evaluating and comparing the parameters of various mixes with varying bitumen content
ii. To compare the properties and performance of asphalt concrete mixes (bulk specific gravity of compacted mix, percentage air voids in compacted mix, voids in mineral aggregates, percentage voids filled with bitumen, stability, and flow) prepared using the modified and neat bitumen to determine the compatibility of modified bitumen
iii. To evaluate the optimum percentage of replacing bitumen with plastic waste and WEO by evaluating and comparing the parameters of various mixes with varying bitumen, plastic waste, and WEO content

## 1.4 Research Questions

The following research questions were formulated to achieve the objective of the study in investigating the performance of plastic waste and waste engine oil as partial replacement of bituminous asphalt concrete in flexible pavements:

i. What is the Optimum Bitumen Content (OBC) of the bituminous concrete mix?
ii. What are the properties asphalt concrete mixes (bulk specific gravity of compacted mix, percentage air voids in compacted mix, voids in mineral aggregates, percentage voids filled with bitumen, stability, and flow) prepared using the modified and neat bitumen to determine the compatibility of modified bitumen?
iii. What is the optimum percentage of replacing bitumen with plastic waste and WEO?

## 1.5 Scope of Study

The proposed experimental research made use of High-Density Polyethylene (HDPE) grade of plastic and WEO to make the blend of modified bituminous mix. The study determined the properties of Ordinary Bitumen of grade 60/70 and WEO (Penetration, Softening Point, and Specific Gravity). It will also determine the properties of coarse and fine aggregates (Los Angeles Abrasion, Aggregate Crushing Value, Aggregate Impact Value, and Water Absorption Test).

Marshall's Stability test was then performed on both neat samples and modified samples and their properties compared to determine suitability of incorporating waste plastic and WEO into the bituminous mix. All sampling and testing were conducted in the University of Nairobi Highways Laboratory. Data collected from tests were presented graphically and comparisons made between the mixes of different replacements. The results were then be discussed and recommendations made.

# CHAPTER TWO

## 2.0 Literature Review

### 2.1 Bituminous Materials

Asphalt contains bitumen, a hydrocarbon, and is obtained in the process of fractional distillation of crude oil. Bitumen is a dense component; therefore, it does not readily evaporate and is collected as residue. Asphalt has several desirable properties that makes it of use. It is strong and readily adhesive which is important in ensuring aggregates stick together. Asphalt enables controllable flexibility to material mixes in which it is applied which is desirable in road construction (The Asphalt Institute, 1989). Asphalt readily liquefies upon heating and can be dissolved in petroleum solvents. Its engineering use include paving roads while in architectural it is applied to roofs to provide waterproofing.

Tar is also another bituminous material that is obtained through the destructive distillation of coal at temperatures of about 1000°C. However, the use of tar in road construction has declined due to environmental concerns arising from air pollution caused by the process of distillation as well as reduced reserves of coal around the world. Figure 2.1 shows the general classification of bituminous material. Over the years, the materials used for construction of road has evolved from when it was just gravel to now when asphalt is used as surface dressing (Nicholls, 1998). The advancement of materials used in road construction has led to advancements in methods used in the process of road construction (Fwa, 2006).

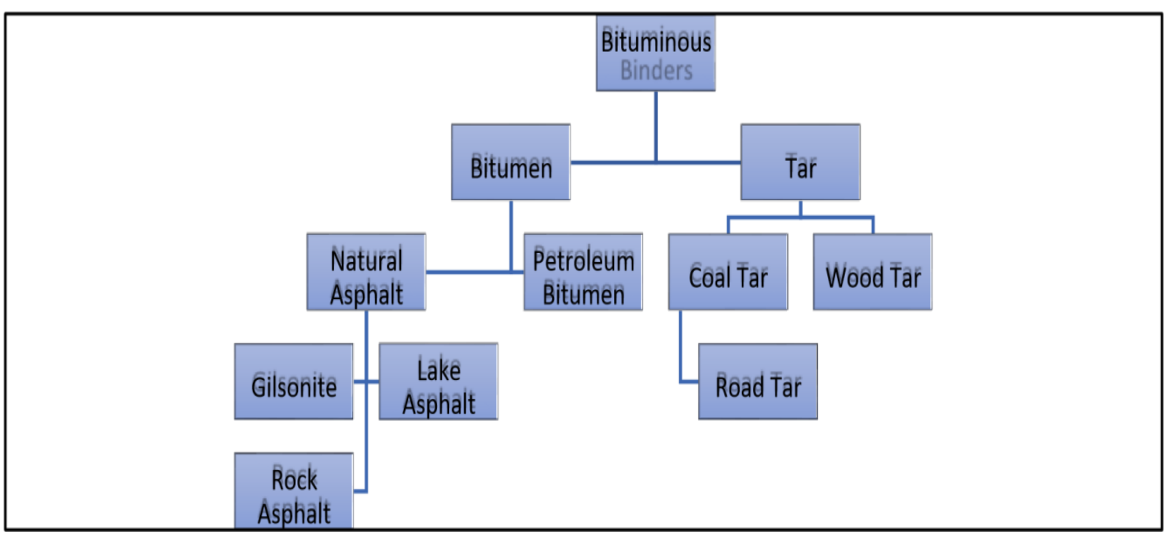



Figure 2.1: General Classification of Bituminous Material (Nicholls, 1998)

A typical road pavement section will consist of a wearing course below which are different material layers which provide for stability and structural support for the wearing course. Pavements can either be flexible where the wearing course is made of hot-mix asphalt concrete or rigid where Portland cement concrete is used to make the wearing course.

The bitumen used in hot-mix asphalt concrete consists of hydrocarbons and its derivatives. It softens when heated becoming a viscous liquid that is black or brown in colour. Bitumen is used since it possesses the following properties that are desirable for road construction:

i. It has a low temperature susceptibility as it does not change its properties with slight changes in temperature
ii. Has good binding properties which is necessary for it to bond well with the aggregates to hold them together and prevent loss of aggregate
iii. It becomes fluid upon heating enabling proper coating of aggregate
iv. It has good affinity to aggregates which is important to prevent stripping off due to flow of water on the surface
v. Its waterproofing property ensures water does not reach the lower layers of the pavement which could cause structural failure

In road construction, bituminous binders are classified into the following groups;

### *2.1.1 Asphalt Cement*

When it is in the natural state in which it occurs or when obtained as by-product of fractional distillation of crude oil, AC is used as a binder for aggregates in pavement construction to ensure aggregates do not fall apart. The aggregate and asphalt cement are both heated prior to mixing to ensure sufficient coating of the aggregates by the AC while in its fluid state.

#### *2.1.1.1 Asphalt Cement Behavior*

AC exhibits the property of being viscoelastic as it exhibits both viscous and elastic behavior (Fwa 2006). This property is hugely affected by the prevailing conditions of temperature and the rate of loading. At high temperatures and conditions where traffic flow is slow, it becomes a viscous fluid and can flow which could lead to permanent deformation of the asphalt mix. At low temperatures and where the traffic flow is rapid, it behaves like elastic solids as it may deform but later on returns to its original form upon removal of the load however cracking may occur supposing the load applied exceeds that allowable load bearing capacity of the mix (Fwa 2006). At temperatures which are out of the extremes, asphalt cement shows both viscous and plastic behaviors.

Asphalt cement is normally graded by its properties of penetration and viscosity at a standard temperature. The properties are important for the determination of consistency of the asphalt which is the viscosity of asphalt at a particular temperature (The asphalt Institute, 1989). The consistency varies with temperature and is measure using viscosity test or the penetration test.

The various available grades of AC are based on measurements from penetration tests carried out at temperature of $25^0$C and include: 40-50, 60-70, 85-100, 120-150 and 200-300. The numbers represent allowable ranges of penetration with 200-300 being the softest grade and maximum penetration is achieved even with slight loading as compared to the 40-50 grade.

### 2.1.2 Cutback bitumen

Asphalt cutback is produced when heated AC is dissolved in petroleum solvents which are volatile in a process known as ‘cutting-back’. The purpose being to make the asphalt liquid so that it can easily be pumped through pipes and also enable spraying through nozzles while laying. Once laid, the solvent evaporates leaving behind the asphalt cement that then performs its function of binding. Asphalt cutback has the advantage of being usable at low temperatures enabling cold laying of plant mixes, road mixes and as surface treatments.

Petroleum solvents used are referred to as cutter-backs and include petroleum products such as naphtha, gasoline, kerosene, jet fuel, diesel oil and fuel oil (The United States Army, 2007). The rate of curing is dependent on the volatility of the solvent used. Based on the type of cutter-back used and the rate of curing, there are three types of asphalt cutbacks:

i. Slow-curing asphalt cutback. Made using asphalt cement and a heavy distillate as solvent such as diesel oil or fuel oil. Have low volatility and viscosity lower than that of asphalt cement. Their rate of curing is low. Applications include use as prime coats and in dust control

ii. Medium-curing asphalt cutback. Made using asphalt cement and a distillate of intermediate volatility such as kerosene or jet fuel. They harden faster than slow-curing cutback although they may have similar consistencies. They are mainly used in the construction of pavement bases, surfaces and surface treatments

iii. Rapid-curing asphalt cutback. Produced by blending asphalt cement with a highly volatile petroleum solvent such as naphtha and gasoline. This enables a rapid change from the liquid form to the solid asphalt cement. They are also used especially in roadways and airfields

The use of asphalt cutbacks is being increasingly replaced with asphalt emulsions due to the increasing environmental concerns arising from the fact that there is use of petroleum solvents that are an environmental hazard. They are also uneconomical as compared to asphalt emulsions due to the increased cost of using petroleum distillates (Fwa, 2006).

### *2.1.3 Bitumen Emulsions*

This is a non-flammable liquid produced by combining a mix of asphalt cement and water and an emulsifying agent such as soap, dust or colloidal clay (The United States Army, 2007). In the manufacturing process, the AC is broken down into small particles and then dispersed in water containing the emulsifying agent. Possession of like charges by the particles prevents their amalgamation prior to spreading.

The product is a liquid which is laid on road pavements with no heating being required to turn the asphalt cement into liquid state as is the case with the other binders. The viscosity of the emulsion determines the ease with which the emulsion can be handled and sprayed. Generally, increasing the percentage of the emulsifying agent while keeping the bitumen content constant increases the electrostatic forces in the particles thereby increasing viscosity.

Upon spraying on the pavement, the asphalt cement separates from the water which then evaporates leaving the asphalt behind to perform its function of bonding.

Asphalt emulsions are of three types based on the electrical charges imposed on the asphalt particles (Fwa, 2006)*:*

i. Anionic emulsions which have negatively charged asphalt particles and are generally used in highway construction and maintenance although its use is restricted as it does not readily bond with the negatively-charged siliceous aggregates used in pavement construction. The breaking process is mainly by evaporation of water while in liquid state this makes anionic emulsions more susceptible to changes in temperature and humidity conditions.

ii. Cationic emulsions have positively charged asphalt particles meaning improved bonding with the negatively-charged siliceous aggregates. They are usually identified by having the letter ‘c’ in front of the name of the emulsifier. Unlike anionic emulsions, they break by the process of chemical coagulation which happens upon contact with silica aggregate. This makes them less susceptible to changes in temperature and are hence more preferred to the anionic emulsions (Nicholls, 1998).

iii. Non-ionic emulsifiers have neutral charge

Asphalt emulsions are further classified into three groups based on the rates of setting they achieve; a) Rapid-setting emulsions have high curing rates and are mainly used for surface dressing. b) Medium-setting emulsions c) Slow-setting emulsions

The ability of being able to be used under wet conditions gives asphalt emulsions an edge over the use of asphalt cutbacks. However, they are not suitable for use in areas of low temperature since the water will readily freeze and break the emulsion. Also, there is the possibility of the emulsion breaking while still stored in unopened drums making storage difficult.

### *2.1.4 Desirable Properties of Asphalt Materials in Road Construction*

So as to achieve a proper dense graded asphalt paving mix for a specified application, it is important that the asphalt material possesses the following characteristics (Garber and Hoel, 2009);

#### *2.1.4.1 Consistency*

The consistency of an asphalt material is determined by carrying out the penetration test. Consistency at a particular temperature determines the grade of the sampled asphalt. Asphalt materials can exist in either liquid or solid states with each having their respective methods of describing their consistency.

In liquid state, consistency is described by its viscosity through carrying out the Saybolt Furol Viscosity test while in solid state it is through the penetration and float tests (Garber and Hoel, 2009). Consistency of an asphalt material depends on either as it varies with changes in temperature or at a certain specified temperature. Different asphalt materials exhibit differing variations in consistency even with the same temperature changes. A sample of paving-grade asphalt heated to the same temperature as that of another sample of blown asphalt will become soft and will liquefy at a much lower temperature.

#### *2.1.1.2 Durability*

Once sprayed on the pavement surface, the asphalt material is immediately exposed to the effect of environmental conditions hence natural deterioration gradually takes place through the process of weathering. The materials lose their plasticity property and become brittle. It is, therefore, important for the asphalt material to be able to resist detrimental effects of environmental conditions that may take place because of:

i. Oxidation which is the chemical reaction that takes place when the material combines with oxygen. The material becomes brittle and loses plasticity
ii. Volatilization occurs when lighter hydrocarbons evaporate from asphalt material causing loss of plasticity characteristics
iii. Temperature affects the rates of both volatilization and oxidation. Increase in temperature causes a corresponding increase in their rates (The Asphalt Institute, 1989)
iv. Exposed surface area of material- the more exposed the material is to the environmental conditions, the more it comes into contact with oxygen and is exposed to the effects of temperature increasing the rates of oxidation and volatilization

#### *2.1.1.3 Rate of curing*

The rate of curing is important as it indicates the time it will take to attain consistency of the asphalt material so that the binder can perform its function.

For cut-back asphalt, the rate of curing is dependent on the petroleum solvent used in terms of its volatility and the quantity used. The more volatile the solvent is the higher the rate of curing as it will evaporate faster leaving behind the Asphalt Concrete (AC). Use of smaller quantities of solvent will also lead to faster rates of curing as less time will be required for evaporation to completely take place. The rate of curing is also affected by external factors of the environment which can’t be controlled or predicted on situ such as temperature, wind speed and surface area to volume ratio (The Asphalt Institute, 1989).

For asphalt emulsions, since the solvent used is water the rate of curing is fully dependent on the rate of water evaporation. The rate of evaporation of water is in turn affected by the environmental conditions of humidity, temperature, and rainfall. High temperature result in high rate of evaporation of water as the water particles have more energy while low humidity and low rainfall means there is low concentration of water vapour in the atmosphere creating a high concentration gradient hence more evaporation.

#### *2.1.1.4 Water Resistance*

It is also important for the asphalt material to maintain its bond to the aggregates in the mix even when there is flow of water because of rainfall causing stripping off of the asphalt binder. Loss of this bond is what leads to separation of aggregates and deterioration of the pavement quality.

## 2.2 Plastics

The word plastics comes from the Greek word 'plasticos' which means to be able to be shaped or molded using heat. Plastics are a type of polymer whose chemical composition is carbon and hydrogen which form molecules that are linked together in long-chain patterns by covalent bonds.

### *2.2.1 Type of Plastics*

Plastics fall into three categories:

i. Natural plastics- occur naturally in form of substances such as amber which forms when the pine tree is fossilized. It is used in making of jewellery
ii. Synthetic plastics- are derived from the cracking process of coal and during the fractional distillation of crude oil. During fractional distillation, the heavy fractions obtained are used in manufacturing lubrication oils and diesel while lighter fractions include gas, petrol, paraffin, and naphtha. Naphtha provides the main chemical building blocks for manufacture of synthetic plastics. During the manufacture of synthetic plastic, the naphtha undergoes a process referred to as a cracking process. During the cracking process, complex organic chemical compounds are separated into smaller molecules based on their molecular weights. The smaller molecules include butane, propylene, ethylene, and other hydrocarbons. The cracking process produces compounds which are further refined to form the base plastic materials

iii. Synthetic and semi-synthetic plastics are further divided into two depending on how they react upon heating:

Thermoplastics- are the plastics that become molten upon heating and can be molded into different shapes which upon cooling become solid. The process of reheating and remoulding can be repeated, and the plastic will still behave in the same way. They include polypropylene, polyethylene.

Thermosetting plastics- they undergo an irreversible chemical change upon heating several times. When they are heated at first, they soften and can be moulded into a desired shape while in that state which then sets upon cooling. However, reapplication of heat will cause burning of the plastic as the chemical structure is then altered. They include polyimides, phenolic and polyester resins used in reinforcing glass works. According to the Society of the Plastics Industry (SPI) (1988), the different types of thermoplastics include Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-Density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS).

The seven types of thermoplastics as identified by the SPI:

i. Polyethylene Terephthalate (PET) - Have good gas and moisture barrier properties and are recyclable. It’s used in making drinking water bottles, bean bags, combs and ropes
ii. High-Density Polyethylene (HDPE) - Have excellent chemical resistance properties and thus provide for good detergent bottles and trash bags. They are recyclable
iii. Polyvinyl Chloride (PVC) - Have good long-term stability and used in making plumbing pipes and fittings, credit cards, carpet backing and shoe soles. They are recyclable
iv. Low-Density Polyethylene (LDPE) - Are tough and flexible and are used in making wires and cables, flexible container lids, squeezable bottles for honey. They are recyclable
v. Polypropylene (PP) - Offer good chemical resistance and are used in making bottle tops, plastic diapers, margarine containers and disposable cups and plates. They are not recyclable
vi. Polystyrene (PS)- Are generally brittle and are used in making of disposable cutlery, fast food trays, coat hangers and packing foams. They are not recyclable
vii. Other e.g., polycarbonate, acrylic, acrylonitrile butadiene, styrene, fiberglass, and nylon

In 1988, SPI developed a system to classify different types of plastic which would allow recyclers and consumers to identify them. Each plastic product is fitted with an SPI number or code (usually moulded into the bottom) by plastic manufacturers. The SPI code provides consumers and recyclers with guidance on the type of plastic they come across (The Society of the Plastics Industry (SPI), 1988).

From the available types of plastic collected from different sources, they are then separated into different grades which are then made available to be blended with bitumen for road construction purposes. It is these different grades that will be investigated for performance and properties when blended with bitumen.

It is evident that with the varying characteristics of the different types of plastics, not all are suitable for use as modifier for bitumen (Al Hossain, 2006). Several factors determine whether a polymer is compatible with bitumen. These factors include: the type of polymer, the polymer's structure, chemical composition, and molecular weight. The compatibility of the two also depends on the characteristics of the base bitumen. Several key factors determine whether a polymer will improve the quality of bitumen. The key factors include: the source of base bitumen, its constituent compound, and the bitumen's grade.

There have been several laboratory trials performed on plastic modified bitumen to determine the most suitable types of plastics for use in the blend. Al- Abdul Wahhab et al. (2002) at the King Fahd University in Saudi Arabia performed tests on some selected polymers. They performed shear modulus test, phase angle test and softening point test using PP, LLDPE, SBS, CRT as polymers for making the blends. With the results they were able to recommend blending temperatures for each of the collected polymers. The recommended blending temperature for some selected polymers are presented in Table 2.1.

Table 2.1: Recommended blending temperatures

| **Polymer Type** | **Recommended blending temperature (°C)** | **Maximum blending temperature (°C)** |
|---|---|---|
| Linear Low-Density Polyethylene (LLDPE) | 160-170 | 200 |
| Polypropylene (PP) | 170-180 | 200 |
| Styrene-Butadiene-Styrene (SBS) | 160-170 | 200 |
| Crumb Rubber | 170-180 | 200 |

Source: (Al Hossain 2006)

#### *2.2.1.1 Type of plastics used in blending with Bituminous Mix*

Thermal recycling involves the heating of thermoplastic material at very high temperatures (300-900°C) until it flows. As the material cools down, it is transformed to new products, without changing the chemical composition of the plastics. This process can only be carried out once without altering the properties of plastic. Only thermoplastics can be used in this method because thermosets degrade when subjected to hot temperatures. Therefore, thermoplastics like High-Density Polyethylene (HDPE) are preferred for use in the blending of polymer-modified bituminous mix.

PVC is not preferred since when heated it produces toxic fumes that are harmful to human health.

### *2.2.2 Plastic Recycling Process*

Mechanical recycling is the processing of waste plastics by use of physical means to make new products. This method of recycling involves various stages as indicated in Figure 2.2.

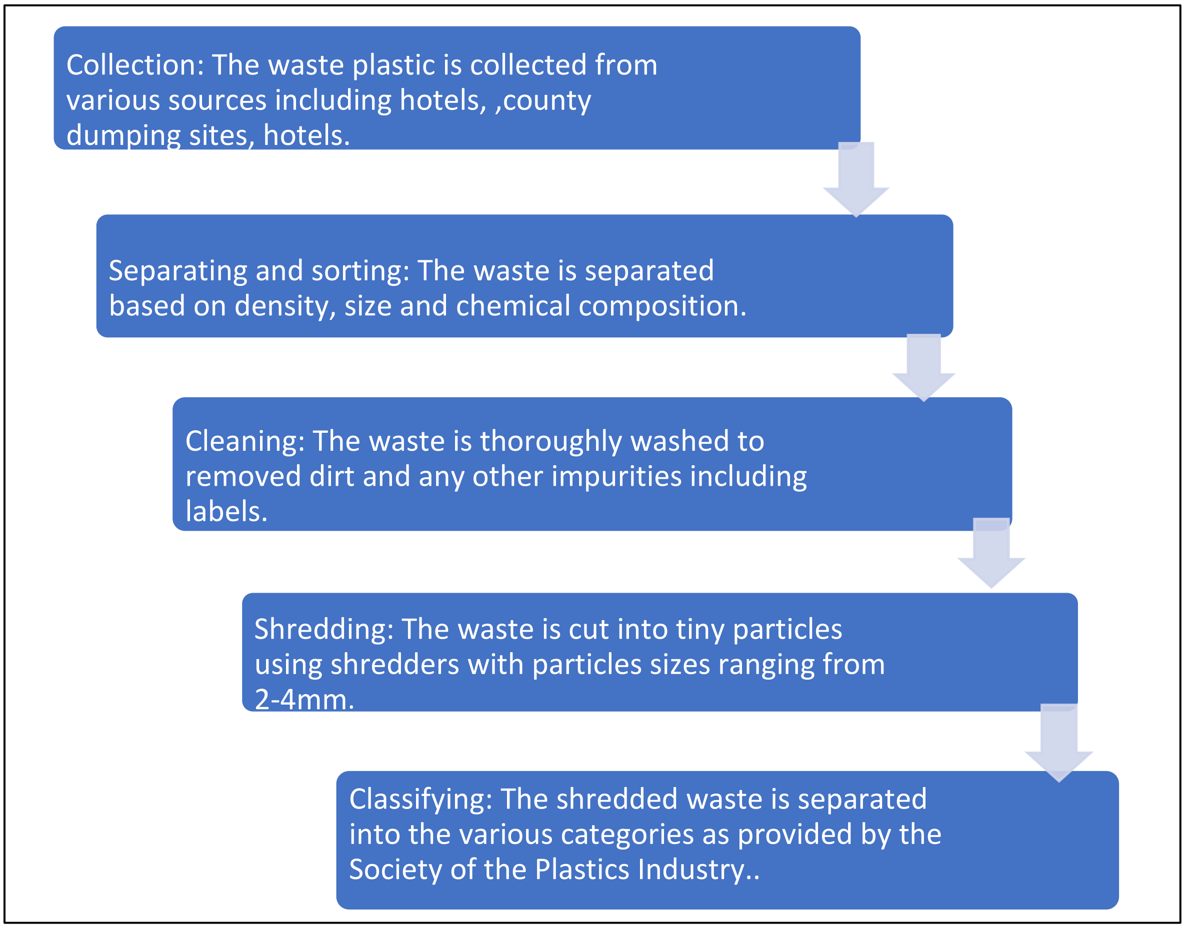



Figure 2.2: The Waste Plastic Recycling Process (The Society of the Plastics Industry (SPI), 1988)

## 2.3 Waste Engine Oil

Waste engine oil can be a useful resource in road paving. In the manufacture and improving the characteristics of engine oil, heavier and thicker hydrocarbon stock base are used. Some additives are also used to improve certain properties of the engine oil. The greater portion of an average engine oil consist of some hydrocarbons, ranging somewhere in between of 18 and 34 C (carbon) particles for each atom. One of the most important characteristics of engine oil is its viscosity. It allows formation a lubricating film in between for the propelling parts in machines. Viscosity can be described as the thickness of a fluid or a fluid's property to resist flow. The viscosity of engine oil should allow keeping up a film of lubrication in the propelling parts and it should also be able to flow through every part of the machine. The viscosity of engine oil is affected by variations in temperature. Waste engine oil has been tested as a modifier for bitumen to reduce dependence on bitumen hence reduce environmental pollution and ensure sustainable construction of road pavements. WEO reduces the softening point of bitumen hence road pavement become less susceptible to high temperatures. Rejuvenating agents, like WEO, are able to restore the chemical structure of aged asphalt by providing lost aromatic. The chemical structure of WEO resembles the molecular structures of asphalt with sufficient aromatic content, which leads to coherent bonding by altering the constituents and rejuvenating the aged asphalt.

When used in asphalt mixes, the low viscosity of waste engine oil has shown to prevent aging hence lower compaction and mixing temperatures (Silva et al., 2012, Lesueur, 2009). WEO is considered a bitumen rejuvenator (DeDene and You, 2014). The use of waste engine oil in road paving is also environmentally friendly as WEO is not totally recyclable (Kuczenski et al., 2014). However, there are disadvantages of using waste engine oil in asphalt mixes. They have shown to have problems such as increased rutting and low recovery for elasticity (Jia et al., 2014). To minimize these problems, it is recommended to use WEO together with a polymer modification. The elastomer styrene-butadiene-styrene (SBS) is considered the most suitable polymer modifier to use with WEO in asphalt mixes (Yildirim, 2007). According to Ahmedzade, (2013), SBS increases the rutting resistance of asphalt mixtures at high temperatures. It also increases the cracking resistance of the mixes at low temperatures. SBS also improves the elastic recovery properties and tensile strength of bituminous concrete.

The current industrial uses of WEO in Kenya include:

i. Fuel for industrial boilers and hotel boilers
ii. Fuel for furnaces in steel processing plants
iii. Reprocessed to be reused as lubricants and regenerated of base oil to manufacture new lubricants

## 2.4 Modified Bitumen

### *2.4.1 Modifiers*

Modifiers are the substances added to another substance for the purpose of altering its properties. The use of modifiers of different types to alter the properties of asphalt has been going ongoing (Fwa, 2006). A patent was granted for an asphalt paving mixture which contained rubber latex as early as 1873. By 1902, rubber-modified asphalt was being laid in France (Nicholls, 1998). The purpose being to not only try and optimize the consumption of bituminous materials whose supply are limited, but also enhance the desirable properties of asphalt in road construction.

Addition of modifiers to asphalt materials could be either through blending directly with the binder or through addition to the asphalt mix. Different types of modifiers have been used to improve on the properties of bituminous materials. Although there are a wide variety of polymers being produced over the world, the ones currently being used for modification of asphalt generally fall in two categories:

i. Crystalline polymers are often referred to as plastomers and include polyethylene, polypropylene, polystyrene, ethylene vinyl acetate (EVA) and ethylene methyl acrylate (EMA)
ii. Thermoplastic rubbers often called elastomers and include polymers such as natural rubber, styrene-butadiene rubber (SBR), styrene-butadiene-styrene (SBS), styreneisoprenestyrene (SIS), polybutadiene (PBD) and polysoprene

### *2.4.2 Bitumen modified with HDPE plastic waste and WEO*

Numerous studies have already been conducted to investigate the use of waste materials in road paving with the aim of reducing the consumption of natural resources such as bitumen. It has been determined that bitumen modified with waste materials can be help decrease the quantity of virgin bitumen used while significantly improving the characteristics of the asphalt mixes (Fuentes Auden, 2008, Zargar, 2012). Polymers, in most cases virgin elastomers and plastomers, have been tested on to determine the suitability of their properties in pavement construction. Polymers such as plastic waste have also been recently included in the tests. Plastic waste improves the bitumen properties and hence the durability and performance of asphalt mixtures. Also, using them in modifying bitumen has an environmental advantage. Also, it has economic advantages since it can be cheaply obtained in large quantities. Bitumen modified with HDPE has decreased penetration, increased softening point temperature. Polymer modified bitumen also improves the mixes' resistance to temperature variation (Al-Hadidy, 2009, Hınıslıoğlu, 2004). When used separately, HDPE and WEO have different advantages in asphalt mixes. Bitumen modified with HDPE and WEO improves the behaviour of the asphalt mixtures such as improving the cracking resistance at low temperatures, reducing thermal susceptibility, and improving the resistance to rutting (Actaplanin, 2011). A HDPE and WEO modified bitumen improve the mechanical characteristics of the final mixes.

Fernandes et al. (2015) investigated the performance of asphalt mixes with bitumen modified with HDPE plastic waste and WEO. The bitumen was classified as 35/50 pen, modified with plastic waste (HDPE) which had been ground to a maximum size of 4mm and modified with untreated waste engine oil from heavy vehicles without any kind of treatment, and ground waste plastic (HDPE) with a maximum size of 4mm. The study used two contents of WEO (10% and 20%) and three contents of HDPE polymer (2.5%, 5%, and 10%). The contents are mixed for 20 minutes at a temperature of 180°C in a high shear mixer at 7200 rpm. The performance of the modified bitumen was compared to that of conventional bitumen, and commercially modified bitumen (styrelf). The optimum binder content was determined as 5% in the study. The compaction temperature was at 160°C. The selected aggregates were graded, and it lay between the lower and upper limits as indicated Figure 2.3.

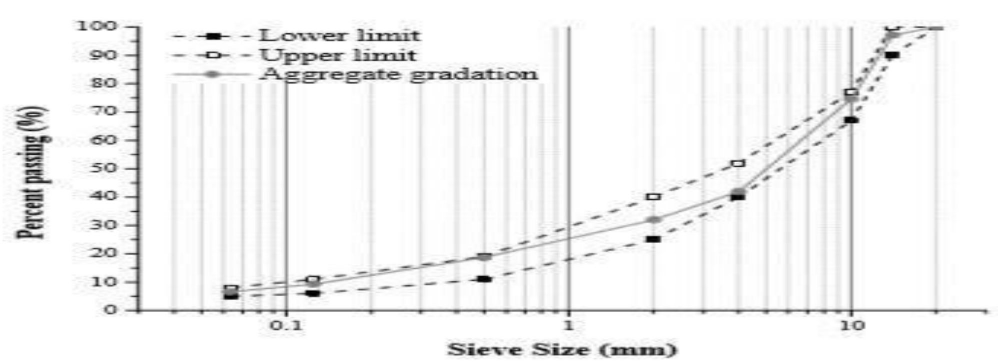



Figure 2.3: Aggregate gradation and lower and upper limits (Fernandes et al., 2015)

Fernandes et al. (2015) determined that increasing WEO (10% and 20%) reduces the softening temperatures and increases the penetration values of conventional bitumen, but no resilient capacity. Increasing the content of plastic waste increases the softening temperatures and reduces the penetration values, and improvement of its resilient capacity. Bitumen modified with 10% WEO and 5% HDPE plastic waste and with 20% WEO and 10% HDPE plastic waste as indicated in Figure 2.4.

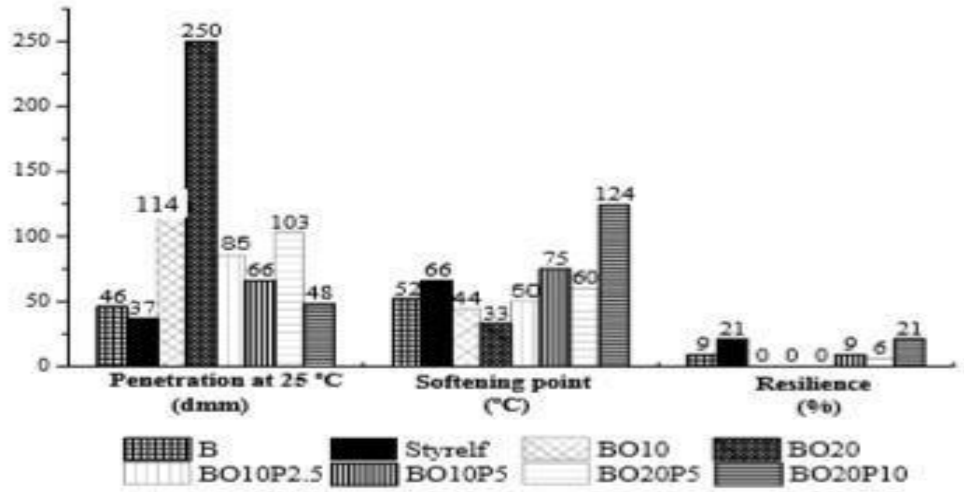



Figure 2.4: Penetration, softening point, and resilience test results of conventional bitumen and modified bitumen (Fernandes et al., 2015)

The bitumen modified with 10% WEO and 5% HDPE was the only modified bitumen with suitable characteristics for paving roads since it showed very good properties at intermediate temperatures because of higher softening and penetration compared to conventional bitumen (Fernandes et al., 2015). The researchers then proceeded to study the mechanical characteristics of the asphalt mixtures such as stiffness modulus, rutting resistance, and water sensitivity.

Gupta and Kumar, (2019) investigated the properties of bituminous paving mixes modified with waste polyethylene. The research tested properties such as percent voids filled with bitumen, percent voids in mineral aggregates, percent volume of bitumen, air voids content, and bulk density. Gupta and Kumar’s experiment was like the current experiment; only difference was in the use of High-Density Polyethylene and Waste Engine Oil. However, the methodology was similar. The results from Gupta and Kumar’s study found that the value of Marshall Stability increased upon the increase of plastic up to a certain percentage before the stability drops. They also found that there was little change on the Marshall Flow value when polyethylene was added to the bituminous mix. The mean values for the Marshall Stability and Flow were considered satisfactory. All volumetric properties such as VMA, VA, and VFB were all considered to be within the design requirements of asphalt mixes for flexible pavements. The researchers further determined that if each kilometre of a regular road would require ten tonnes of bitumen, then a road constructed with a polymer-modified mix, then the road would only require nine tonnes of bitumen and one tonne of plastic waste for the mix. Therefore, the incorporation of plastic waste in the construction of flexible pavements saves one tonne of bitumen for every kilometre. Therefore, plastic roads have economic and environmental benefit. Gupta and Kumar's study is useful in incorporating various wastes in construction of road.

### *2.4.3 Method of blending waste plastic in bituminous mix*

Blending of waste plastic in bituminous mix can be done either through dry blending or wet blending methods. In the dry blending method, the plastic waste is added to already heated aggregate. On the other hand, in the wet blending method, the plastic waste is added to hot bitumen to form a polymer-bitumen binder which is then added to the aggregates.

#### *2.4.3.1 Dry Process*

In the dry process, aggregates are first heated to around 165°C before mixed with plastics that have been shredded to around 2-4mm in size. The mixing occurs for 30 seconds while maintaining the same temperature. Coating aggregates with plastic improve certain qualities of the aggregate such as voids, soundness, and moisture absorption. It also reduces porosity of the aggregates (Al Hossain, 2006). Generally, aggregate coated with plastic are of better quality and perform better in flexible pavements. Figure 2.5 shows the dry process.

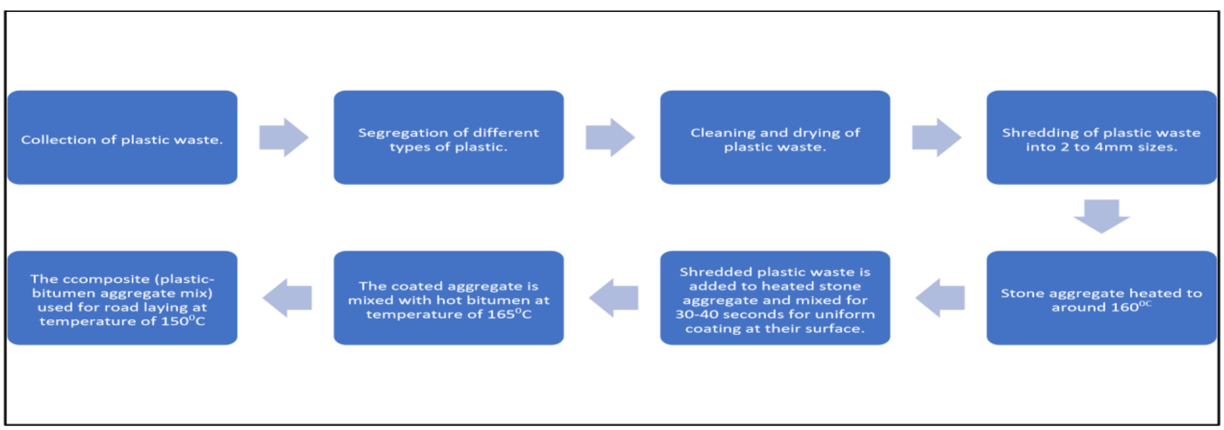



Figure 2.5: The Dry Process (Al Hossain, 2006)

#### *2.4.3.2 Wet Process*

The wet process requires a special equipment to blend polymer. In the wet process, either low or high shear mixing is used in mixing the asphalt with the polymer. The process requires a cooking/blending system. The primary parts of this cooking/blending system include controlled heating facilities, a mechanical stirrer with shear blade, and a container. The polymer can be in any form (powder, latex, pellet, shredded) when added to bitumen and the mixture is continuously stirred until it is completely blended. The blending temperature and time and speed of stirrer depend on the type of polymer used. Figure 2.6 shows the wet process.

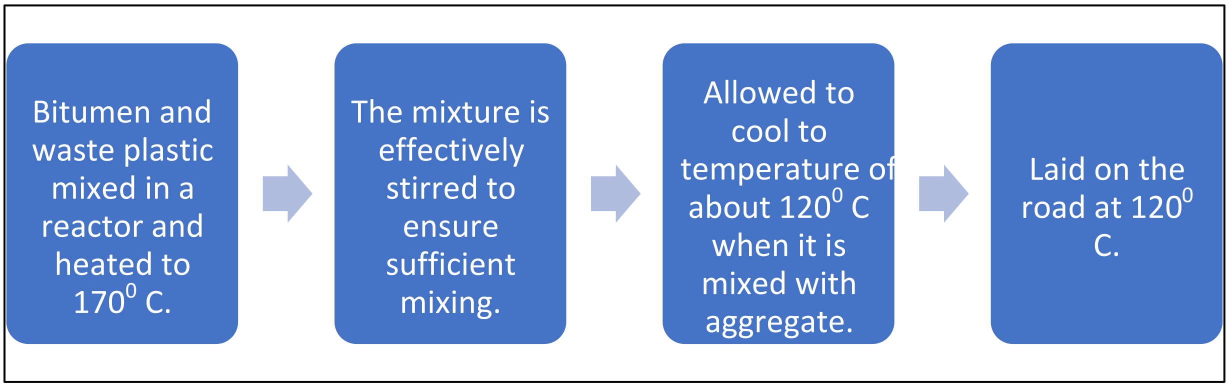



Figure 2.6: The wet process (Chakrapani, 2014)

### *2.4.4 Uses of Modified Bituminous Mix*

Some construction practices with modified bitumen include (Al Hossain, 2006):

i. In hot mix pavement which is the main use. This makes use of the dry and wet process of incorporating polymer into bitumen. Proper mixing leads to formation of a uniform coat of plastic around the aggregates. The coated aggregates are then mixed with bitumen at 160°C to produce modified asphalt mix

ii. In surface treatments. In most cases, the failure of a pavement starts from the surface of the pavement necessitating surface treatment over time as part of road maintenance. Use of modified bitumen in treating surfaces can reduce cracks and bleeding as well as stripping (Chavan, 2013). Also enhances the impermeability property of the pavement preventing intrusion of water. The use of modified asphalt to treat road surfaces reduces the maintenance costs and extends the life of pavements (Punith and Veeraragavan, 2006)

iii. Making of slurry surfacing by mixing additives, polymer modified emulsion, and graded aggregates. A special paver mounted on a self-propelled components or truck are metered into a pug mill. It is then mixed and spread on the surface. Slurry surfacing is applied as a slurry seal for the purpose of preventive and corrective maintenance treatments in cracked pavements. It could also be used as a micro surfacing where it is cold applied to remove minor surface irregularities, improve surface friction, reduce the intrusion of water, fill ruts, and reduce oxidation and ravelling

In crack sealing where it is placed in existing cracks in the pavement to reduce water intrusion into the flexible pavement thereby reducing the effects of abrasion by the water and reduce the saturation of the base materials. It is however important that the modified bitumen has high elasticity and low susceptibility to temperature variation hence able to resist formation of cracks in regions of low temperature.

### *2.4.5 Advantages and Limitations of the Use of Modified Bituminous Mixes*

#### *2.4.5.1 Advantages*

Generally, the polymers reduce the temperature susceptibility of the asphalt material such that its viscosity does not vary greatly within the prevailing temperature conditions of the site (Transport Research Laboratory, 2002). High temperature conditions of 45°C-60°C will cause the bitumen to become fluid and rutting of the pavement will follow while very low temperatures of below -10°C will make it become stiff and brittle causing breaking off of aggregates.

Polymers have also been noted to improve the cohesive properties of the bituminous binder. Cohesion is the measure of the tensile strength required to break the bond between particles of the bituminous material. Polymers have improved the cohesion of the modified binder such that even when under stress due to traffic loading it is able to retain the aggregate chippings.

Polymers have also been shown to improve the early adhesive characteristics of a polymer modified binder. Adhesion is a measure of the strength of the bond between particles of different nature in this case, particles of the bituminous binder and of the aggregate material. Polymer modified binders have shown improved early adhesion properties hence traffic can be allowed on such roads earlier than roads constructed with conventional unmodified (Southern African Bitumen Association (Sabita), 2015).

Polymer-modified binders also show improved durability and resistance to ageing. Polymers have improved the ability of binders to resist the influence of ageing on their properties of elasticity.

Ageing is usually brought about by temperature effects and time-related conditions and results in hardening and loss of elastic properties which is important in flexible pavements.

The use of polymers in road construction helps reduce the impact plastics have on environmental degradation. The process makes use of plastics that would rather have been laying idle on land hence a cleaner and healthier environment. Use of polymers in road construction also reduces instances of clogging of water drains which causes health hazards.

#### *2.4.5.2 Limitations*

Prevailing temperature conditions greatly affect the placement and compaction of normal asphalt mixes but is more critical when considering the use of polymer modified bitumen that are especially placed in thin layers.

For small projects, the cost of purchasing the equipment for production of the modified bitumen is significant as compared to in larger projects and this could lead to increase in the unit cost of production that affects the overall cost of the project.

The use of polymers also comes with the potential risk of having air pollution through the release of toxic fumes and also odour since the process involves heating of the plastic and if the fumes are released to the environment without proper treatment, it affects the environment.

According to the Kenya Road Design Manual, Kenya has got variable climatic conditions which are majorly governed by the altitude of the place (Kenya Ministry of Transport 1987). The climates are;

a) Afro-alpine climate which is characterized by daily fluctuations in temperature which are sharp and go as low as $0^0$C at night. Areas that experience this type of climate are the mountainous areas of Mt. Elgon and Mt. Kenya.

b) Equatorial climate that has no dry season, but a double-maxima rainfall period occurs in May and October. Also, temperatures are high throughout the year. Coastal and lake-basin regions e.g., Mombasa and Kisumu are areas that experience this climate.

c) Wet-tropical climate where due to high relief, the areas have cool and wet climate with areas such as Meru receiving 1320mm of rainfall per year (Onyando, 2006). Day temperatures are cool while nights are chilly.

d) Semi-arid climate where rainfall of less than 500mm is experienced annually although it could greatly vary over the year and temperatures vary between $22^0$ C and $27^0$ C. Areas in the Eastern region of Kenya experience this climate (Onyando, 2006).

e) Arid climate which is experienced in the stretch of Northern Kenya where rainfall of less than 250mm is experienced and temperatures of as high as $30^0$C during the day with large daily temperature variations of $15^0$C.

Temperature control is critical in achieving good performance of modified bitumen making the use in construction a challenge given that weather conditions may change rapidly in most of the areas in Kenya.

## 2.5 Mix Design

The properties of modified bitumen are also affected by phase transition, viscosity, and temperature, same as conventional binders. However, they exhibit improved viscoelastic properties that remain within the acceptable limits within a wider range of temperature and conditions of loading. There are four modes of interactions between bitumen and modifiers:

i. Modifier existing as a separate phase within the bitumen
ii. Bitumen existing as a separate phase within the modifier resulting in properties of the modifier being more prominent in the blend
iii. Modifier forming an interface with bitumen thus enhancing the viscoelastic properties of the blend
iv. Modifier forming a molecular bond with bitumen giving greater elasticity and stiffness

### *2.5.1 Composition of Modified Bitumen*

Based on the interaction between the polymer and the bitumen, the modified bitumen can be divided into two groups:

i. Homogenous binder: The polymer and bitumen completely blend to form a single-phase that behaves as a single interwoven material e.g., plastometric
ii. Non-homogenous binder: There are two distinct phases resulting in there being localized differences in properties e.g., bitumen-rubber blend.

Hot-mix asphalt is composed of aggregates uniformly mixed and coated with asphalt cement. Both the aggregates and asphalt are heated prior to mixing to ensure proper mixing and enhance the workability of the mix during paving (The Asphalt Institute, 1989). The principal characteristics of the asphalt mix are determined by the quantity and grade of asphalt used; the amounts of both coarse and fine aggregates passing the No.8 sieve; and the amount of mineral filler passing No.200 sieve.

It is crucial to ensure that bituminous mix are suitably designed so that they can withstand heavy traffic loads under adverse climatic conditions. Suitable design of bituminous mix is also important to ensure the structural requirements and pavements surface characteristics are met. The key objective of any bituminous mix design is to determine an economical blend through several trial mixes. To ensure good performance of the pavement during its use, a proper design of the asphalt concrete mixture is required considering the following desirable mix properties (The Asphalt Institute, 1989):

a) Stability. The pavement should be able to undergo little deformation due to imposed loads. The stability of the mix is influenced by the internal friction and cohesive properties of its components. Internal friction increases with the surface texture and angularity of aggregates. Good gradation and shape of particles increases the interlocking resistance of the aggregates increasing stability. With increase in the density of the mix, the mix becomes more stable as it is more compacted. Excessive quantity of asphalt in the mix will act as a lubricant compromising on the stability.

   Cohesion is important in the mix as it is the force that binds the aggregates together. It is directly proportional to the rate of loading, loaded area and viscosity of the asphalt. With an increase in the quantity of asphalt, cohesion increases up to an optimum point and then starts to decrease.

b) Durability. It’s the ability to resist degradation of the quality of the pavement from the effects of air, water, temperature, and imposed loads. Environmental effects bring about weathering which causes oxidation and volatilization of asphalt, freezing and thawing of the pavement. In the design process, durability is enhanced by high asphalt contents, dense aggregate gradations and well-compacted pavement layers which are impervious.

c) Flexibility. The asphalt mix should be able to undergo slight bending, due to the gradual differential settlement of the base and subbase layers of the road, without cracking. It is enhanced by incorporating high asphalt contents and relatively open-graded aggregates.

d) Fatigue resistance. It is the ability to withstand repeated flexing as a result of reoccurring wheel loads. Higher asphalt contents and use of dense-graded asphalt mixes result to increased fatigue resistance.

e) Permeability. Imperviousness to water and air is important to the durability of the paving mix. The void content and the interconnection of voids is an indication of the susceptibility to passage of water and air.

f) Workability. It is the ease with which paving mixtures can be placed and compacted. Problems with workability are usually encountered during the paving process and it is then that adjustments can be made to the mix design.

The mix design procedure for hot mix paving mixtures depends upon the aggregate gradation, maximum size of aggregate, axle wheel loading together with traffic frequencies and the rheology of the binder. The three primary bituminous mix design methods used are the Marshall Method, the Super pave Method, and the Hveem Method. Throughout the world, the Marshall Mix design method is the most used method. In the Marshall method, a load is applied to a cylindrical sample of bituminous mix. The specimen is observed until failure occurs as indicated in the ASTM standard (ASTM D1559). Based on the load which causes failure, stability of the mix is determined.

### *2.5.2 Theoretical Mix Design: Modified Binder Mix Design*

Marshall Mix design method for dense graded paving mixtures using modified bituminous binder is preferred. The design for the mix design depends on rheological properties of the modified bitumen which include elasticity and viscosity. When partial replacements of waste materials, that is, plastic waste and WEO are used in a small percentage, the conventional mix design procedure can be used. However, when the percentages of the partial replacements are high, a modified mix design method must be used to account for the significant changes in mechanical and physical properties of the modified bitumen.

The plastic waste has to be properly shredded and sorted (size of approximately 2-4mm is recommended). This would ensure the plastic melts completely and binds properly with the aggregates. Bituminous concrete mix design is then performed while varying the percentage of plastic as 10%, 20%, 30% and 40% of the mass of bitumen.

The Marshall Test procedure is used in the evaluation and design of bituminous mixes. The Marshall test of designing mixes has two major features: stability-flow test and density-voids analysis. Marshall Stability refers to the strength of a bituminous mix following the specification of ASTM D 1559 (2004). Marshall Stability is defined as the maximum load that can be carried by a compacted specimen at a standard test temperature of 60°C. In the Marshall Test procedure, a compressive load is applied to the specimen until the specimen breaks. The temperature of 60°C is used to replicate the condition when a bituminous pavement is at its weakest.

The flow value of a bituminous mix refers to the flexibility of the mix and is measured as the change in diameter of a specimen sample in the direction of applied load between the beginning of load application and at the time of maximum load. A dial gauge is attached to the specimen during the application of load as it measures the specimen's plastic flow (deformation) as a result of the load application. The plastic flow associated with the specimen at the time of material failure is referred to as the flow value. The analysis of density-voids is achieved through the volumetric properties of the mix as described in the American Society for Testing and Materials (1988).

#### *2.5.2.1 Gradation of Aggregates*

It is one of the most important considerations in the design of hot mix asphalt. Sieve analysis is performed, and the blending is selected according to the specified limits. Figure 2.7 shows the gradation of aggregate to determine their appropriateness for use in the mix design.

| Sieve Size (mm) | ***Design Specifications*** *Percentage passing sieve size %* |
|---|---|
| 20 | 100 |
| 14 | 90-100 |
| 10 | 70-90 |
| 6.3 | 55-75 |
| 4 | 45-63 |
| 2 | 33-48 |
| 1 | 23-38 |
| 0.425 | 14-25 |
| 0.3 | 12-22 |
| 0.15 | 8-16 |
| 0.075 | 5-10 |

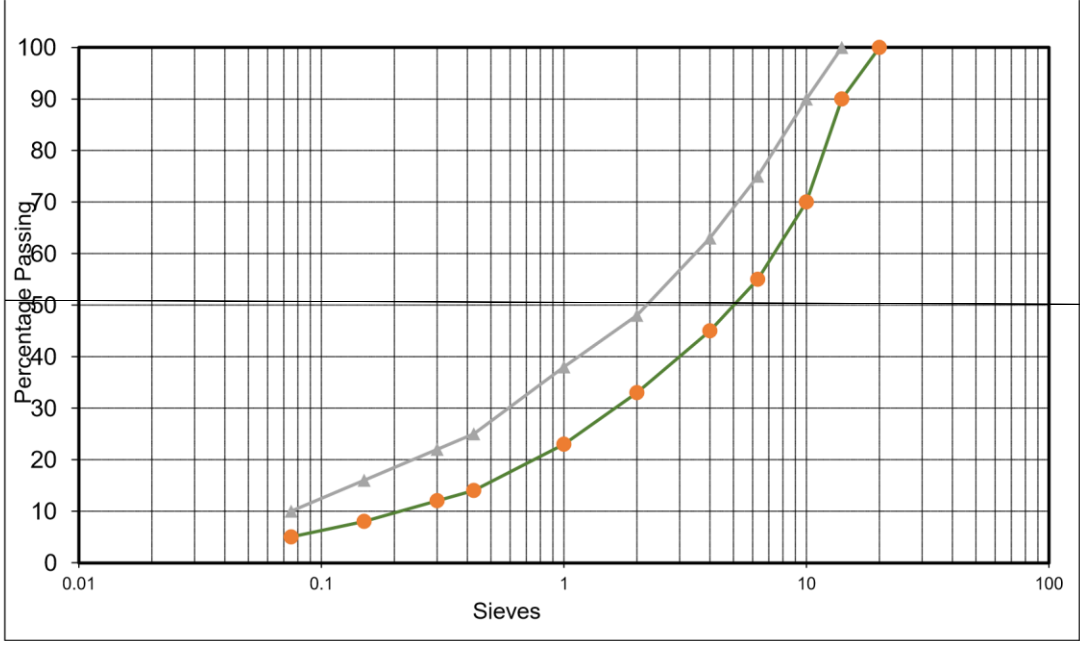



Figure 2.7: Gradation of a typical 12.5mm open-graded course showing the grading envelope (The Asphalt Institute, 2014)

The evaluation and selection of aggregate for the mix design is to ensure it meets the same quality required for conventional bituminous pavement. The physical properties of the aggregates are determined for properties such as toughness, abrasion, durability, particle shape and surface texture. The desired properties and their methods of testing are:

a) Size

Particle distribution is described in BS 812: Part 103 and involves carrying out the sieve and sedimentation tests. Using a nest of sieves, you can grade the material in both the wet and dry grading.

Aggregates retained on the 3.35mm sieve are the coarse aggregates while those which pass in substantial amounts are the fine aggregates. Fine aggregates could be in the form of natural sand, crushed rock fines or a mixture of both.

b) Dust

Dust refers to materials which pass through the 75 µm sieve (BS 812). Dust is harmful to the bituminous mix and affects the binder content in the mix and also impacts bitumen's ability to bond well to the surface of the aggregate (Nicholls, 1998). The aggregate fines are accessed using the Plasticity Index to determine their suitability to the mix, as recommended by BS specifications. For dust that is considered sound, 1.0% by mass of dust is acceptable while for dust considered unsound in nature, a maximum of 0.5% by mass of dust is acceptable (Craig, 1991).

c) Shape

In terms of shape, aggregate particles are classified based on how they relate to the mean size and their physical dimensions.

The BS 812: Section 105.1 makes use of the flakiness index, which is determined by separating the flaky particles, which are particles that have the least dimension less than 0.6 their mean size, and indicating their mass as a percentage of the mass of the sample total mass.

d) Relative density and water absorption

According to BS 812: Part 2, the relative density of aggregate can either be its apparent value, saturated surface-dry value, or dried value (The Asphalt Institute, 1989). Water absorption of aggregates refers to the difference in mass after a sample of aggregates is oven-dried at 105$^{o}$C for 24 hours.

***2.5.2.2 Volumetric Properties***

Mix design determines the volume of aggregates and bitumen binder needed to produce an asphalt mix which has suitable properties. In the mix design, the designer takes the measurements of the bitumen binder and aggregate weight and use specific gravities to determine their volume. The designer considers properties such as bulk specific gravity of compacted mix, percentage air voids in compacted mix, voids in mineral aggregates, percentage voids filled with bitumen, stability, and flow.

The purpose of mix design is to determine volume of bitumen binder and aggregates required to produce a mix design that possesses the desirable properties. Weight measurements are taken and converted to volume by use of specific gravities.

Properties that are considered include theoretical maximum specific gravity, bulk specific gravity of the mix, percentage air voids, percentage volume of bitumen, percentage void in mineral aggregate and percentage voids filled with bitumen.

The bulk specific gravity, $G_{sb}$, is the bulk specific gravity for total aggregates and is given by:

$$G_{sb} = \frac{P_1 + P_{2+}P_3}{P_1/G_1 + P_2/G_2 + P_3/G_3}$$

Where: $P_1$, $P_2$, $P_3$- The individual percentages by weight of aggregates.

$G_1$, $G_2$, $G_3$- Individual bulk specific gravity of aggregates.

Theoretical maximum specific gravity, $G_{mm}$ is calculated as per ASTM D2041-95 as:

$$G_{mm} = \frac{A}{A - C}$$

The bulk specific gravity refers to the actual specific gravity of the mix $G_{mb}$ while including the air voids and is calculated in accordance with D1188-96 by:

$$G_{mb} = \frac{A}{B - C}$$

Where; A- Mass of specimen in air (g)

B- Mass of surface dry specimen after immersion (g)

C- Weight of specimen in water

The effective specific gravity of aggregate, $G_{se}$ is given by;

$$G_{se} = \frac{100 - P_b}{100/G_{mm} - P_b/G_b}$$

Where: $P_b$- Bitumen content as percentage of total weight.

$G_{mm}$- Maximum specific gravity of mixed material

$G_b$- Specific gravity of bitumen

The bulk specific gravity is determined by measuring the volume of the mix and its weight. Displacement method is used in determining the volume of the sample. The sample is placed in water and the amount of water it displaces is quantified. The sample is covered in a thin film of paraffin to prevent the sample from absorbing water. The volume of paraffin used to coat the surface of the sample is known, therefore, it is subtracted from the volume of water dispersed. Bitumen binder coats the aggregate particles resulting in some of the binder being absorbed by the aggregates. The aggregates are also surrounded by a film of binder (which had not been absorbed by the aggregates). HMA is made up of four general components which include air, the bitumen which has not been absorbed by the aggregate (effective bitumen), absorbed bitumen, and aggregate. These components are shown in Figure 11 below.

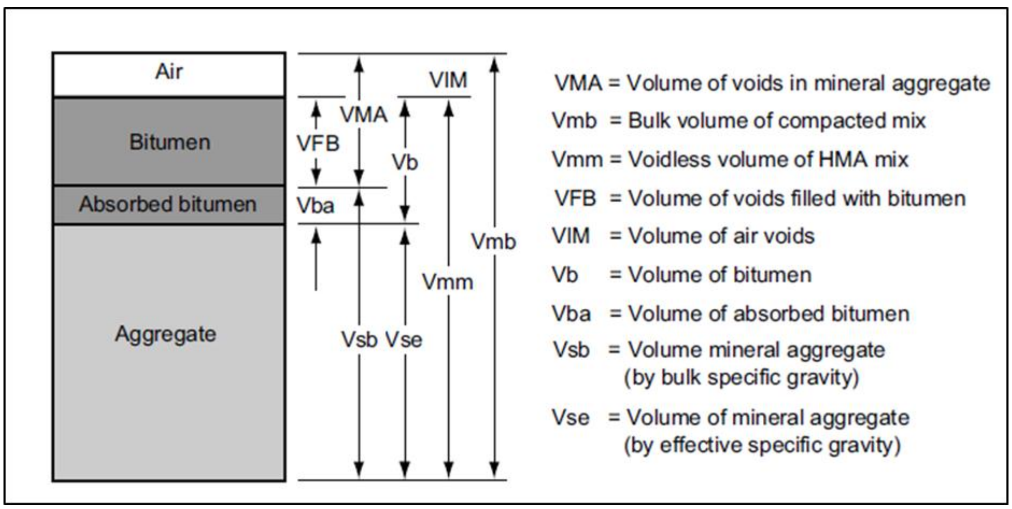



*Figure 1: Phase diagram of the bituminous mix (Transport Research Laboratory 2002)*

The bitumen absorption, $P_{ba}$, refers to the volume of binder which has been absorbed into the aggregate's pore structure and is expressed as a percentage of the aggregate weight. It is given by:

$$P_{ba} = \frac{100(G_{se} - G_{sb})G_b}{G_{se}G_{sb}}$$

Where; $G_{se}$- Effective specific gravity of aggregate.

$G_{sb}$- Bulk specific gravity of total aggregates.

$G_b$- Specific gravity of bitumen.

The effective bitumen content, $P_{be}$ refers to the total bitumen content in a mix minus the bitumen binder absorbed by the aggregate and is determined as;

$$P_{be} = P_b - \frac{P_{ba} P_s}{100}$$

Where; $P_b$-Bitumen content by percent of total weight of mix.

$P_{ba}$-Absorbed bitumen.

$P_s$- Aggregate content percent by total weight of mix.

The percent air voids in compacted mix VIM refers to total volume occupied by air pockets in between the aggregates coated with bitumen throughout the compacted mix. It is expressed as a percentage of the bulk volume of the mix. It is obtained in accordance with the D3203-94 test method where:

$$VIM = \frac{(G_{mm} - G_{mb})}{G_{mm}} * 100$$

Voids in mineral aggregate, VMA, refers to the total volume of voids in the aggregate mix that are not filled with bitumen. It is expressed as a percentage of the total volume of the mix and is determined as:

$$VMA = 100 - [\frac{(G_{mb} * P_s)}{G_{sb}}]$$

Where; $G_{mb}$-bulk specific gravity of compacted mix.

$P_s$ is the fraction of aggregates present by total weight of mix.

$G_{sb}$ is the bulk specific gravity of mixed aggregates

Voids filled with bitumen, VFB, is the voids filled with the binder representing the volume of effective bitumen content. It is inversely proportional to the air voids present and is expressed as:

$$VFB = [\frac{(VMA - VA)}{VMA}] * 100$$

#### *2.5.2.3 Specimen mixing*

Stirring could be done using either a mechanical mixer or vigorous manual mixing and should be done just after the addition of binder to the aggregate for a maximum duration of two minutes (Southern African Bitumen Association (Sabita), 2015). In cases where complete coating of aggregate has not been achieved within the specified mixing time, temperature could be increased to reduce viscosity.

### 2.6 Polymer-modified Bitumen in Road Construction: A Case Study of India

Nearly 8,300 million tonnes of plastics have been produced all over the world, as of 2017. Out of this, only an estimated 9% is recycled, and another 12% is incinerated. This means about 79% of the plastic produced globally ends up in the landfills or the natural environment. Researchers have spent a lot of time and resources to provide solutions for the ever-growing problem of plastic waste disposal. One of the possible solutions that has been developed is the use of plastic waste in the construction of flexible pavements. The Union Government of India, in 2015, provided guidelines for the implementation of plastic wastes in the construction of roads of National Highways on pilot basis.

As per a 2018 report, India consumes an estimated 16.5 million tonnes of waste. Also, 43% of India's plastics are used in packaging and in most cases are only used once, according to industry body FICCI. This means, about 80% of the total plastic produced in India is discarded to the landfills or the natural environment or burnt hence resulting to air pollution. Some also end up in clogs drains, consequently, choking animals who eat or are trapped by the plastic bags. Plastics that end up in the fields prevent germination of crops and blocks absorption of rainwater into the ground. This leading to pools of water that are contaminated and unhealthy for the environment and human population around surrounding areas.

Experiments to partially replace bitumen with plastic have conducted in the laboratory and the results were positive. The plastic waste is mixed with heated bitumen and the resulting mixture used to coat over aggregates. Therefore, the use of plastic waste has been implemented in various parts of India. In 2006, the Central Pollution Control Board (CPCB), conducted a performance appraisal for the plastic roads. The CPCB determined that the plastic roads had some advantages over the normal roads constructed using bitumen only. The plastic roads did not develop familiar defects such as edge flaw, ravelling, rutting, and potholes, even after four years. In addition to improve environmental sustainability, plastic roads were found to be cost-effective and more durable. Since both plastic and bitumen are petroleum products, they bond well together. The combination of plastic and bitumen enhances the ability of the road to carry load and also its self-weight. Plastic roads showed greater resistance to damages caused by heavy rains.

Further investigation on the potential to partially replace bitumen with plastic waste also showed that the modification of bitumen with shredded plastic waste results in a marginal increase in cost of paving by about Rs. 2500 per tonne. However, the marginal increase in cost is offset by the increase in the volume of the total mix. Therefore, using plastic waste helps in environmental conservation and better overall performance of the bituminous mix. In 2015, the implementation of using plastic in the construction of flexible pavements gained momentum. The use of plastic wastes with hot mixes for roads around urban areas was formalized by the Union government upon the issuance of guidelines to guide the production. In addition, guidelines for the use of plastic waste in wearing course were issued by the Ministry of Road Transport and Highways. The guidelines offered directions on a pilot basis. Plastic roads have been constructed in various parts of India such as Tamil Nadu for about 11km length and approximately 1km length in the state of Kerala. As is seen, the use of plastic has been gradually introduced into India’s transport system. From pilot basis to roads around urban areas, the ministry also issued mandatory use of plastic waste on roads which were being renewed with hot mixes and in wearing coat of service road on National Highways within 50km periphery of urban regions with populations of over 5 lakhs. These guidelines have been put in place by the government to ensure reduced usage of bitumen in road construction and to ensure a sustainable environment.

Several road construction works have been carried out in India using polymer-modified bitumen mix for over 15 years now. Figure 2.8 and 2.10 show plastic roads in India. In 2001, road construction projects were pioneered in Tamil Nadu and Karnataka States of India for the purpose of making use of the plastic waste lying around in the environment. According to India’s Central Pollution Control Board, the country generates more than 15,000 tons of plastic every day. To date, over 16,000km of rural roads in India have been constructed using the technology (Chakrapani, 2014).


*Figure 2.8: Plastic Road in India (The Logical Indian, 2015).*

As developed by Dr. Vasudevan, a chemistry professor at the Thiyagaraja College of Engineering, the technology could either be a 'dry' or 'wet' process. The dry process, highlighted in Figure 2.9, involves making of a mixture of aggregates and waste plastic chippings of thickness of about 40-70µm. The mix is then heated to 150-170$^0$C before being added to hot bitumen while maintaining the same temperature. On the other hand, the wet process involves mixing of plastic chippings to hot bitumen at 150$^0$C which is then followed by mixing with hot aggregate. Both processes lead to coating of the aggregates with a film of a mix of bitumen and the polymer forming plastic-modified bituminous aggregate mix. The mix is then hot laid during road construction.

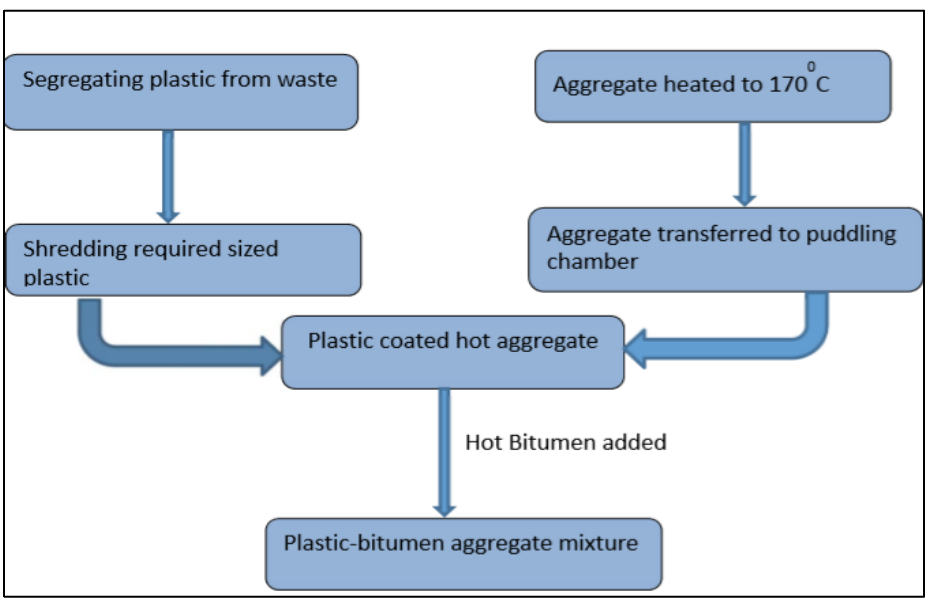



*Figure 2.9: The Dry Process of Making Polymer-modified Bitumen (Chakrapani, 2014)*

Use of the technology has been noted to have the advantage of enhancing the properties of strength, durability and stability of the road pavement (Chakrapani, 2014). As compared to traditional flexible pavements, they also have the benefit of reducing consumption of bitumen and improving water resistance of the pavement preventing damage. There has also been noted an increase of resistance to deformation by formation of potholes and rutting. The environmental benefit of making it easy to dispose of plastic wastes should also not be understated.

However, there have also been various challenges encountered in the implementation. There are limited types of plastics that have been able to be mixed with bitumen to successfully make the mix. The heating of PVC releases harmful gases to the environment and is thus not considered suitable. Absence of schedule rates of processed plastic wastes has brought about varying costs in production. There has also been inadequate training of plastic collection workers on the specific types of plastics that are desirable accompanied by poor compensation of the workers leading to low morale.


*Figure 2.10: Plastic Road in India (The Logical Indian, 2015).*

## 2.7 Synthesis of Literature Review

Extensive research has been conducted to investigate the potential use of waste materials as replacement for bitumen (a natural resource getting depleted) in road paving. Binder modified with HDPE has shown to improve characteristics of conventional bitumen with slightly higher penetration and high softening point temperatures. Experimental results have also shown that modified binder improves the mechanical properties of the pavement and provides better binding properties, density and better in waterproofing. In the long run, using modified asphalt mixes in paving roads reduces the quantity of bitumen used hence cutting down the expenses of road construction. The new binder can be considered as a sustainable solution for road paving since it meets both environmental and economic considerations. When used in asphalt mixes, the low viscosity of waste engine oil has shown to prevent aging hence lower compaction and mixing temperatures. WEO is considered a bitumen rejuvenator. However, little research has been conducted to study the performance of bitumen modified with a combination of HDPE plastic waste and WEO. WEO as a bitumen replacement increases rutting and low recovery for elasticity hence disadvantageous. To minimize these problems, it is recommended to use WEO together with a polymer modification. The proposed study will specifically address knowledge gaps concerning how WEO improves the characteristics and performance of polymer-modified bitumen. It will look to provide more information in using a combination of HDPE plastic waste and WEO as partial replacement for bitumen in asphalt mixes.

# CHAPTER THREE

## 3.0 Methodology

### 3.1 Overview of Methodology

The current study aimed to investigate the performance of an asphalt mix modified with plastic waste and Waste Engine Oil. New modified asphalts were produced by adding varying amounts of waste polymer (High-Density Poly Ethene- HDPE) and Waste Engine Oil (WEO) to virgin asphalt. Tests were conducted on the specimen of modified bitumen mixes. The data collected was analysed to establish the difference in characteristics of the mixes with different quantities of WEO and plastic waste.

### 3.2 Materials

The materials used in the laboratory investigations were plastic wastes, waste engine oil, bituminous binder, and aggregates. These were sourced from various local suppliers. The materials were prepared and tested as required by various codes.

Ordinary bitumen of grade 60/70 was used in the experimental investigation. The bitumen was sourced from a local provider of bitumen- Quality Bitumen Limited, Baba Dogo in Nairobi.

Quality Bitumen Limited's production of bitumen was considered to be meet the requirements set out in AASHTO and the guidelines of the Kenya Bureau of Standards. The following tests were conducted on the bitumen:

*i.* Penetration at 25°C, 100g, 5s *(ASTM D5 Test)*
*ii.* Softening point, ring-and-ball *(*ASTM *D36 Test)*
iii. Specific gravity at 25°C *(AASHTO Test T228)*

The coarse and fine aggregates were sourced from the Mlolongo quarry along Mombasa Road in Machakos County. Aggregate sizes of 14/6 and 0/6 were used as chippings for the test. Appendix 1 shows the preparation of the aggregates for testing. Sieve grade analysis, following guidelines in ASTM E11, were done on a sample of the oven-dried aggregates to obtain a batch that lies within the grading envelope. Appendix 2 shows the apparatus for the sieve grade analysis. Wet sieve analysis of the quarry dust was also carried out. Sampling of the aggregates was done using the riffle box quartering to ensure a good representation of the aggregates was sampled. The mechanical properties of the aggregate such as strength, toughness, hardness, water absorption, were investigated to ensure that they were within the specifications as stated by the Kenya Road Design Manual. Aggregates of sufficient strength, hardness, and toughness were used. The following tests were conducted on the aggregates:

i. Los Angeles abrasion (ASTM C131)
ii. Aggregate crushing value (BS812 Part3)
iii. Aggregate impact value (BS812 Part3)
iv. Water absorption test (ASTM C127*)*

Plastic can be used as a binder. Also, it can be used with another binder such as bitumen to improve the plastic's binding property. Crushed waste plastic materials were obtained from EcoPost Limited, a plastic waste recycling company located in Baba Dogo, Nairobi. The company is the only known source of quality shredded plastic that has been separated into the different types of plastic available. At EcoPost Limited, the plastic waste was segregated into the different types of plastics according to the guidelines provided by the Society of Plastic Industry. The plastics were then cleaned before to eliminate impurities being dried off followed by shredding. HDPE type of plastic was chosen for this test. The plastics were prepared by washing and sun-drying before being sieved.

The low viscosity of engine oil is its most exceptional characteristic hence making it a suitable material for partial replacement with bitumen. Engine oil in asphalt mixes prevents aging hence lower temperatures in compaction and mixing. Waste engine oil is not totally reusable hence using it as a partial replacement for bitumen is environmentally friendly. For this investigation, the waste engine oil was obtained from a lube bay at Shell Petrol Station on Latema road in Nairobi City. The waste engine oil obtained was the multi-grade oil SHELL HELIX HX5 15W-40 whose properties are known. The following tests were conducted on the waste engine oil:

*i.* Penetration at 25°C, 100g, 5s *(ASTM D5 Test)* indicated in Appendix 4
ii. Softening point, ring-and-ball *(ASTM D36 Test)* indicated in Appendix 3
iii. Specific gravity at 25°C *(AASHTO Test T228)*

### 3.3 Mixes

After the tests were carried out on the specific materials, bitumen, aggregates, and waste engine oil, the optimum content of bitumen was determined. Marshall stability and flow tests together with volumetric tests were carried out to determine the optimum bitumen content (OBC) and optimum modifier content (OMC) of the bituminous concrete mix. The bituminous concrete specimen was prepared with 4%, 5%, 6%, 7%, and 8% of bitumen by weight of aggregates as per the ASTM 1599 test procedure. Two specimens were prepared for each batch and an average of values used for analysis.

Partial replacement of bitumen with plastic waste were done based on the optimum bitumen content. The bitumen content was replaced by 10%, 20%, 30%, and 40% of plastic waste. For example, at 6% optimum bitumen content (which is 66g of bitumen) the replacements would be 6.6g plastic & 59.4g bitumen, 13.2g plastic & 52.8g bitumen, 19.8g plastic & 46.2g bitumen, 26.4g plastic & 39.6g. The optimum replacement percentage was determined. From this percentage of plastic, 10%, 20%, 30%, and 40% of WEO was added to the mix. For example, at 20% optimum plastic content (which is 13.2g of plastic and 52.8g bitumen) the replacements would be 1.32g WEO & 11.88g plastic & 52.8g bitumen, 2.64g WEO & 10.56g plastic & 52.8g bitumen, 3.96g WEO & 9.24g plastic & 52.8g bitumen, 5.28g WEO & 7.92g plastic & 52.8g bitumen. Two specimens were prepared for each batch for the Marshall test ASTM D6927-22 and an average of values used for analysis. The optimum percentage for WEO was determined.

### 3.4 Marshall Stability Test

Knowing the optimum bitumen content to use with the specified aggregate gradation, the Marshall, flow, and volumetric tests were performed on specimens whose bitumen content had partially been replaced by plastic waste and waste engine oil. The bitumen content as a percentage of the mass of aggregates was replaced with various combinations of plastic and engine oil (as indicated in the table) to determine the optimum replacement for the combination of both wastes.

A modified dry process of blending waste plastic (to include WEO) in bituminous mix was used for the experimental procedure. The plastic obtained from EcoPost had already been segregated into different plastics, cleaned, and dried, and shredded into 2-4mm sizes. The quantity of aggregate was measured and heated to around 160°C. The shredded plastic chippings were then added to the heated aggregates and mixed thoroughly for 30 – 40 seconds for uniform coating at their surface. The coated aggregate was mixed with hot bitumen and WEO at temperature of 165°C, in quantities required for each batch. The composite mixture of plastic, WEO, bitumen, and aggregates were used for experimental investigation at a temperature of 150°C. The prepared samples are indicated in Appendix 5.

Following the ASTM 1599 test procedure, the Marshall stability test was conducted on all specimens made up of different percentages of bitumen, plastic waste, and waste engine oil. The Marshall stability test is based on the principle that bituminous mixture formed into cylindrical specimens resist plastic flow when loaded on the lateral surface. Marshall stability is the capacity of the mix at $60^{o}$C to carry a load. This parameter is given in kg. The total weight of the mix should be 1200g. Readings for all samples were then recorded and comparisons made. The data obtained on the various parameters were analysed graphically with the aim of making comparisons for the mixes with different composition of binders. The data was compared to the standard required of the mixes. The following parameters were determined from the Marshall Stability test:

i. Bulk specific gravity of compacted mix (Gmb)
ii. Percent air voids in compacted mix (VIM) (%)
iii. Voids in mineral aggregate (VMA) (%)
iv. Percent voids filled with bitumen (VFB) (%)
v. Stability (N)
vi. Flow (mm)

**Procedure for Analysis of Volumetric properties:**

The purpose of mix design was to determine volume of bitumen binder and aggregates required to produce a mix design that possesses the desirable properties. Weight measurements were taken and converted to volume by use of specific gravities.

Properties that were considered include theoretical maximum specific gravity, bulk specific gravity of the mix, percentage air voids, percentage volume of bitumen, percentage void in mineral aggregate and percentage voids filled with bitumen.

The bulk specific gravity, $G_{sb}$, is the bulk specific gravity for total aggregates and is given by:

$$G_{sb} = \frac{P_1 + P_{2+}P_3}{P_1/G_1 + P_2/G_2 + P_3/G_3}$$

Where: $P_1$, $P_2$, $P_3$- The individual percentages by weight of aggregates.

$G_1$, $G_2$, $G_3$- Individual bulk specific gravity of aggregates.

Theoretical maximum specific gravity, $G_{mm}$ was calculated as per ASTM D2041-95 as:

$$G_{mm} = \frac{A}{A - C}$$

The bulk specific gravity is the actual specific gravity of the mix $G_{mb}$ while including the air voids and was calculated in accordance with D1188-96 by:

$$G_{mb} = \frac{A}{B - C}$$

Where; A- Mass of specimen in air (g)

B- Mass of surface dry specimen after immersion (g)

C- Weight of specimen in water

The effective specific gravity of aggregate, $G_{se}$ is given by;

$$G_{se} = \frac{100 - P_b}{100/G_{mm} - P_b/G_b}$$

Where: $P_b$- Bitumen content as percentage of total weight.

$G_{mm}$- Maximum specific gravity of mixed material

$G_b$- Specific gravity of bitumen

The bulk specific gravity is determined by measuring the volume of the mix and its weight. Displacement method is used in determining the volume of the sample. The sample is placed in water and the amount of water it displaces is quantified. The sample is covered in a thin film of paraffin to prevent the sample from absorbing water. The volume of paraffin used to coat the surface of the sample is known, therefore, it is subtracted from the volume of water dispersed. Bitumen binder coats the aggregate particles resulting in some of the binder being absorbed by the aggregates. The aggregates are also surrounded by a film of binder (which had not been absorbed by the aggregates). HMA is made up of four general components which include air, the bitumen which has not been absorbed by the aggregate (effective bitumen), absorbed bitumen, and aggregate. These components are shown in Figure 11 below.

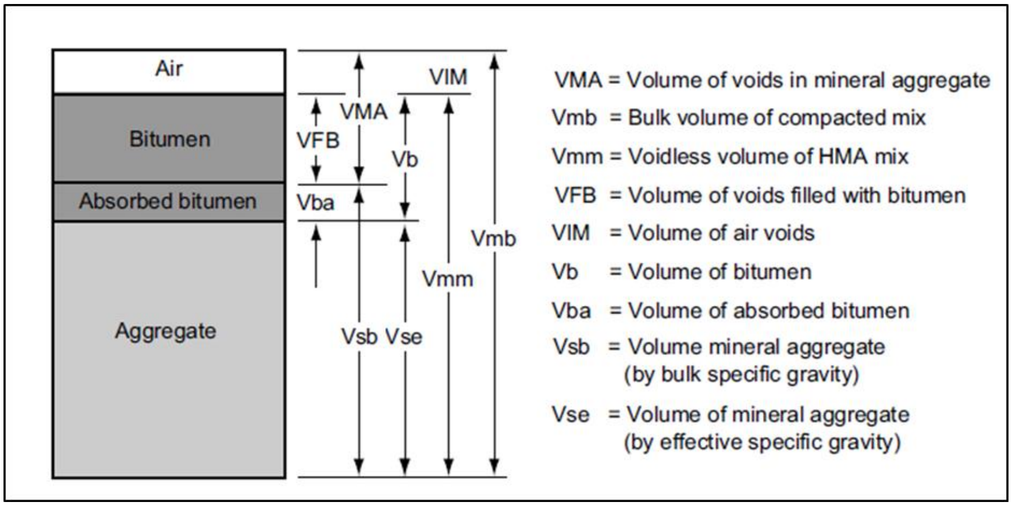


*Figure 2: Phase diagram of the bituminous mix (Transport Research Laboratory 2002)*

The bitumen absorption, $P_{ba}$, refers to the volume of binder which has been absorbed into the aggregate's pore structure and is expressed as a percentage of the aggregate weight. It is given by:

$$P_{ba} = \frac{100(G_{se} - G_{sb})G_b}{G_{se}G_{sb}}$$

The effective bitumen content, $P_{be}$ refers to the total bitumen content in a mix minus the bitumen binder absorbed by the aggregate and is determined as;

$$P_{be} = P_b - \frac{P_{ba}P_s}{100}$$

Where; $P_b$-Bitumen content by percent of total weight of mix.

$P_{ba}$-Absorbed bitumen.

$P_s$- Aggregate content percent by total weight of mix.

The percent air voids in compacted mix VIM refers to total volume occupied by air pockets in between the aggregates coated with bitumen throughout the compacted mix. It is expressed as a percentage of the bulk volume of the mix. It is obtained in accordance with the D3203-94 test method where:

$$VIM = \frac{(G_{mm} - G_{mb})}{G_{mm}} * 100$$

VMA refers to the total volume of voids in the aggregate mix that are not filled with bitumen. It is determined as:

$$VMA = 100 - [\frac{(G_{mb} * P_s)}{G_{sb}}]$$

Where; $G_{mb}$-bulk specific gravity of compacted mix.

$P_s$ is the fraction of aggregates present by total weight of mix.

$G_{sb}$ is the bulk specific gravity of mixed aggregates

VFB is the voids filled with the binder representing the volume of effective bitumen content. It is inversely proportional to the air voids present and is expressed as:

$$VFB = [\frac{(VMA - VA)}{VMA}] * 100$$

Table 3.1 shows the recommended values for the design parameters for bituminous pavements (American Society for Testing and Materials, 1988).

*Table 3.1: Design criteria for bituminous pavements*

| **Design Parameter** | **Design Criteria** |
|---|---|
| Percent air voids (VA) | 3%-5% |
| Percent voids in mineral aggregate (VMA) | Min. 17 |
| Stability value | Min. 6200N |
| Flow value | 2-4mm |
| Retained stability | Min. 70% |
| Drain down at production temp. | Max. 0.3% |

# CHAPTER FOUR

# 4.0 Results, Data Analysis, and Discussion

## 4.1 Tests on Bitumen

The tests that were done to evaluate the properties of the binder included the ring-and-ball softening point and the penetration test. These tests were done in accordance to the AASHTO procedures. The results are presented as shown on Table 4.1.

*Table 4.1: Results of tests on bitumen*

| | |
|---|---|
| Penetration at $25^0$C, 100g, 5s *(ASTM D5 Test)* | 64 |
| Softening Point, ring-and-ball *(ASTM D36 Test)* | $55.0^0$C |
| Specific gravity at $25^0$C *(AASHTO Test T228)* | 1.01 |

Based on the results, the bitumen was classified as being of penetration grade 60/70. Bitumen with penetration grade 60/70 is recommended for flexible pavements in countries with hot climate.

## 4.2 Tests on Aggregates

The physical properties which were determined by the aggregate gradation as well as mechanical properties which included durability, toughness, and hardness of aggregate which greatly impact the properties of the mix. The compacted specimen would be 63.5 ± 1.27 mm high. The amount of aggregate required for each specimen for the Marshall test was confirmed through a trial sample. 1.2kg of blended aggregate was determined as the quantity of aggregate at the estimated optimum bitumen content.

### *4.2.1 Coarse Aggregate*

Crushed gravel was used as coarse aggregate for this study; passing through 25mm sieve but retained on No. 8 sieve. The gradation and quality of coarse aggregate determines the characteristics of bituminous mixes. The characteristics of coarse aggregate used determine the value of Marshall

Stability of the bituminous mix. Therefore, it is crucial to select an appropriate coarse aggregate of desired gradation as shown in Figure 4.1. It was also essential to ensure that the aggregate was clean, tough, and durable free from vegetable matter, soft particle, and other objectionable matter. The maximum size of coarse aggregate that was used in the mix is 14mm. Specific gravity test was performed using the AASHTO T85 procedure and was found to be 2.55.

### *4.2.2 Fine Aggregate*

Aggregate passing sieve #8 and retained #200 was the fine aggregate used in the test procedure. It consisted of natural sand and stone screenings. It was ensured that the fine aggregate was composed of angular, rough surfaced, hard durable particles, clean, and angular, free from clay balls, soft particles, vegetable matter, or other objectionable matter. The specific gravity of the fine aggregate as determined using the AASHTO T84 was found to be 2.60.

### *4.2.3 Mineral Filler*

In addition to the quality of the aggregates and binder, the properties of the filler are also key in the properties of the bituminous mix. Mineral filler used for this test was Portland cement which passes #200 sieve. Portland cement was selected due to its binding properties. 100g of filler was added to the aggregate mix. It was ensured that the filler was non-plastic and free from foreign and other objectionable material. Factors such as specific gravity of the filler, micro-coarseness, the grading and shape of the grains, and the amount and mineral composition influence the characteristics of bituminous mixes. The specific gravity of mineral filler as determined using the AASHTO T100 procedure was found to be 3.12.

### *4.2.4 Mechanical Properties of Aggregates*

The mechanical properties of the aggregate such as strength, toughness, hardness, water absorption, were investigated to ensure that they were within the specifications as stated by the Kenya Road Design Manual. The results were found to be within the allowable limits of bituminous concrete mix. Table 4.2 shows the results of tests on aggregate.

*Table 4.2: Results of tests on aggregate*

| **Type of Test** | **Result** | **Specification (Maximum allowable %)** |
|---|---|---|
| Los Angeles Abrasion *(ASTM C131)* | 17.2% | 35% |
| Aggregate Crushing Value *(BS812 Part3)* | 17.98% | 28% |
| Aggregate Impact Value *(BS812 Part3)* | 6.95% | 30% |
| Water Absorption Test *(ASTM C127)* | 1.87% | 2% |

### *4.2.5 Aggregate Gradation*

To produce durable and stable mixes, it was important to use well-graded aggregates which are responsible for producing dense mixes. Also, well graded mixes require minimum bitumen content. The aggregate gradation used for this research for testing both neat and modified samples was as shown in Appendix 6. Figure 4.1 shows the grading curve (highlighted in red and orange) fell within the grading envelope (highlighted in green).

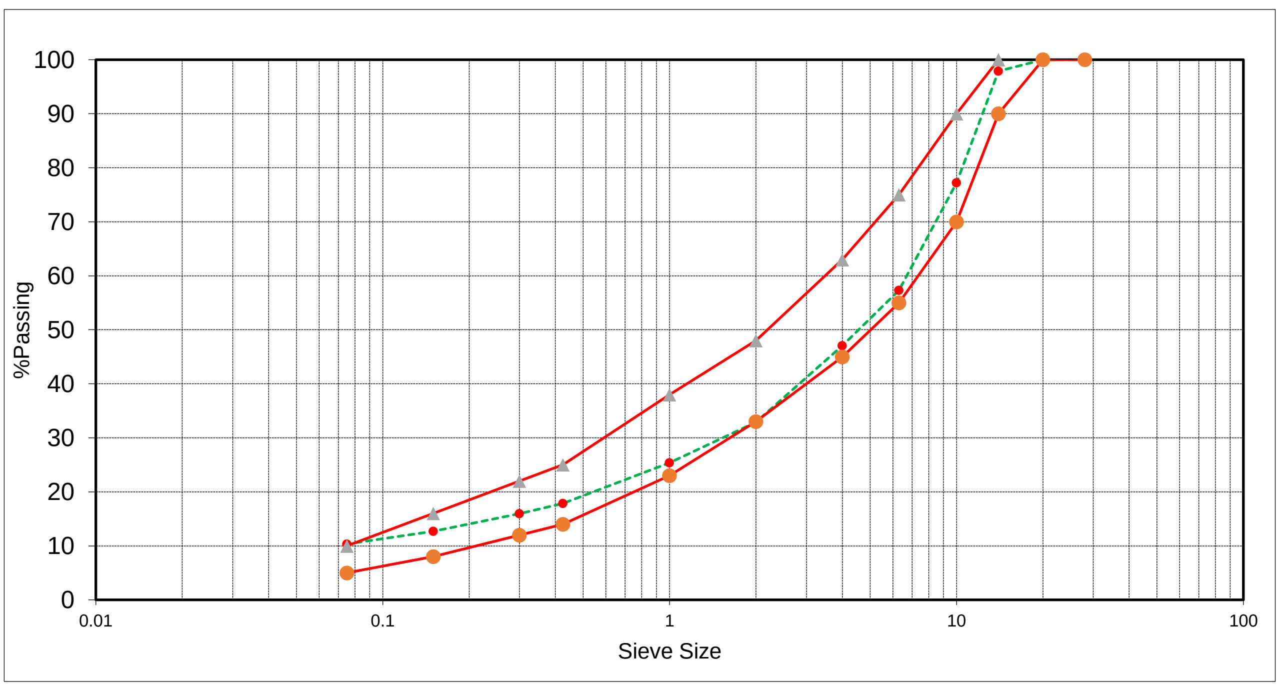



*Figure 4.1: Aggregate grading used in the mix design and design specifications*

## 4.3 Marshall Test

### *4.3.1 Tests on neat samples*

Marshall Stability and flow tests together with volumetric tests were carried out to determine the optimum bitumen content (OBC) and optimum modifier content (OMC) of the bituminous concrete mix. The bituminous concrete specimens were prepared with 4%, 5%, 6%, 7% and 8% of bitumen by weight of aggregates as per the ASTM 1599 test procedure. Two specimens were prepared for each batch and an average of values was used for analysis. The summary of the test results for the neat samples was as shown on Table 4.4.

*Table 4.4: Test Results for Neat Samples*

| %Bitumen Content | Bulk Specific gravity of Compacted mix (Gmb) | Maximum Specific gravity of mixed material (Gmm) | Percent air voids in compacted mix (VIM) (%) | Voids in Mineral Aggregate (VMA) (%) | Percent voids filled with Bitumen (VFB) (%) | Stability (N) | Flow (mm) |
|---|---|---|---|---|---|---|---|
| 4 | 2.110 | 2.248 | 6.1466 | 19.268 | 65.670 | 7090.67 | 2.624 |
| 5 | 2.224 | 2.345 | 5.1556 | 17.615 | 67.441 | 9455.96 | 2.753 |
| 6 | 2.350 | 2.451 | 4.1384 | 16.071 | 69.705 | 8337.44 | 2.870 |
| 7 | 2.255 | 2.356 | 4.2739 | 17.015 | 72.933 | 6931.86 | 2.716 |
| 8 | 2.126 | 2.208 | 3.7213 | 19.654 | 76.026 | 6149.57 | 2.508 |

### *4.3.2 Test Results for Samples modified with Plastic Waste*

Knowing the optimum bitumen content to use with the specified aggregate gradation, the Marshall flow and volumetric tests were performed on specimens whose bitumen content had partially been replaced by plastic. The bitumen content as a percentage of the mass of aggregates was replaced with 10%, 20%, 30% and 40% of plastic to determine optimum plastic percentage. The test results are summarized in Table 4.5.

*Table 4.5: Test Results for Polymer-Modified Samples*

| **%Plastic Content** | **Bulk Specific gravity of Compacted mix (Gmb)** | **Maximum Specific gravity of mixed material (Gmm)** | **Percent air voids in compacted mix (VIM) (%)** | **Voids in Mineral Aggregate (VMA) (%)** | **Percent voids filled with Bitumen (VFB) (%)** | **Stability (N)** | **Flow (mm)** |
|---|---|---|---|---|---|---|---|
| 0 | 2.35 | 2.451 | 4.14 | 16.1 | 69.71 | 8337.4 | 2.87 |
| 10 | 2.2200 | 2.304 | 3.6614 | 25.5739 | 85.7278 | 8449.2090 | 2.5019 |
| 20 | 2.1562 | 2.235 | 3.5392 | 25.5385 | 85.7340 | 8573.2435 | 2.0765 |
| 30 | 2.1265 | 2.199 | 3.3166 | 25.3549 | 86.9206 | 8213.5800 | 2.0638 |
| 40 | 2.1260 | 2.195 | 3.1501 | 25.0343 | 87.5837 | 8107.7315 | 2.0193 |

### *4.3.3 Test Results for Samples modified with Plastic Waste and Waste Engine Oil*

Knowing the optimum bitumen and plastic contents to use with the specified aggregate gradation, the Marshall flow and volumetric tests were performed on specimens whose bitumen and plastic contents had partially been replaced by waste engine oil. The bitumen and plastic content as a percentage of the mass of aggregates was replaced with 10%, 20%, 30% and 40% of waste engine oil to determine optimum WEO percentage. The test results are summarized as below:

*Table 4.6: Test Results for Samples Modified with Plastic Waste and WEO*

| **%WEO Content** | **Bulk Specific gravity of Compacted mix (Gmb)** | **Maximum Specific gravity of mixed material (Gmm)** | **Percent air voids in compacted mix (VIM) (%)** | **Voids in Mineral Aggregate (VMA) (%)** | **Percent voids filled with Bitumen (VFB) (%)** | **Stability (N)** | **Flow (mm)** |
|---|---|---|---|---|---|---|---|
| 0 | 2.1562 | 2.235 | 3.5392 | 25.5385 | 85.7340 | 8573.2435 | 2.0765 |
| 10 | 2.0369 | 2.103 | 3.1301 | 23.3797 | 88.0425 | 8688.3216 | 2.5019 |
| 20 | 1.9783 | 2.040 | 3.0257 | 23.3473 | 88.0488 | 8815.8663 | 2.8699 |
| 30 | 1.9511 | 2.008 | 2.8354 | 23.1795 | 89.2675 | 8446.0243 | 2.8524 |
| 40 | 1.9506 | 2.005 | 2.6930 | 22.8864 | 89.9485 | 8337.1803 | 2.7909 |

#### *4.3.3 Analysis of Neat Samples*

#### *4.3.3.1 Bulk Density of the Mix*

As shown in Figure 4.2, the value of specific gravity increased with increasing bitumen content from 4% up to 6% from where it started decreasing up to 8%. Therefore, based on the specific gravity of the mix, the optimum bitumen content is 6%.

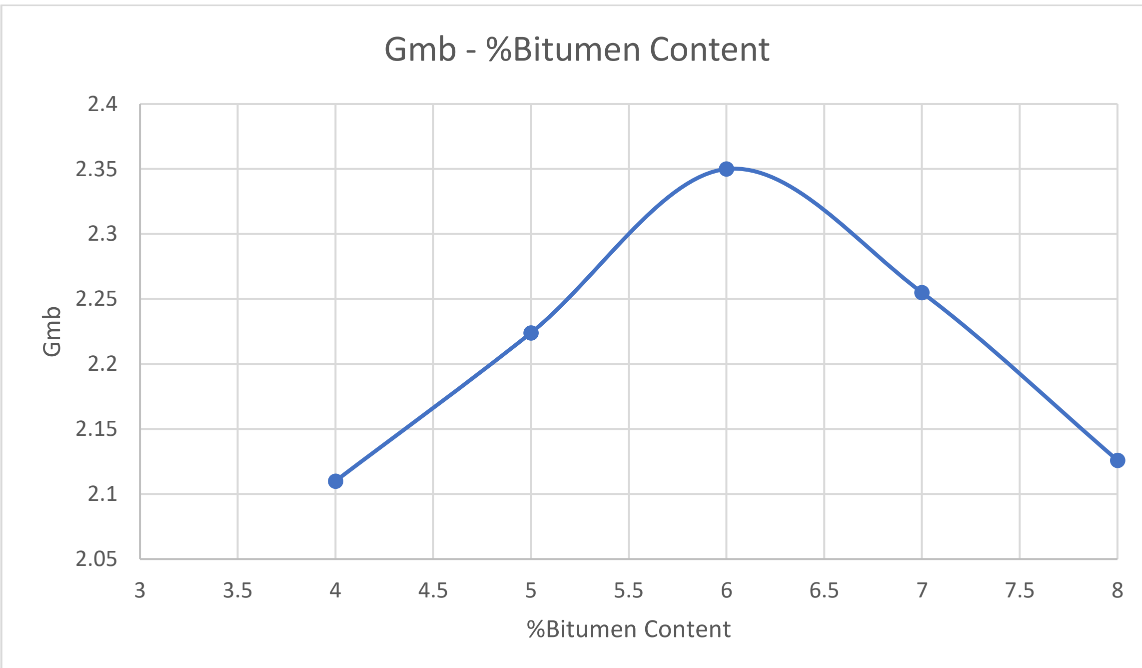



*Figure 4.2: Bulk Density against %Bitumen content*

#### *4.3.3.2 Voids in Mineral Aggregates (VMA)*

As shown in Figure 4.3, the value of percentage voids in mineral aggregates decreased with increasing bitumen content from 4% to 6% from where it increased up to 8%.

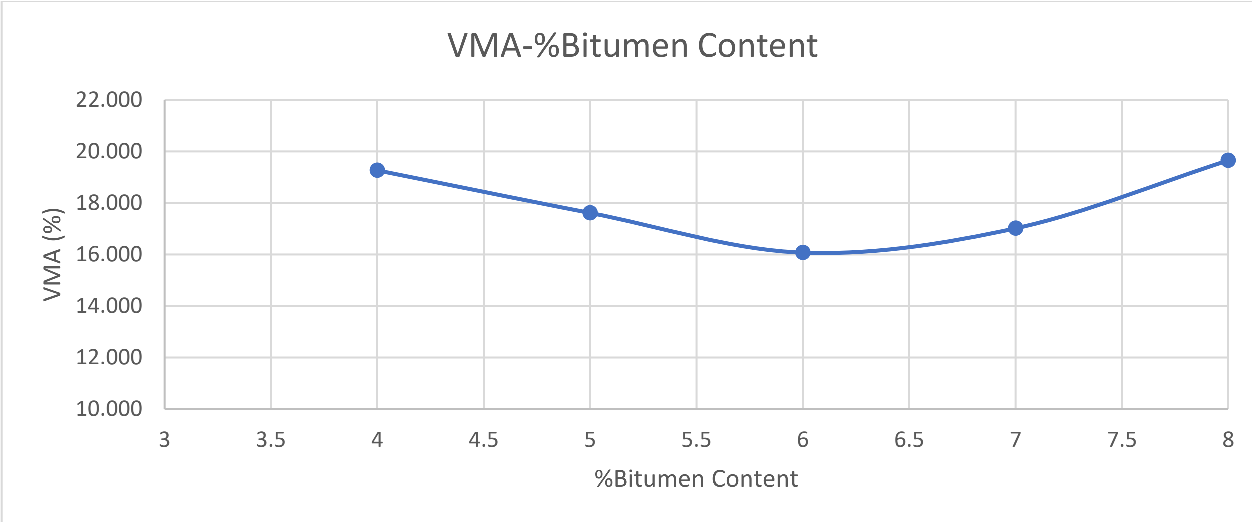



*Figure 4.3: VMA against %Bitumen content*

***4.3.3.3 Voids filled with Bitumen (VFB)***

As shown in Figure 4.4, the percentage of voids filled with bitumen increased with increasing bitumen content which good for the durability of the pavement but also it should be within the specified range of 65-78% to avoid bleeding when there is rise in temperature.

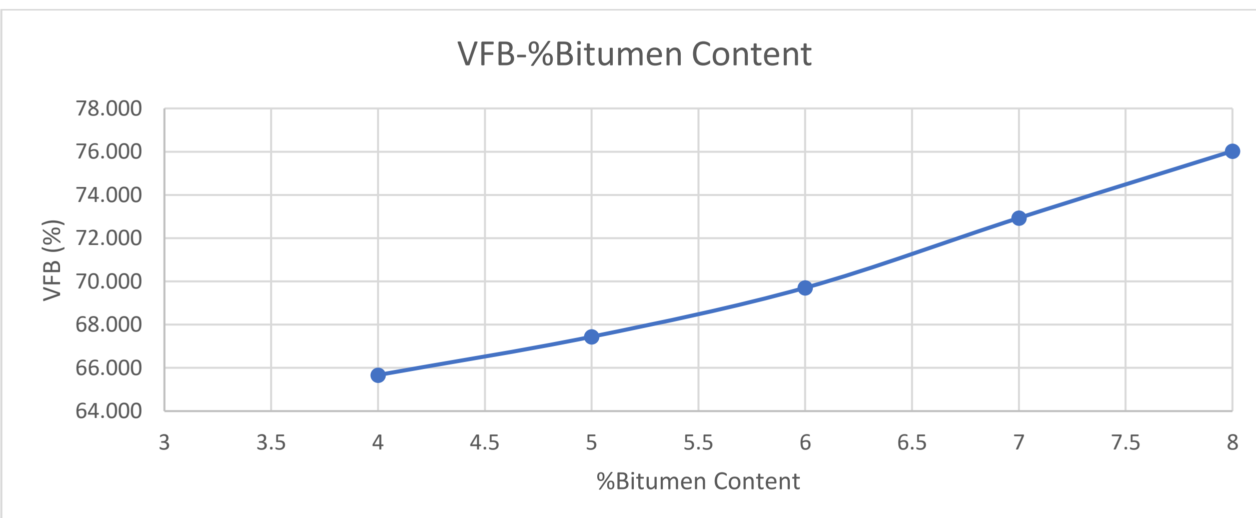



*Figure 4.4: VFB against %Bitumen content*

***4.3.3.4 Percent Air Voids in Compacted Mix (VIM)***

Figure 4.5 shows the value for VIM against percentage Bitumen content.

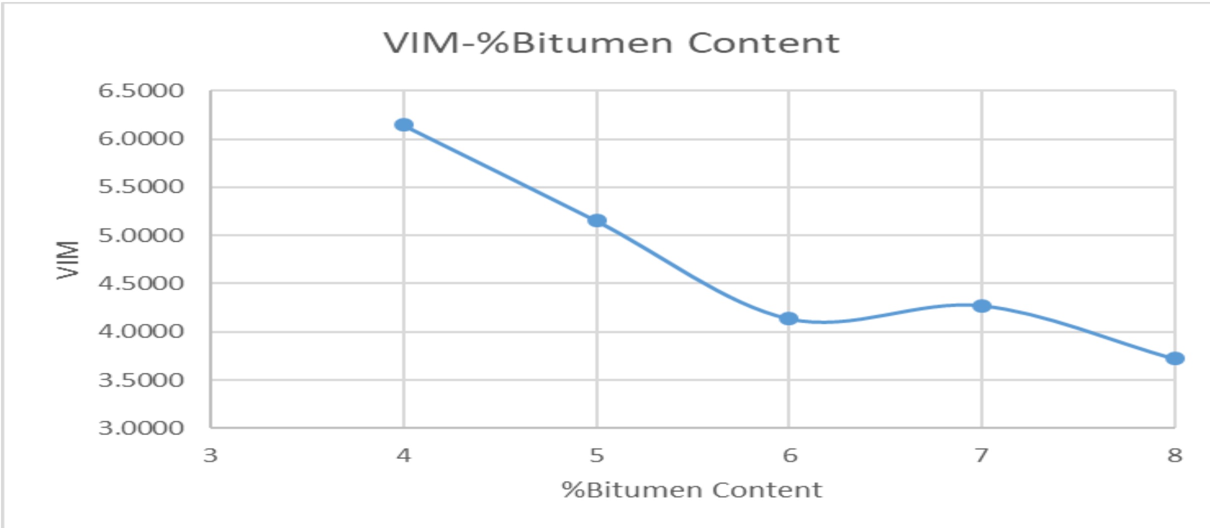



*Figure 4.5: VIM against %Bitumen content*

#### *4.3.3.5 Flow*

Figure 4.6 shows the values of flow against the percentage bitumen content. The value of flow was at a maximum at 6% bitumen content.

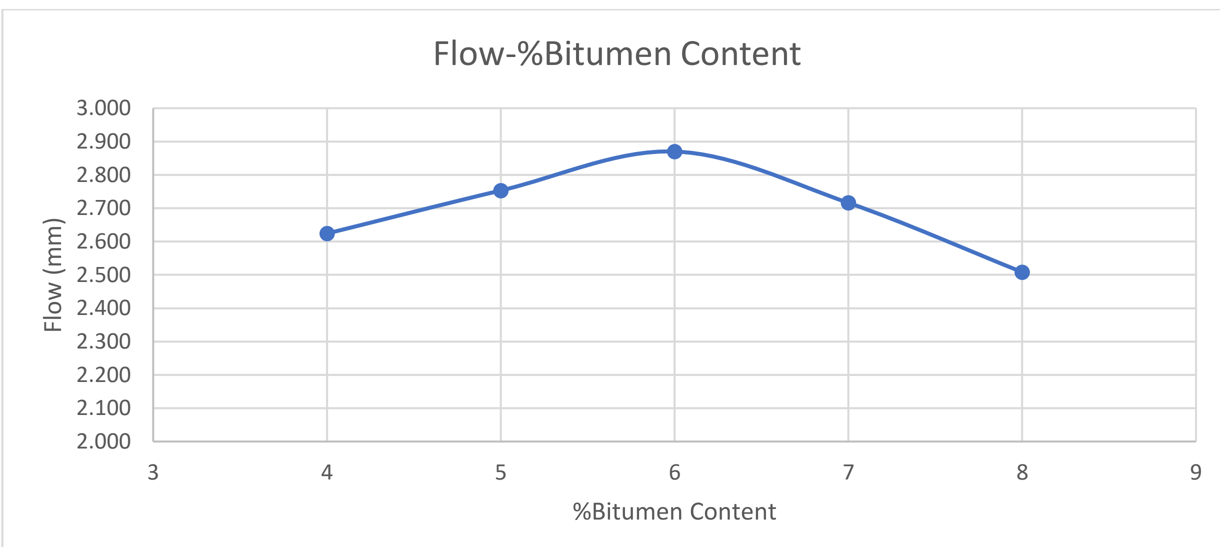



*Figure 4.6: Flow against %Bitumen content*

#### *4.3.3.6 Stability*

Figure 4.7 shows the values of stability against the percentage bitumen content. The value of stability reached a maximum of 9500N at 5% which is then used to determine the optimum bitumen content.

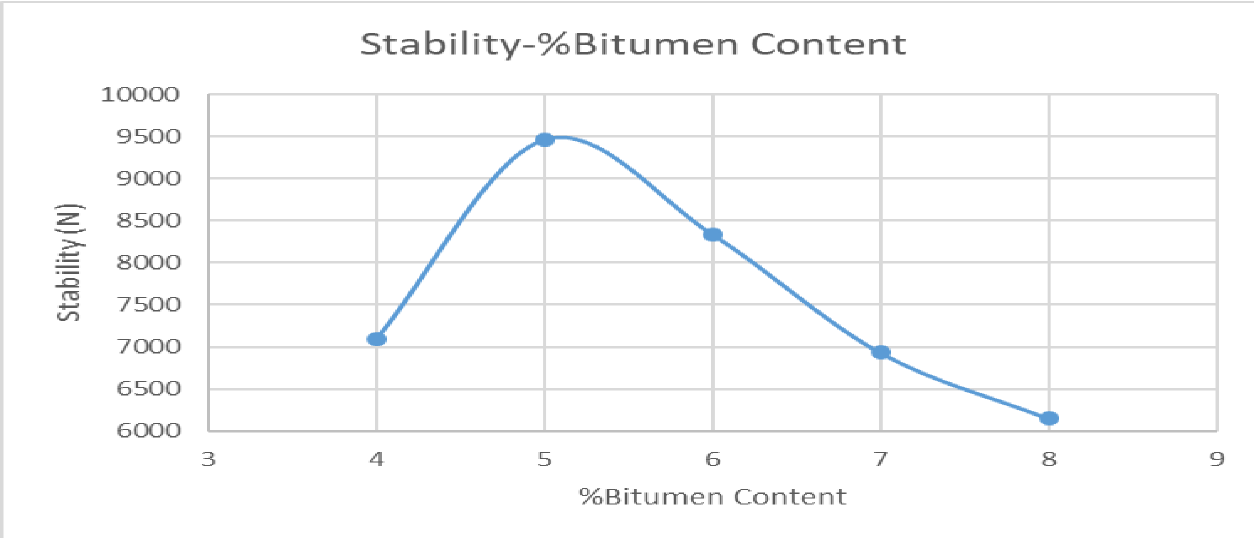



*Figure 4.7: Stability against %Bitumen content*

#### *4.3.4 Optimum Bitumen Content*

The optimum bitumen content was obtained as an average of the percentage of bitumen content from the respective plots displaying the following characteristics:

1. Maximum unit weight- 6%
2. Maximum stability- 5%
3. Percent air voids in compacted mixture using the mean of limits (4%) - 6%

The optimum bitumen content was determined as 6%. This is the bitumen content that was then used in preparing the polymer-modified bituminous mix. The properties of the paving mixture containing the optimum bitumen content in comparison with the requirements as set out by AASHTO were as shown in Table 4.7.

*Table 4.7: Test Aggregate Properties and Specifications (Source: Asphalt Institute, 2014)*

| Mix Properties | 6% Bitumen Content | Mix criteria |
|---|---|---|
| VIM | 4.14% | 3-5% |
| VMA | 16.1% | 13% min. |
| VFB | 69.71% | 65-78% |
| Stability (N) | 8337.4 | 7000 min. |
| Flow (mm) | 2.87 | 2-4 |

#### *4.3.5 Analysis of Polymer-Modified Bituminous Mix Samples*

##### *4.3.5.1 Bulk Density*

Bulk density is calculated as the dry weight of sample divided by its volume expressed in g/cm$^3$. The volume includes that of particles and pores in the sample. Properties of the samples such as voids in mineral aggregate, voids in mix and voids filled with bitumen are calculated through the value of bulk density. The density of compacted mixes decreased with the increase of waste plastic content in bitumen. The reduction in density of the compacted mixes can be attributed to the fact that the specific gravity of pure bitumen is slightly higher than that of bitumen blended with plastic waste. Figure 4.8 shows the bulk density of the mixes against plastic content.

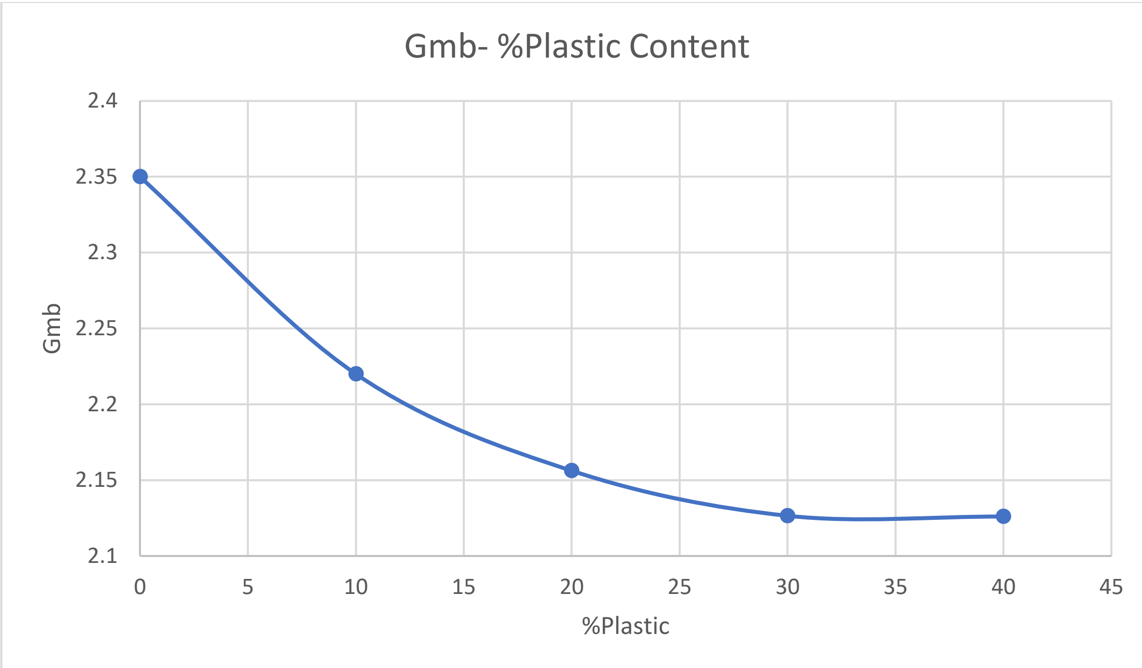



*Figure 4.8: Bulk Density against %Plastic content*

#### *4.3.5.2 Voids in Mineral Aggregates (VMA)*

Insufficient VMA results in lack of capacity to add adequate asphalt binder to coat the individual aggregate particles in the mixture while excessive of it causes instability. As per the results in Figure 4.9, of the VMA analysis, the VMA value increased with the inclusion of waste plastic content. The minimum value of VMA as specified in Road Note 19 is 13% while that which was achieved at 5.5% plastic content was 23%, an increase from 13% for neat sample.

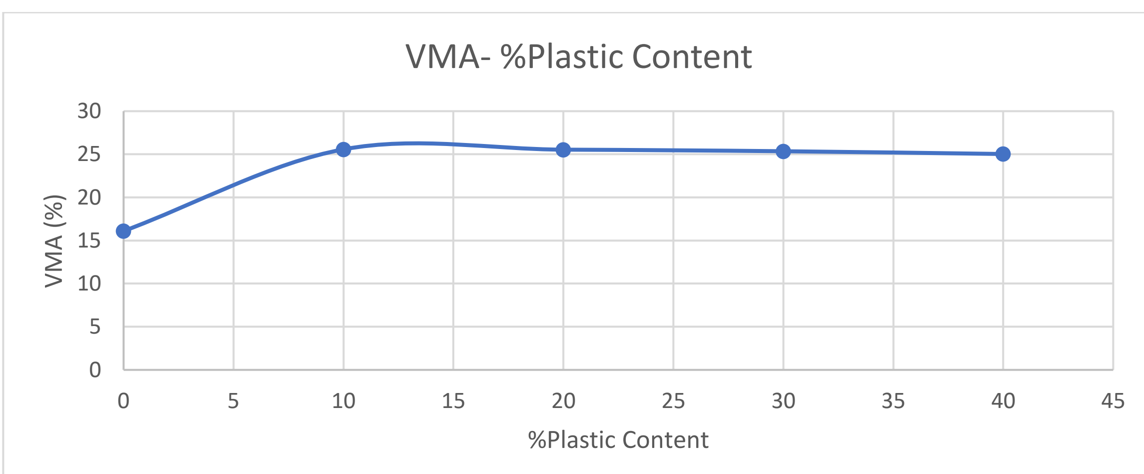



*Figure 4.9: VMA against %Plastic content*

#### *4.3.5.3 Voids Filled with Bitumen (VFB)*

The voids filled with bitumen increased with the addition of waste plastic. The objective of the VFB analysis was to limit maximum levels of VMA and substantially maximize the levels of binder content. VFB also restricts the allowable air void content in compacted mixes. However, the percentage of voids filled with bitumen should be limited so as to prevent the possibility of bleeding. The allowable range of values of VFB is 65-75%. As shown in Figure 4.10, at 4.6% plastic content the voids filled with bitumen was 76% while that of the neat sample was 70%. Blending with plastic caused the value of VFB to fell outside the acceptable range.

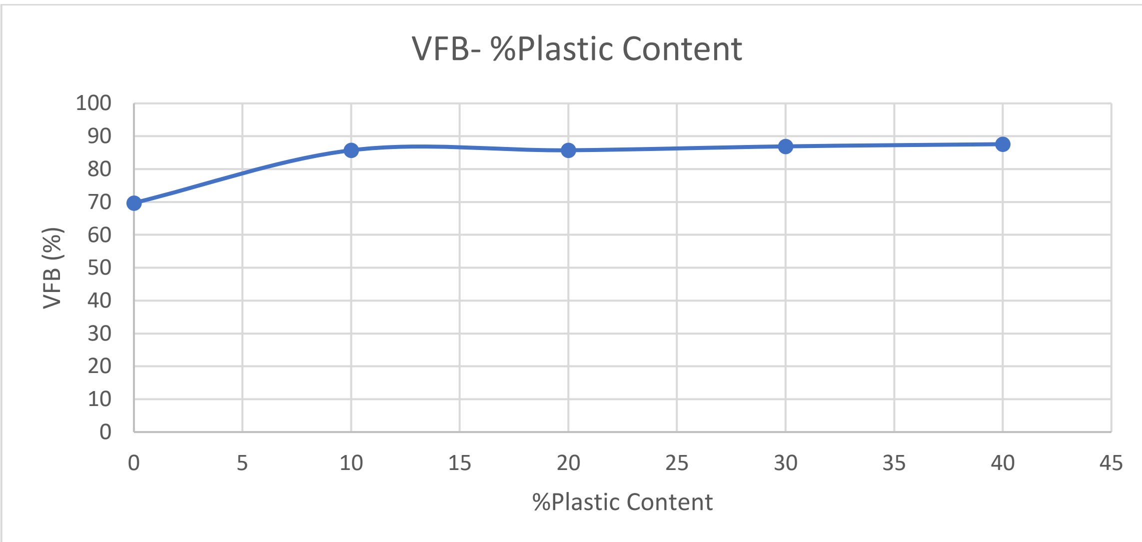



*Figure 4.10: VFB against %Plastic content*

#### *4.3.5.4 Percent Air Voids in Compacted Mix (VIM)*

The percentage air voids in the mix decreased with increasing concentration of polymer in the mixes in an almost linear relation. The percentage of air voids in the bituminous mix is crucial in the design criteria of the mix. The mix requires adequate air voids so that the binder can properly coat the aggregate while at the same time also ensuring the percentage of air voids is not too high to result in bleeding when the pavement mix is exposed to high temperatures. Road Note 19 specifies an acceptable range of 3%-5%. Figure 4.11 highlights VIM against the percentage plastic content.

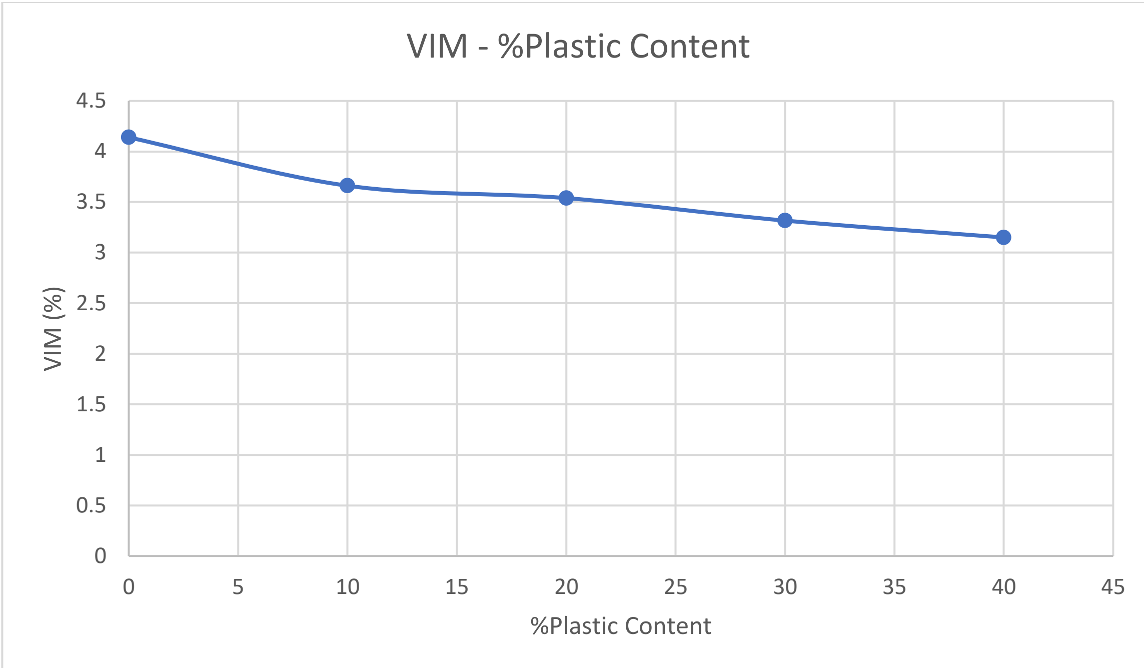



*Figure 4.11: VIM against %Plastic content*

#### *4.3.5.5 Flow*

From the results obtained, as shown in Figure 4.12, the flow value reduced with increasing plastic content. The range of flow specified in Road Note 19 is 2mm-4mm.

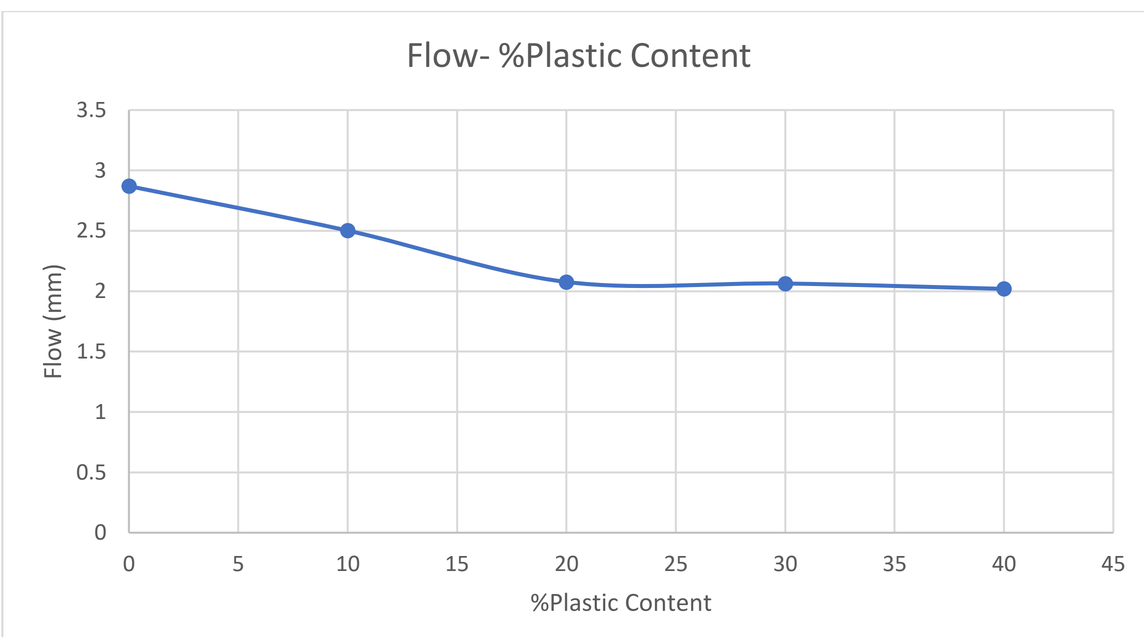



*Figure 4.12: Flow against %Plastic content*

*4.3.5.6 Marshall Stability*

It is seen from the graph in Figure 4.13 that the stability for all mixes increases up to an optimum percent of plastic content from which further increase in the plastic content causes a reduction in the stability value of the mix. A plastic content of 18% gives the highest stability value.

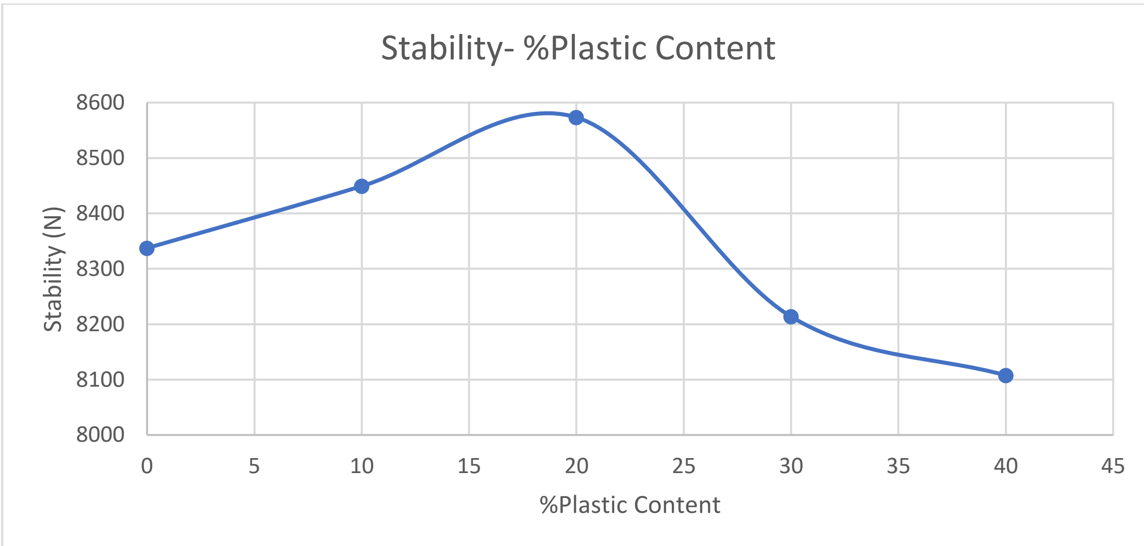



*Figure 4.13: Stability against %Plastic content*

***4.3.6 Optimum Plastic Content***

The optimum plastic content was to be determined from the average of:

- Point of maximum stability- 18%
- Point of 80% voids filled with bitumen- 6%
- Point of 4% air voids in total mix- 3%

Based on the value of stability alone, an optimum plastic content of 18% was selected for use.

***4.3.7 Analysis of Bituminous Mix Samples Modified with Plastic Waste and Waste Engine Oil***

***4.3.7.1 Bulk Density***

Bulk density is calculated as the dry weight of sample divided by its volume expressed in g/cm$^3$. The volume includes that of particles and pores in the sample. Properties of the samples such as voids in mineral aggregate, voids in mix and voids filled with bitumen are calculated through the value of bulk density. As indicated in Figure 4.14, the density of compacted mixes decreased with the increase of waste engine oil in polymer-modified bitumen. The reduction in density of the compacted mixes can be attributed to the fact that the specific gravity of pure bitumen and plastic is slightly higher than that of waste engine oil.

This may happen since the specific gravity of WEO blended with polymer-modified bitumen is slightly less than that of pure bitumen and plastic.

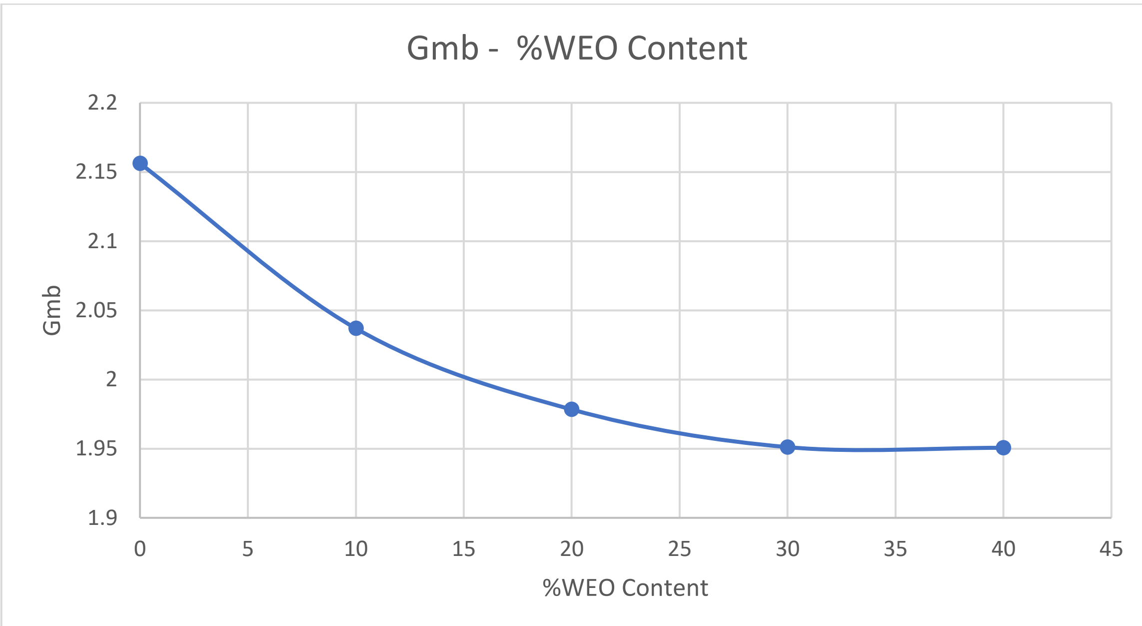



*Figure 4.14: Bulk Density against %WEO content*

#### *4.3.7.2 Voids in Mineral Aggregates (VMA)*

Insufficient VMA results in lack of capacity to add adequate asphalt binder to coat the individual aggregate particles in the mixture while excessive of it causes instability. As per the results of the VMA analysis, as shown in Figure 4.15, the VMA value decreased slightly with the inclusion of WEO. The minimum value of VMA as specified in Road Note 19 is 13% while that which was achieved at 6% WEO content was 23.4%, an increase from 16% for neat sample.

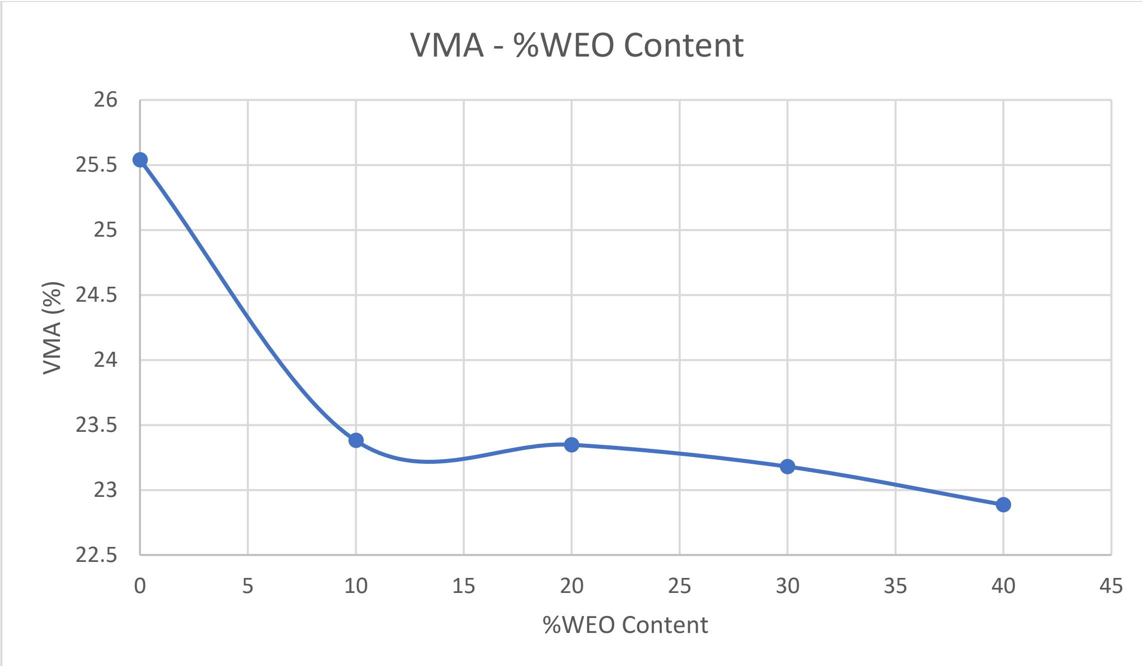



*Figure 4.15: VMA against %WEO content*

#### *4.3.7.3 Voids Filled with Bitumen (VFB)*

The voids filled with bitumen increased with the addition of waste plastic. The objective of the VFB analysis is to limit maximum levels of VMA and substantially maximize the levels of binder content. However, the percentage of voids filled with bitumen should be limited to prevent the possibility of bleeding. The allowable range of values of VFB is 65-75%. At 6% WEO content, as shown in Figure 4.16, the voids filled with bitumen was 87.5% while that of the neat sample was 70%. Blending of the polymer-modified bituminous mix with WEO caused the value of VFB to fall outside the acceptable range.

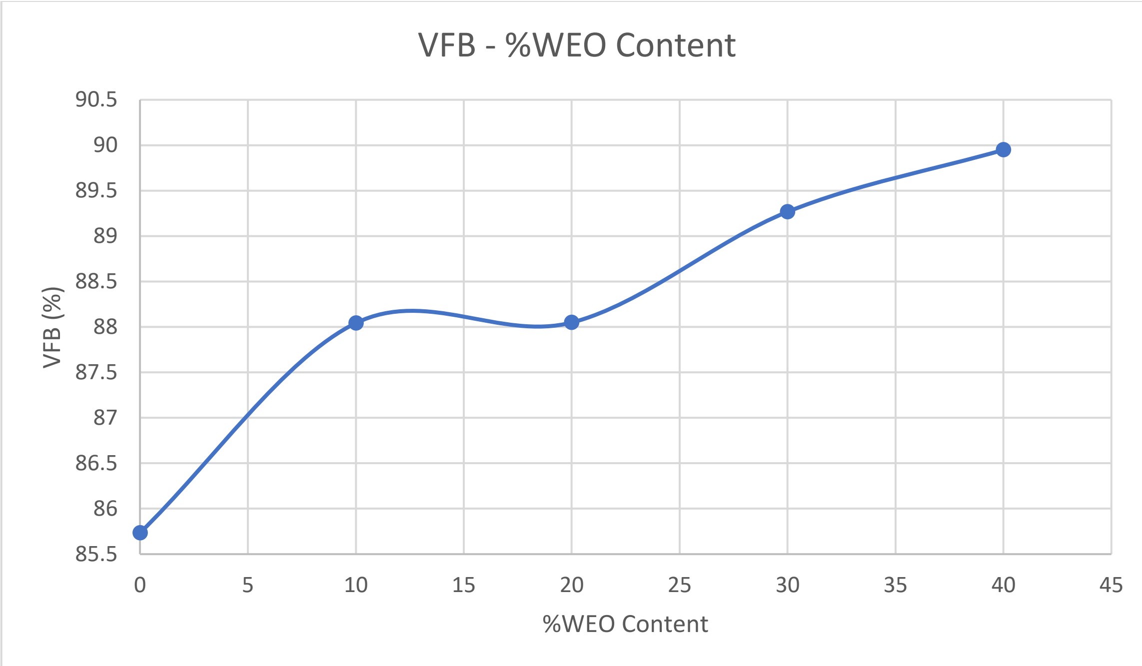



*Figure 4.16: VFB against %WEO content*

#### *4.3.7.4 Percent Air Voids in Compacted Mix (VIM)*

As indicated in Figure 4.17, the percentage air voids in the mix decreased with increasing concentration of WEO in the mixes in an almost linear relation. The percentage of air voids in the bituminous mix is crucial in the design criteria of the mix. The mix requires adequate air voids so that the binder can properly coat the aggregate while at the same time also ensuring the percentage of air voids is not too high to result in bleeding when the pavement mix is exposed to high temperatures. Road Note 19 specifies an acceptable range of 3%-5%.

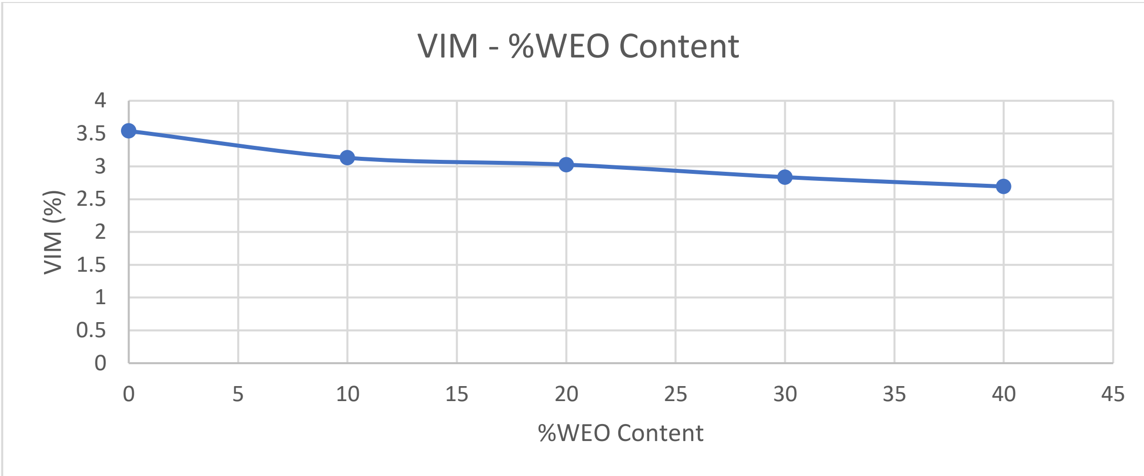



*Figure 4.17: VIM against %WEO content*

#### ***4.3.7.5 Flow***

From the results obtained, shown in Figure 4.18, the flow value increased with increasing WEO content. The flow value of the mix refers to the maximum deformation at which a Marshall specimen fails, therefore, it is a measure of deformation. The higher the flow value, the lower the rigidity. WEO enhances the fluidity of the bitumen binder. The results indicate that the partial replacement of bitumen with WEO increases the workability of the bituminous mix. The range of flow specified in Road Note 19 is 2mm-4mm.

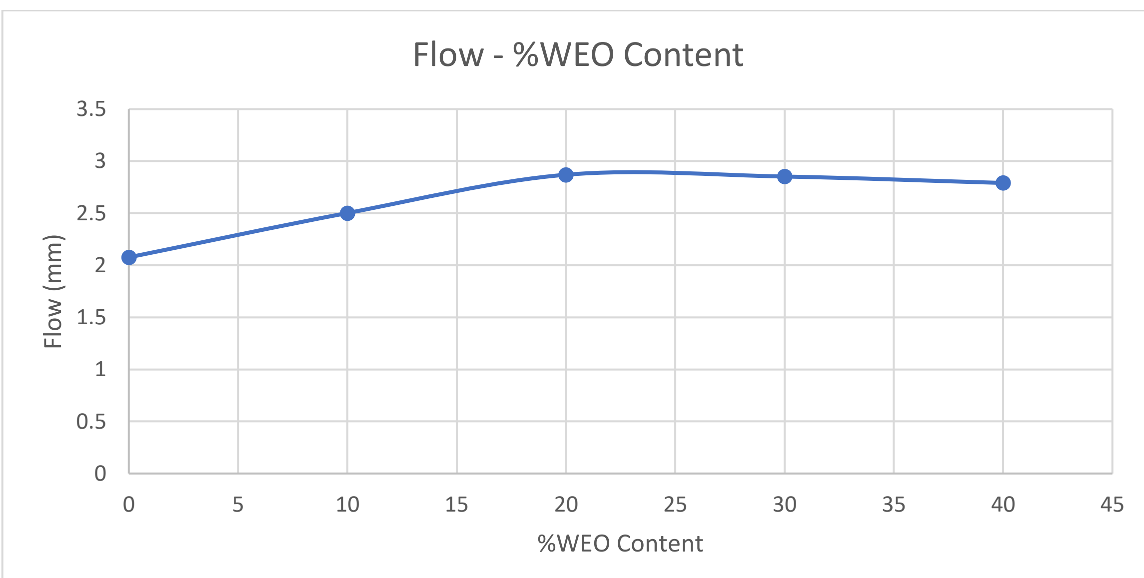



*Figure 4.18: Flow against %WEO content*

#### *4.3.7.6 Marshall Stability*

It is seen from the graph, shown in Figure 4.19, that the stability for all mixes increases up to an optimum percent of WEO content from which further increase in the WEO content causes a reduction in the stability value of the mix. A WEO content of 19% gives the highest stability value.

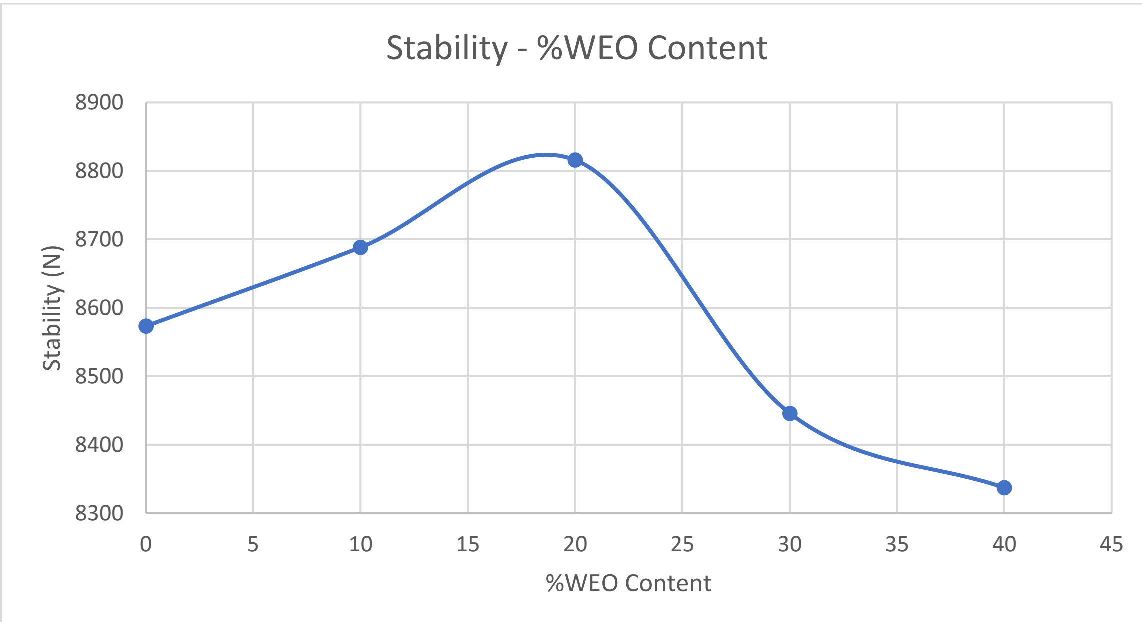



*Figure 4.19: Stability against %WEO content*

**Optimum WEO Content**

The optimum plastic content was to be determined from the average of:

- Point of maximum stability- 19%

Based on the value of stability alone, an optimum WEO content of 19% can be selected for use.

**Discussion**

More studies still need to be conducted to guide the partial replacement of bitumen by waste engine oil and plastic waste to stabilize the bituminous mix. The use of plastic waste as a stability enhancer in mixes in which the bitumen has been partially replaced by waste engine oils and a stabilizer is most beneficial due to its cost benefit ratio and its sustainability for the environment. Waste engine oil also plays a key role in the rejuvenation of the aged bitumen or reclaimed bitumen pavements. The partial replacement of bitumen with plastic wastes and waste engine oil introduces an alternative that is more environment friendly in the pavement industry. For cycle tracks, foot paths, rural roads, and low volume roads whose load carrying capacity can be compromised then the partial replacement of bitumen with plastic waste and waste engine oil will be useful.

For the better performance of roads, recycled plastic with aggregates is used. The coating of the plastic waste on the aggregates reduces the voids. The reduction in air voids for bituminous mixes prevents the absorption of moisture and subsequent oxidation of bitumen by the entrapped air. Therefore, there is reduction in rutting travelling and reduction in pothole formation. There is a slight reduction in the load carrying capacity of pavements constructed with the modified bitumen, from 9500N for the neat sample, to 8580N for the mix modified with plastic, and to 8830N for the mix modified with both plastic and WEO. However, the reduction is not significant and the values for Marshall Stability obtained from the investigation are still within the required standard. The analysis of the results indicate that plastic waste and waste engine oil can be used to partially replace bitumen in pavement construction without significant compromise on the quality of the bituminous mix. Plastic waste and waste engine oil as alternative binders are beneficial without incurring much cost leading hence resulting to efficient, economic, and effective laying of flexible pavements. It ensures the reuse of plastic waste.

The world is currently heading towards the point of peak oil demand which is the point at which oil demand will reach a maximum (Deffeyes, 2006). Thus, there is the need to carefully utilize the available oil resources while at the same time minimize usage of oil where possible. Plastics occurring in various forms as post-consumer products are found to form a majority of the solid wastes in many towns across the world. With the increasing human population, there is also substantial increase in consumption of plastic product worldwide. Legal frameworks have been set up by various governments in a bid to control their usage such as the ban on the importation, use and manufacture of plastic carrier bags in Kenya in 2017 (Kenya Ministry of Environment, 2017). Despite this, it has proven to be impossible to completely ban the use of plastic creating the need to manage wastes.

Plastic wastes not only reduce the aesthetics of the environment where they occur, but also cause environmental degradation since they are not biodegradable reducing soil quality. They also cause blockage of sewerage and water drainage systems which results to flooding during the raining season. Plastic wastes lying in the environment could also lead to death of animals after consuming them. Efforts are, therefore, being made to reduce the number of plastic wastes lying around in the environment through methods such as incineration and land-filling. Incineration has proven to have adverse environmental impacts due to air pollution while land-filling compromises on the aesthetics of the dumpsite. This has led to coming up of innovative ways of reusing and recycling plastic wastes. These include reprocessing the waste materials into more useful products or combining with other materials to form new products thereby reducing the quantities of raw materials required in forming the product. Globally, there has been increasing awareness on environmental health and safety, therefore, more consideration is being given on reusing and recycling a wide variety of waste materials including plastic wastes and waste engine oil (A. Veeraragaran, 2006). One of the innovative ways of recycling post-consumer plastics that has begun being implemented in various countries in the world e.g., India, is the incorporation of plastic wastes into the making of asphalt concrete during road construction (A.J, 2013). In the process, aggregate is coated with recycled plastic waste before being mixed with bitumen then laying on the road surface. Experimental results have shown that this improves the mechanical properties of the pavement and provides better binding properties, density and better in waterproofing. In the long run, the process greatly reduces the amount of bitumen required lowering the cost of road construction.

The main advantage of partially replacing bitumen with plastic waste and WEO in asphalt mixes is the reduction in cost of production of asphalt pavements. However, according to the results obtained in the current study, there is a slight reduction in the stability of pavements but still within the required standard. The environmental benefit of incorporating these waste materials in asphalt mix production is that the amount of plastic waste going into landfills is reduced. Plastic roads are an effective solution to reduce road construction and maintenance carbon footprint. The use of plastic waste in the construction of flexible roads contributes to the conservation of fossil fuels, as well as to the decrease of carbon dioxide emissions.

However, apart from the slight reduction in stability of the pavements, another potential impact of plastic roads is the potential for plastic micro-particles to enter the food chain. Vehicles on the road cause wear and tear which would create micro-particles of plastic on roads. These particles find their way into the air and water where they can be ingested by animals and eventually make their way into the food chain. This can have serious health implications for people and also a negative impact on the environment. Another disadvantage of plastic roads is that, they are non-biodegradable hence could take years to break down. This means plastic roads could be a potential source of long-term pollution. The lifespan of plastic roads may be extended through careful maintenance, however, over time they will eventually have to be recycled.

# CHAPTER FIVE

# 5.0 Conclusions and Recommendations

## 5.1 Conclusions

The main objective of the research was to investigate the use of plastic waste and waste engine oil as partial replacements of bitumen in the making of asphalt concrete. Based on the tests performed and their analysis, the following conclusions were reached:

i. From the Marshall Stability tests of the neat samples, it was determined that the Optimum Bitumen Content for the mix was 6%. This percentage provided a guide to how much binder replacement should be done

ii. From the Marshall Stability tests carried out on the modified mixes, it was found that the stability of the mix increased with increasing plastic content up to a plastic content of 18% as the mass of bitumen used from where the stability started decreasing. 18% plastic content could be taken as the optimum plastic content for use in making of the modified mix based on stability alone. Optimum replacement of Waste Engine Oil was determined at 19%; also, with an increased stability of the mix. The increase in stability is an added advantage together with reducing the amount of bitumen used in road construction

iii. The properties of asphalt mixes of modified and neat bitumen varied. The VMA varied from 6% for the neat sample, to 26% for the mix modified with plastic, and to 23.4% for the mix modified with both plastic and WEO. The VFB varied from 70% for the neat sample, to 88% for the mix modified with plastic, and to 88% for the mix modified with both plastic and WEO. The VIM varied from 3% for the neat sample, to 3.5% for the mix modified with plastic, and to 3% for the mix modified with both plastic and WEO. The Flow varied from 2.2% for the neat sample, to 2.1% for the mix modified with plastic, and to 2.8% for the mix modified with both plastic and WEO. The Marshall Stability varied from 9500N for the neat sample, to 8580N for the mix modified with plastic, and to 8830N for the mix modified with both plastic and WEO

## 5.2 Recommendations

With the research showing that plastic waste and waste engine oil could be used as partial replacements of bitumen in road construction, the following recommendations are made so as to promote the technology in Kenya:

i. Further studies should be done on the use and performance of plastic waste and waste engine oil in the blend of bituminous mixes to develop standard procedures for application of the practice. Also, economic feasibility studies should be done to ensure that an economic benefit is realized once the technique is applied in road construction
ii. Based on the test results, Marshall test is suitable for testing of polymer-modified bituminous mixes therefore Government agencies involved with road construction in the country such as; KeNHA, KeRRA and KURA should develop field trials of determining the suitability of blending waste plastic with bituminous mix. Based on the results of the investigation, for cycle tracks, foot paths, rural roads, and low volume roads whose load carrying capacity can be compromised then the partial replacement of bitumen with plastic waste and waste engine oil will be useful
iii. The government should team up with organizations in the private sector and also non-governmental organizations so as to create an efficient model of waste plastic and waste engine oil management and collection throughout the country which could be put into more beneficial use in road construction
iv. For the successful incorporation of waste plastic into the bituminous mix, it was found that a mixing temperature of $165^0$C was necessary for effective blending. Manual blending was possible for the purpose of the research however, mechanical blending would be necessary for large-scale production of the polymer modified bituminous mix. The mixing temperature was also low enough to ensure no toxic gases were produced from the heating of the waste plastic
v. The current study did not perform tests to determine the specific grade of WEO used. It is therefore recommended that further studies to be carried out to determine specific grade of WEO on performance on bituminous asphalt concrete in flexible pavements. Further long-term study to be done on a project to determine stability of the modified asphalt mix.

# REFERENCES


Ahmedzade, P. (2013). The investigation and comparison effects of SBS and SBS with new reactive terpolymer on the rheological properties of bitumen. Construction and Building Materials, 38, 285-291. doi: 10.1016/j.conbuildmat.2012.07.090

Al-Hadidy, A., & Yi-qiu, T. (2009). Effect of polyethylene on life of flexible pavements. Construction and Building Materials, 23(3), 1456-1464. https://doi.org/10.1016/j.conbuildmat.2008.07.004

Al Hossain, A. (2006). *A Study on the Rheological Properties of Polymer Modified Bituminous Binder and Mixes* (Postgraduate). Bangladesh University of Engineering and Technology.

Al-Abdul Wahhab, H., Asi, I., Abaker, I., & Baig, M. (2002). Performance Modification of SaudiAsphalt Binders Using SABIC Polymers. *The 6Th Saudi Engineering Conference, KFUPM, Dhahran*, *2*, 379-393.

American Society for Testing and Materials. (1988). Standard Test Method for Softening Point of Bitumen. *Pennsylvania: American Society for Testing and Materials*.

Anastasiou, E., Liapis, A., & Papayianni, I. (2015). Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. *Resources, Conservation and Recycling*, *101*, 1-8. doi: 10.1016/j.resconrec.2015.05.009

Attaelmanan, M., Feng, C., & AI, A. (2011). Laboratory evaluation of HMA with high density polyethylene as a modifier. Construction and Building Materials, 25(5), 2764-2770. https://doi.org/10.1016/j.conbuildmat.2010.12.037

Chakrapani, D. (2014). *Use of Plastics in Road Construction*. Investigative Report, Andhra Pradesh, India: Centre for Innovations in Public Systems.

Chavan, A. (2013). Use of Plastic Waste in Flexible Pavements. *International Journal of Application or Innovation in Engineering & Management*, *2*(4), 540-552.

Costa, L., Peralta, J., Oliveira, J., & Silva, H. (2017). A New Life for Cross-Linked Plastic Waste as Aggregates and Binder Modifier for Asphalt Mixtures. *Applied Sciences*, *7*(6), 603. doi: 10.3390/app7060603

Costa, L., Silva, H., Oliviera, J., & Fernandes, S. (2013). Incorporation of waste plastic in asphalt binders to improve their performance in the pavement. *International Journal of Pavement Research and Technology*, 457-464.

DeDene, C., & You, Z. (2014). The performance of aged asphalt materials rejuvenated with waste engine oil. *International Journal of Pavement Research and Technology*, 145-152.

Deffeyes, K. (2006). *Beyond oil*. New York: Hill and Wang.

Fernandes, S., Costa, L., Silva, H., & Oliveira, J. (2015). Utilization of waste materials to improve asphalt mixtures performance. Proceedings of the 6th International Conference on Mechanics and Materials in Design, 2039-2046. Retrieved 23 April 2021.

Fuentes-Audén, C., Martínez-Boza, F., Navarro, F., Partal, P., & Gallegos, C. (2007). Formulation of new synthetic binders: Thermo-mechanical properties of recycled polymer/oil blends. *Polymer Testing*, *26*(3), 323-332. doi: 10.1016/j.polymertesting.2006.11.002

Fuentes-Audén, C., Sandoval, J., Jerez, A., Navarro, F., Martínez-Boza, F., Partal, P., & Gallegos, C. (2008). Evaluation of thermal and mechanical properties of recycled polyethylene modified bitumen. Polymer Testing, 27(8), 1005-1012. https://doi.org/10.1016/j.polymertesting.2008.09.006

Fwa, T. (2006). *The handbook of highway engineering*. Boca Raton: Taylor & Francis.

Garber, N., & Hoel, L. (2009). *Traffic and highway engineering* (4th ed.). Toronto: University of Virginia: Cengage Brain.

Hınıslıoglu, S. (2004). Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix. Materials Letters, 58(3-4), 267-271. https://doi.org/10.1016/s0167577x(03)00458-0

Jia, X., Huang, B., Bowers, B., & Zhao, S. (2014). Infrared spectra and rheological properties of asphalt cement containing waste engine oil residues. *Construction and Building Materials*, *50*, 683-691. doi: 10.1016/j.conbuildmat.2013.10.012

Kenya Ministry of Environment. (2017). *The Environmental Management and Co-ordination Act*. The Kenya Gazette, March 14: 1077.

Kenya Ministry of Transport. (1987). *Road Design Manual*. Materials and Pavement Design for New Roads., August 15: 218.

Kuczenski, B., Geyer, R., Zink, T., & Henderson, A. (2014). Material flow analysis of lubricating oil use in California. *Resources, Conservation and Recycling*, *93*, 59-66. doi: 10.1016/j.resconrec.2014.10.001

Lesueur, D. (2009). The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification. *Advances in Colloid and Interface Science*, *145*(12), 42-82. doi: 10.1016/j.cis.2008.08.011

Metwally, M., & Williams, R. (2010). *Development of Non-Petroleum Based Binders for Use in Flexible Pavements (Final Report)*. Ames, IA, USA.

Moretti, L., Di Mascio, P., & D'Andrea, A. (2013). Environmental Impact Assessment of Road Asphalt Pavements. *Modern Applied Science*, *7*(11). doi: 10.5539/mas.v7n11p1

Moretti, L., Mandrone, V., D'Andrea, A., & Caro, S. (2017). Comparative "from Cradle to Gate" Life Cycle Assessments of Hot Mix Asphalt (HMA) Materials. *Sustainability*, *9*(3), 400. doi: 10.3390/su9030400

Nicholls, C. (1998). *Asphalt Surfacing*. London: E & FN Spon.

Punith, V., & Veeraragavan, A. (2006). Laboratory Fatigue Studies on Bituminous Concrete Mixes Utilizing Waste Shredded Plastic Modifier. *Department of Civil Engineering, Bangalore University, Bangalore, India*.

Silva, H., Oliveira, J., & Jesus, C. (2012). Are totally recycled hot mix asphalts a sustainable alternative for road paving? *Resources, Conservation and Recycling*, *60*, 38-48. doi: 10.1016/j.resconrec.2011.11.013

Southern African Bitumen Association (Sabita). (2015). *Technical Guideline: The use of modified bituminous binder in road construction*. Howard Place: Southern African Bitumen Association (Sabita).

Takouleu, J. (2019). KENYA: Geocycle wants to eliminate 3 million litres of used engine oil per year | Afrik 21. Afrik 21. Retrieved 22 April 2021, fromhttps://www.afrik21.africa/en/kenya-geocycle-wants-to-eliminate-3-million-litres-ofusedengine-oil-per-year/.

The Asphalt Institute. (1989). *The Asphalt Handbook*.

The Asphalt Institute. (2014). *The Asphalt Handbook*.

The Logical Indian. (2015). *Plastic Roads in India*.

The Society of the Plastics Industry (SPI). (1988). *Plastic Classification System*. Washington D.C.

The United States Army. (2007). *Army Field Manual FM 5-436 (Paving and Surfacing Operations)*.

World Bank. (2020). Battling Kenya's Plastic Waste: Young Kenyan Woman is Transforming Waste into Sustainable and Affordable Building Materials. World Bank. Retrieved 22 April 2021, from https://www.worldbank.org/en/news/feature/2021/03/11/battlingkenyaplastic-waste-young-kenyan-woman-transforming-waste-into-sustainable-andaffordablebuilding-materials#:~:text=NAIROBI%2C%20March%2011%2C%202020%20%E2%80%93,city%20of%204.4%20million%20people.

Transport Research Laboratory. (2002). *Overseas Road Note 3: A guide to surface dressing in tropical and sub-tropical countries*.

Yildirim, Y. (2007). Polymer modified asphalt binders. *Construction and Building Materials, 21*(1), 66-72. doi: 10.1016/j.conbuildmat.2005.07.007

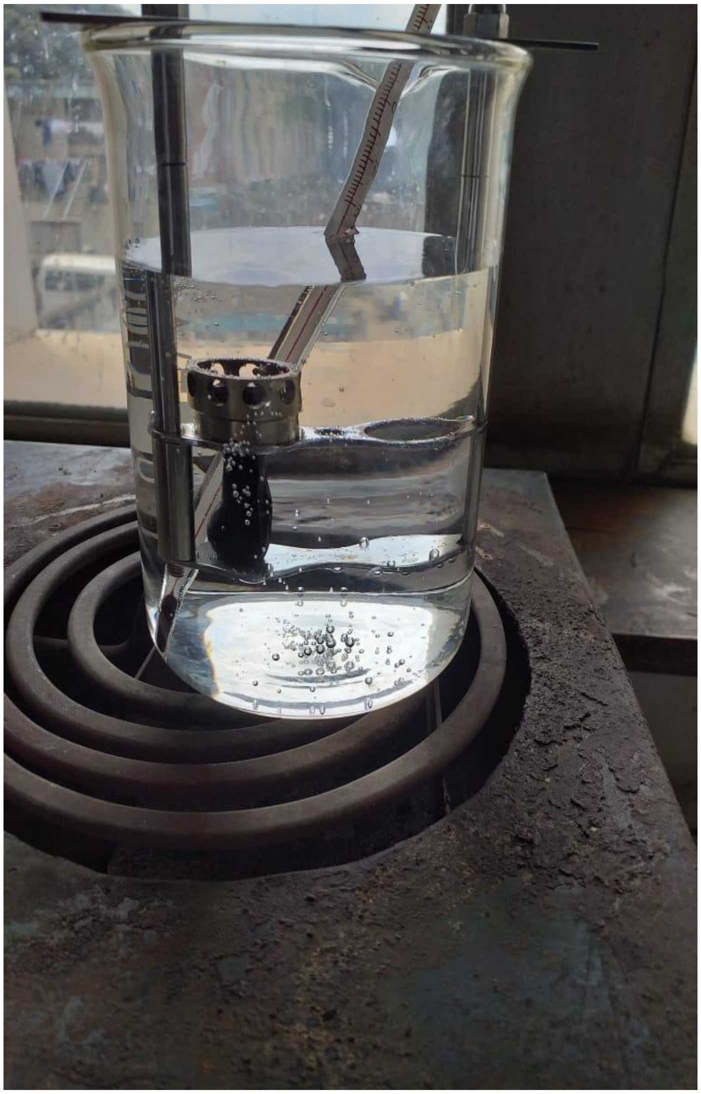
Zargar, M., Ahmadinia, E., Asli, H., & Karim, M. (2012). Investigation of the possibility of using waste cooking oil as a rejuvenating agent for aged bitumen. Journal of Hazardous Materials, 233234, 254-258. https://doi.org/10.1016/j.jhazmat.2012.06.021

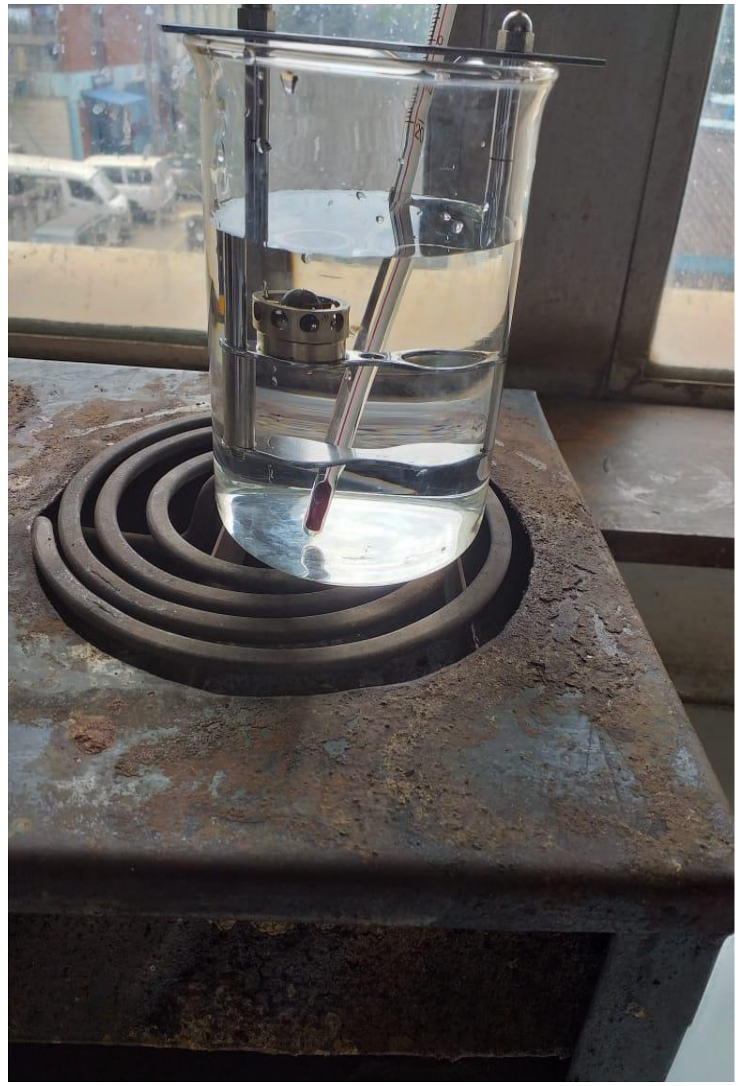
# APPENDICES

## Appendix 1: Preparation of aggregates for testing

# Appendix 2: Sieve Analysis


## Appendix 3: Ring and Ball softening point





# Appendix 4: Penetration test on bitumen sample

# Appendix 5: Prepared samples for Marshall test