ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

GRADUATE STUDIES

PARTIAL REPLACEMENT OF ASPHALT BITUMEN WITH SUGARCANE MOLASSES

By

Timaj Abdulahi

Thesis submitted to school of civil and environmental engineering of Addis Ababa institute of technology in partial fulfilment of the requirements for the degree of

Master of Science

In

Civil Engineering

(Road and Transport Engineering)

Advisor

Habtamu Melese (PHD, PE)

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Addis Ababa, Ethiopia

Addis Ababa University

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DECLARATION

I certify that research work titled *"Partial Replacement of Asphalt Bitumen with Sugarcane Molasses"* is my own work. The work has not been presented elsewhere for assessment and award of any degree or diploma. Where material has been used from other sources it has been properly acknowledged / referred.

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Road and Transport Engineering

Date: May, 2017

ABSTRACT

Hot Asphalt Mixtures (HMA) is particulate composite material consisting of mineral aggregates, asphalt binder and air voids. Asphalt binder is considered as the most expensive and economically variable material. Because of the increase in energy cost, the need for improvement of pavement quality as well as concern over pollution and alternative binders are needed to modify, partially or totally replace asphalt binder. This research study is intended for partially replacement of asphalt binder with Molasses.

The study compares neat asphalt binder and asphalt binder containing molasses using laboratory tests including rheological and conventional test, Marshall flow and stability with corresponding volumetric properties and moisture susceptibility using Indirect Tensile Strength (ITS) test. Including the control specimen six binders were obtained by mixing the asphalt binder with five different percentages of Molasses by weight of asphalt binder (3%, 6%, 9%, 12% and 15%).

The rheological binder tests were conducted using a Dynamic Shear Rheometer (DSR). Three rheological tests were conducted namely Amplitude Sweep Test (AST), Frequency Sweep Test (FST) and Multi-Stress Creep and Recovery (MSCR). The AST was conducted to determine the Linear Visco-Elastic (LVE) Range, FST were conducted to construct the master curve and the MSCR test was conducted to determine the rut parameter (J_{nr}). The AST and FST are conducted at three temperatures (21.1°, 37.8°, and 54.4 °C) while the MSCR test were conducted at four temperatures (52°, 58°, 64° & 70°C).The asphalt mixture testing includes the Marshall mix design which was used to determine the Optimum Bitumen Content (OBC) for the conventional HMA. The asphalt binder was replaced by the five percentages of Molasses using the OBC. The same HMA compositions were tested for moisture susceptibility using ITS.

The research concludes that partial replacement of molasses improves the stiffness and rutting resisting performance of binders at high temperature ranges and has a little effect on the HMA mixture however; it is highly moisture susceptible for all the mixes including the conventional mix. Overall, the research indicates that, it is feasible to partially replace asphalt binder with Molasses up to 9%.

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LIST OF ABBREVATIONS

AASHTO	American Association of State Highway and Transportation Officials
AST	Amplitude Sweep Test
DSR	Dynamic Shear Rheometer
ERA	Ethiopian Road Authority
FST	Frequency Sweep Test
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
LVER	Linear Viscoelastic Range
MSCR	Multiple Stress Creep and Recovery
OBC	Optimum Bitumen Content
PG	Performance Grade
Superpave	Superior Performing Pavements

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: Introduction

1.1. Background

As a developing country, roads and highways play an important role to connect a place to another, hence good road network is a key for the development of our country. Mostly, roads in Ethiopia are flexible pavement type. Flexible pavement typically consists of asphalt mixture placed over granular base layer supported by the compacted soil, referred to as the subgrade. Flexible pavement structure consists of subgrade, subbase, base, base coarse and surface coarse. The surface coarse is the upper layer which is directly in contact with traffic load. It is made of asphalt concrete which consists of high quality and expensive materials compared to other materials in other layers.

Asphalt concrete is composed of basically two components, aggregates and asphalt binder. Aggregates are hard, inert materials such as sand, gravel, crushed stone, slag, or rock dust and based on their particle size they are classified in to three coarse aggregate, fine aggregate and filler. Aggregates constitute total of 90 to 95 percent of the mixture by weight. Whereas asphalt binder is a dark, cement-like material produced by the non-destructive distillation of crude oil during petroleum refining, to which aggregates are added. It is the most expensive and economically variable material in the Hot-Mix Asphalt (HMA). It has been used for centuries for the purpose of waterproofing and as an adhesive. Nowadays, in the road construction industry, asphalt binder is mainly used as an intermediate and surface layers of flexible pavement to provide tensile strength to resist distortion, protect the asphalt pavement structure and subgrade from moisture, and provide a smooth, skid-resistant riding surface that withstands wear from traffic.

The increase in energy cost, need for improvement of pavement quality, strong worldwide demand for petroleum as well as concern over pollution and climate change has encouraged the development of alternative binders to modify or totally replace asphalt binder.

One of these replacement alternatives that are sustainable, nontoxic and environmentally friendly material is sugar cane by-product called molasses. Molasses is the final effluent obtained in the preparation of sugar by repeated crystallization. In other words, it is the liquid left after all the sugar that can be economically extracted has been taken from sugar cane or sugar beet, usually 3-4% of the cane juice. It is a dark, almost black liquid of varying viscosity, but generally very thick. It has been used for different purpose i.e. as an additive in tobacco, as an additive in livestock feeds, as a source for yeast production, as a stock for ethanol fermentation to produce an alternative fuel.

Molasses has been produced in Ethiopia since 1954/55 when the first sugar factory was established, Wonji. Currently, there are three factories operating. Two of the factories produce ethanol from molasses while the other one trade molasses for use as a livestock and as yeast which is considered very small in quantity.

Since asphalt binder is imported and concrete is regarded as expensive, a substitute that would provide a satisfactory road surface, a suitable performance, economical and at the same time make use of industrial by-product is worthy of consideration. The purpose of this research is to experiment and examine molasses as an alternative partial replacer for asphalt binder to create a low-cost, less polluting and locally available paving material for road construction.

1.2. Problem statement

Most of Ethiopian roads are flexible pavement type which are considered as cheap compared to the rigid pavement but still expensive for a developing country. The increase in road construction cost has been common in Ethiopia and many projects are being delayed or denied because of limited budget and asphalt binder is known for its enormous contribution of the construction cost for flexible pavements.

Due to this problem it has been necessary to find an alternative binder to replace asphalt binder. As a result, the use of molasses which is locally available material as an alternative replacer for asphalt binder in HMA might be a possible solution.

Use of molasses as an alternative replacer is not a new idea in the construction industry. Few studies were conducted and one of the important studies was made by an Australian research and Development Company which has completely replaced asphalt binder with non-petroleum based material which was mainly made from molasses. And the result was an asphalt that is non-toxic, comes in a dry granulated form, requires no hot storage, has 50% higher durability, greater resistance to fatigue, wear, cracking, fading and solvents, low volatile emissions, and unlike current bitumen road surfaces, a safer non-slip surface, generally it has a better performance than the regular HMA.

Since Ethiopia has planned a growth and development plan for sugar factories for the coming 15 years with the objective of becoming one of the 10 top sugar exporters, molasses production will increase by 30% from the current production. The use of molasses as an alternative replacement for asphalt binder is useful in that it reduces construction cost, may improve pavement performance, make use of locally available material and also helps to increase Gross Domestic Product (GDP) since the quantity of asphalt binder imported will decrease. Therefore, it is important to study the effect of replacing asphalt binder with molasses partially for HMA pavement.

1.3. Objective

1.3.1. General objective

The general objective of this research is to investigate the possibility of partial replacement of asphalt binder with molasses for asphalt concrete pavement.

1.3.2. Specific objective

The specific objectives of this research are:

- To study of the conventional and rheological behavior of the asphalt binder containing molasses,
- To evaluate the volumetric and marshal properties of HMA composed of aggregate, asphalt binder and Molasses at a specific binder content and

- To evaluate the sensitivity of the HMA composed of aggregate, asphalt binder and Molasses for moisture at a specific binder content.

1.4. Study Limitations

The results of this study depended on set of limitations and criteria that were taken into account during the experimental work. Because of time and budget constraints it was not possible to determine the optimum molasses content.

1.5. Organization

Chapter one defines the overall importance of the problem areas and provides an introduction into what the research is all about, chapter two deals with literatures on basic pavement concepts and pavement materials and past studies and works on pavements using Molasses as a construction material. Chapter three describes how the experimental work is done with detailed procedures and the results are analyzed and discussed in chapter four. Conclusions derived from experimental results and recommendations for this study and other further studies are presented in chapter five.

CHAPTER 2: Literature Review

2.1. Introduction

Pavement consists of more than one layer of different material supported by a layer called sub grade. Generally pavement is of three types; rigid pavement, flexible pavement and composite pavement. Rigid pavement is a pavement structure which distributes loads to the subgrade having, as the main load bearing coarse, a Portland cement concrete slab of relatively high-bending resistance. Flexible pavement is a pavement consists of asphalt mixture placed over granular base layer supported by the compacted soil, the subgrade. While composite pavement is the combination of both pavement types i.e. rigid and flexible pavement. Flexible pavements are so named because the total pavement structure deflects, or flexes, under loading. It support loads through bearing rather than flexural action, as rigid pavements do. They comprise several layers of carefully selected materials designed to gradually distribute loads from the pavement surface to the layers underneath. The design ensures the load transmitted to each successive layer does not exceed the layer's load bearing capacity. Typical flexible pavement structure consisting of:

- Surface coarse: - This is the top layer and the layer that comes in contact with traffic that's why it contains superior quality materials. It may be composed of one or several different HMA sub layers. HMA is a mixture of coarse and fine aggregates and asphalt binder. Generally this surface prevents the penetration of surface water to the base coarse; provides a smooth, well-bonded surface free from loose particles, resists the stresses caused by aircraft loads; and supplies a skid-resistant surface without causing undue wear on tires.

- Base coarse: - This is the layer directly below the HMA layer. The base coarse serves as the principal structural component of the flexible pavement and it distributes the imposed wheel load to the pavement foundation, the subbase and the subgrade. The quality of the base coarse is a function of its composition, physical properties, and compaction of the material. This layer is used in areas where frost action is severe or the subgrade soil is extremely weak. Generally consists of aggregate (either stabilized or un-stabilized).

- Sub-base coarse: - This is the layer (or layers) under the base layer. It functions like the base coarse i.e. it provides additional help to the base and the upper layers in distributing the load., but the material requirements for the subbase are not as strict as those for the base coarse since the subbase is subjected to lower load stresses. A sub-base is not always needed. It consists of stabilized or properly compacted granular material

A typical flexible pavement section is shown in Figure 2-1, presenting the various layers composing it. This study will only concentrate on the top layer (surface), i.e., the hot mix asphalt layer or the asphalt concrete layer.

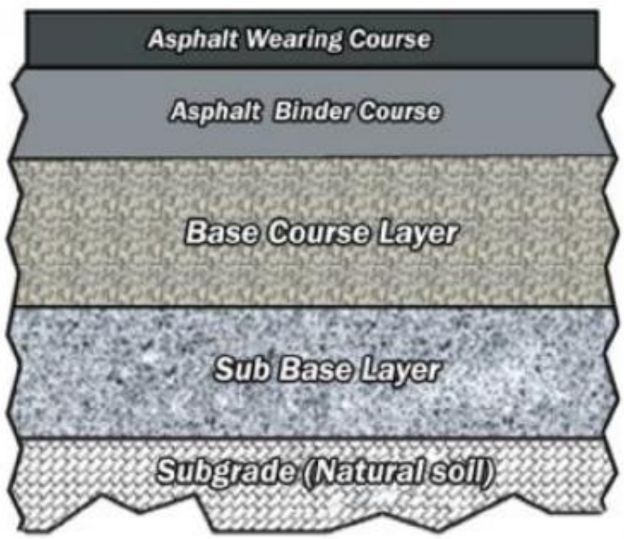


Figure 2-1 Typical flexible pavement vertical section structure (Mohammed, 2013)

2.2. Asphalt Concrete (Bituminous Mixture)

Asphalt concrete is a composite material commonly used in construction projects such as road surfaces, airports and parking lots. It consists of asphalt (used as a binder) and mineral aggregate mixed together, then are laid down in layers and compacted. Mixing of asphalt and aggregate is accomplished in one of several ways:

- Hot mix asphalt concrete (HMA) is produced by heating the asphalt binder to decrease its viscosity, and drying the aggregate to remove moisture from it prior to mixing. Mixing is generally performed with the aggregate at about 300 °F (roughly 150 °C) for virgin asphalt then paving and compacting will be performed while the asphalt is sufficiently hot.
- Warm mix asphalt Concrete (WMA) is produced by adding either zeo-lites waxes, asphalt emulsions, or sometimes even water to the asphalt binder prior to mixing. This allows significantly lower mixing and laying temperatures and results in lower consumption of fossil fuels, thus releasing less carbon dioxide, aerosols and vapors. Not only are working conditions improved, but the lower laying-temperature also leads to more rapid availability of the surface for use, which is important for construction sites with critical time schedules. The usage of these additives in hot mixed asphalt (above) may afford easier compaction and allow cold weather paving or longer hauls.
- Cold mix asphalt concrete is produced by emulsifying the asphalt in water with (essentially) soap prior to mixing with the aggregate. While in its emulsified state the asphalt is less viscous and the mixture is easy to work and compact. The emulsion will break after enough water evaporates and the cold mix will, ideally, take on the properties of cold HMA. Cold mix is commonly used as a patching material and on lesser trafficked service roads.
- Cut-back asphalt concrete is produced by dissolving the binder in kerosene or another lighter fraction of petroleum prior to mixing with the aggregate. While in its dissolved state the asphalt is less viscous and the mix is easy to work and compact. After the mix is laid down the lighter fraction evaporates.
- Mastic asphalt concrete or sheet asphalt is produced by heating hard grade blown bitumen (oxidation) in a green cooker (mixer) until it has become a viscous liquid after which the aggregate mix is then added. Then bitumen aggregate mixture is cooked (matured) for around 6-8 hours and once it is ready the mastic asphalt mixer is transported to the work site where experienced layers empty the mixer and either machine or hand lay the mastic asphalt contents on to the road

- Natural asphalt concrete can be produced from bituminous rock, found in some parts of the world, where porous sedimentary rock near the surface has been impregnated with upwelling bitumen.

2.3. Hot Mix Asphalt

Hot mix asphalt (HMA) is a generic term that includes many different types of mixtures of aggregate and asphalt cement (binder) produced at elevated temperatures in an asphalt plant. It's known by many different names: HMA, asphaltic concrete, plant mix, bituminous mix, bituminous concrete, and many others.

Requirements of Hot Mix Asphalt (HMA)

The bituminous mixture should possess following properties

- Resistance to permanent deformation: -the mix should not distort or displace under traffic loading. The true test will come during high summer temperatures that soften the binder and, as a result, the loads will be predominantly carried by the aggregate structure.
- Resistance to fatigue and reflective cracking: - This is inversely related to the stiffness of the mix. While stiffer mixes are desirable for rut resistance, design for rut resistance alone may be detrimental to the overall performance of the HMA if fatiguing or reflective cracking occurs. Fatigue and reflective crack resistance is primarily controlled by the proper selection of the asphalt binder. Application of a specialty designed crack-resistant interlayer is another option for mitigating cracking
- Resistance to low temperature (thermal) cracking:-cooler regions of are particularly confronted with thermal cracking concerns. Thermal cracking is mitigated by the selection of an asphalt binder with the proper low temperature properties.
- Durability: - The mix must contain sufficient asphalt cement to ensure an adequate film thickness around the aggregate particles. This helps to minimize the hardening and aging of the asphalt binder during both production and while in service. Sufficient asphalt binder content will also help ensure adequate

compaction in the field, keeping air voids within a range that minimizes permeability and aging.

- Resistance to moisture damage (Stripping): - Loss of adhesion between the aggregate surface and the asphalt binder is often related to properties of the aggregates. The assumption on the part of the mix designer should be that moisture will eventually find its way into the pavement structure; therefore, mixtures used at any level within the pavement structure should be designed to resist stripping.
- Workability: - Mixes that can be adequately compacted under laboratory conditions may not be easily compacted in the field. Adjustments may need to be made to the mix design to ensure the mix can be properly placed in the field without sacrificing performance.
- Skid Resistance: -This is a concern for surface mixtures that must have sufficient resistance to skidding, particularly under wet weather conditions. Aggregate properties such as texture, shape, size, and resistance to polish are all factors related to skid resistance.

2.4. Components of Hot Mix Asphalt

HMA is a mixture that contains aggregate and bitumen fastened in to a strong mixture. Aggregates play an important role in determining the nature and characteristics of pavement in preparing the structure of mutual-lock while the binder acts as glue between aggregate particles with layer below the surface of the road.

The performance and property of HMA is mainly function of the characteristics of its constituents: asphalt binder and aggregate along with the quality of the construction process.

2.4.1. Aggregates

Aggregates (or mineral aggregates) are hard, inert materials such as sand, gravel, crushed rock, slag, or rock dust. Properly selected and graded aggregates are mixed with the asphalt binder to form HMA pavements. Aggregates are the principal load-supporting components of HMA pavement.

Aggregates can be classified to three types according to their size distribution: coarse aggregates, fine aggregates, and mineral filler. Coarse aggregates are generally defined as those retained on the 2.36-mm sieve i.e. it comprise the portion of the aggregates that has large particle sizes. Fine aggregates are those that pass through the 2.36-mm sieve and are retained on the 0.075-mm sieve. That is, the aggregate particles that can fill the voids created by the coarse aggregates in the mixture (Prowell et al., 2005). Mineral filler is defined as that portion of the aggregate passing the 0.075-mm sieve. It consists of very fine, inert mineral with the consistency of flour, which is added to the hot mix asphalt to improve the density and strength of the mixture. (Chen, 2009). Mineral fillers can also be classified in two based on their ability to react with asphalt binder these are active fillers and inactive fillers.

2.4.1.1 Aggregate Gradation

An aggregate's particle size distribution, or gradation, is one of its most influential characteristics. In HMA, gradation influences almost every important property including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage. Because of this, gradation is a primary concern in HMA mix design and thus most agencies specify allowable aggregate gradations. Inappropriate selections of aggregate gradation, aggregate properties, and binder grade, type and content are major contributors to rutting and cracking of HMA pavements. The effect of gradation on HMA performance has long been a controversial issue. Strong opinions exist among industry experts as to which gradation type, ranging from fine to coarse to open-graded or stone matrix bituminous gradations, will provide the best performance (Hand et al., 2002).

The mixture resistance to permanent deformation is highly dependent on the aggregate structure. Several research studies have agreed that giving more importance to the aggregate gradation would be the solution for pavement rutting (Karakouzian, 1996). Aggregates are expected to provide a strong stone skeleton to resist repeated load applications. Shape, surface texture, angularity and gradation have a great influence on HMA performance.

HMA mixtures are divided into four main mixture categories: dense-graded; open-graded; gap-graded and Stone-matrix asphalt as a function of the aggregate gradation used in the mix.

- Dense-Graded Mixes: - are well-graded HMA has good proportion of all constituents are also called Dense bituminous macadam. When properly designed and constructed, a dense-graded mix is relatively impermeable. Dense-graded mixes are generally referred to by their nominal maximum aggregate size and can further be classified as either fine-graded or coarse-graded. Fine-graded mixes have more fine and sand sized particles than coarse-graded mixes. It is Suitable for all pavement layers and for all traffic conditions. It offers good compressive strength.
- Open-graded mixes: - are produced with relatively uniform-sized aggregate typified by an absence of intermediate-sized particles. Mixes typical of this structure are the permeable friction coarse and asphalt-treated permeable bases. Because of their open structure, precautions are taken to minimize asphalt drain-down by using modified binders like “asphalt rubber,” or fibers. Stone-on-stone contact with a heavy asphalt cement particle coating typifies these mixes.
- Gap-graded mixes use an aggregate gradation with particles ranging from coarse to fine with some intermediate sizes missing or present in small amounts. The gradation curve may have a “flat” region denoting the absence of a particle size or a steep slope denoting small quantities of these intermediate aggregate sizes. These mixes are also typified by stone-on-stone contact and can be more permeable than dense-graded mixes or highly impermeable.
- Stone matrix asphalt, sometimes called stone mastic asphalt: - is a gap-graded HMA originally developed in Europe to maximize rutting resistance and durability in heavy traffic road. It has a high coarse aggregate content that interlocks to form a stone skeleton that resists permanent deformation. The stone skeleton is filled with a mastic of bitumen and filler to which fibers are added to

provide adequate stability of bitumen and to prevent drainage of binder during transport and placement

2.4.1.2 Properties Of Aggregates

During production, construction, and during the service life of the road, the aggregates may be subjected to the effects of weather, climate, and a range of mechanical processes which together contribute to the deterioration in its physical condition. Therefore, when the construction of a road is necessary, it is important to obtain a material sufficiently durable to last the design life of the road in order that its performance is not affected by deterioration or degradation of the material.

The qualities required of aggregates are described in terms of shape, hardness, durability, cleanliness, bitumen affinity and porosity. In addition to these properties, the micro texture of the aggregate particles will also strongly influence the performance of a compacted HMA layer. Smooth-surfaced river gravel, even partly crushed, may not generate as much internal friction as a totally crushed aggregate from particles having a coarse micro texture. Therefore aggregates should have the following characteristics. Aggregates should be

- Angular and not excessively flaky in order to provide good mechanical interlocking between each other.
- Clean and free of clay and organic material.
- Strong enough to resist crushing during mixing, laying and providing service.
- Resistant to abrasion and polishing when exposed to traffic.
- Non-absorptive since highly absorptive aggregates are wasteful of asphalt binder and also give problem in mix design.

Have good affinity with bitumen, hydrophilic aggregates may be acceptable only where protection from water can be guaranteed or a suitable adhesion agent is used.

2.4.2. Asphalt Binder

Bitumen is a category of organic liquids which are highly viscous, black, sticky and wholly soluble in carbon disulfide. Bitumen molecules can contain thousands of carbon atoms. This make bitumen one of the most complex molecules found in nature. On average, Bitumen is composed of 83.2% Carbon, 10.4% Hydrogen, 4.8% Sulphur, 0.94% Oxygen and 0.36% Nitrogen (wikipidia, 2006).

Bitumen is the residual product obtained by fractional distillation of crude oil at the bottom fraction. It is one of the most complex molecules found in nature and the one with the highest boiling point .At ambient temperature in-situ, bitumen is solid and virtually non-volatile and the vapor pressure of in-situ bitumen is below the limit of detection for normal instrumentation. Normally bitumen is heated to >140^{o}C to become liquid to facilitate transportation and handling (Asphalt Institute, 2011).The physical properties of asphalt binder vary considerably with temperature. At high temperatures, asphalt binder is a fluid with low consistency similar to that of oil. At room temperature most asphalt binders will have the consistency of soft rubber. At subzero temperatures, asphalt binder can become very brittle.

Generally there are two sources of asphalt. These are: -

A. Natural asphalt is obtained from nature in that it is found in so called "asphalt lakes" around the world. Pit Lake, Trinidad; Gard, Auvergne, Ain and Haute Savoie in France; Central Iraq; Butin Island, Indonesia, etc are some of the sources for natural asphalt. Further, there is a huge deposit of Athabasca tar sands in northern Alberta which currently produces about 95% of all natural asphalt in the world (Meyer, 1991).
B. Petroleum asphalt is obtained during the refinery process of heavy crude oils. Asphalt used for road construction is mainly produced from the refinery process. Different types and grades of asphalt can be produce by using various operations. Vacuum and atmospheric distillations are the basic processes used in oil refineries to produce asphalt and other useful products

2.4.1.1. Asphalt Rheology

Rheology, by definition, is the study of the flow and deformation of matter under the influence of an applied stress. Regarding the asphalt binder, the response to a stress is both dependent on temperature and loading time and consequently the rheology of asphalt binder can be expressed by its stress-strain-time-temperature response.

Asphalt binders deform when subjected to loads and their properties also change with varying temperatures. The deformation is a combination of elastic response and viscous flow (Lay, 1990). The magnitude of deformation, or mechanical response, is dependent on load magnitude, duration, and rate of application and the temperature state of the material (Peterson et al., 1999). Since asphalt binders display both elastic and viscous response properties, they are classified as viscoelastic materials. An elastic material experiences recoverable deformation when subjected to a constant load and will immediately deform and maintain a constant strain when loaded. Also, the material will immediately return to its initial shape when the creep load is removed. A viscous Newtonian material, when subjected to a constant load, will deform at a constant rate until the load is removed. The deformation of the viscous material, however, will remain after the load is removed; hence, a viscous material experiences non-recoverable deformation. A viscoelastic material, when subjected to a creep load, experiences an immediate deformation followed by a continued time-dependent deformation (Kim et al., 2003). The immediate deformation corresponds to the material's elastic response and the time-dependent deformation corresponds to the material's viscous response. Once the load is removed, the viscous deformation component immediately ceases, but this deformation is not recovered. The delayed elastic deformation component is slowly recovered at a decreasing rate. Thus, a viscoelastic material experiences only a partial recovery of the deformation resulting from creep loading (Roberts et al., 2002). The viscoelastic behavior of asphalt can be characterized by its deformation resistance and the relative distribution of that resistance between the elastic component and the viscous component within the linear range (Kern and Carpenter, 1999). The relative distribution of the resistance between the elastic component and the viscous component is dependent on the asphalt cement characteristics and temperature and loading rate. The previous loading-response descriptions are for responses within the linear range, which is characterized by the deformation being directly proportional to the applied load at any time and temperature. Nonlinear loading responses are difficult to model for viscoelastic materials such as asphalt. Linear response models, however, are sufficient for the engineering analysis of asphalt binder response to the loading conditions and environmental stresses encountered in the field.

2.4.1.2. Asphalt Binder Characteristics

Asphalt binder has the following five characteristic properties.

- Adhesion

Bitumen has excellent adhesive qualities provided the conditions are favorable. However in the presence of water the adhesion does create some problems. Most of the aggregates used in road construction possess a weak negative charge on the surface. The bitumen aggregate bond is because of a weak dispersion force. Water is highly polar and hence it gets strongly attached to the aggregate displacing the bituminous coating.

- Elasticity

When one takes a thread of an asphalt binder from a sample and stretches or elongates it, it has the ability to return to a length close to its original length eventually. This property is referred to as the elastic character of bitumen.

- Plasticity

When temperatures are raised, as well as when a load is applied to bitumen, the bitumen will flow, but will not return to its original position when load is removed. This condition is referred to as plastic behavior.

- Visco-elasticity

Asphalt binder has a Viscoelastic character. Its behavior may be either viscous or elastic depending on the temperature or the load it is carrying. At higher temperatures and slow loading condition there is more flow or plastic behavior, while at a lower temperatures, bitumen tends to be stiff and elastic. At intermediate temperatures it tends to be a combination of the two.

- Aging

Aging refers to changes in the properties of asphalt binder over time, which is caused by external condition. There are two stages of a pavement's life where oxidation can occur in the field.

- Hot mixing and construction: During the mixing and placement process the asphalt binder is exposed to elevated temperatures and a large contact area with the aggregates which can lead to rapid aging by volatilization and oxidation. The aging mechanism which includes the loss of volatiles and chemical oxidation that result from elevated mixing and placement temperatures falls under the primary process which is followed by oxidation in a secondary process during long term service.

- In-service: The constituent asphalt binder slowly ages as the oxygen from the surrounding environment percolates through the HMA and chemically reacts during the life of an in-service HMA pavement (Anderson, 1995).

2.4.1.3. History of Asphalt Binder

Natural bitumen is probably the oldest petroleum product to be used by man. It has been used for centuries in a variety of ways which include the preservation of mummies by Egyptians and the waterproofing of bathes by the Babylonians (ascelibrary,2005). Through the ages it has been used in Middle Eastern countries, i.e. for water-proofing and constructional jobs. Bitumen was obtained from natural seepages out of the ground in various parts of the Middle East.

Most geologists believe that naturally occurring deposits of bitumen are formed from the remains of ancient, microscopic algae and other once-living things. These organisms died and their remains were deposited in the mud on the bottom of the ocean or lake where they lived. Under the heat and pressure of burial deep in the earth, the remains were transformed into materials such as bitumen, kerosene, or petroleum.

Bitumen was used in its natural state until the distillation of crude oil began in the early 1900s. Then modification of asphalt binder began in the early 1950s. Seeking for a better quality of bitumen, which was more versatile than the former asphalt binder lead to the development of modification. Modified Bitumen is one of the important construction materials for flexible pavements which has improved bitumen properties by reducing the distress faced by a conventional flexible pavement thereby increasing the demand of asphalt binder.

Currently, about 2 billion tonnes of asphalt bitumen are used annually around the world and demand is growing dramatically despite its negative effect on the environment (ECOS, 2005).

Bitumen is manufactured by an energy intensive process from rare, heavy-grade crude oil. It is then developed into aggregated asphalt road surfacing using further petrochemical by-products and solvents. This process omits toxic fumes and residues at all stages of production. Increased environmental regulations and the rising costs of asphalt binder have encouraged researchers to investigate alternative binders that can be used for HMA. Though, on a limited scale, a number of not worthy research works are being conducted worldwide on producing bio-binders from biological resources such as vegetation and forest waste, yard waste, and sugar cane molasses (Mills-Beale et al, 2014).

2.5. Molasses

The history of the Word ‘molasses’ derived from the Romanic languages. It occurs in the same word and the same meaning in French, la mélasse, i.e. syrup or sugar honey and it has its counterparts in other Romanic languages, melassa (Italian), melaza (Spanish), melaço (Portuguese), honey-like. Accordingly, it originally was used in the context (substantia) mellacea, i.e. honey- like substance. The name Molasses is applied to the final effluent obtained in the preparation of sugar by repeated crystallization. Molasses is the dark, sweet, syrupy byproduct made during the extraction of sugars from sugarcane and sugar beets.

Cane molasses is a major byproduct of the sugar industry. The amount of molasses obtained, its quality and composition provide information about the nature of the cane i.e. local conditions of growth and effects of the weather, and the processing in the sugar factory, such as the efficiency of the juice clarification, the method of crystallization during boiling, and the separation of the sugar crystals from the low-grade massecuite. Depending on the source from which they are obtained, Molasses can be beet molasses, cane molasses, black strap molasses, refinery molasses and high test molasses.

2.5.1. Molasses Production

During the sugar making process, juice extracted from sugarcane or sugar beets is boiled down until the sugars crystallize and precipitate out. The syrup left over after crystallization is referred to as molasses (Olbrich, 1963). Usually, sugar cane juice undergoes three cycles of boiling and crystallization to extract as much sugar as possible. With each successive cycle, the left over molasses can vary in color, sweetness, and nutritional content depending on the variety or how much sugar has been extracted. Depending on this molasses are classified as follows.

- **Light Molasses**: This is the syrup left over after the first boiling cycle of sugarcane juice. This molasses is the lightest in color, has the highest sugar content, and the least viscous texture because comparatively little sugar has been extracted from the source.
- **Dark Molasses**: Dark molasses is the byproduct of the second boiling cycle of sugarcane. This molasses is darker and more viscous than light molasses, and contains less sugar.
- **Black Strap Molasses**: This is the final by product of the third boiling cycle in the sugar making process. This variety of molasses contains the least sugar and has the highest concentration of vitamins and minerals. Black strap molasses has a very dark colour and is extremely viscous in texture. Because this type of molasses is highly concentrated, it has a deep, spicy flavor. Blackstrap has the lowest sugar content of any molasses, and is noted for containing a higher nutritional content — particularly manganese, calcium, iron, potassium, magnesium, copper and vitamin B6 — than any other refined sugar.

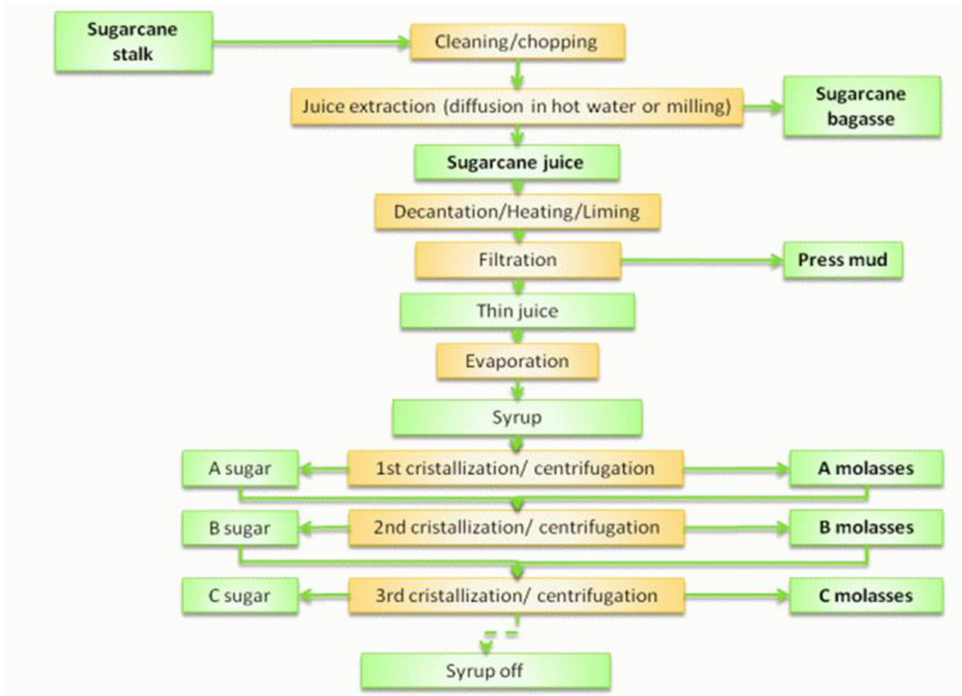


Figure 2-2 Molasses and sugar production process (feedipedia.org)

2.5.2. Chemical Composition of Molasses

The exact composition of molasses is difficult to predict. The reason is that molasses composition is influenced by the soil where the cane is grown, climatic conditions, variety and maturity of the cane and the processing conditions at the factory. It is for that reason only ranges with indicative averages of the composition are usually given (Ndegwa,J.K, Julius K.M and Shitote S.M., 2012).

Molasses is not just one chemical compound, but many. The main content is sugar sucrose. The rest is complex and will vary depending if the molasses is from sugar beets, cane sugar (the two most common sources), or other. The total sugar content in molasses is approximately 50%. Major mineral elements found in cane molasses are potassium followed by sodium, calcium, silicon and magnesium. Their content depends mainly on soil type and water availability. Additionally, the calcium and sodium content is influenced by processing practices.

In Germany, Hubert Olbrich has been reported as the world average of molasses composition as follows.

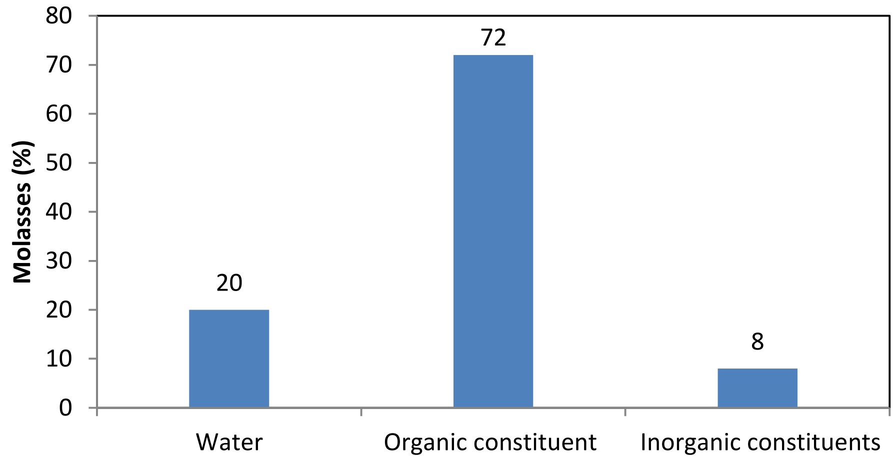


Figure 2-3 Average composition of cane molasses

Source: Hubert OLBRICH, 2006

According to the study conducted by Ethiopian Sugar Corporation in 2016 for quality of Molasses in in the three sugar factories, the following was obtained.

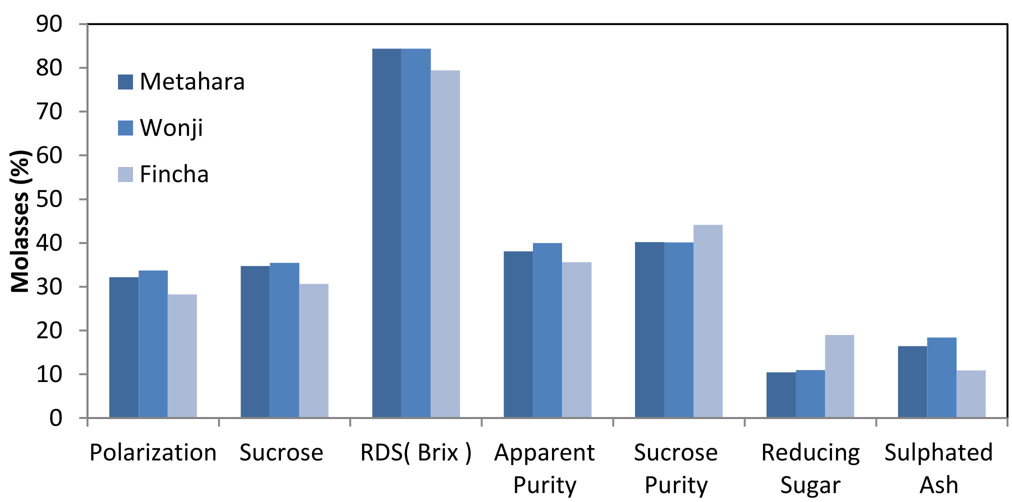


Figure 2-4 Quality of Molasses in Ethiopia (April 2016)

Source: Sugar Corporation Research and Training, Sugar and Co-products Laboratory, Monthly analysis of plantation of Final Molasses

2.5.3. Uses of Molasses

Molasses can be converted into many value-added products by application of modern technologies. Many products can be made theoretically but in actual practice, the production of only a few products is commercially viable (Rao (1997) and Paturau (1989)).

Some of the uses of Molasses are listed below.

- **Additive in livestock feeds: -**Molasses can reduce the dusty powdery nature of some finely ground feeds. In this role, it makes a feed mixture more palatable and edible to livestock. Molasses can be added to replace missing sugar and trace minerals and help with fermentation in cases of low quality forages especially with low sugar levels.
- **Source for yeast production**
- **Baked Goods:**-In the United States, molasses is a common sweetener and flavoring in many baked goods such as gingerbread, Boston brown bread, and shoofly pie. Molasses is also responsible for the classic, sweet, rich flavor of baked beans.
- **Stock for ethanol fermentation (Alcohol):**-Molasses is the sugar used to make rum. Rum is therefore common in regions of the world where sugarcane or sugar beets are heavily cultivated because of the abundance of molasses. Molasses is also sometimes used to brew dark ales like stout.
- **Brown Sugar: -**Molasses is responsible for the dark, rich flavor and texture of brown sugar. Brown sugar is produced by combining refined white sugar with approximately 5% molasses.
- **Tobacco:**-Molasses is added to some tobacco products for flavor. Tobacco flavored with molasses is particularly popular in the Middle East for use in hookahs.
- **Rust Remover: -**Removing rust using Molasses uses a process known as Chelating. Without a good, scientific explanation, the process can be described as "Reverse Oxidation", wherein certain acids or chemicals in the molasses solution strip the oxygen from the Iron Oxide, leaving the iron behind.

- **Dust controller:** - When applied to gravel roads, molasses coats individual road particles with a thin adhesive-like film that binds particles together allowing the particles to pack closer together for a stronger surface.

2.6. Molasses in the Construction Industry

Many researches have taken place regarding molasses as one of additives in construction materials. Some findings of few literatures will be discussed.

I. Molasses as a Concrete Retarder

A delay in the setting of cement paste can be achieved by adding a retarder to the concrete mix. Retarders generally slow down the hardening of the cement paste by stopping the rapid set shown by tricalcium aluminate but do not alter the composition of hydration products (Neville 2006; Lea 1988). The delay in setting of the cement paste can be exploited to produce architectural finish of exposed coarse aggregate (Neville, 2006). Sugar, carbohydrate derivatives and some salts exhibit retarding action (Neville, 2006; Lea 1988; Ramachandran et al., 1993). Sugar belongs to the type of retarders that can hold up setting and hardening indefinitely. It is believed that retarders modify crystal growth or morphology, becoming absorbed on rapidly formed membrane of hydrated cement and slowing down the growth of calcium hydroxide nuclei thus forming a more efficient barrier to further hydration than is the case without a retarder (Neville, 2004). The retarder is believed to be finally removed from solution by being incorporated into the hydrated material without necessarily forming different complex hydrates (Young, 1972). Sugar is used in producing retarders (Shetty, 2004).

Molasses (sugar) as a retarder has been used in the England- France channel construction in the early 1990s to prevent the setting of residual concrete since washing out underground was no possible (Neville, 2006). However, Portland cement concrete without special treatment has been known to be attached bysugar solutions. Light refined molasses are stated to have a more aggressive action than dark molasses on concrete (Lea, 1988).

II. Molasses as Soil Stabilizer

Some of the elements that are found in molasses were found in lime. But not much is known about stabilization of expansive soil with molasses. Indeed there is scarce information in literatures regarding the effect of molasses on strength properties of compacted clay soil (M'Ndegwa, 2011).

According to O'Flaherty (1974), the use of molasses as a soil stabilizing agent is mainly in soil-aggregate. The soil-aggregate could be defined as a soil material that was stabilized by altering the gradation of the original soil. The stability of this material was obtained from well distributed particle-size fractions that gave a dense homogeneous mass with high interlock between particles. The purpose of molasses in this case was to minimize the moisture loss during the construction of pavement layers. That means molasses in this case acted as a moisture content sustainer for soil-aggregate. The sustenance of moisture content was caused by hygroscopic properties of molasses. Suriadi et al. (2002) found out that structural strength of sodic clay soil could be increased through mixing soil with molasses. As regards soil-aggregate, molasses improves the adherence between soil particles thus enabling formation of a strong interparticle bond that enhances the stability of the constructed pavement (O'Flaherty, 1974).

Molasses also enhance soil cohesion (shear strength parameter) which leads to strong cementation of soil particles. The use of molasses for stabilization increases the unconfined compressive strength and CBR value of soils. It can be said that molasses plays a role in enhancement of soil cohesion, which is a shear strength parameter which ultimately lead to increment in unconfined compressive strength (E. Ravi, Animesh S, A.T.Manikandan, G.karthick, A.Abdul J., 2015)

III. Molasses as a De-icing Agent

According to a recent article from the Associated Press, a shortage of road salt combined with rising prices has many communities looking for new ways to extend their salt supplies or to find alternative methods to de-ice roads. Traditionally, chloride salt pellets have been used to de-ice roads due to their ability to lower the freezing temperature of water or, in the cases of calcium chloride and magnesium chloride, by creating heat via an exothermic reaction.

The use of molasses as a de-icing was approved. And the first U.S. patent to describe the use of de-sugared sugar beet molasses as a de-icing agent was issued in 2000.

It's not clear how de-sugared sugar beet molasses exactly acts, whether it can melt ice as effectively as chloride salts. However, compared to other de-icing agents, de-sugared sugar beet molasses is more readily available at low cost, effective at temperatures below freezing, suitable for use in conventional sprayers, non-corrosive, environmentally safe, and non-offensively smelling.

IV. Molasses For Road Construction

Molasses has already proved to be useful for road construction in some countries.

A. In India

Of the many materials used in the construction of roads molasses is probably the most unusual material, yet an experimental molasses road in India has successfully withstood two years of heavy traffic. According to the Imperial Institute of Sugar Technology at Cawnpore India, the advantages claimed for a molasses surface are that it is in a perfect liquid state at the time of application and it won’t melt in hot weather, will not wear under heavy traffic, and is cheaper than most other preparations in India.

In the manufacture of this surface the molasses was mixed with coal tar and asphalt in the presence of an agent, sulphuric acid. The carbohydrates in the molasses combined with the phenolic bodies in the asphalt and coal tar to form a gluey compound, which is perfectly insoluble in water. Then the surface of the paving was sealed by the liquid mixture in the proportions of one pound of molasses to one gallon of coal tar. And it was found to be a satisfactory road surfacing with estimated cost of preparation of material considerably less than that of tar, macadam, or concrete in India (Bulletin. P, 1939).

Another interesting detail regarding the Indian experiments were given in the report of the meeting of the Indian Roads Congress in 1941, which stated that two series of experiments were done for molasses as a road construction material.

In the first series, molasses was mixed with water then spread on the road surface formed of lime kankar, which is a lime found in India (an impure concretionary carbonate of lime, usually occurring in nodules, in alluvial deposits). After the mixture was allowed to soak for half an hour, coarse sand was spread over it immediately. After a fortnight the sand and molasses were worked together thoroughly into the interstices by the traffic. The method has been found to give a smooth and dustless surface in the dry season.

The second series of experiment was conducted to prevent the molasses from being washed out during rainy season, since molasses is mainly composed of sucrose which is easily washed by water. The experiment was conducted by mixing slaked lime with molasses before applying it to the surface. There was also addition of a small quantity of charcoal powder which quicken the setting action. The addition of burnt lime to molasses produce tricalcium sucrate, which is insoluble in water, and therefore it won't be washed out as easily as the pure molasses would. For application, the road, after being cleaned, was coated with a priming coat made up of molasses and water in proportion of about one to four. For the final coat the molasses was mixed with slaked lime and charcoal in the proportion of one, a half, a quarter, by volume, and then applied over the priming coat. After setting, coarse sand was spread over it, and rolled by road roller. It was found that a satisfactory road surfacing composition from molasses can be prepared with a very low cost as compared to asphalt concrete road.

Another minor study was conducted in India to partially replace bitumen with molasses. At first marshal specimens were prepared for 100% asphalt binder to obtain the optimum binder content (OBC). Then by maintaining the OBC constant i.e. OBC obtained in 100% asphalt, percentage of bitumen was decreased thereby increasing the percentage of molasses. Lime was added in the mix in order to control the water absorption of the sample when kept in water bath.

The behavior of molasses modified bituminous mix was found to possess an improved Marshall Characteristics. It was observed that marshal stability value increased up to 13% molasses addition and then decreased. Also flow value decreased upon addition of molasses. The parameters such as voids in mineral aggregate (VMA), air voids (VIA) and voids filled with bitumen (VFB) were within the requirement specified in the standard used. Therefore, it was considered adding molasses to a HMA could give more stable and durable mix. It gave an improved pavement characteristics such as road safety, visibility, long life, strength, recycling, workability and another one that is environment. The use of molasses to the bituminous mix, reduced the amount of carbon dioxide released to the environment. Molasses modified bituminous mix reduces the void present in the mix which prevents moisture absorption and oxidation of bitumen entrapped air.

Generally, roads constructed with molasses modified asphalt binder withstand heavy traffic and give better service. Modification of asphalt binder with molasses not only adds value to molasses but will also develop technology which is eco-friendly.

B. In Australia

An Australian research and development company has developed what it claims “a world first”, commercially viable, non-petroleum-based, asphalt bitumen substitute for roads which was mainly made from the waste material derived in refining sugar cane, molasses with some portion of plant waste and recycled materials.

It has taken more than 20 years of extensive testing to develop the road-grade bitumen substitute, GEO320, and the result was an asphalt that is non-toxic, comes in a dry granulated form, requires no hot storage, has 50% higher durability, greater resistance to fatigue, wear, cracking, fading and solvents, low volatile emissions, and unlike current bitumen road surfaces, a safer non-slip surface. The main reasons when designing GEO320 were road safety and the environment. This is why GEO320 is such an important invention.

Ecopave Australia developed the GEO320 bitumen technology already back in the nineties to address some of the residue bitumen’s non-fit for purpose problems such as fuming, low durability, fuel resistance and slipperiness on the road. GEO320 was originally designed to be a hydrocarbon based bitumen replacement that was safer to use with higher durability, solvent resistance and with increased structural road performance.

The increasing global environmental awareness and demand for safer non-toxic products was a key factor in Ecopave choosing to completely replace the traditional hydrocarbon bitumen model in 1997 with non-petroleum based ingredients made from renewable resources such as Sugar and Molasses. Ecopave Australia performed a highly successful GEO320 “clean hydrocarbon” bitumen field trial in 2000 with Boral’s keen participation, the prototype field trial was designed to be a precursor for the up-coming sugar and molasses product and would establish pavement durability, strength and mix design specifications.

In 2002, GEO320 was tested by ARRB Transport Research to compare its performance properties with normal road grade residue bitumen, i.e. Shell Class 320. Standard tests used to characterize bitumen to Australian Standard AS2008 were applied to both products. The result showed that

- GEO320 was less soluble in standard laboratory solvents; the reduced solubility is noted to be advantageous to the end-user.
- GEO320 durability is significantly better than typical class 320 bitumen.
- GEO320 possesses increased mechanical and rheological properties to that of normal road grade residue
- Normal residue bitumen requires hot storage to remain in a viscous suspension until the time of asphalt mixing process while GEO320 bitumen is stored in a dry granulated form which is added to the hot aggregate mix at the time of asphalt manufacturing, this not only eliminates wastage (oxidized) bitumen and fuming but saves on fuel costs.

GEO320 is now getting many international enquires but the company is holding back because of need for venture capital assistance(sustainable built environment, National Research center).

2.7. Molasses production in Ethiopia

Ethiopia has started sugar production in 1954/55, and first sugar factory was Wonji with total production of15,843 tons of white sugar. Followed by Showa Sugar Factory in 1962 and Metahara in 1969.

Currently, there are five large-scale sugar establishments in the country. These are Wonji/shoa, Metahara, Fincha, Tendaho and Kesem. Tendaho and Kesem are in provision stage while the others are productive with total daily crushing capacity of 42,250 Tonne of cane per day with approximately 11% of sugar and 3-4% of molasses production.

The current total molasses production in all the sugar factories is about 1,268 ton per day. The molasses produced in Metahara and Fincha factories is used to produce ethanol. While the molasses produced in Wonji/shoa is slightly used as yeast, animal feeds and as a dust controller in that specific area.

The ethanol produced mainly used as a source of power for vehicles and as an alcohol for alcoholic beverages. Back in the late 1970s to 1990s, Ethiopia used to export molasses to different countries which was mainly used for the production of ethanol; as the technology was not available for production of ethanol in the country.

According to the sugar development program launched by Ethiopia, with objective of boosting sugar production to satisfy the domestic sugar demand as well as to become one of the top 10 exporters in the coming 15 years, there are some sugar factories that are under construction ,i.e. Beles, Wolkait, Kesem, and OmoKuraz. After the construction of the factories and expansion of the existing once, the current daily crushing capacity will be expected to increase to 1,041,000 ton of cane per day, i.e. an increase by 2,253%, in the coming 15 years with 30% molasses production (Ethiopian Sugar Development Corporation, 2014).

Compared to the past, the current molasses utilization has been improved by small extent but still as compared to other countries, there is still less utilization in Ethiopia mainly due to low market availability and awareness. From the study conducted by the Ethiopian Sugar Development Corporation in December 2015, molasses stalk reached approximately 35,000 tonnes and it has been a big concern for the corporation. With this in mind, the current molasses stalk with the future production if not properly utilized it could be a loss for the country.

2.8. Summary

Generally, the literature review describes basic materials for HMA which are aggregate and asphalt binder. And how modification or replacement of asphalt binder was introduced and the main reasons behind it. Basically this research mainly focuses on utilization of Molasses in HMA. Molasses as an alternative binder has been applied successfully in other countries and it will be beneficial to apply it in our country as well.

After reviewing the previous studies related to utilization of Molasses in the asphalt mix, materials are prepared for conducting laboratory tests.

CHAPTER 3: METHODOLOGY

3.1. Introduction

For this research the type of method that is used is experimental method. There are three main parts of this experiment. The first part includes investigation of traditional and rheological properties of asphalt binder with molasses. The second part consists of preparation of mix design for asphalt binder, aggregate and molasses. And the third part investigates the sensitivity of the mix composed of asphalt binder, aggregate and molasses for moisture.

3.2. Material properties

Materials needed for this study are the constituents of hot mix asphalt and molasses, Table 3-1 present sources of these materials.

Table 3-1 Material Sources

Material	**Source**
Aggregates	Crushed Stone
Bitumen	60/70 Penetration Grade Bitumen
Molasses	Metahara Sugar Factory

3.2.1. Aggregate

A wide variety of mineral aggregates have been used to produce asphalt concrete mixtures. The aggregate selected for this study was a crushed rock obtained from CRBC of four different sizes. In order to define the properties of these aggregates, number of laboratory tests have been conducted, these tests include:

- Sieve Analysis (AASHTO T 27)
- Specific gravity test (AASHTO T 85)
- Water absorption (AASHTO T 85)
- Los Angles abrasion (AASHTO T 96)
- Flakiness Index (%), (BS 812 Part 105.1)

- Soundness loss by NaSO4 , (AASTO T 104)
- Aggregate Crushing Value , (BS 812 Part 110)
- Ten Percent Fines Value (BS 812 Part 111)

Results of the aggregate properties are presented in **Appendix A -** Materials quality test result of the Research paper.

3.2.2. Asphalt Binder

Asphalt binder 60/70 was used in this research. In order to evaluate bitumen properties number of laboratory tests have been performed. These tests include

- Penetration (AASHTO T 49)
- Specific gravity (AASHTO T 228-06)
- Ductility (AASHTO T 51)
- Flash point (AASHTO T 48)
- Softening point (ASTMD36-2002)

Results of the bitumen properties are presented in **Appendix A-** Materials quality test result of the Research paper.

3.2.3. Molasses

For this research the molasses from Wonji sugar factory was used which is the final Molasses from three and half cycles.

Results of the molasses properties are presented in **Appendix A-** Materials quality test result of the Research paper.

3.3. Binder tests

As presented earlier, asphalt binder is a viscoelastic material; it simultaneously shows the behavior of an elastic material (e.g. rubber band) and a viscous material (e.g. molasses). Therefore asphalt binder property should be studied to characterize the relative distribution of the resistance between the elastic component and the viscous component. For this research, two performance measuring methods were conducted. The first performance measuring techniques used are the conventional performance measuring techniques these are penetration point, softening point and ductility. While the second performance measuring technique is the recently developed performance measuring method by superpave system i.e. using an oscillatory instrument known as Dynamic Shear Rheometer (DSR).

3.3.1. Conventional methods

Different tests were performed on the prepared samples according to established Standards to characterize the properties of asphalt binder mixed with different percentages of Molasses by weight of the asphalt bitumen. The different percentages of Molasses concentration employed in this process provides a wider range of results which helps in analyzing each type of the blend at that particular concentration. These tests include penetration at 25ºC, softening point and ductility tests.

3.3.1.1. Experimental design

These tests were performed on asphalt binder mixed with different percentages of Molasses varying between 3%-15% by weight of the bitumen. First the asphalt binder was heated to a temperature of 135-170 ^{o}C then the necessary amount of molasses was added to asphalt binder by contentiously stirring the mixture for 15-20 minutes at a constant temperature to ensure good homogeneity, then the following different tests were performed.

3.3.1.1.1. Penetration

According to AASHTO T 49 a sample of about 100g of asphalt binder with molasses was heated in an oven for enough time to completely soften. Then it was transferred into a 15mm penetration test cup and allowed to cool to room temperature. The sample was then placed in a temperature controller set to 25°C and allowed to condition for about 1 hour. It was then removed, dried quickly and placed under the needle of the penetrometer. Then three readings were taken for a single penetration cup after placing tip of the penetrometer needle precisely at the surface of the cup before the instrument was started. The average of three samples were taken for each sample and recorded.

3.3.1.1.2. Softening Point

According to AASTO T 53, the same samples were poured into two small brass rings and allowed to cool. A heated knife blade was used to trim the surface of the samples to the level of the brass rings. The prepared samples were then conditioned in a temperature controller at 4°C for at least 30 minutes before the test. A steel ball bearing (weighing 3.55 g) were centered on each specimen and placed in transparent glass jar. An electric heater and thermometer was fitted into the beaker filled with clean, distilled water. The temperature at which each bitumen specimen touches the base plate was recorded to the nearest degree. The average of the three readings were taken and rounded to the nearest whole degree.

3.3.1.1.3. Ductility

According to AASHTO T 51, the samples were heated and poured in the mould assembly placed on a plate. The samples were cooled in the air and then in water bath at 25 °C temperature. Then the excess bitumen was cut until the surface was leveled using a hot knife. Then the mould with assembly containing sample was kept in water bath of the ductility machine for about 90 minutes. The sides of the moulds were removed, the clips were hooked on the machine and the machine was operated. The distance up to the point of breaking of thread is the ductility value which is reported in cm.

3.3.1.1.4. Rolling Film Oven Test

According to AASTO T 240, the Rolling Thin-Film Oven test was conducted in order to investigate the loss of volatiles inspite of various other factors that contribute to asphalt binder aging. The asphalt's viscosity is increased due to the loss of volatiles from the asphalt binder which mainly occurs during the processes of manufacturing and placement. These processes age the asphalt binder by driving off a substantial amount of volatiles when exposed to elevated temperatures.

In order to determine the short-term aging process, the mixed samples, i.e. asphalt binder mixed with Molasses, were poured in a small jar which was then placed in a circular metal carriage that rotates within the oven. The binder remains in the rolling- film oven for 85 minutes at 163°C with continuously supplied air.

Then effect of heat and air that incurred in physical properties were measured after the oven treatment by other test methods i.e. penetration & ductility tests were performed.

3.3.2. Dynamic Shear Rheometer (DSR)

The DSR evaluates the behavior of an asphalt binder specimen by subjecting it to oscillatory stresses. A thin asphalt specimen is sandwiched between two parallel metal plates held at a constant temperature medium, with bottom plate fixed and top plate oscillating, at different angular frequencies with respect to each other. A DSR loading cycling is shown in Figure 3-1.

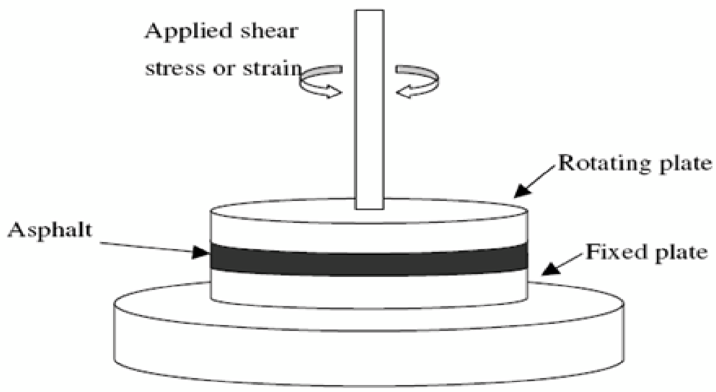


Figure 3-1 Schematic configuration and loading mode of DSR (Zaniewski, 2004).

During rheological tests in oscillation, a sample is exposed to a continuous sinusoidal excitation of either a strain (controlled strain mode) or a shear stress (controlled stress mode). Depending on the type of excitation, the material will respond with a stress (in controlled strain mode) or a strain (controlled stress mode).Then it evaluates the specimen’s response and calculates several parameters of the asphalt, such as complex shear modulus, dynamic viscosity, phase angle, accumulated strain or stress, etc. The complex shear modulus, phase angle, and accumulated strain or stress of a binder are indicators of the asphalt’s resistance to shear deformation in the viscoelastic region. Theses parameters help in predicting the rutting potential and fatigue life of hot mix asphalt pavements (Kose et al., 2000).

The shear complex modulus (G*) consists of two components: one is the storage modulus, G’ and the other is the loss modulus, G” .The G’ is the elastic (recoverable) component and it represents the amount of energy stored in the sample during each loading cycle. While the G" is the viscous (non-recoverable) component, represents the amount of energy lost during each loading cycle.

The δ, the angle made with the horizontal axis, indicates the relative amounts of temporary and permanent deformation (Delgadillo et al., 2004). When the phase angle is zero degrees, purely elastic , the complex modulus consists solely of the storage modulus (G'). Likewise, when the phase angle is 90 degrees, purely viscous, the complex modulus consists solely of the loss modulus (G"). It is therefore necessary to determine both the complex modulus and the phase angle within the viscoelastic range of response to characterize asphalt binders.

In order to ensure repeatability, the complex modulus must be measured within the linear viscoelastic range, which is the region of behavior in which the shear modulus is independent of shear stress or strain. The limit of linear viscoelastic behavior is the point beyond which the complex modulus decreases to 95% of the measured value at zero-strain, as shown in Figure below.

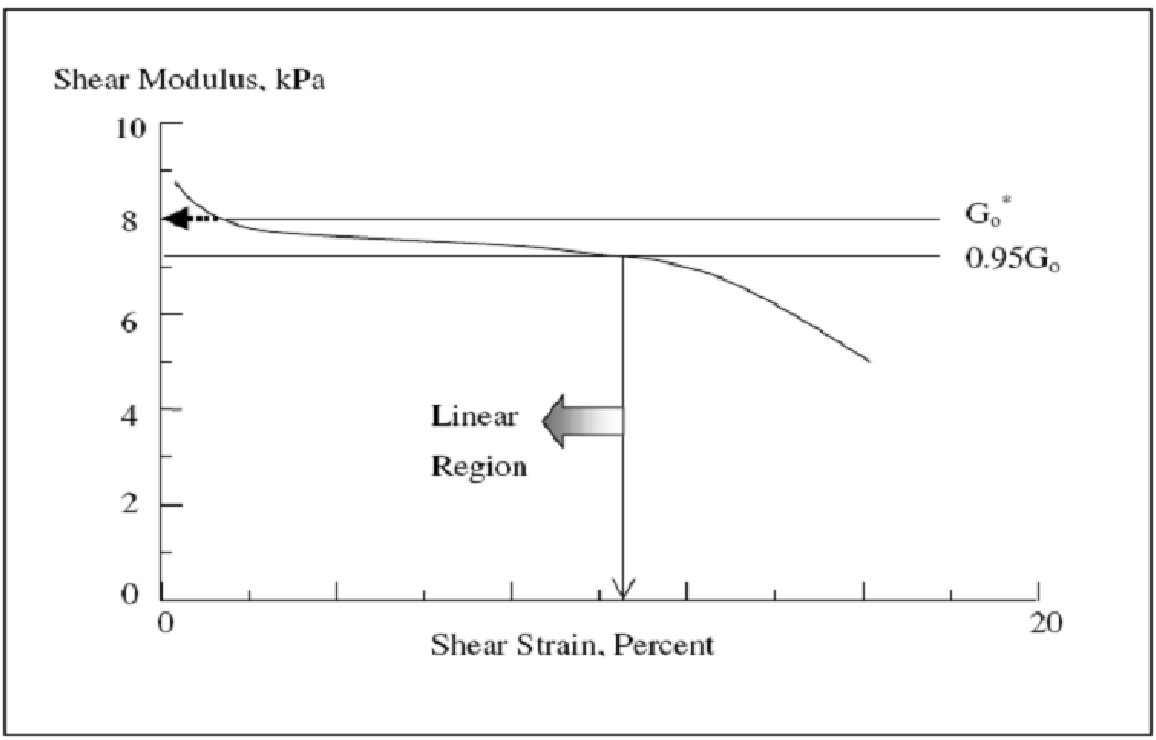


Figure 3-2 Linear viscoelastic region of asphalt binder (Peterson et al., 1999).

Accordingly, three main types of tests were conducted using DSR in this research to determine the binder properties. These are:-

I. Amplitude Sweep test
II. Frequency Sweep Test
III. Multiple Stress Creep and Recovery

I. **Amplitude Sweep Test (AST): -** During an amplitude sweep the amplitude of the deformation or alternatively the amplitude of the shear stress is varied while the frequency is kept constant until the microstructure breaks down and the rheological material functions are not independent of the set parameter anymore. Amplitude sweeps are mainly used to determine the linear-viscoelastic range of a material.

II. **Frequency Sweep Test (FST):-** During the frequency sweep the frequency is varied while the amplitude of the deformation or alternatively the amplitude of the shear stress is kept constant. DSR frequency sweep tests are designed to construct master curves of binder complex shear modulus (G*) and phase angle (δ). The master curves characterize binder rheological properties over a wide range of temperature or frequency. The master curves can be used to estimate binder G* and δ values at any interested temperature and frequency.

III. **Multiple Stress Creep and Recovery (MSCR):-** The MSCR test creep and recovery test concept to evaluate the binder's potential for permanent deformation. A one-second creep load is applied to the asphalt binder sample. After the 1-second load is removed, the sample is allowed to recover for 9 seconds. Normally the test is started with the application of a low stress (100Pa) for 10 creep/recovery cycles then the stress in increased to 3200Pa and repeated for an additional 10 cycles. In the MSCR test, higher levels of stress and strain are applied to the binder, better representing what occurs in an actual pavement.

3.3.2.1. Experimental design

For this research DSR machine known as MARVEL BOHLIN INSTRUMENT, is used to characterize the viscous and elastic behavior of asphalt binder with molasses at different temperatures. The DSR is used to determine both the viscous and the elastic properties of a material.

3.3.2.1.1. **Testing Procedure**

AASHTO T-315-10 “Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)” defines the protocol for conducting the dynamic shear rheometer test. The test temperature is set, as per AASHTO TP 62-03. The size of the plate used for the DSR depends on the temperature and the aged condition. Hence, for intermediate temperature (i.e.4^{o}C - 40^{o}c) and aged samples 8 mm in diameter plate is used with a 2mm gap between the upper and lower platens. Whereas, for high temperature (i.e. > 46^{o}c)and unaged samples 25 mm in diameter plate with a 1mm gap between the upper and lower platensis used.

Prior to testing a sample, a gap measurement verification procedure, called setting the zero gap, must be conducted to ensure that the micrometer reading and the actual gap between the platens is the same. The zero gap is set by lowering the upper platen in small increments until the upper and lower plates just touch, or reach zero gap. The micrometer wheel is then set to zero, when zero gap between the platens have been achieved. Before setting the zero gap, the temperature controller is turned on and the environmental chamber is preheated, or cooled, to the desired test temperature. The zero gap is then set after the medium surrounding the platens stabilizes at that temperature. The accuracy of the gap measurement is directly related to the accuracy of the specimen evaluation, hence this procedure is essential.

Up on conducting the DSR test, asphalt specimen has to be properly placed on the fixed plate allowing the upper platen to squeeze the asphalt specimen. The upper plate has to be lowered such that the gap between the two plates is0.05 mm greater than the test gap. The excess asphalt that has to be squeezed from between the platens has to be removed by trimming around the periphery of the platens then the sample was bulged so that the gap between the upper and lower platensis 2mm for 8mm plate and 1mm for 25mm plate.

After the asphalt sample is correctly placed in the DSR and the test temperature appears stable, the sample has to be allowed for few minutes for the temperature of the specimen to equilibrate to the test temperature before conducting the test.

3.3.2.1.2. Sample Preparation

The first step on preparing the sample was heating the asphalt binder at stove around 110^{o}C until fluid. Then Molasses was added in five volume fractions by weight of asphalt binder, i.e. 3, 6 and 9%, producing a total of 4 mix types with the controlled mix. Up on adding Molasses the mix was contentiously stirred for 15-20 min at a constant temperature to ensure good homogeneity. Then each sample was aged using Rolling-thin Film Oven (RTFO) in accordance to AASHTO T 240.

Then the heated asphalt was poured into a mould and allowed to cool until solid enough to be removed from the mould. After removal from the mould, the asphalt disk was placed between the fixed plate and the oscillating spindle of the DSR for testing.

I. Amplitude Sweep Test

Using the rheometer software a frequency of 10 rad/sec or 1.596 Hz was applied. The test was conducted at three different temperatures i.e. at 21.1, 37.8 and 54.4 using 8mm diameter plate size. The dynamic rheological properties were tested by measuring the required shear stress to achieve a preset strain level for both aged and unaged mixes. The strain level should be large enough so that it is measurable and also small enough so that the required stress does not exceed the capacity of the testing device or damage the sample. The controlled stress level for AST was from 100Pa to 90,000Pa.The complex shear modulus G* versus strain plot was used to determine the linear viscoelastic region.

II. Frequency Sweep Test

In this study, frequency sweep tests were also performed on the same temperatures as AST i.e. at 21.1°, 37.8^{o} and 54.4 °C. The tests were run on 8mm parallel plate after the samples were allowed to equilibrate for few minutes at each temperature prior to testing. The shear strain applied was 1% for all the samples, i.e. 0%, 3%, 6% and 9%. And the frequency range used was 0.1Hz to 25Hz.

III. Multiple Stress Creep and Recovery

Before conducting the MSCR test performance grade determination was conducted to decide the test temperatures for the MSCR test using the same device. Then the repeated shear creep loading test was performed. In this study a controlled-stress mode was applied. A constant shear stress of 100Pa and 3200 Pa was used to samples having 25-mm diameter using a 1-mm gap between the platens. The shear loading and unloading were applied for total of 10 seconds i.e. 1 second creep load followed by 9 seconds recovery. The test is started with the application of a low stress 100Pa for 10 creep/recovery cycles, i.e. sample conditioning then another 100Pa 10 creep/recovery cycles were repeated then the stress was increased to 3200Pa and repeated for an additional 10 cycles a total of 30 cycles or 300seconds.

3.4. MARSHAL MIX DESIGN

In this method, the resistance to plastic deformation of a compacted cylindrical specimen of bituminous mixture is measured when the specimen is loaded diametrically at a deformation rate of 50 mm per minute. There are two major features of the Marshall method of mix design.

- ✓ Density-voids analysis and
- ✓ Stability-flow tests.

The Marshall stability of the mix is defined as the maximum load carried by the specimen at a standard test temperature of 60°C. The flow value is the deformation that the test specimen undergoes during loading up to the maximum load. Flow is measured in 0.25 mm units. In this test, an attempt is made to obtain optimum binder content for the type of aggregate mix used and the expected traffic intensity.

The first step in conducting marshal test is blending of aggregates. Asphalt mix requires the combining of two or more aggregates, having different gradations, to produce an aggregate blend that meets the gradation specifications for asphalt mix.

Available aggregate materials, coarse aggregate (14-20), intermediate aggregate (6-14 and 3- 6), fine aggregate (0- 3) and filler, were integrated in order to get the proper gradation within the allowable limits according to ERA specifications using mathematical trial method.

Table 3-2 **Particle Size Distribution for wearing Coarse for Nominal Size 12.5 mm(** ***ERA, 2013)***

Sieve size	Percentage passing
19	100
12.5	90-100
4.75	44-74
2.36	28-58
0.300	5-21
0.075	2-10

The mathematical method depends on suggesting different trial proportions for aggregate materials from whole gradation. The percentage of each size of aggregates is to be computed and compared to specification limits. If the calculated gradation is within the allowable limits, no further adjustments need to be made; if not, an adjustment in the proportions must be made and the calculations must be repeated. The trials are continued until the percentage of each size of aggregate are within allowable limits. The aggregate blending proportion established were 11%, 40%, 14%, 33% and 2% for nominal size of 14-20 mm, 6-14mm, 3-6mm, 0-3mm and filler respectively. Aggregates blending results are presented in the Figure 3-3 below.

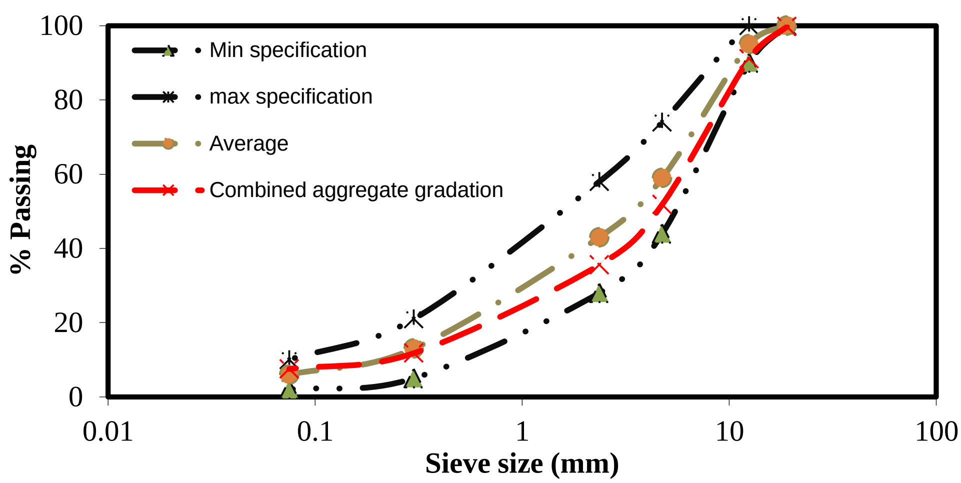


Figure 3-3 Combined aggregate gradation

3.4.1. Optimum Bitumen Content

15 samples each of 1200 gm in weight were prepared using five different bitumen contents i.e. Three samples for one- bitumen content to have an average value. First the aggregates were heated to a temperature of 175^{o}C to 190^{o}Cthe compaction mould assembly and rammer were cleaned and kept pre-heated to a temperature of 100^{o}C to 145^{o}C. The bitumen was also heated to a temperature of 135-170^{o}C and the required amount of first trial of bitumen was added to the heated aggregate and thoroughly mixed. The mix was placed in a mould and compacted with 75 number of blows. The sample is taken out of the mould after minimum of an hour using sample extractor.

Marshall Properties of the asphalt mix such as stability, flow, density and volumetric properties were obtained for various bitumen contents. Then the following graphs were utilized in order to determine the optimum bitumen content for the mix.

- Stability vs. Bitumen Content
- Flow vs. Bitumen Content
- Bulk Specific Gravity vs. bitumen Content
- Air voids (Va) vs. Bitumen Content
- Voids Filled with Bitumen (VFB) vs. Bitumen Content

According to Asphalt Institute the optimum bitumen content (OBC) for proposed mix is the average of three values of bitumen content i.e. Bitumen content at the highest stability, bitumen content at the highest value of bulk density and bitumen content at 4% of air voids

Then properties of the asphalt mix using optimum bitumen content such as stability, flow, bulk density and volumetric properties (i.e. Va, VMA and VFA) are obtained and checked against specifications range.

3.4.1.1. Volumetric Properties of HMA Mixes

The volumetric properties of HMA mixes are air voids, voids in mineral aggregates and void filled with asphalt. These properties indicate the performance of the mixes in the field. The volumetric component diagram of HMA is shown in Figure 8 below.

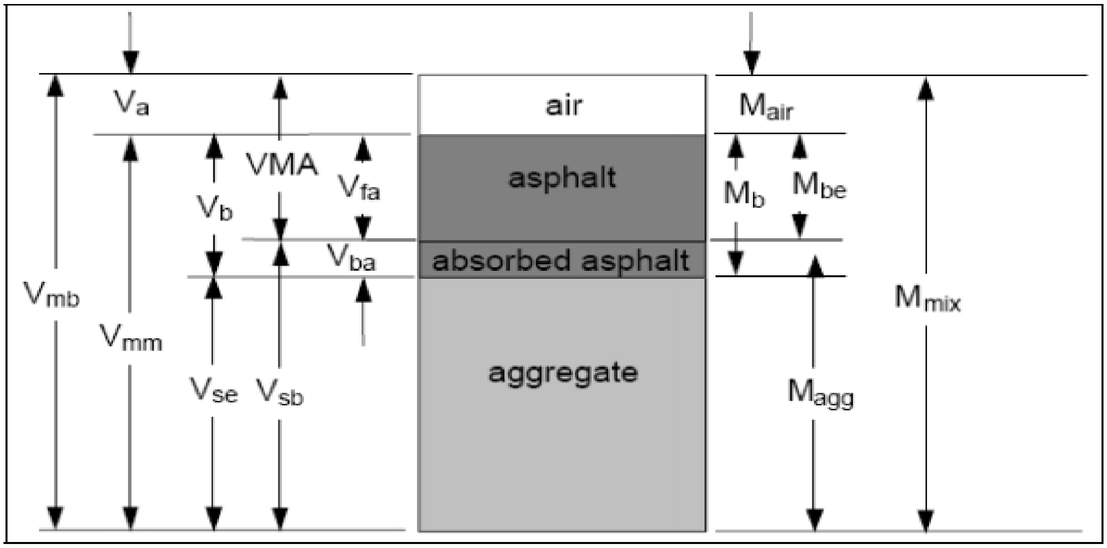


Figure 3-4 Mass and volume relationships in asphalt mixtures (FHWA Superpave, 1995)

All the components are defined in the following:

VMA = Volume of voids in mineral aggregate
V_{mb} = Bulk volume of compacted mix
V_{mm} = Voidless volume of paving mix
V_{fa} (VFA) = Volume of voids filled with asphalt
V_a = Volume of air voids
V_b = Volume of asphalt binder
V_{ba} = Volume of absorbed asphalt binder
V_{sb} = Volume of mineral aggregate (by bulk specific gravity)
V_{se} = Volume of mineral aggregate (by effective specific gravity)
M = Total mass of asphalt mixture
M_{be} = Mass of effective asphalt binder
M_{agg} = Mass of aggregate
M_{air} = Mass of air = 0
M_b = Mass of asphalt binder

For many years, three other volumetric parameters Va, VMA, and VFA, have been widely used and at various times have formed critical design thresholds (Christensen and Bonaquist, 2005). They are:

- ✓ **Percent Air Voids in compacted Mixture:-** The small air spaces between the coated aggregate particles in the total compacted paving mixture are called air voids. It can be determined by using the equation below.

$$Va = 100 * \frac{Gmm - Gmb}{Gmm}$$

Where, Va = Air voids in compacted mixture, percent of total volume, Gmm= maximum specific gravity of paving mixture, Gmb= bulk specific gravity of compacted mixture

- ✓ **Percent VMA in compacted Paving Mixture:-** It is the intergranular void space between the aggregate particles in a compacted paving mixture. It includes the air voids and the effective asphalt content, expressed as a percent of the total volume. The objective is to furnish enough space for asphalt binder so as to provide adequate adhesion required to bind the aggregate. It is calculated as

$$VMA = 100 - \frac{Gmb}{Gsb} * Ps$$

Where, VMA = voids in the mineral aggregate, percent of the bulk volume, Gsb= bulk specific gravity of total aggregate, Gmb = bulk specific gravity of the compacted mixture, Ps = aggregate content, percent by mass of total mixture

- ✓ **Percent VFA in Compacted Mixture:-** The percentage of the voids in mineral aggregates that contain asphalt, and not the absorbed asphalt is called Voids filled with asphalt (VFA). It is determined as

$$VFA = 100 * \frac{VMA - Va}{VMA}$$

Where, VFA = Voids filled with asphalt, percent of VMA , VMA = Voids in mineral aggregates, percent of the bulk volume, Va = Air voids in compacted mixture, percent of total volume.

3.4.2. Specimen preparation

After obtaining OBC, 36 samples were prepared at OBC to evaluate the effect of adding molasses to asphalt mixture samples by considering five different proportions of molasses (3, 6, 9, 12, 15% of molasses by the weight of OBC)

The procedure of incorporating molasses in asphalt mix can be summarized as follows. First Asphalt binder was heated then the necessary amount of molasses was added to asphalt binder by continuously stirring the mixture for 15-20 min at a constant temperature to ensure good homogeneity. At the same time the aggregates were heated to a temperature of 175^{o}C to 190^{o}C the compaction mould assembly and rammer were cleaned and kept pre-heated to a temperature of 100^{o}C to 145^{o}C. Then the asphalt binder mixed with molasses was mixed with the aggregate. Then the mix was placed in a mould and compacted with 75 number of blows. The sample was taken out of the mould after minimum of one hour and half using sample extractor. Finally the marshal properties of all the asphalt mix samples were determined.

3.4.3. Moisture Susceptibility

Moisture is a key factor in the deterioration of asphalt pavement. Factors that influence moisture damage include aggregate, asphalt binder, type of mix, weather and environmental effects, and pavement subsurface drainage. Since Molasses is washable by water, it may induce stripping effect in the mix when ex]\posed to water or moisture. Hence moisture susceptibility should be checked for the mix.

This part of the research evaluates the moisture damage for the mix composed of aggregate, asphalt binder and molasses using indirect tensile strength.

The ITS test is a performance test which is often used to evaluate the moisture susceptibility of a bituminous mixture. Tensile strength ratio (TSR) is a measure of water sensitivity. It is the ratio of the tensile strength of water conditioned specimen, (ITS wet, 60˚C, and 24 h) to the tensile strength of unconditioned specimen (ITS dry) which is expressed as a percentage. A higher TSR value typically indicates that the mixture will perform well with a good resistance to moisture damage. The higher the TSR value, the lesser will be the strength reduction by the water soaking condition, or the more water-resistant it will be.

The indirect tensile test involves loading a cylindrical specimen with compressive loads which act parallel to and along the vertical diametrical plane. To distribute the load and maintain a constant loading area, the compressive load is applied through a ha1f-inch-wide stainless steel loading strip which is curved at the interface with the specimen. This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane, which ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter. Then the tensile stress in the center of the specimen can be calculated using the following equation:

$$S_t = \frac{2000P}{\pi DT}$$

Where St= Tensile strength(KPa)
P= Applied force(N)
D= Diameter of specimen(mm)
T= thickness of specimen(mm)

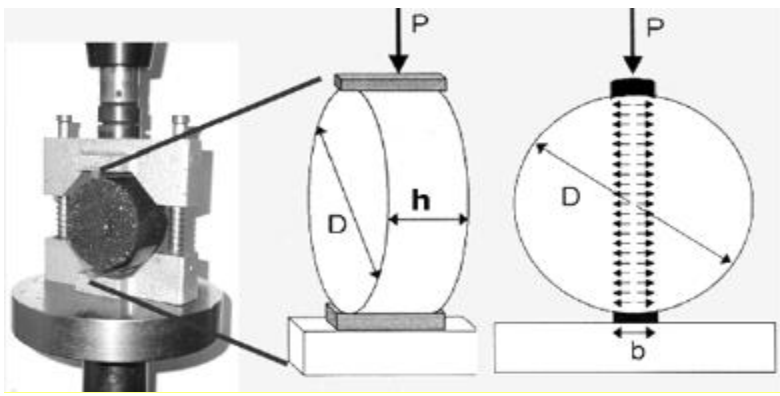


Figure 3-5 A typical ITS apparatus (Researchgate.com)

3.4.3.1. Experimental design

A total of 36 Marshall specimens for 6 binder mixes were prepared. The first group was immersed in a water bath at 60˚C, for a period of 24 hours (conditioned sample). The samples were then removed from the water bath and kept at a temperature of 25˚C for a period of 2 hours. Other set of samples (unconditioned sample) were kept at a temperature of 25˚C for a period of 2 hours without soaking. These specimens are then mounted on CBR testing apparatus loading the ITS ring and loaded at a deformation rate of 50mm/min and the load at failure is recorded at each case. Then the tensile strength of water conditioned as well as unconditioned specimen for each mixture was determined. Then the tensile strength ratios were calculated using the following equation:

$$TSR = \frac{S_{t(cond)}}{S_{t(Uncon)}}$$

Where: TSR = Tensile strength ratio

$St(con)$ = average tensile strength of the conditioned (Kpa);

$S_{t(Uncon)}$ = average tensile strength of the unconditioned (Kpa).

3.5. Summary

Laboratory experimentation was conducted to investigate the partial replacement of asphalt binder with molasses. Different laboratory investigations were carried out to test both the binder and HMA properties of asphalt binder containing molasses. The binder tests carried out are of two types; conventional and rheological. The conventional tests include penetration, softening point, ductility and RTFO. And the rheological tests include AST, FST and MSCR. The rheological tests are conducted using a DSR machine which studies the binder properties at different temperatures and predicts the performance mainly the stiffness and rutting parameter.

The second part of the laboratory investigation studies the HMA containing Molasses and compares it with the conventional HMA using Marshall parameters. This part of the investigation also evaluates the moisture susceptibility of the HMA containing Molasses using ITS.

CHAPTER 4: RESULTS AND ANALYSIS

This chapter presents the result on the asphalt binder property change up on addition of Molasses as a replacer for both binder and mix properties. Then the tests results are used to draw conclusions on the performance of the two types of materials and their ability to meet specifications.

4.1. The effect of Molasses on conventional properties of Asphalt Binder

4.1.1. The Effect of Molasses on Penetration

Figure 4-1 represents the effect of variable concentrations of Molasses on the penetration properties of asphalt binder. From the graph, the addition of 3% Molasses doesn't affect the penetration at all but as the percentage increases to 6% the penetration value slightly increase from 64dmm to 65 mm. Still, as the percentage of Molasses increase to 15%, the degree of penetration increases and its value becomes 74 mm. From this observation we can predicts that the material will show further increase in penetration value as Molasses percentage further increase. Hence, the increase in the penetration ability of the asphalt binder as the Molasses content increases implies a decrease in the hardness properties of the binder and makes it soft. As stated by Habib et al., 2011 the hardening of the bitumen can be beneficial as it increases the stiffness of the material, thus the load spreading capabilities of the structure.

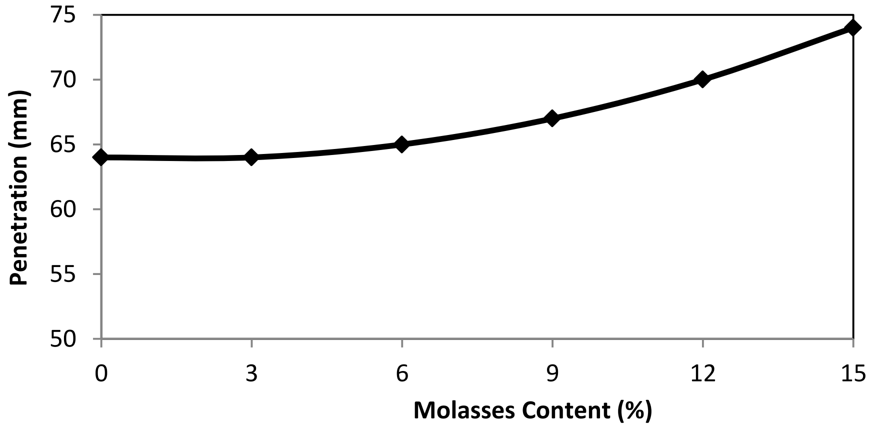


Figure 4-1 Penetration test result

4.1.2. The Effect of Molasses on Softening Point

From Figure 4-2, it can be observed that addition of Molasses offer lesser variation in the softening point of the asphalt binder. In the plot below, the softening temperature can be observed to dip as Molasses percentage increase. The decrease in softening point shows negative effect on the property of asphalt binder. According to Noor et al., the increases in the softening point reflect in better rutting resistance at higher temperature.

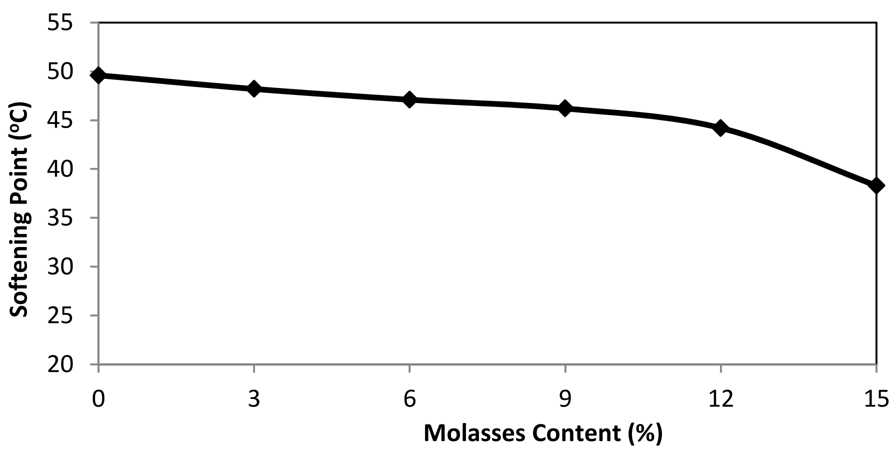


Figure 4-2 Softening point test result

4.1.3. The Effect of Molasses on Ductility

A summary of the average values of the ductility test is presented in Figure 4-3 below. The result of ductility test shows decrease in ductility values up on increasing percentage of Molasses. The decrease in ductility value implies the breaking of the binder rapidly under a standard testing condition. And it is generally considered that a binder with a very low ductility will have poor adhesive properties.

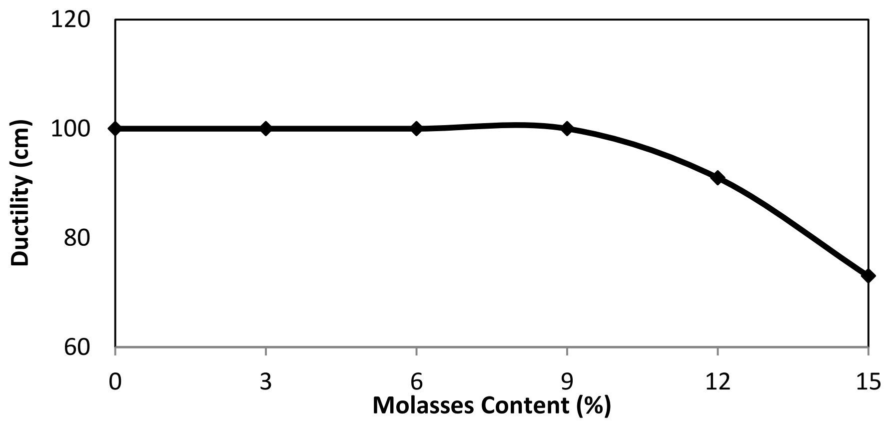


Figure 4-3 Ductility test result

4.1.4. Effect of Aging

After aging Penetration and Ductility tests were conducted for each percentage of mixes i.e. for virgin asphalt binder, 3% Molasses, 6% Molasses and 9% Molasses. Whereas, for 12% and 15% Molasses it was not possible to conduct any testing because of formation of crystals and segregation because of addition of higher percentage of Molasses with respect to the others.

After aging the result for the penetration decreased as expected because of volatization and oxidation which makes it stiffer for all the mixes and the decrease in the value of penetration was similar for the virgin binder and for the other mixes. While the ductility value showed no variation before and after RTFOT. The following Figure 4-4 and Figure

4-5 below show the decrease in penetration and ductility test results before and after RTFO.

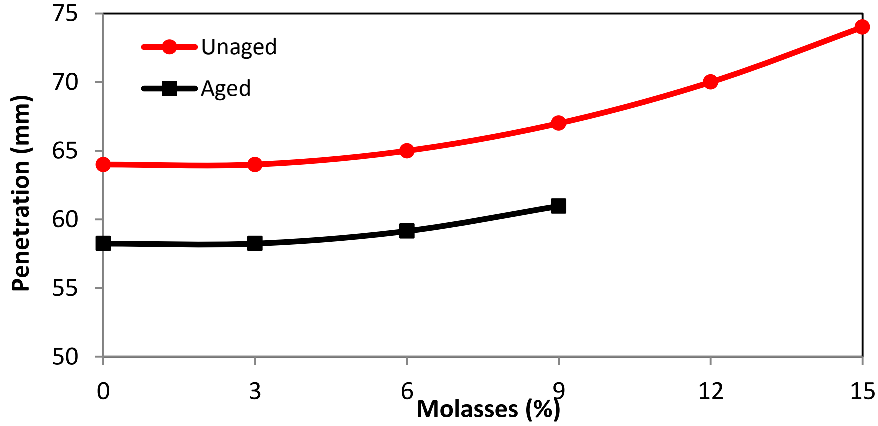


Figure 4-4 Comparison between penetration for aged and unaged binder

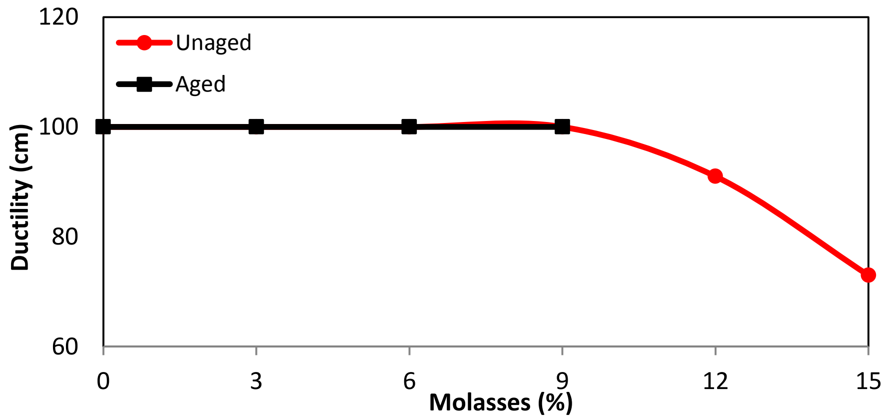


Figure 4-5 Comparison between ductility for aged and unaged binder

4.2. The effect of Molasses on The Rheological Property of Asphalt Binder

4.2.1. The Effect of Molasses on Amplitude Sweep Test

Test results from the DSR amplitude sweep are presented graphically in the figures below. The main reason for conducting the AST is to determine the linear visco-elastic range (LVER). The limit of LVER is determined as the point beyond which the complex modulus decreases to 95% of the measured value at zero-strain. A typical LVER is determined for 3% Molasses at 21.1^{o}C (Figure 4-6).

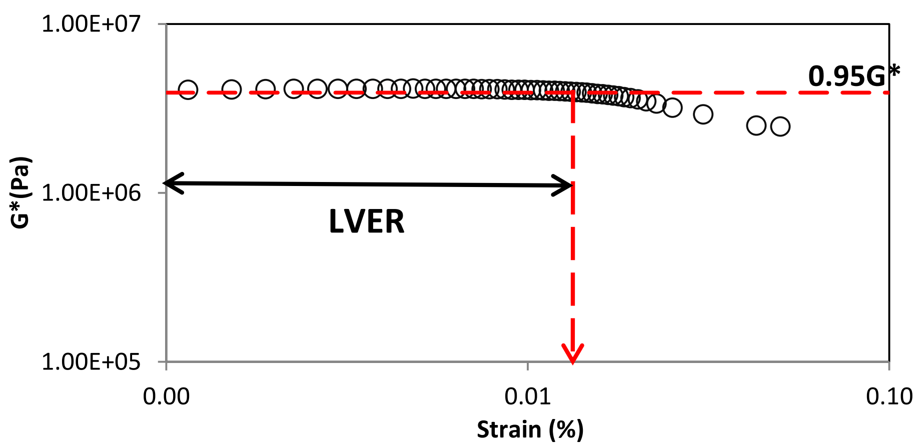


Figure 4-6 A typical LVE range for 3% Molasses (37.8^{o}C)

Table 4-1 shows the Visco-elastic Range for all of the binders tested and a typical LVER. As it can be seen, as the molasses content increases the LVER increases and as the temperature also increases the LVER increases. This is because at high temperature the binder becomes viscous.

Table 4-1 Visco-elastic region for aged and unaged binder mixes

Binder Type	Temperature (^{o}C)	LVER Strain Value (%)	
		Unaged	Aged
Virgin Binder	21.1	1.4	< 1.3
	37.8	11.0	6.0
	54.4	103.0	40.0
3% Molasses	21.1	1.5	1.3
	37.8	13.0	7.8
	54.4	110.0	39.0
6% Molasses	21.1	>2.0	3.1
	37.8	15.0	20.3
	54.4	119.0	100.3
9% Molasses	21.1	>3.0	3.4
	37.8	19.0	20.5
	54.4	123.0	101.0

The addition of different percentage of Molasses influenced the rheological property of asphalt binder differently. As it can be seen from the figure 16 below addition of 3% Molasses has almost no effect on the rheological property asphalt binder while the addition of 6% and 9% Molasses has almost the same effect on the rheological property asphalt binder, thus influencing the linear visco-elastic Range (LVER). Similarly, the addition of Molasses in asphalt binder increased the LVER.

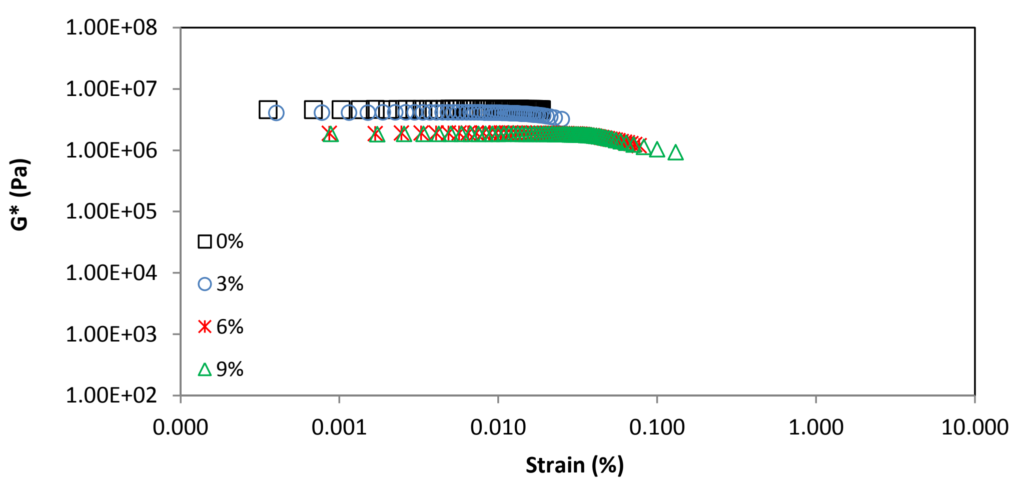


Figure 4-7 The effect of Molasses on Asphalt binder on a typical temperature (21.1^{o}C)

From the AST result, the complex modulus decreased almost ten times with increasing temperature. This is because as temperature increases the materials will have a larger viscous component there by decreasing the complex modulus and increasing the phase angle. Figure shows a typical complex Modulus VS strain for aged 3% Molasses. More figures related to AST results are presented in **Appendix B.**

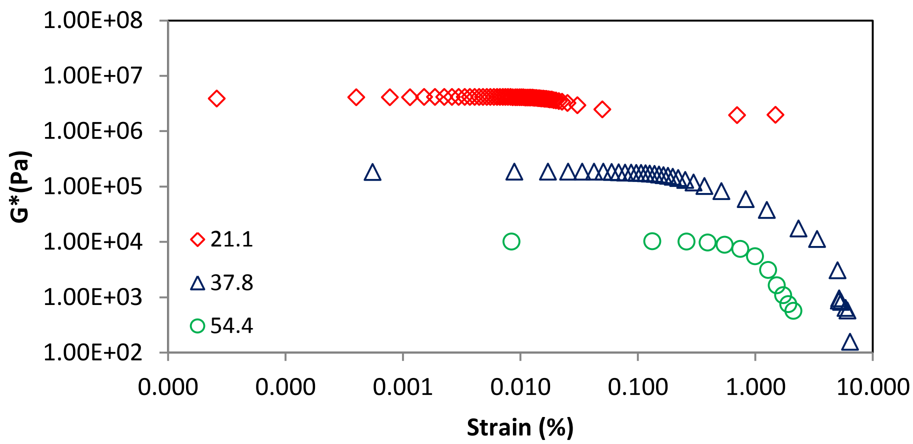


Figure 4-8 Complex Modulus verses strain for aged 3% Molasses

4.2.2. The Effect of Molasses on Frequency Sweep Test

The Figures below present the DSR frequency sweep test results (complex modulus Vs Frequency and phase angle Vs Frequency) for a typical Molasses percentage.

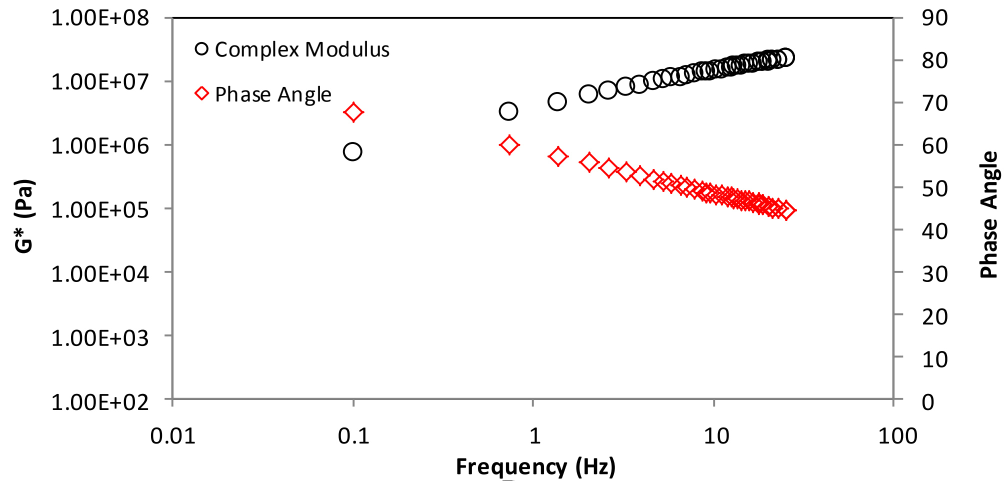


Figure 4-9 Frequency sweep test result for aged 3% Molasses (21.1°C)

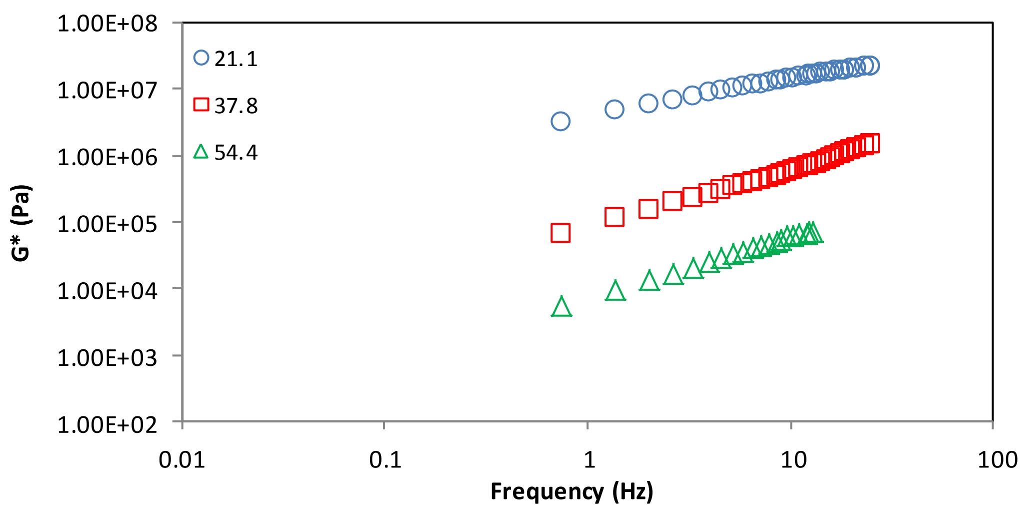


Figure 4-10 Complex modulus verses frequency for aged 3% Molasses

As seen from the Figures above, complex modulus values have increased with the increase in frequency, while they decreased with the increase of the temperature. And the phase angle values have increased with the decrease in frequency, while they increased with the increase of the temperature as it did for AST.

In general, the increase in complex modulus due to the increase of the frequency is based on the fact that the material is in the plastic region at low frequencies (high values for phase angle). More figures related to FST results are presented in **Appendix C.**

Generally, frequency sweep tests are performed in order to construct master curves that will determine the rheological properties of mixes. Dynamic shear complex moduli at different test temperatures and frequencies could be determined by using the time-temperature superposition principle. In constructing the master curves using the time-temperature superposition principle, test data collected from the DSR at different temperatures and loading times, in terms of stiffness (shear complex modulus & Phase angle), are compared to a reference temperature, which is in our case 21.1 °C. The data at any other temperatures were shifted with respect to time until various curves overlap almost perfectly to form a single master curve. Different scholars use different models for shifting to single reference temperatures. But a research developed at the University of Maryland showed that the master curve for binders can be represented by a sigmoidal function (Design Guide, 2004) defined by equation

$$\log(G^*) = \delta - \frac{\alpha}{1 + e^{(\beta + \gamma \log(f_r))}}$$

$$\phi = -90 * \delta\alpha - \frac{\exp^{(\beta + \delta(\log f_r))}}{[1 + e^{(\beta + \delta(\log(f_r))}]^2}$$

Where G* = dynamic modulus

fr = loading frequency at the reference temperature (reduced frequency)

Φ= phase angle

δ = minimum modulus value

δ + α = maximum modulus value

β, γ = parameters describing the shape of the sigmoidal function

In this research the master curves is constructed fitting a sigmoidal function to the measured complex modulus test data using nonlinear least squares regression, which can be done using the Solver Function in the Excel spreadsheet. The shifting could be done by solving shift factors simultaneously with the coefficients of the sigmoidal function, using any available shifting function to solve reduced frequency (f_r) as a function of temperature.

For complex modulus master curve, parameter γ influences the steepness of the function (rate of change between minimum and maximum) and β, the horizontal position of the turning point. Parameters β and γ, on the other hand, depend on the characteristics of the asphalt binder and the magnitude of δ and α (Design Guide, 2004).

Accordingly the DSR data from the three test temperatures (21.1°, 37.8°, and 54.4°C) were used to construct the master curves for asphalt binder and asphalt binder containing Molasses both aged and unaged, and the following shift factors have been developed to construct the master curves for complex modulus.

Table 4-2 Shift factors for complex modulus master curves for aged and unaged binder

Aging Condition	Molasses Content(%)	α	β	γ	δ	$a_{21.1}$	$a_{37.8}$	$a_{54.4}$
RTFO	0	52.29	-1.85	-38.88	0.13	0.00	-1.41	-2.69
	3	51.38	-2.46	-40.79	0.18	0.00	-2.05	-3.23
	6	51.40	-2.43	-40.74	0.17	0.00	-1.77	-3.12
	9	51.76	-2.27	-40.39	0.16	0.00	-1.67	-3.07
Unaged	0	55.81	-2.57	-47.53	0.26	0.00	0.00	-0.70
	3	51.79	-2.20	-40.31	0.17	0.00	-1.71	-2.84
	6	51.47	-2.35	-40.69	0.18	0.00	-1.75	-2.98
	9	51.60	-2.27	-40.54	0.18	0.00	-1.67	-2.83

The parameter α is defined as minimum stress level that would cause the damage; δ + α are defined as the maximum stress that would cause instantaneous damage; and the β and γ are described as the shape of the sigmoidal function. All of these values vary for each binder type. As for the temperature shift factors, $a_{21.1}$ is zero for all the binder types because all the parameters are shifted to 21.1°C. Whereas for $a_{37.8}$ and $a_{54.4}$the values are all negative because the stiffness parameters are shifted to reduced temperature which is 21.1°C.

Figure 4-11 and Figure 4-12 below present the complex modulus master curves for aged and unaged binders.

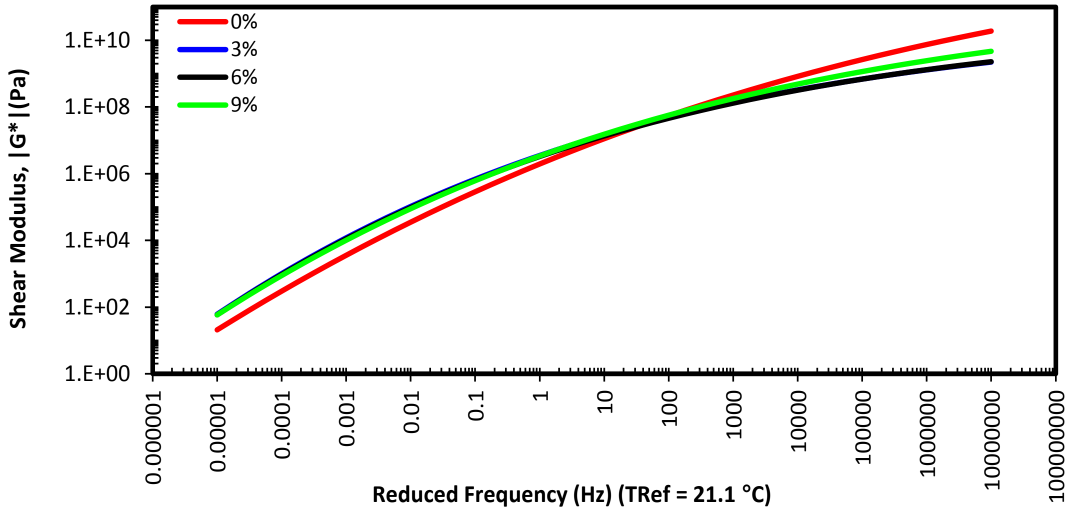


Figure 4-11 Complex modulus master curve for aged binder mixes

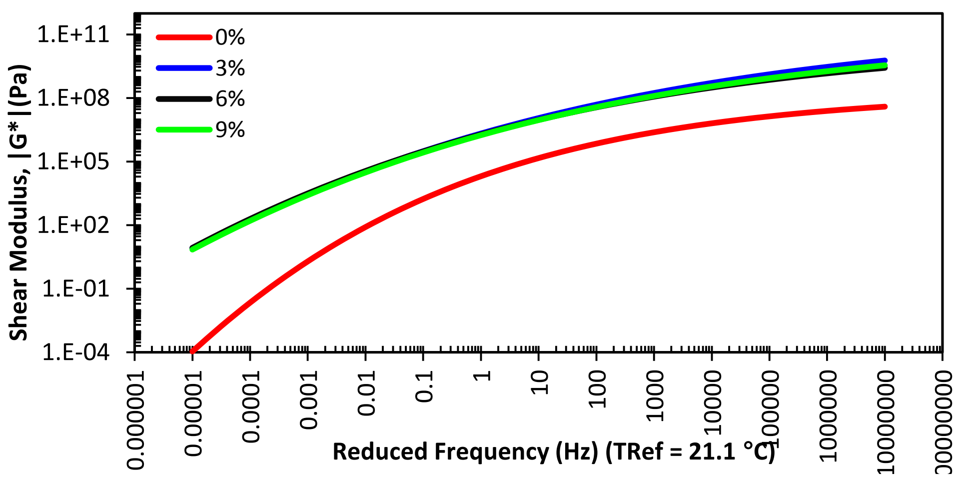


Figure 4-12 Complex modulus master curve for unaged binder mixes

From the above figure it can be seen that for aged binder mixes at high temperature and low loading frequency addition of Molasses has a positive effect on asphalt binder thereby increasing its stiffness i.e. showing a modification property.

As for unaged binder, addition of Molasses has a significant advantage thereby improving the property of asphalt binder for all loading frequencies or temperature conditions.

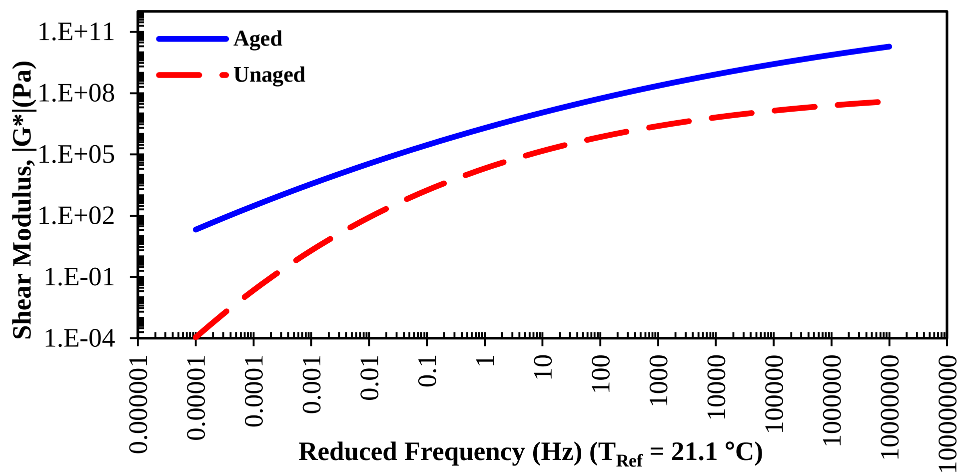


Figure 4-13 The effect of aging on neat asphalt binder

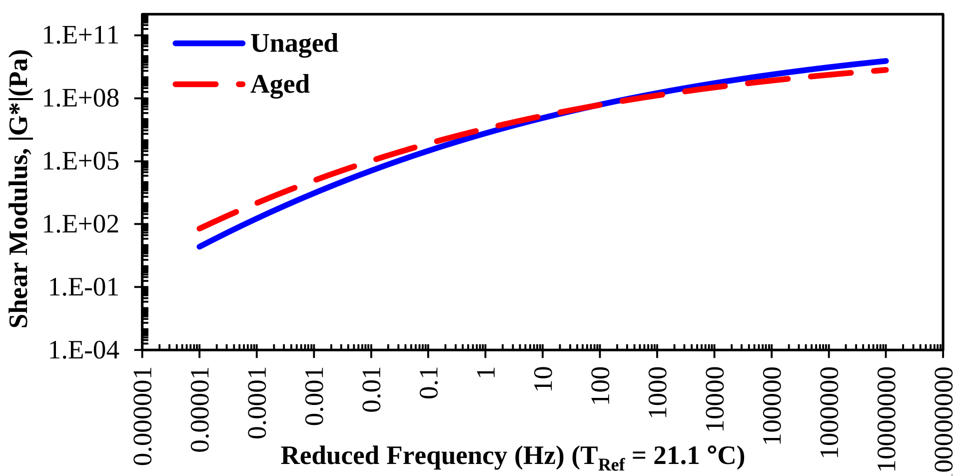


Figure 4-14 The effect of aging on 3% Molasses

From the above two figures it is clearly seen that the asphalt binder containing Molasses is less affected with aging compared to the virgin asphalt binder which is also an advantage for the mixed binder i.e. the presence of Molasses reduces the aging effect of a binder. This may be due to the fact that bitumen contains Sulphur and as the molasses content increases the percentage of bitumen decreases there by decreasing sulfur content. John mentioned that sulfur plays an important role in the ageing of bitumen because it is more chemically reactive than hydrogen or carbon, and can oxidise more easily than the hydrocarbons

Frequency sweep data were also used for the construction of phase angle Master curves. Phase angle Master curves are shown below.

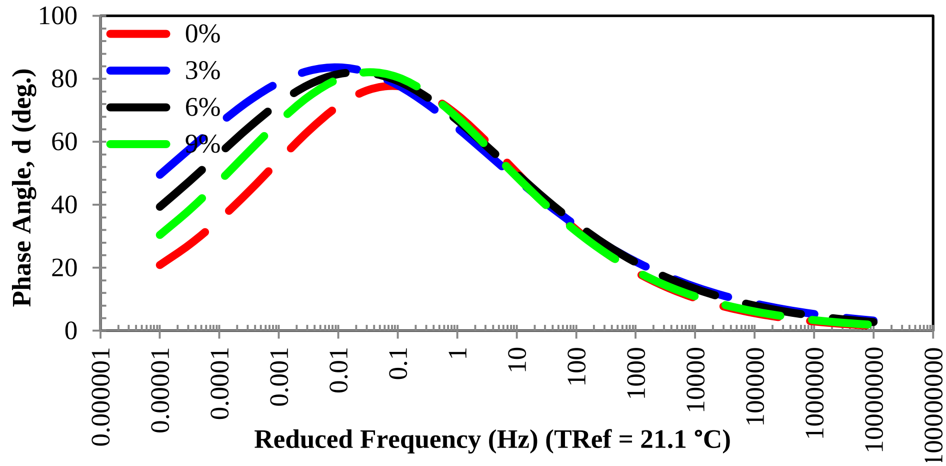


Figure 4-15 Phase angle master curve for aged binder mixes

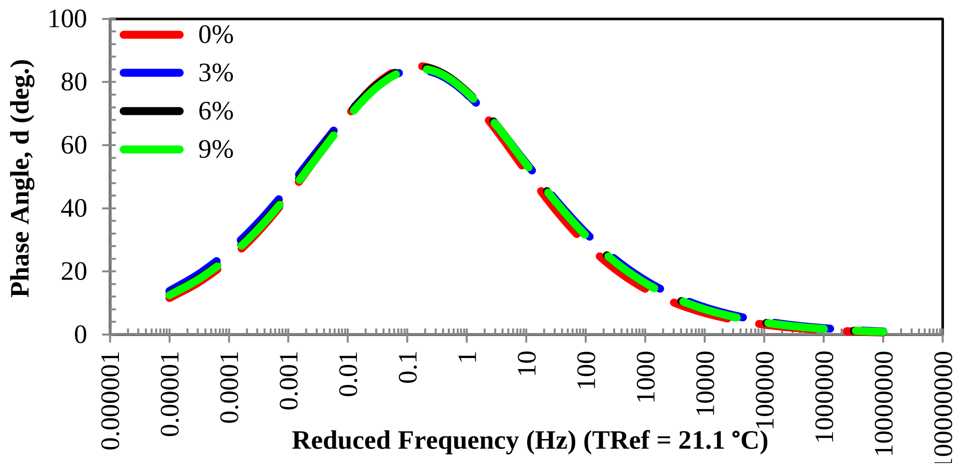


Figure 4-16 Phase angle master curve for unaged binder mixes

At low temperature and high frequency addition of Molasses in asphalt binder has almost no effect. While at high temperature and low loading conditions Molasses has high effect on asphalt binder.

Additional FST related results are presented in **Appendix C.**

4.2.2.1. Statistical Analysis of FST Result Using ANOVA

Succeeding the laboratory procedures and data collection, statistical analysis was performed to evaluate the significance of addition of Molasses to asphalt binder using one-way analysis of variance (ANOVA).

A one-way ANOVA uses two different estimates of sample variance. The first estimate is called the between-group variance, and it involves finding the variance of the means. The second estimate, the within-group variance, is made by computing the variance using all the data and is not affected by differences in the means.

The four groups of independent variables i.e. 0%, 3%, 6% and 9%, were considered. For this analysis the statistical model below is adopted.

$$Y_{ik} = \mu + \alpha_k + e_{ik}$$

Where Y_{ik}= i^{th} score in the k^{th} group

μ = Grand mean of the population.

$\alpha_k = \mu_k - \mu$ = effect of belonging to group k

e_{ik}= Random error associated with this group

On this research the ANOVA consists of two random samples from each of four independent groups. And the null hypothesis (Ho) is that the neat asphalt binder and the three percentages of Molasses are equally effective. This means, there is no rheological behavior change in asphalt binder up on addition of different percentages of Molasses.

Therefore the null hypothesis Ho: $\mu1 = \mu2 = \mu3 = \mu4$

Whereas the alternative hypothesis H1: at least one percentage has a change in rheological property of asphalt binder up on addition of Molasses

This analysis testing of the hypothesis is done at 0.1 level of significance at three frequencies i.e. at 10^7, 10 and 10^{-5} Hz. The test statistics for one way ANOVA is the F ratio i.e. the ratio of between the group variance and the within group variance. For each of the four percentages two samples were tested.

For F test, degree of freedom for between-group variance is k-1, where k is the number of groups and the degree of freedom within-group variance N- k, where N is the sum of the sample sizes of the groups. Therefore, degree of freedom for between-group variance is 4-1= 3 and degree of freedom within-group variance is 8- 4= 4. From the ANOVA the results are summarized and presented in the table below. Details of ANOVA hypothesis testing is presented in **Appendix D** of the research paper.

Table 4-3 Summary of ANOVA hypothesis testing

Frequency (Hz)	F-Value	P- Value	F Critical	Decision
10^{-5}	4.307	0.096	4.19	Reject
10	1.676	0.308		Accept
10^{7}	6.082	0.057		Reject

The decision to accept or reject the null hypothesis is made by comparing the test statistics computed F with the critical value from the table. If the computed F value exceeds the critical value, the hypothesis is rejected; if not, the hypothesis is not rejected. The ANOVA result for FST result i.e. Master Curve, indicates that the F value exceeds the critical value from the table for frequency of 10^{7} and 10^{-5} Hz at 0.1 level of significance. While for 10Hz the reverse is true, the critical value from the table exceeds the calculated F value. Therefore the null hypothesis is rejected for frequency of 10^{7} and 10^{-5} Hz and it is accepted for frequency of 10Hz. Hence this research accepted that addition of Molasses on asphalt binder affects the rheological property of asphalt binder at high frequency (low temperature) and low frequency (high temperature) while it doesn't affect it at intermediate temperature.

4.2.3. The Effect of Molasses on Multiple Stress Creep and Recovery

The repeated shear creep test is performed using the Dynamic Shear Rheometer (DSR) by applying a controlled shear stress (100 and 3200Pa) using a load for 1 second followed by a 9-second rest period. During each cycle, the asphalt binder reaches a peak strain and then recovers before the next cycle stress is applied again. The permanent strain is then accumulated for 10 cycles total of 100 seconds. Multi stress creep recovery test gives extremely important practical information regarding asphalt binder. Since asphalt pavements (flexible pavements) are designed to be flexible, they must quickly return to their original configuration after loading. Rutting is one of the few failure mechanisms associated with inelastic or permanent deformation**.** Even though the quality and gradation of the aggregate are important parts of the asphalt mix performance, the creep response of the binder is also a contributing factor.

For this study, repeated shear creep testing was conducted at four temperatures 52°, 58°, 64° and 70 °C after determination of performance grade for each binder mix. Test result for Performance Grade determination is presented on **Appendix E**.

Figures below show that the total strain was influenced by addition of Molasses. As the Molasses percentage increases the total strain value decreases showing improving behavior. The smallest total strain values were obtained for Molasses of 9%, followed by the 6% and 3% Molasses.

Figure 4-17 and Figure 4-18 and Figure 4-19 below show effect of temperature on MSCR and the effect of addition of Molasses on the MSCR test result respectively.

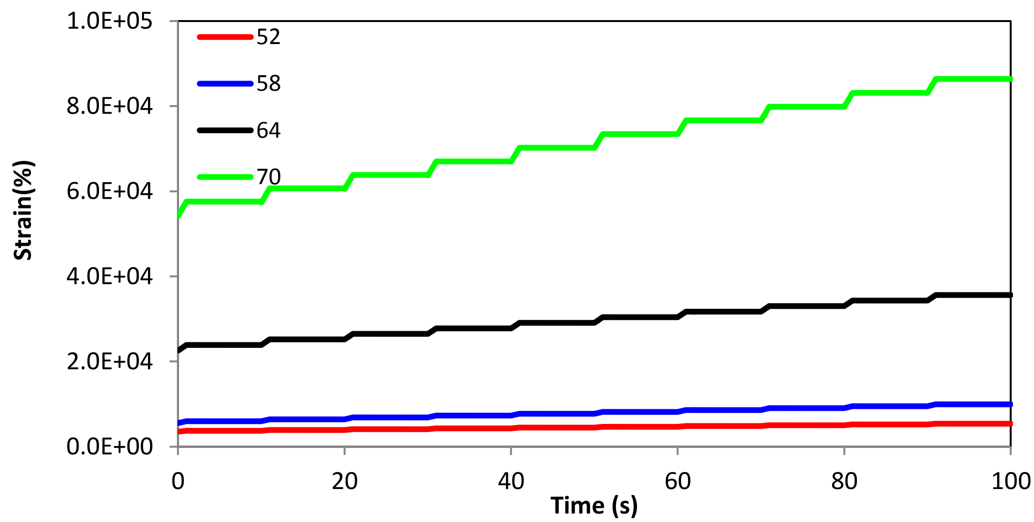


Figure 4-17 Effect of temperature on MSCR for 6% Molasses content (3.2kPa)

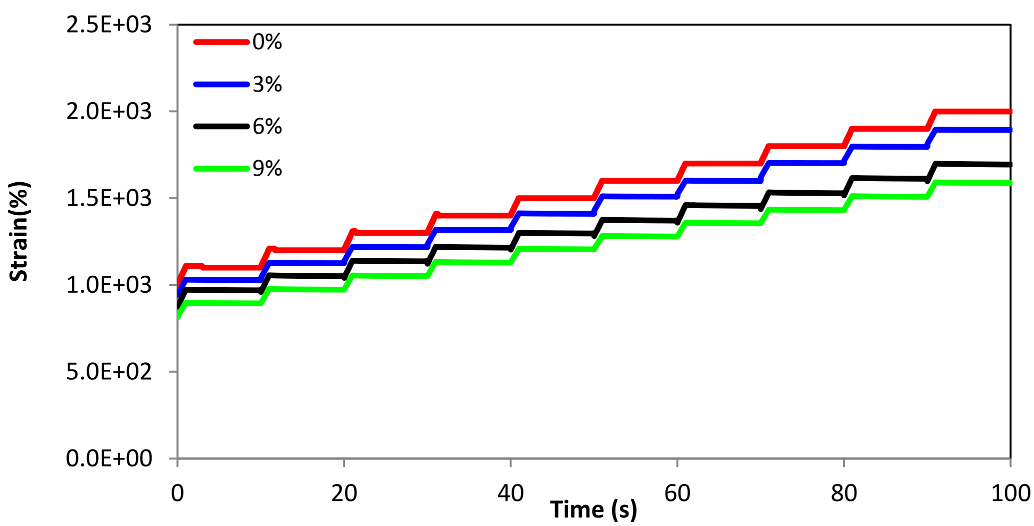


Figure 4-18 Effect of Molasses on strain at 0.1 kPa (70°C)

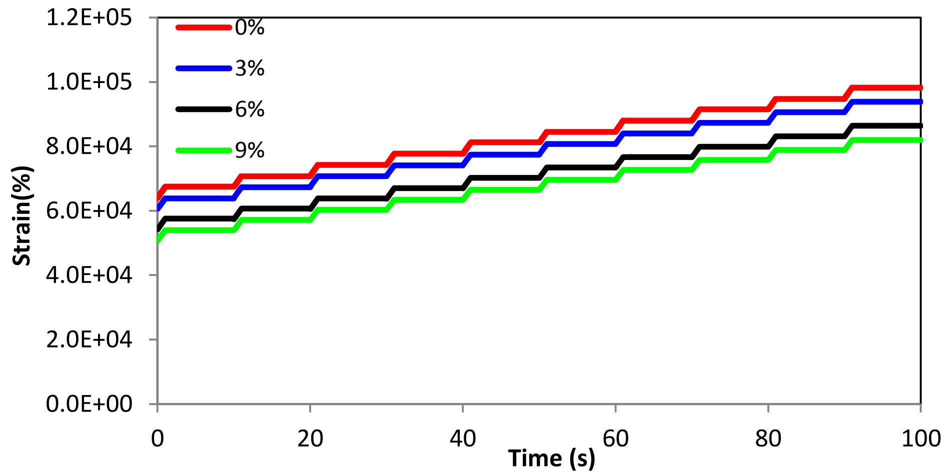


Figure 4-19 Effect of Molasses on strain at 3.2 kPa (70°C)

MSCR test is conducted to determine the rutting parameter (Jnr). The Jnr is calculated as:-

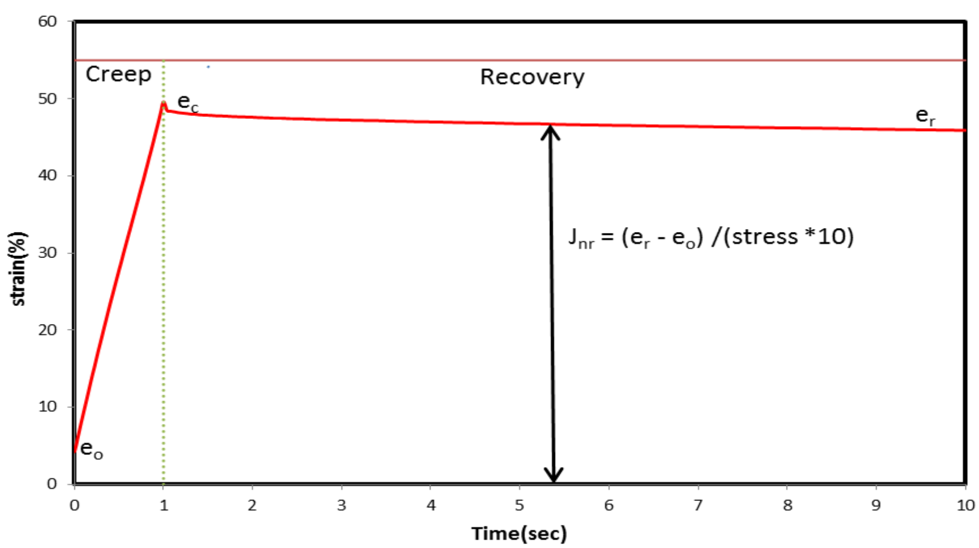


Figure 4-20 Determination of the rutting parameter (Jnr)

From the figures below it is shown that the rutting parameter (Jnr) decreases as the percentage of Molasses increase and increases as the temperature increases. This refers that addition of Molasses could improve the resistance of asphalt pavements to rutting at all temperatures especially at lower temperatures. Table shows the rutting parameter

(Jnr) and percentage recovery (PR) for all the binder mixes. Other MSCR test results are shown in **Appendix F** of the research paper.

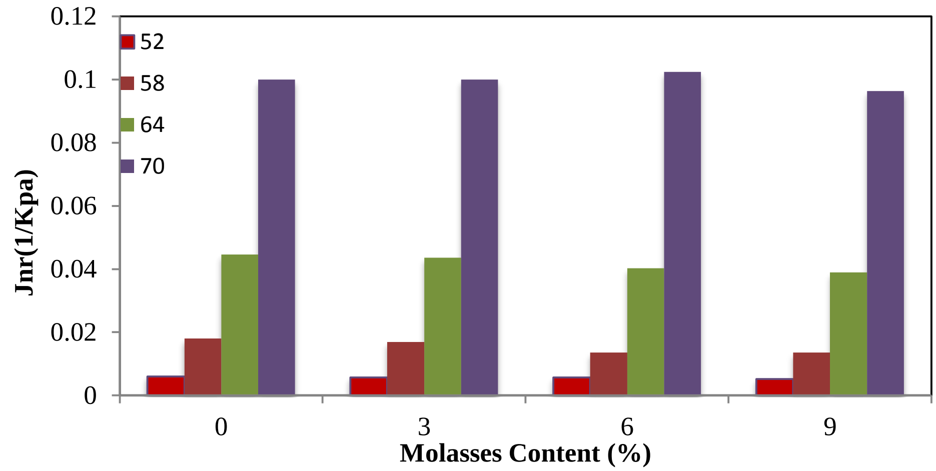
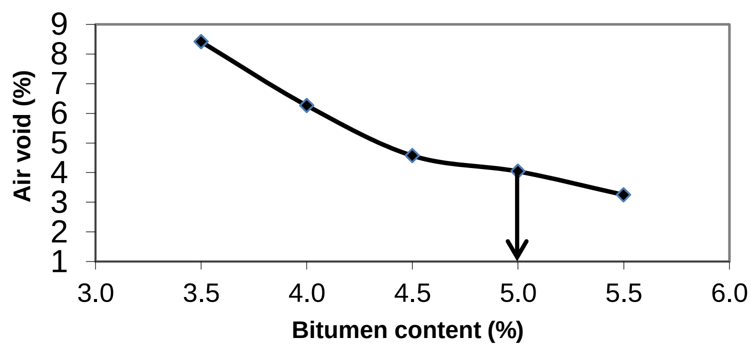


Figure 4-21 The effect of temperature and molasses content on J_{nr} (3.2kPa)

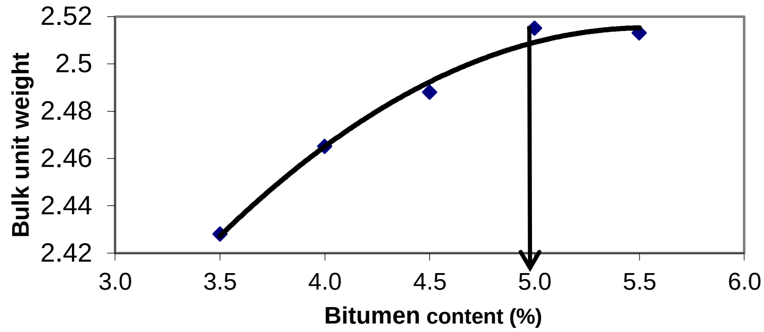
4.3. The Effect of Molasses on HMA Properties

4.3.1. Optimum Binder Content

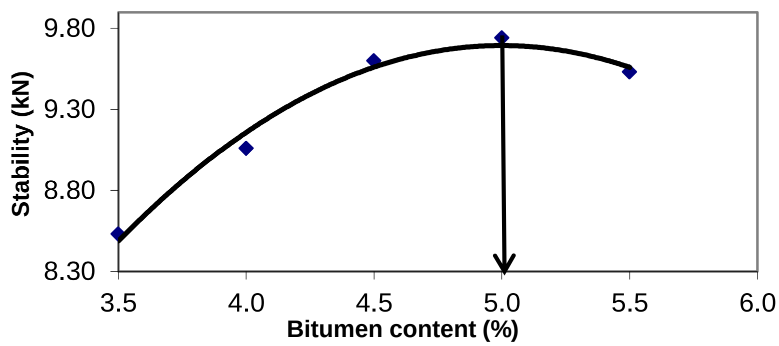
As mentioned earlier the optimum Binder Content was found out by taking the average value of the bitumen content correspond to maximum stability, the bitumen content correspond to maximum unit weight. And from the figures below the corresponding optimum bitumen content for the mix was found to be 5%. Detail laboratory test results are presented in **Appendix G** of the paper.



(a)



(b)



(c)

Figure 4-22 Optimum Bitumen content determination (a) Bitumen content versus Va (b) Bitumen content verses (C) Bitumen content verses stability

4.3.2. The Effect of Molasses on Marshall Properties

4.3.2.1. Effect of Molasses on Marshall Stability

The inclusion of Molasses has influenced the behavior of the asphalt concrete mixes. The Figure below shows the relationship between Marshal Stability and Molasses content. The general trend shows that as the Molasses content increases to 3%, the stability slightly decreases and continues to decreases as the Molasses content increases. Even though, stability slightly decreased with increase in Molasses content, the stability of mixes at Molasses content up to 11% were within the limits of Marshall Criteria for heavy traffic, i.e., above 8 kN.

Generally, the stability of HMA prepared by partially replacing asphalt binder with Molasses decreases as the Molasses content increases. As the molasses content increases to 3% the stability of the HMA is not affected but as the molasses content further increases the stability decreases by 1.5%, 17%, 22% and 27% for molasses contents of 6%, 9%, 12% and 15% respectively. The decrease in stability value in addition of Molasses on HMA can be explained as a result of relatively poor adhesion, as compared to conventional asphalt mix, developed between bitumen and aggregates due to intermolecular bonding. A better adhesion improves intermolecular attractions which in turn enhance strength of asphalt mix, which help to increase durability and stability of the asphalt mix.

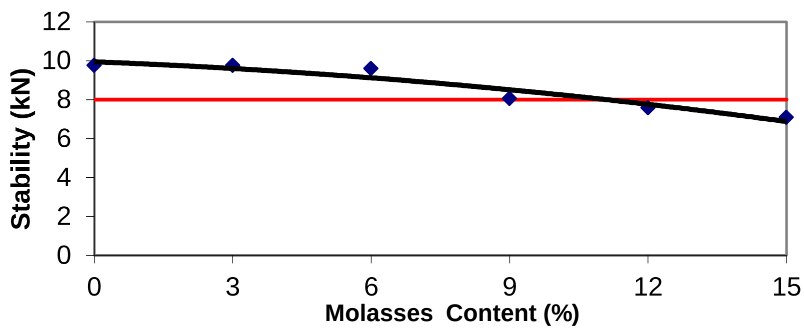


Figure 4-23 The effect of Molasses Content on Marshal Stability

4.3.2.2. Effect of Molasses on Flow Value

Generally, the flow property of the mixture, as shown in Figure, unaffected as the Molasses content increases to 3% then it slightly decreases by 1.9% from the initial flow value at 6% Molasses content then it decreases by 7.3% at 9% then decreases by 13% at 12% and finally decreases 22% at 15% molasses content. with further increase in the amount of Molasses. This may imply that as Molasses content increases the interlocking between particles decreases compared to the conventional HMA.

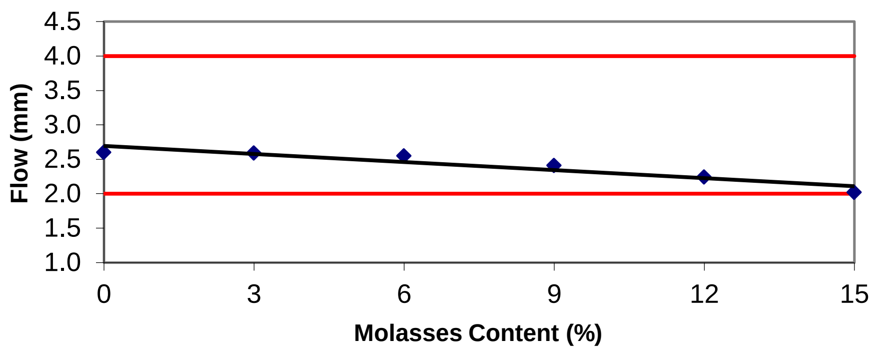


Figure 4-24 The effect of Molasses Content on Flow Value

4.3.2.3. Effect of Molasses on Bulk Specific Gravity

The partial replacement of Molasses has influenced the unit weight of the asphalt concrete mixes as shown in the Figure below. The general trend shows that the bulk specific gravity decreases as the molasses content increase. The maximum bulk specific gravity is 2.515g/cm^3 which the unit weight of the conventional HMA and the minimum unit bulk unit weight is 2.456g/cm^3 at 15% Molasses content.

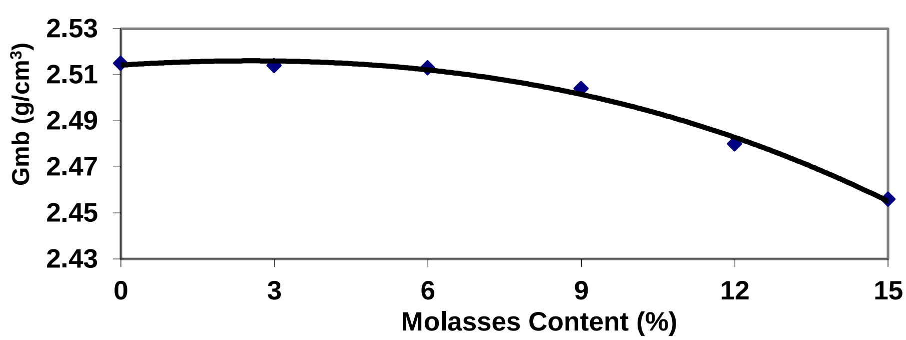


Figure 4-25 The effect of Molasses Content on Flow Value

4.3.2.4. Effect of Molasses on Air Void (Va)

In general, the Va of HMA Prepared using Molasses shows almost no effect, i.e. Va of 4%, as the Molasses content increased to 6%. However, further increase in Molasses content has visible change thereby reducing the Va

Generally HMA Prepared using Molasses decreases the Va% though, the decrease is within the limit given in Asphalt Institute Manual Series No. 2 MS-2 which is 3-5%. Figure shows a graphical representation of air void verses Molasses content.

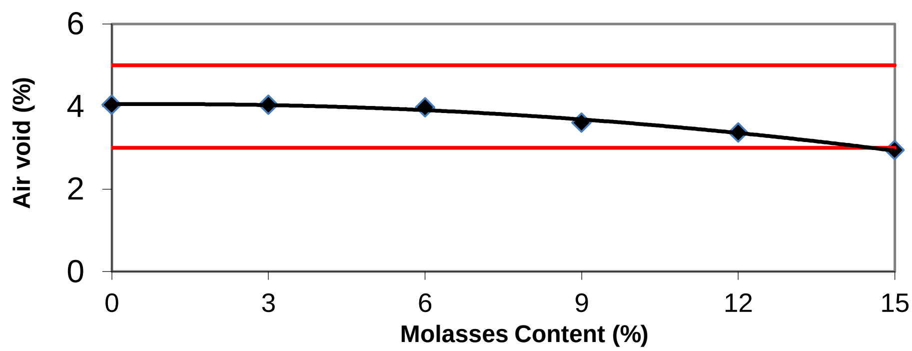


Figure 4-26 The effect of Molasses content on Air void

4.3.2.5. Effect of Molasses on VMA and VFA

Studying VMA is important because it represents the space that is available to accommodate the effective volume of asphalt and the volume of air voids necessary in the mixture. Therefore, minimum VMA is necessary to achieve an adequate asphalt film thickness, which results in a durable asphalt pavement. Increasing density of aggregate gradation to a point where below minimum VMA values are obtained leads to thin films of asphalt and low durability mix. The effect of Molasses on VMA percentage was evaluated. As the percentage of Molasses increases, the unit weight of compacted mix decreases thus increasing the VMA percentage. It is important to indicate that the values obtained for VMA are within the specification, i.e. ≥ 13%The VMA results are shown in the Figure below.

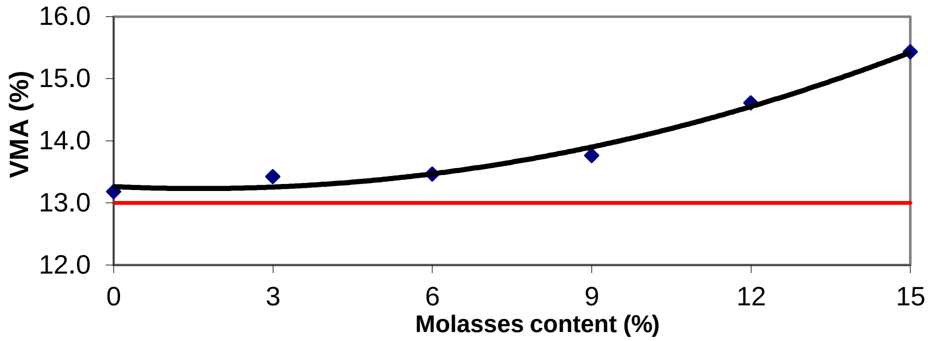


Figure 4-27 The effect of Molasses content on VMA

As indicated in the figure below, the VFA of the mixes increases with increase in Molasses content. The reason for such increase can be attributed to the increase of VMA and decrease of Va as Molasses content increases. It is important to point out that the values obtained for VFA are within the specification limits given in the Asphalt Institute Manual Series No. 2 MS-2 up to 9% Molasses content, i.e., 65 to 75%.

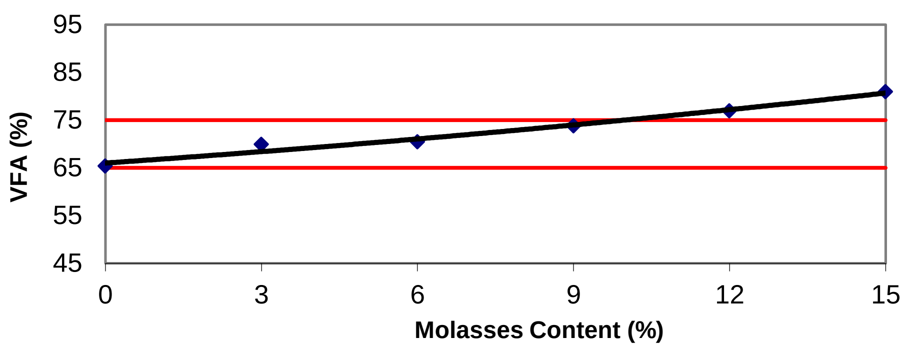


Figure 4-28 The effect of Molasses content on VFA

4.3.3. The effect of Molasses on Moisture susceptibility

A comparison of tensile strength characteristics for all the mixes were evaluated and the result showed that as the Molasses content increases, the tensile strength decreases for both conditioned and unconditioned specimens. Figure 4-29 below shows the tensile strength result for both conditioned and unconditioned samples.

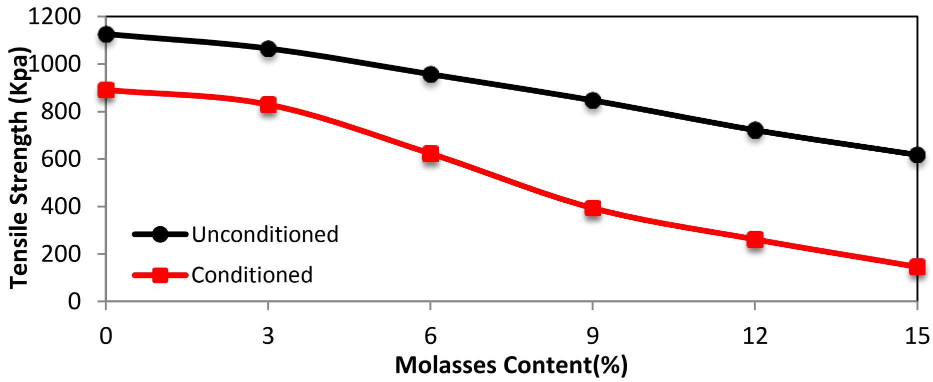


Figure 4-29 Indirect tensile strength

The higher amount of Molasses in the mixture doesn't have beneficial effect as can be seen from the result. The increase in the amount of Molasses leads to higher surface area that must be coated by Molasses, and consequently, when conditioning it in water for 24 hours at 60^{o}C the Molasses will eventually be washed by water resulting in lower tensile strength.

The TSR of all the specimens prepared for moisture susceptibility tests used in this research are shown in the table below. The result indicates that as the Molasses content increases in the HMA, the TSR value decreases which makes the HMA prepared with Molasses more vulnerable to moisture compared to the conventional HMA. It can also be seen that 3% Molasses has almost no effect on the TSR. From the test result it can be observed that the mixes including the conventional mix are moisture susceptible i.e. less than 80%. This may be due to the fact that the aggregates used for the preparation of the mixes are marginal or beyond the specification required for aggregate quality specifically water absorption. Generally, increasing the percentage of Molasses leads to a mixture that is more moisture sensitive.

Table 4-4 Indirect tensile strength results

Molasses Content (%)	ITS (kpa)		TSR (%)	Specification
	Unconditioned	Conditioned		
0	1126	891	79	≥80%
3	1066	829	78	
6	957	623	65	
9	847	393	46	
12	722	262	36	
15	617	146	24	

4.4. Summary

Based on the laboratory study presented in this chapter, the following conclusions can be drawn

- The penetration value increased, the softening point decreases, the ductility decreases as the Molasses content increased.
- The LVER of the binder increased as the Molasses content increased.
- At high temperature and low loading condition the stiffness of the binder increased as the percentage of molasses increased which shows addition of molasses improves asphalt binder properties at high temperatures.
- The strain value and the rutting parameter Jnr decreased as the molasses content increased which implies addition of molasses in asphalt binder reduces rutting of pavements.
- The HMA containing Molasses shows inferiority on all the Marshall stability and the volumetric properties compared to the conventional HMA but still within the requirements of the specification up to 10% Molasses content.
- All the mixes the conventional and the mixes containing molasses are highly affected by moisture.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

The main goal of this research study was to partially replace asphalt binder with Molasses in order to have more economical pavement structure and locally available material. Accordingly, it has been found that the addition of Molasses to asphalt binder has influenced on overall property of asphalt binder.

5.1.Conclusion

This study tries to study the conventional and rheological properties of binder mixes, HMA made from this binder mixes and their sensitivity to moisture. In doing so, test parameters were evaluated. Based on the results obtained from this study, the following conclusions can be made:

- Neat asphalt binder was more affected by aging compared to asphalt binder containing Molasses. Meaning addition of Molasses to asphalt binder decreases the aging effect of HMA mixtures.
- Addition of Molasses has affected rheological behavior of asphalt binder thereby making the asphalt binder stiffer at high temperatures which results in a durable binder.
- From test result obtained from FST, the master curve shows an improving behavior for asphalt binder up on addition of Molasses. Addition of Molasses on asphalt binder increases the stiffening property of asphalt binder at high temperatures (low loading frequencies).
- From the test result obtained from MSCR, the smallest total strain value was obtained for Molasses of 9%, followed by the 6% and 3% Molasses. Therefore addition of Molasses improves the resistance of asphalt pavements to rutting.
- The replacement of asphalt binder with Molasses at optimum binder content of 5%, decreased the stability, flow, unit weight and the Va% of the HMA, while the VMA and VFA percentages increased as the percentage of Molasses increased. The increment and reduction value of these properties of HMA up to 10% Molasses is within the Marshall criteria for heavy traffic.

- 3% Molasses has almost no effect on the TSR and all the mixes prepared for ITS test were found to be moisture susceptible and they are below the criteria specified.
- Because of time and economical limitations detailed mixes were not conducted in order to determine the optimum Molasses content since the recommended molasses content for this research is applicable only for optimum binder content of 5%.
- In general the aim this research which is addition Molasses to asphalt binder was to provide an economical and locally available binder which maintains the property of neat asphalt binder. Therefore it can be concluded that it is possible to partially replace asphalt binder with Molasses for wearing coarse up to 9% at dry areas.

5.2. Recommendation

Based on the study results the following recommendations are made.

- Molasses can be used as partial replacer for asphalt bitumen.
- It may be possible to use relatively lower asphalt bitumen when molasses is used.
- 9% Molasses can be used to partially replace asphalt binder for a binder course at dry areas and for wet areas the same percentage could be used with addition of antistripping agents (adheres).

5.3. Future Study

There is always the opportunity for future research in the area of asphalt binders and mix characterization. For this reason, future research work may include:

- Further studies are needed to characterize binders composed of Molasses and asphalt binder using different grade bitumens.

- Further studies are needed to characterize the chemistry of binders composed of Molasses and asphalt binder.

- This study determines the suitable molasses content at 5% optimum binder content. Therefore further investigations are needed to determine the Optimum Molasses content.

- Life cycle cost analysis must be conducted for roads constructed using molasses in comparison to those constructed using conventional asphalt binder.

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Appendix A – Materials Quality Test Result

Table A 1Aggregate gradation result

Sieve Size (mm)	Coarse Aggregate	Intermediate Aggregate		Fine Aggregate
	(14-20)	(6-14)	(3-6)	(0-3)
20.00	100.0	100.0	-	-
12.50	99.6	99.0	-	-
9.50	0.4	78.7	100.0	-
4.75	0.0	10.2	93.3	100.0
2.36	-	0.8	29.6	95.4
1.18	-	-	6.0	59.9
0.600	-	-	1.8	33.8
0.300	-	-	-	21.6
0.150	-	-	-	15.6
0.075	-	-	-	12.1

Table A 2 Aggregate quality test result

Type of tests	Result	Specification (ERA)
LAA (%),	22	< 30 (wearing coarse)
Flakiness Index (%),	18	< 45 %
Soundness loss (%)	2.3	< 12 %
ACV (%),	23	< 25
TFV Dry (KN)	205	-
TFV Wet (KN)	170	-
Coarse And Intermediate Aggregate (6-20)		
Bulk specific gravity (oven Dry)	2.59	N/A
Bulk specific gravity (SSD)	2.64	N/A
Apparent specific gravity	2.76	N/A
Water Absorption (%)	1.75	< 1
Fine Aggregate (0-3)		
Bulk specific gravity (oven Dry)	2.57	N/A
Bulk specific gravity (SSD)	2.62	N/A
Apparent specific gravity	2.75	N/A
Water Absorption (%)	2.04	< 2
Filler		

Bulk specific gravity (oven Dry)	2.59	N/A
Bulk specific gravity (SSD)	2.63	N/A
Apparent specific gravity	2.72	N/A
Water Absorption (%)	1.83	< 2

Table A 3 Bitumen quality test result

Test	Results	ERA specifications limits
Penetration(0.01mm)	64	60-70 (60/70bindergrade)
Ductility (cm)	100	Min50
Softening point(^{o}C)	49.6	(46-56)
Flashpoint(^{o}C)	312	Min 232^{o}C
Specific gravity (g/cm^{3})	1.021	0.97-1.06

Table A 4 Molasses quality test result

Property	Value
Color	Dark Brown
Appearance	Syrupy
Purity (%)	48.1
Brix (%)	70.3

Appendix B - Amplitude Sweep Test Results

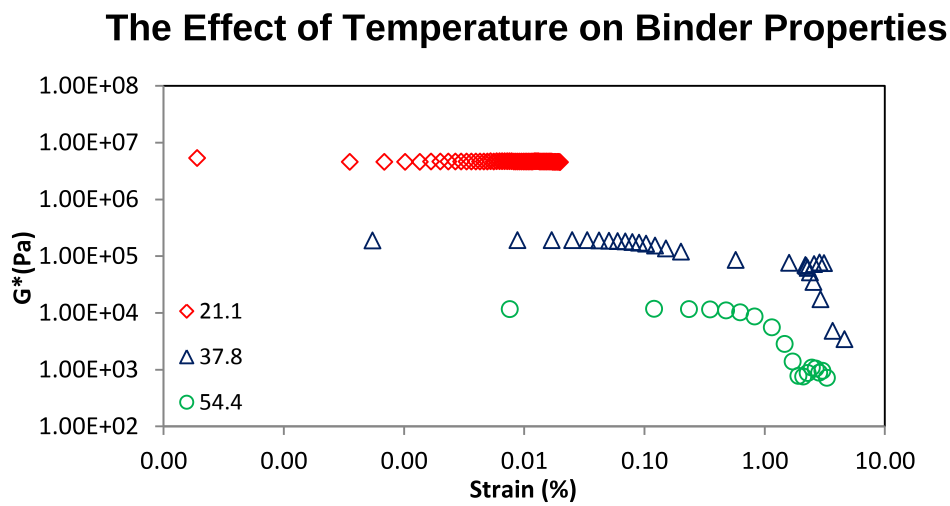

Figure B 1 AST Result for aged 0% Molasses

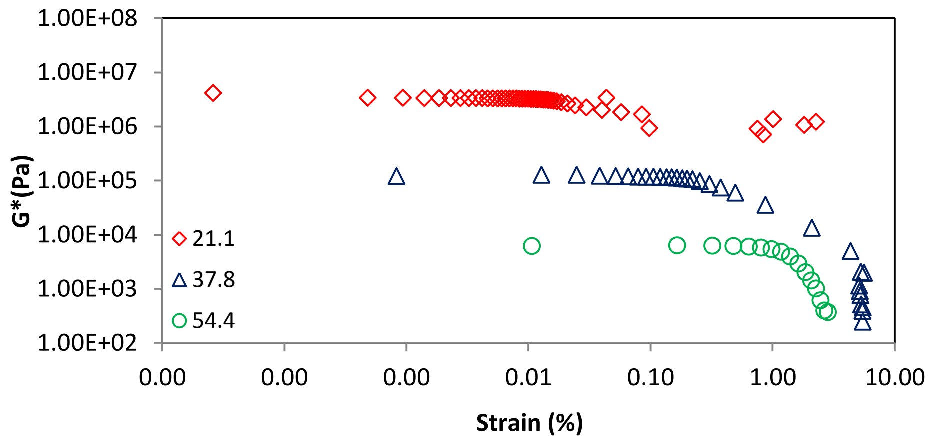

Figure B 2 AST Result for unaged 3% Molasses

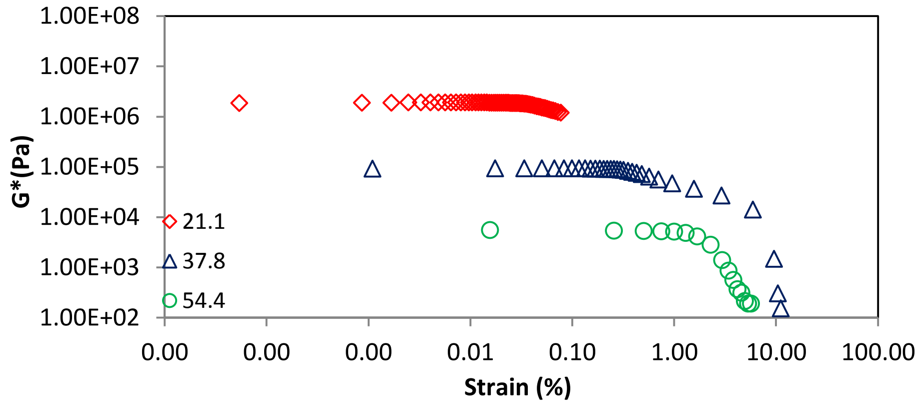

Figure B 3AST Result for aged 6% Molasses

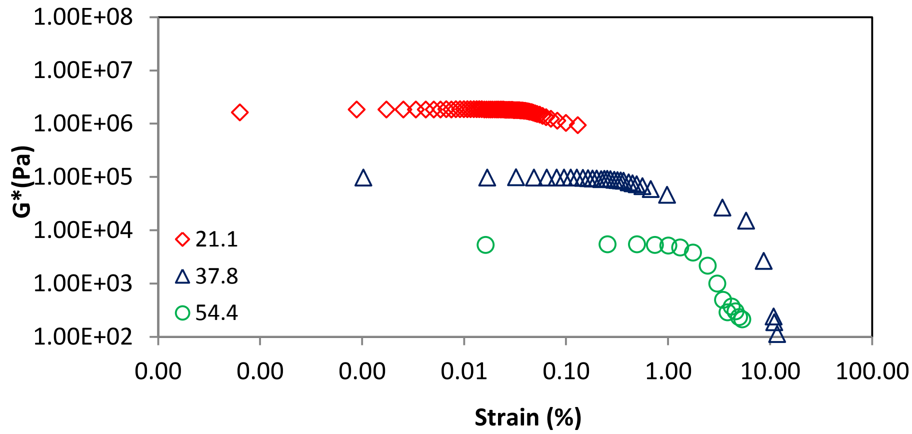

Figure B 4 AST Result for aged 9% Molasses

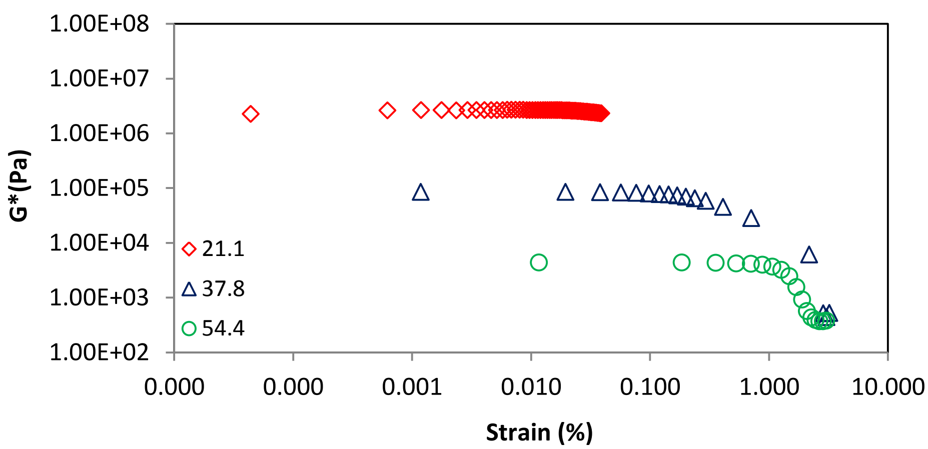

Figure B 5 AST Result for unaged 9% Molasses

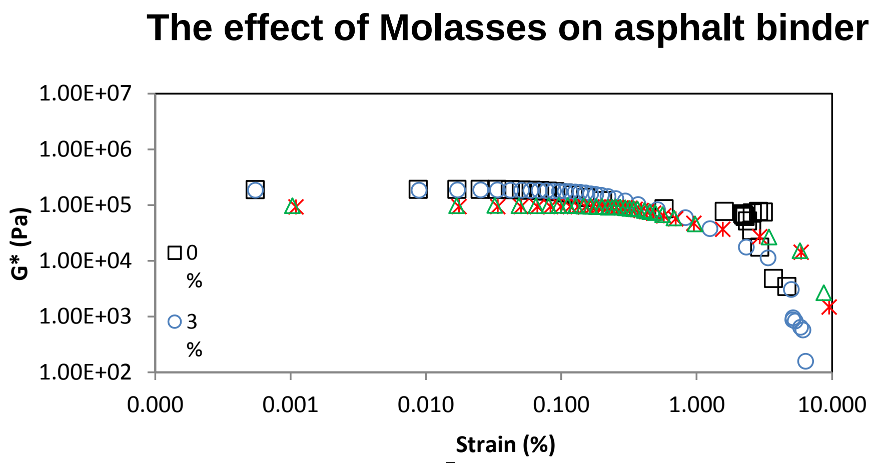

Figure B 6 The effect of Molasses on asphalt binder at 37.8°C

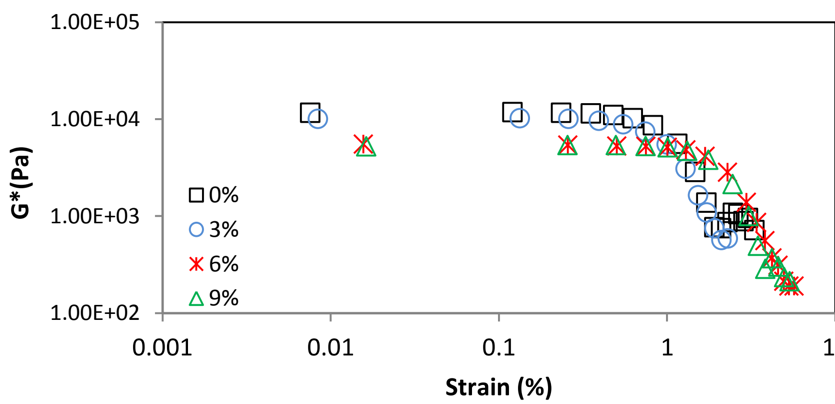

Figure B 7 The effect of Molasses on asphalt binder at 54.4°C

Appendix C - Frequency Sweep Test Result

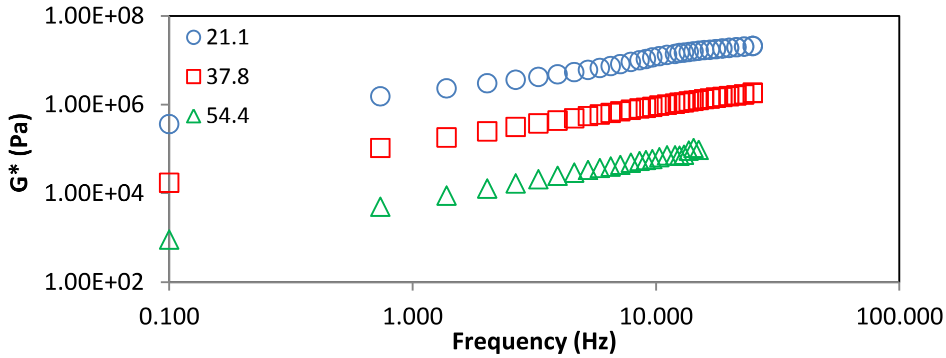

Figure C 1Aged Neat asphalt Binder

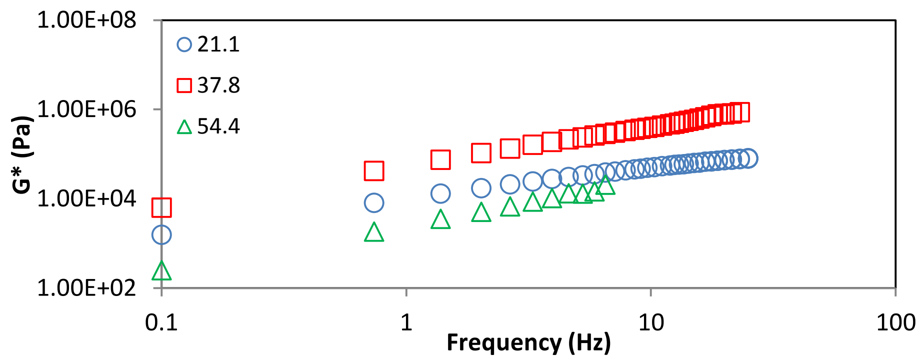

Figure C 2 Unaged Neat asphalt Binder

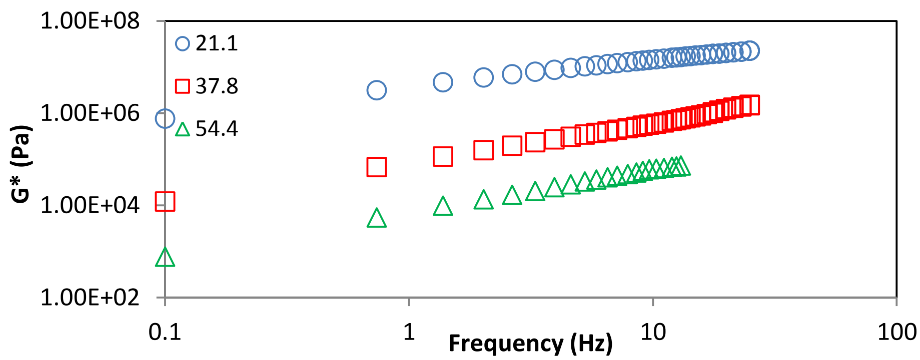

Figure C 3 Aged 3% Molasses

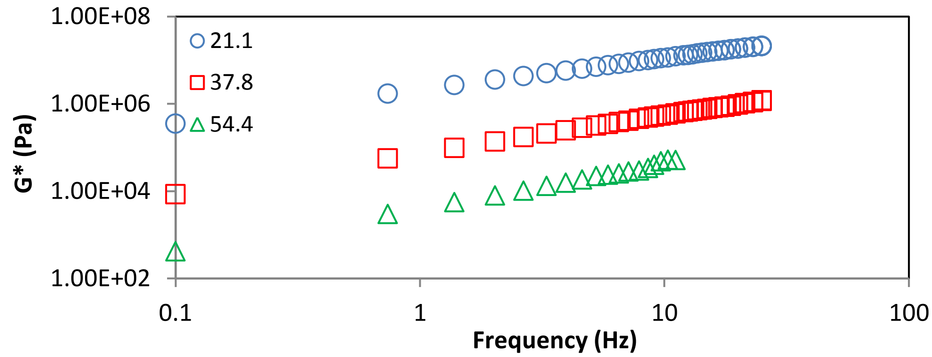

Figure C 4 Unaged 3% Molasses

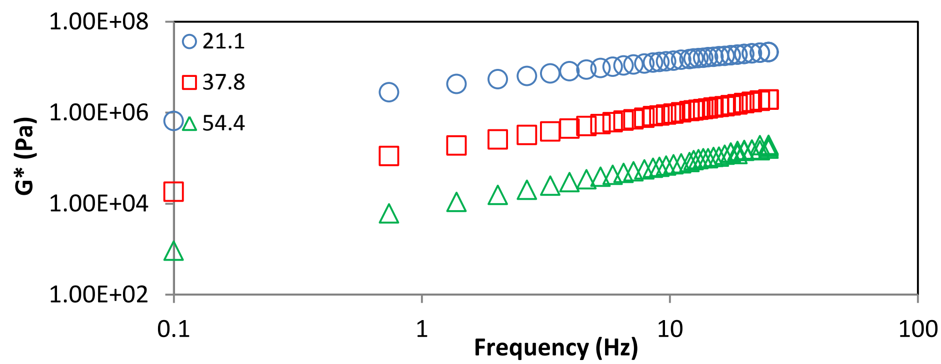

Figure C 5 Aged 6% Molasses

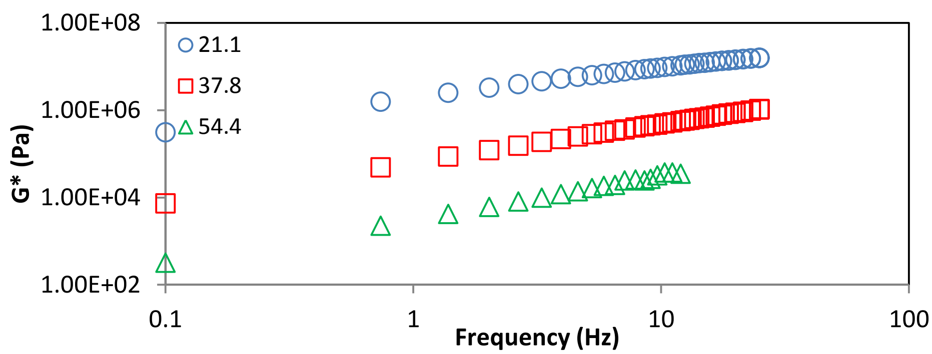

Figure C 6 Unaged 6% Molasses

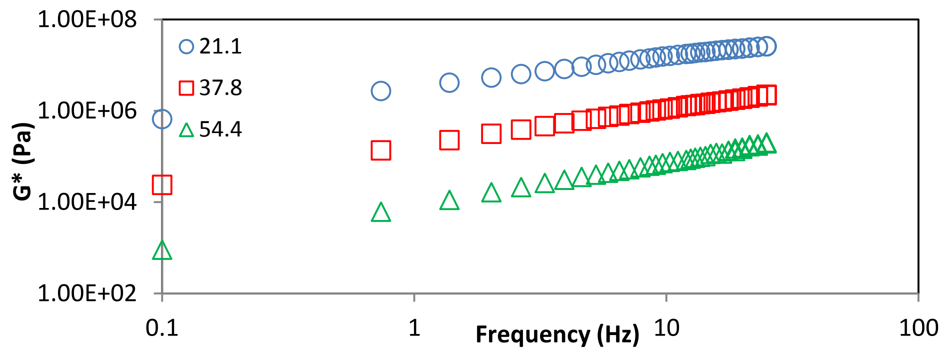

Figure C 7 Aged 9% Molasses

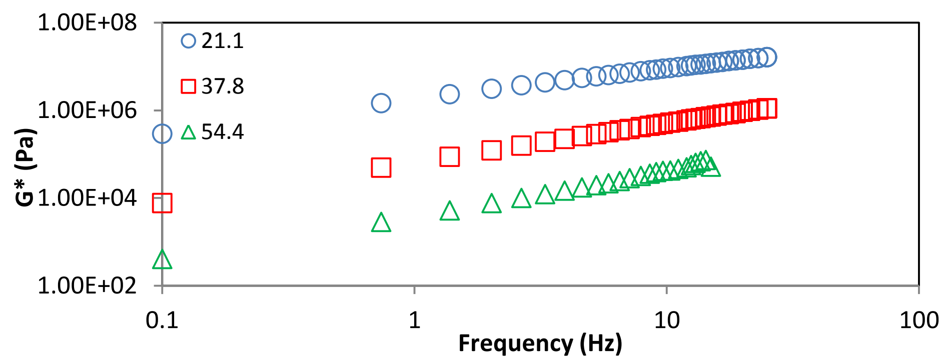

Figure C 8 Unaged 9% Molasses

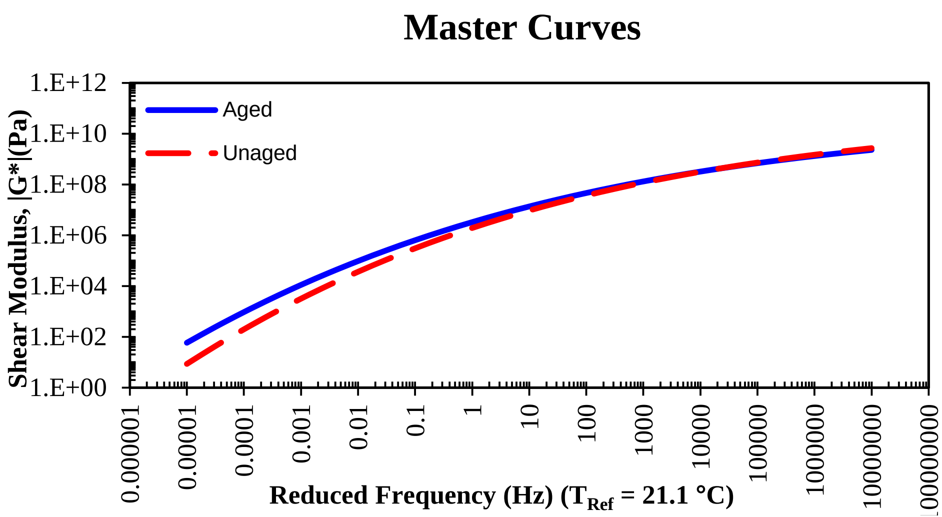

Figure C 9 The effect of aging on 6% Molasses

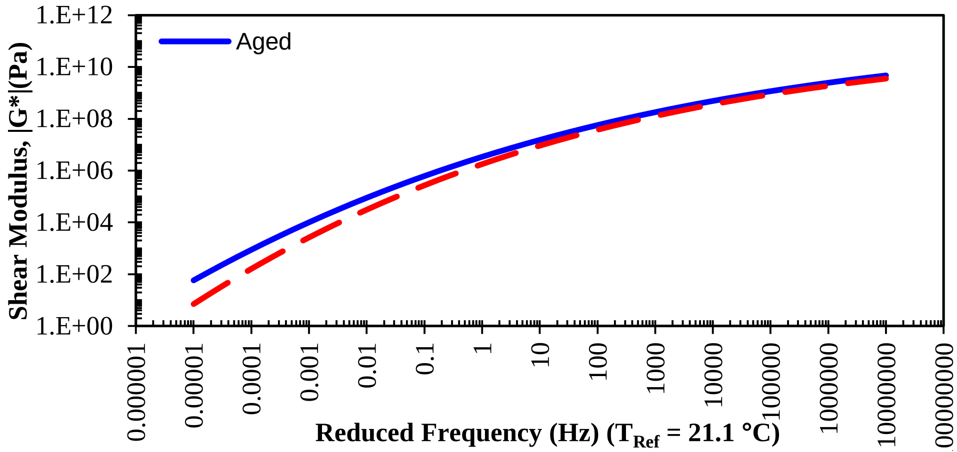

Figure C 10 The effect of aging on 6% Molasses

Appendix D – Statistical Analysis Using ANOVA

Table D 1 Statistical analysis for FST at f = 10^7 Hz using ANOVA method of treatment

Binder Type	**0%**	**3%**	**6%**	**9%**
Sample 1	4.59E+09	2.42E+09	2.44E+09	4.59E+09
Sample 2	2.71E+09	2.00E+09	2.09E+09	4.99E+09
Mean (*X*)	3.65E+09	2.21E+09	2.27E+09	4.79E+09
Variance (*Si*)	1.77E+18	9.08E+16	6.04E+16	7.95E+16
Grand Mean (*XGM*)	2.93E+09			
N= 8		K=4		
Between Group	$S_B{}^2 = \frac{\Sigma n_i\,(X_i - X_{GM})^2}{k-1}$			
	$S_B{}^2 = \frac{2\,[(3.23\,X\,10^9 - 3.65\,X\,10^9)^2 + (3.23\,X\,10^9 - 2.21\,X\,10^9)^2 + (3.23\,X\,10^9 - 2.27\,X\,10^9)^2 + (3.23\,X\,10^9 - 4.79\,X\,10^9)^2\,]}{4-1}$			
	$S_B{}^2 = 3.04\,X\,10^{18}$			
With In Group	$S_W{}^2 = \frac{\Sigma(n_i - 1)\,S_i{}^2}{\Sigma(n_i - 1)}$			
	$S_W{}^2 = \frac{(2-1)\,[1.77\,X\,10^{18} + 9.08\,X\,10^{16} + 6.04\,X\,10^{16} + 7.95\,X\,10^{16}]}{8-4}$			
	$S_W{}^2 = 5\,X\,10^{10}$			
F	F= $\frac{S_B{}^2}{S_W{}^2}$	P Value	F from table (α=0.1)	
	F= 6.08	0.057	F = 4.19	

Table D 2 Statistical analysis for FST at f = 10 Hz using ANOVA method of treatment

Binder Type	0%	3%	6%	9%
Sample 1	1.37E+07	1.44E+07	1.41E+07	1.52E+07
Sample 2	7.60E+06	1.43E+07	1.31E+07	1.53E+07
Mean (X)	1.06E+07	1.44E+07	1.36E+07	1.53E+07
Variance (Si)	1.85E+13	1.14E+09	5.16E+11	6.94E+08
Grand Mean (XGM)	1.25E+07			
N= 8		K=4		
Between Group	$S_B{}^2 = \frac{\Sigma n_i (X_i - X_{GM})^2}{k-1}$			
	$S_B{}^2 = \frac{2\,[(1.25\,X\,10^7 - 1.06\,X\,10^7)^2 + (1.25\,X\,10^7 - 1.44\,X\,10^7)^2 + (1.25\,X\,10^7 - 1.36\,X\,10^7)^2 + (1.25\,X\,10^7 - 1.53\,X\,10^7)^2]}{4-1}$			
	$S_B{}^2 = 7.98\,X\,10^{12}$			
With In Group	$S_W{}^2 = \frac{\Sigma(n_i - 1)\,S_i{}^2}{\Sigma(n_i - 1)}$			
	$S_W{}^2 = \frac{(2-1)\,[1.85\,X\,10^{13} + 1.14\,X\,10^9 + 5.16\,X\,10^{11} + 6.94\,X\,10^8]}{8-4}$			
	$S_W{}^2 = 4..76\,X\,10^{12}$			
F	F= $\frac{S_B{}^2}{S_W{}^2}$	P Value	F from table (α=0.1)	
	F= 1.68	0.308	F = 4.19	

Table D 3 Statistical analysis for FST at f = 10^{-5} Hz using ANOVA method of treatment

Binder Type	0%	3%	6%	9%
Sample 1	6.59E+01	5.95E+01	5.40E+01	4.50E+01
Sample 2	5.52E+01	5.85E+01	6.63E+01	3.86E+01
Mean (X)	6.06E+01	5.90E+01	6.02E+01	4.18E+01
Variance (Si)	5.67E+01	5.41E-01	7.52E+01	2.03E+01
Grand Mean (XGM)	5.98E+01			
N= 8		K=4		
Between Group	$S_B{}^2 = \frac{\Sigma n_i (X_i - X_{GM})^2}{k-1}$			
	$S_B{}^2 = \frac{2 [(5.98X\ 10^1 - 6.59\ X\ 10^1)^2 + (5.98\ X\ 10^1 - 5.9\ X\ 10^1)^2 + (5.98\ X\ 10^1 - 6.02\ X\ 10^1)^2 + (5.98X\ 10^1 - 4.18\ X\ 10^1)^2]}{4-1}$			
	$S_B{}^2 = 164.4$			
With In Group	$S_W{}^2 = \frac{\Sigma(n_i - 1)\, S_i{}^2}{\Sigma(n_i - 1)}$			
	$S_W{}^2 = \frac{(2-1)\,[5.67\ X\ 10^1 + 5.41\ X\ 10^1 + 7.52\ X\ 10^1 + 2.03\ X\ 10^1]}{8-4}$			
	$S_W{}^2 = 38.16$			
F	F= $\frac{S_B{}^2}{S_W{}^2}$	P Value	F critical (α=0.1)	
	F= 4.31	0.0961	F = 4.19	

Appendix E - Performance Grade Test Result

Table E 1Performance Grade Determination for neat RTFO Aged asphalt binder

Temperature (°C)	Frequency (Hz)	Phase Angle (°)	Complex Modulus (Pa)	Elastic Modulus (Pa)	Viscous Modulus (Pa)	Complex Viscosity (Pas)	Shear Stress (Pa)	Strain (5)
52.0	1.60E+00	83.18	1.34E+04	1.59E+03	1.33E+04	1.34E+03	1.33E+03	9.96E-02
58.0	1.60E+00	85.31	5.10E+03	4.17E+02	5.08E+03	5.09E+02	5.08E+02	9.97E-02
64.0	1.60E+00	86.93	2.22E+03	1.19E+02	2.21E+03	2.21E+02	2.23E+02	1.01E-01
70.0	1.60E+00	87.88	9.47E+02	3.49E+01	9.46E+02	9.44E+01	1.01E+02	1.07E-01

Table E 2Performance Grade Determination For RTFO Aged asphalt binder Containing 3% Molasses

Temperature (°C)	Frequency (Hz)	Phase Angle (°)	Complex Modulus (Pa)	Elastic Modulus (Pa)	Viscous Modulus (Pa)	Complex Viscosity (Pas)	Shear Stress (Pa)	Strain (%)
52.0	1.60E+00	82.98	1.51E+04	1.84E+03	1.49E+04	1.50E+03	1.51E+03	1.00E-01
58.0	1.60E+00	85.21	5.82E+03	4.86E+02	5.80E+03	5.80E+02	5.84E+02	1.01E-01
64.0	1.60E+00	86.86	2.31E+03	1.27E+02	2.31E+03	2.30E+02	2.32E+02	1.01E-01
70.0	1.60E+00	87.82	1.07E+03	4.07E+01	1.07E+03	1.07E+02	1.07E+02	1.00E-01

Table E 3 Performance Grade Determination For RTFO Aged asphalt binder Containing 3% Molasses

Temperature (°C)	Frequency (Hz)	Phase Angle (°)	Complex Modulus (Pa)	Elastic Modulus (Pa)	Viscous Modulus (Pa)	Complex Viscosity (Pas)	Shear Stress (Pa)	Strain ( )
52.0	1.60E+00	83.38	1.51E+04	1.74E+03	1.50E+04	1.50E+03	1.50E+03	9.99E-02
58.0	1.60E+00	85.45	5.77E+03	4.58E+02	5.75E+03	5.75E+02	5.79E+02	1.01E-01
64.0	1.60E+00	86.93	2.53E+03	1.35E+02	2.53E+03	2.52E+02	2.54E+02	1.01E-01
70.0	1.60E+00	87.5	1.05E+03	4.60E+01	1.05E+03	1.05E+02	1.14E+02	1.08E-01

Table E 4 Performance Grade Determination For RTFO Aged asphalt binder Containing 3% Molasses

Temperature (°C)	Frequency (Hz)	Phase Angle (°)	Complex Modulus (Pa)	Elastic Modulus (Pa)	Viscous Modulus (Pa)	Complex Viscosity (Pas)	Shear Stress (Pa)	Strain (%)
52.0	1.60E+00	82.9	1.64E+04	2.02E+03	1.63E+04	1.63E+03	1.67E+03	1.02E-01
58.0	1.60E+00	85.02	6.46E+03	5.60E+02	6.43E+03	6.44E+02	6.47E+02	1.00E-01
64.0	1.60E+00	86.67	2.70E+03	1.57E+02	2.69E+03	2.69E+02	2.68E+02	9.94E-02
70.0	1.60E+00	87.46	1.20E+03	5.31E+01	1.20E+03	1.20E+02	1.21E+02	1.01E-01

Appendix F - Multi Stress Creep Recovery Test Results

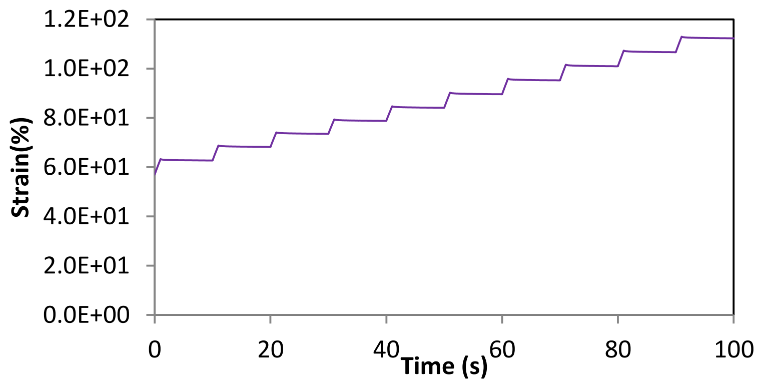

Figure F 1 3% Molasses at 52 °C at stress 100Pa

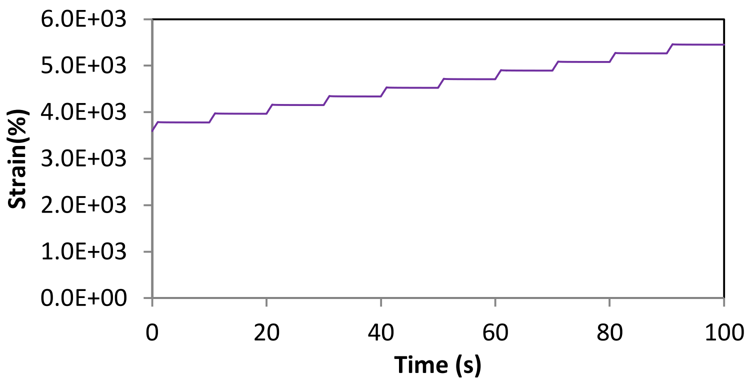

Figure F 2 3% Molasses at 52 °C at stress 3200Pa

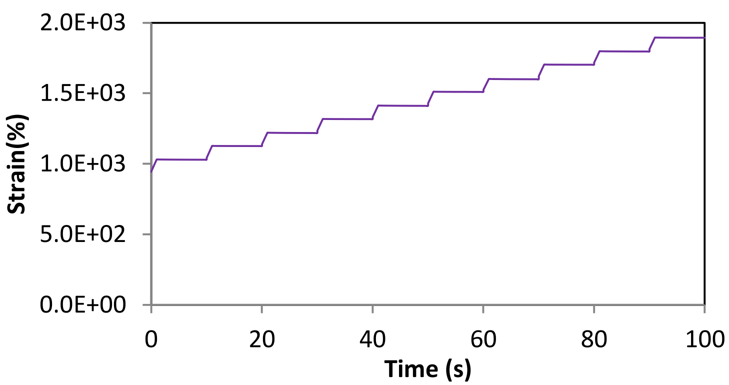

Figure F 3 3% Molasses at 70 °C at stress 100Pa

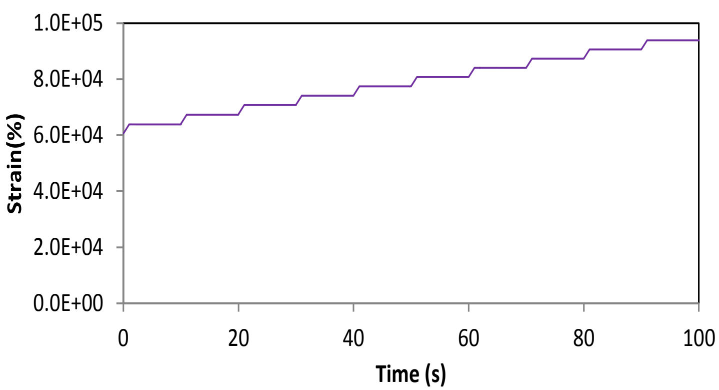

Figure F 4 3% Molasses at 70 °C at stress 3200Pa

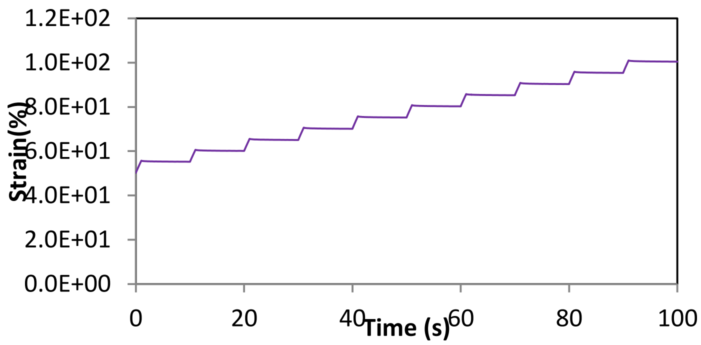

Figure F 5 9% Molasses at 52 °C at stress 100Pa

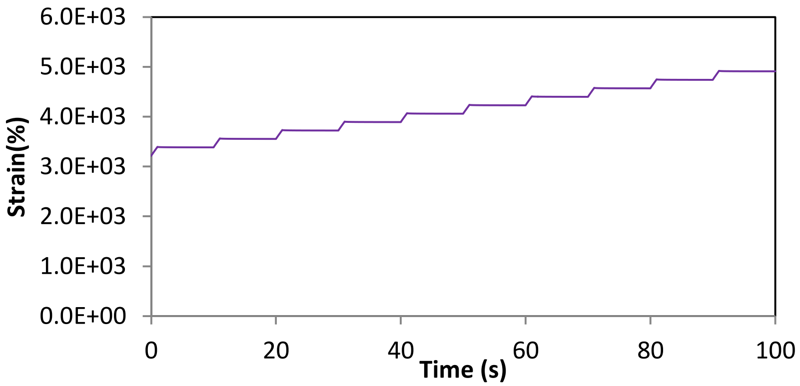

Figure F 6 9% Molasses at 52 °C at stress 3200Pa

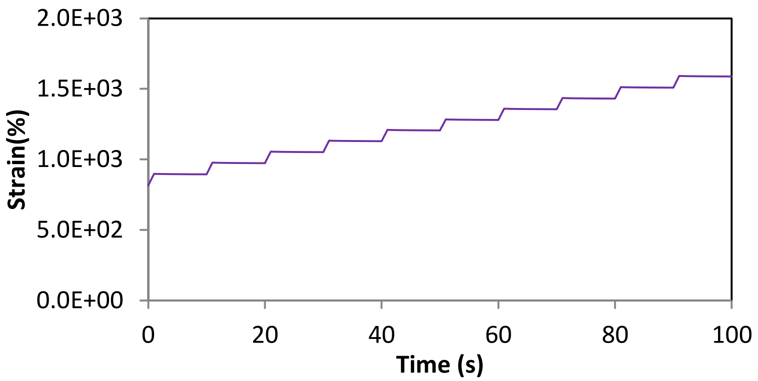

Figure F 7 9% Molasses at 70 °C at stress 100Pa

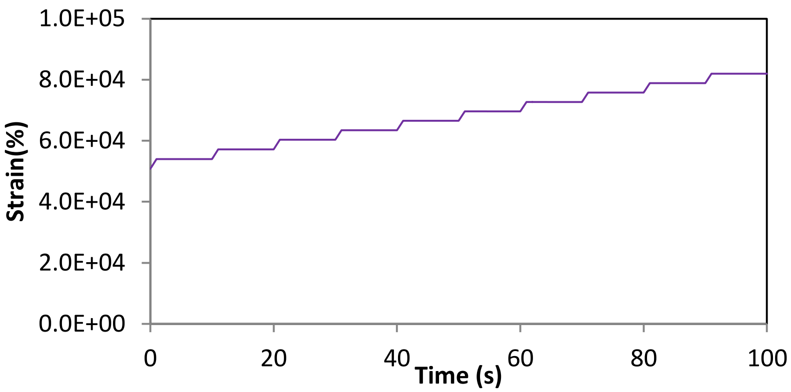

Figure F 8 9% Molasses at 70 °C at stress 3200Pa

Table E 5Summary of MSCR result

Molasses Content (%)	Temperature (°C)	J_{nr} (1/kPa)		PR (%)	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
0	52	0.006	0.006	6.98	5.71
	58	0.017	0.018	4.98	2.63
	64	0.042	0.045	3.203	0.000
	70	0.100	0.105	3.636	0.000
3	52	0.005	0.006	9.699	5.307
	58	0.016	0.017	7.514	1.874
	64	0.037	0.044	5.410	0.447
	70	0.081	0.100	2.405	0.085
6	52	0.005	0.006	12.276	5.931
	58	0.008	0.014	9.401	2.475
	64	0.035	0.040	6.630	0.562
	70	0.093	0.102	4.797	0.040
9	52	0.005	0.005	9.569	5.664
	58	0.009	0.014	4.770	1.872
	64	0.033	0.039	0.852	0.576
	70	0.076	0.096	4.993	0.081

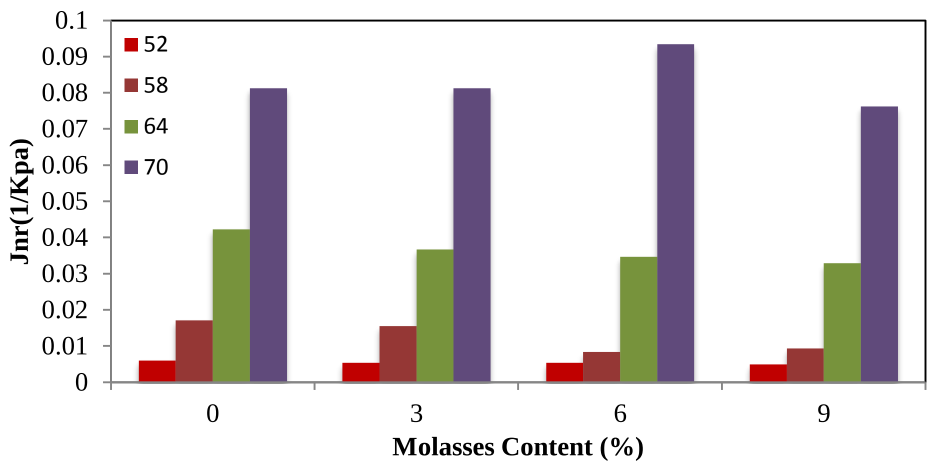

Figure F 9 The Effect of Molasses % on Jnr at 100Pa Stress

Appendix G - Determination of OBC

Table G 1OBC determination

Item No	%AC by weight of total mix (Pb)	%AC by weight of aggregate	Bulk S.G of agg Combined	Max SG of paving mix (G_{mm})	Weight grams In Air	Weight grams In water	Weight grams Air SSD	Bulk Volume CC	Bulk S.G. Comp. Mix (gm/cc)	Air Void (%)	VMA (%)	VFA (%)	Unit weight PCF (mg/m^3)	Stability (KN) Read	Stability (KN) Corrected Stability	Flow (1/100")
								H	I	J	K	L				
	A	B	C	D	E	F	G	G - F	E / H	(D-I)*100/D	100-(100-B)*I/C	(K-J)*100/K				
A	3.5	3.63			1228.5	738.6	1238.3	499.7	2.458	8.41	14.94	43.73	2458	10.80	8.54	2.30
B	3.5	3.63			1231.2	726.1	1239.4	513.3	2.399	8.41	14.94	43.73	2399	11.30	8.44	2.05
C	3.5	3.63	2.75	2.651	1229.5	732.2	1238.7	506.5	2.427	8.41	14.94	43.73	2427	11.60	8.60	2.22
								Average =	**2.428**	**8.41**	**14.94**	**43.73**	**2428**	**11.23**	**8.53**	**2.19**
A	4.0	4.17			1236.8	748.3	1248.9	500.6	2.471	6.26	14.12	55.67	2471	11.50	9.10	2.40
B	4.0	4.17			1231.3	746.6	1242.9	496.3	2.481	6.26	14.12	55.67	2481	11.80	9.05	2.20
C	4.0	4.17	2.75	2.630	1242.1	741.9	1250.0	508.1	2.445	6.26	14.12	55.67	2445	11.00	9.02	2.30
								Average =	**2.465**	**6.26**	**14.12**	**55.67**	**2465**	**9.06**	**9.06**	**2.30**
A	4.0	4.17			1263.3	748.8	1254.5	505.7	2.498	4.57	13.18	65.32	2498	11.50	9.56	2.40
B	4.0	4.17			1251.8	747.7	1252.8	505.1	2.478	4.57	13.18	65.32	2478	11.80	9.62	2.45
C	4.0	4.17	2.75	2.607	1254.2	751.6	1255.9	504.3	2.487	4.57	13.18	65.32	2487	11.00	9.63	2.54
								Average =	**2.488**	**4.57**	**13.18**	**65.32**	**2488**	**9.60**	**9.60**	**2.46**

A	5.0	5.26			1244.5	751.8	1245.3	493.5	2.522	4.04	13.38	69.82	2522	11.30	9.58	2.65
B	5.0	5.26			1241.3	748.8	1242.6	493.8	2.514	4.04	13.38	69.82	2514	9.10	9.92	2.56
C	5.0	5.26	2.75	2.621	1239.4	748.4	1242.2	493.8	2.510	4.04	13.38	69.82	2510	11.20	9.75	2.60
							Average =		**2.515**	**4.04**	**13.38**	**69.82**	**2515**	**10.53**	**9.75**	**2.60**
A	5.5	5.82			1241.2	749.6	1242.4	492.8	2.519	3.25	13.98	76.74	2519	9.30	9.30	2.88
B	5.5	5.82			1244.8	758.5	1247.0	488.5	2.548	3.25	13.98	76.74	2548	9.50	9.50	2.80
C	5.5	5.82	2.75	2.597	1252.4	746.6	1253.5	506.9	2.471	3.25	13.98	76.74	2471	9.80	9.40	2.75
							Average =		**2.513**	**3.25**	**13.98**	**76.74**	**2513**	**9.53**	**9.40**	**2.81**

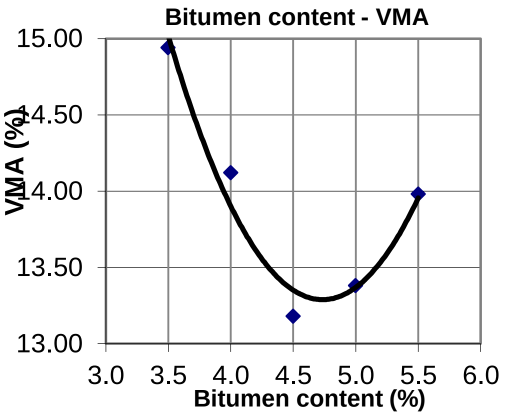

Figure G 1 Bitumen content vs VMA

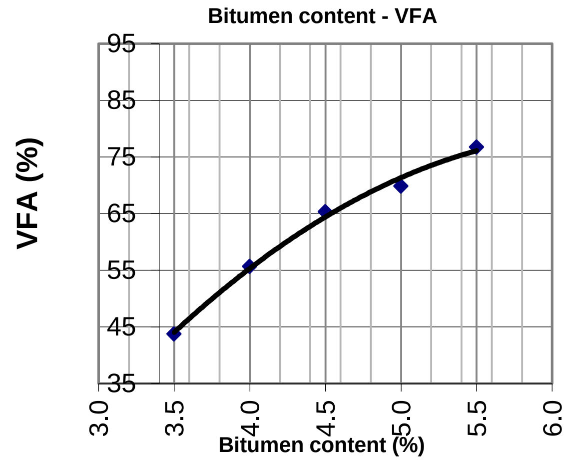

Figure G 2 Bitumen content vs VFA

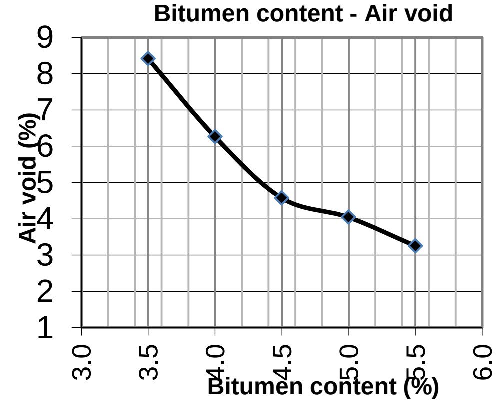

Figure G 3 Bitumen content vs Va

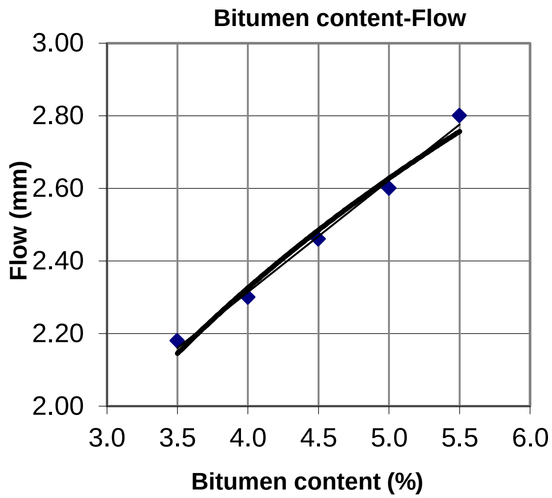

Figure G 4 Bitumen content vs flow

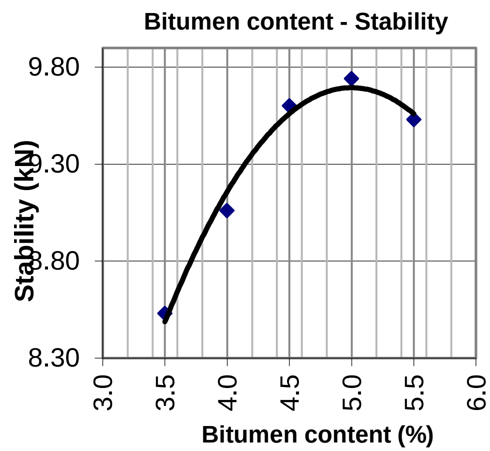

Figure G 5 Bitumen content vs Stability

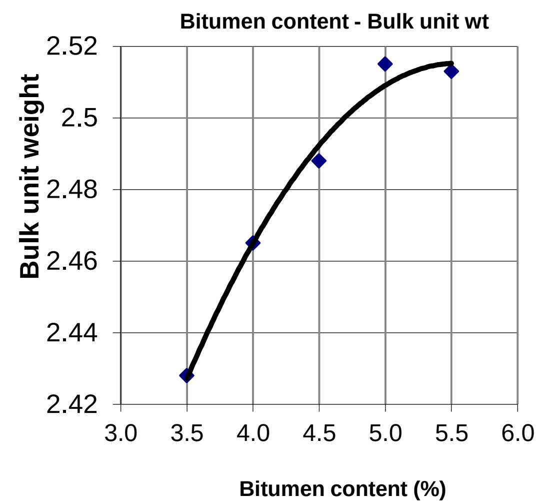

Figure G 6 Bitumen content vs unit eight