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SCHOOL OF GRADUATE STUDIES

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

MOISTURE SUSCEPTIBILITY AND RUTTING TEST OF RECLAMIED ASPHALT PAVEMENT ON MOLASSES MODIFIED HOT MIX ASPHALT

A Thesis Submitted to School of Graduate Studies of Addis Ababa Institute of Technology in Partial Fulfillment of the Requirements for Master Degree in Road and Transport Engineering

By:

Gelila Dawit

Advisor: Robeam Solomon (PhD)

January, 2022

Addis Ababa, Ethiopia

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In
Road and Transport Engineering

Approved by Board of Examiners:

Dr. Robeam Solomon	______________	______________
Advisor	Signature	Date
______________	______________	______________
External Examiner	Signature	Date
______________	______________	______________
Internal Examiner	Signature	Date
______________	______________	______________
Chair Person	Signature	Date

Declaration

I, the undersigned, declare that this thesis is my original Work performed under the supervision of my research advisor **Dr. Robeam Solomon** and has not been presented as a thesis for a degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

Name Gelila Dawit

Signatures

Place Addis Ababa Institute of Technology

Addis Ababa University,

Addis Ababa.

Date January, 2022

Abstract

In Ethiopia, every year, various projects on road repair, upgrading, new road construction, and routine maintenance projects are undertaken, all of which rely on the usage of natural and industrial resources. Reclaimed asphalt pavement material (RAP), the usage of RAP in Ethiopia is very limited , due to lack of clear standard and recommendations on how to use asphalt pavement wastes. Reclaimed asphalt pavement has advantages in terms of environmental benefits, cost savings, land fill, and, but it also has drawbacks such as ductility loss and harsh mixtures when it is optimized. This research studies the effect of RAP on HMA with binder treated with molasses. The marshal mix method was used to create hot mix asphalt in the labratory. The volumetric test, stability, flow, moisture susceptibility, and rutting tests were performed on four different Reclaimed asphalt pavement contents (10, 20, 30, and 40%) HMA with a 3% molasses modified binder. Based on this study, when compared to the control mix, all of the modified mixes performed better in the tests undertaken for this study. When compared to other RAP and molasses-modified mixes, the RAP and molasses-modified mixes had better moisture resistance and lower rut depth. The RAP and molasses modified mixes performed better in terms of stability, flow, and volumetric qualities when compared to the other mixes, however because the RAP percentages utilized were 10%, 20%, 30%, and 40%, these attributes improved on the higher RAP (30 & 40) percentages this may be due to the softening effect of molasses. Mixes with RAP and molasses showed better resistance for moisture and lower rut depth, but more studies should be conducted for different molasses and RAP contents with more performances tests to have more reliable data.

TO

ELIAS KEBEDE FREHIWOT

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List of Abbreviations

AASHTO – American Association of State Highway and Transportation Officials

ASTM - American Society for Testing and Materials

CCCC – China Communication Construction Company

DS - Dynamic Stability

DSR - Dynamic Shear Rheometers

HMA – Hot Mix Asphalt

ITS – Indirect Tensile Strength

LAA – Los Angles Abrasion

OBC – Optimum Bitumen Content

PG – Pavement Grade

RAP - Reclaimed Asphalt Pavement

TSR – Tensile Strength Ratio

VFA – Voids Filled with Asphalt

VFB – Voids filled with Bitumen

VG – Viscosity Grade

VMA – Voids in Mineral Aggregate

Va – Air void

Chapter 1: Introduction

1.1 Background of study

The physical and chemical property of HMA is complicated as it is made up of different components in addition to its exposure to different types of distress over time, which comes from weather change and increment of heavy traffic loads due to world civilization. Asphalts have better behavior in stability, workability, skid resistance and durability and also bad performance in resisting stripping, fatigue cracking, thermal cracking and bleeding. The rapidly increasing cost of paving materials and increased awareness towards environmental damage have led researchers to come with a more economical and environment friendly pavement construction technology. Construction and maintenance of asphalt roads requires a huge amount of expenditure with foreign currency. For instance, over the nineteen years of the RSDP, physical works have been undertaken on a total of 128,470 km of roads and a total budget for the planned works during this period amounted to ETB 232.5 billion (USD 15.9billion). (ERA Road Sector Development Program: 19 Years Assessment, (2016) cited in (GIDIRSA, 2020)

Constructing a long-lasting road pavement has been the key challenge for the rising problems in increased cost of construction materials, environmental safety, health protection and energy saving. Different modifiers have been used in order to improve the performance of asphalt mixture and have a sustainable pavement. The usage of RAP in asphalt mixtures helps in improvement of mixture performance and also reduces the cost of new asphalt mixture as it is removed material from old asphalt pavements in addition to conserving natural resources. Molasses is a modifier that used to improve the properties of the asphalt binder. Reclaimed asphalt pavement have been used as a substitute, as well as other as modifiers like extender, rubber, plastic, fiber and others, to improve the performance of asphalt materials. RAP was first used in 1973, but only in small amounts due to a lack of understanding of its impact on the performance of asphalt mixes. Nowadays, higher percentages are being used (Ahmad et. al., 2016). According to research conducted by the Federal Highway Administration (FHWA) in the United States, approximately thirty million tons of Recycled Asphalt Pavement (RAP) are recycled each year. This is the most recycled material in the United States of America. (Onyebuchi Nwabueze Mogbo, 2020)

In Ethiopia, there is no written standard and guideline to utilize asphalt pavement wastes by reprocessing to different pavement layer structures. Ethiopian Roads Authority (ERA, 2013) presented some recommendations of RAP usage even if, there is no specifications and directions to use recycled material and there is no a clear experience of utilizing RAP as an important construction material._In Addis Ababa, yearly on average more than 25, 000m3 of asphalt concrete wastes were removed from an existing pavement due to maintenance reasons that will be for patching or rehabilitation (AACRA Annual maintenance report, 2018/19) cited in (Fisha, 2019)

When RAP is properly crushed and screened, it consists of high-quality aggregates for new pavement layers, which can be used to replace an amount of virgin aggregate and asphalt binder in the mixture. The use of RAP has the potential to become viable and attractive alternative material for construction. The use of RAP grants environmental and economic benefits, such as the reduction of contaminant emissions, natural resource exploitation, raw material transportation, mixture production costs, energy consumption, fuel usage, and pressure on landfill disposal sites (Ana E. Hidalgo et. Al., 2020). In spite of all the advantages, RAP also has disadvantages such as loss of ductility or a lower cohesion inside the mixture (due to the higher stiffness and lower adhesion provided by the aged bitumen contained in the RAP) and being harsh mix (difficult for compaction). To compensate these drawbacks, soft new bitumen can be used (which would be blended with the aged one to recompense for its deteriorated rheological properties), or rejuvenating agents can be added to restore part of the chemical composition of the aged binder (Ana E. Hidalgo, 2020). The main objective of this study is to evaluate the effects of RAP on hot mix asphalt by improving the virgin bitumen with molasses.

Asphalt mixture was designed for the virgin aggregate and virgin bitumen in the laboratory utilizing the marshal mix design process. Various tests were conducted on molasses modified mixes that contained four different RAP contents to compare the performance of the mixtures with that of the unmodified mixtures. Stability, flow, volumetric properties, moisture susceptibility and rutting test were performed.

1.2 Problem Statement

In Ethiopia, high budget is invested for rehabilitation of existed roads. Even if the usage of asphalt concrete wastes doesn’t have clear specification ERA manual presents recommendation on the usage of the recycled material. Having a sustainable road pavement to overcome the rising budgets for rehabilitation of old road pavements and problems from increased cost of construction materials, environmental safety, health protection and energy saving in addition to the improvement of the road’s performance. Due to the complicated property of hot mix asphalt different researches has been made on materials to be used as substitute and modifiers of the individual components of asphalt mixture in order to have long-lasting road pavement. In the world, reclaimed asphalt pavement have been used as a substitute, as well as other as modifiers like extender, rubber, plastic, fiber and others, to increase the performance of asphalt mixtures. Even if the RAP usage experience is lower in Ethiopia (GIDIRSA, 2020). The use of RAP has advantages on increasing the performances of asphalt mixtures and also environmental problems, such as the reduction of contaminant emissions, natural resource exploitation and raw material transportation. RAP also has disadvantages such as loss of ductility or a lower cohesion inside the mixture and being harsh mix (difficult for compaction). To improve these drawbacks, soft new bitumen can be used or rejuvenating agents can be added to restore part of the chemical composition of the aged binder and also using modifiers which helps to improve the properties of virgin binder to renew the aged binder (Ana E. Hidalgo, 2020). The main objective of this study is to evaluate the effects of RAP on hot mix asphalt by modifying the virgin bitumen by molasses. Effects of RAP on molasses modified mixtures have been checked by conducting rutting, moisture susceptibility, stability, flow and also volumetric tests.

1.3 Objectives of the study

1.3.1 General objective

To study the effect of adding RAP on molasses modified mixture on the volumetric properties, rutting and moisture susceptibility of asphalt mixture.

1.3.2 Specific Objectives:

1. To analyze the effect of RAP on hot mix asphalt on marshal properties, volumetric properties, rutting and moisture susceptibility of asphalt mixture.
2. To analyze the effect of molasses on hot mix asphalt on marshal properties, volumetric properties, rutting and moisture susceptibility of asphalt mixture.
3. To analyze the effect of RAP and molasses on hot mix asphalt on marshal properties, volumetric properties, rutting and moisture susceptibility of asphalt mixture.

1.4 Organization of Thesis

Chapter I: Introduces HMA, asphalt pavement failure and modifiers. Chapter II gives more detail on how HMA mixes were designed and improvements in asphalt mixes due to the addition of RAP and fiber modifiers. It also covered further detail on each asphalt pavement failure. Chapter III deals with methodology which includes material selection, mix designs, mixing and compaction procedures, performance testing procedures. The test results of the conducted tests were analyzed in Chapter IV. Chapter V included the conclusions, recommendation and future study recommendations.

Chapter 2: Literature Review

In the world, Hot mix asphalt (HMA) is the most commonly used paving material. Asphalt binder and mineral aggregates are the main components. The binder works as a paste,binding aggregate particles together to for a cohesive mass. The bounded asphalt binder and mineral aggregate form a stone like structure that gives the pavement system strength and toughness. (Berg, 2016)

The properties of the individual components and their reaction system will affect the characteristics of HMA. Several mixture design methods have been developed over time, the purpose of which is developing a mixture that is capable of providing acceptable performance based on certain predefined set of criteria. This is normally achieved by selecting an optimum design asphalt cement content that will achieve a balance among the desired volumetric properties. (Asphalt Institute SP-2, 2001).

Hot mix asphalt pavement consists of different layers and also made up of different components. The components reaction system and qualities of the each material affect the characterstics of hot mix asphalt in addition to the traffic load and weather change. There are three major and most common asphalt pavement failure modes, these are: fatigue cracing, low temperature cracking and rutting.

Surface depression in the wheel path is known as rutting. Pavement uplift may occur along the sides of the rut. Ruts are particularly evident after a rain when they are filled with water. There are two basic types of rutting: mix rutting and subgrade rutting. Rutting can occur as a result of pavement being plastic and depressed by heavy loads, or by the grinding effect of studded tires. Moreover, inadequate compaction during construction will also result in rutting because once the pavement is opened to traffic; it will continue to compact in the wheel paths under traffic loading. Wheel paths with rutting can easily be filled with water from rain and snowmelt. (Towhidul Islam et al., 2020)

Moisture susceptibility is the tendency of HMA toward stripping. Moisture affects asphalt pavements in two ways. Firstly, it can enter the interface between the bitumen and aggregate destroying the bond between those two key components of the pavement. Second, moisture can penetrate the bitumen itself and it will make it soft and reduces its cohesive strength. [Asres Simeneh, 2013]

Stripping is the loss of bond between the aggregate and binder so that the strength loss of HMA can be sudden. Stripping usually begins at the bottom of HMA layer and moves upward to the upper surface. This upward movement will cause a loss of strength over the years and make stripping identification difficult by causing surface manifestations like rutting, corrugations, raveling, cracking, and etc. Physical factors like influence of aggregate, void content, Addition of anti-strip additives (ASAs), mixing temperature, HMA storage time and engineering and construction considerations like inadequate pavement drainage, inadequate compaction, excessive dust coating on the aggregate, action of the traffic, inadequate drying of aggregates and weak aggregates affect stripping. Usage of anti-stripping agents, liquid anti-stripping agents, and lime additives and also by controlling the construction considerations will help in controlling the effects of moisture susceptibility. [Asres Simeneh, 2013]

Due to the modernization of the world, the seek for the long lasting road pavement increased. Different researches has been made to increase the quality and performance of hot mix asphalt by using substitute materials like Reclaimed Asphalt Pavement and adding different modifiers like rubber, fiber, molasses.

2.1 Reclaimed Asphalt Pavement (RAP) studies

Reclaimed Asphalt Pavement (RAP) is reprocessed binder and aggregates removed from laid asphalt pavement by milling or full depth removal.

The use of reclaimed asphalt pavement has become relatively common practice in most countries, as it is both an environmentally and economically attractive proposition. A survey conducted by the Federal Highway Administrations RAP expert task group shows that the average RAP content in hot mix is only 10 – 20% as used in the United States, even though specifications allow up to 30%. The primary reason for this limited use is the uncertainty of the long-term performance of RAP. Recycling old asphalt pavement materials reduced such as amount of waste sent to landfills. Using RAP also conserves valuable natural resources such as binder and aggregates. These can lead to increased savings for contractors, taxpayers, and government.

Reclaimed asphalt pavement may also help create jobs in the recycling and manufacturing industries (A. Rangaraj et. al., 2020).

The most use of RAP in hot asphalt mix is mixing RAP with new or "virgin" aggregates, neat asphalt binder, and/or recycling agents in a central hot mix plant to produce a recycled mix. The percentage of RAP permitted in a recycled mix varies by agency as well as guidelines as to where the recycled mix can be used in the pavement structure. Some agencies allow 15% or fewer RAPS while others permit larger amounts of RAP.

Higher RAP percentages require modifications in mix design and binder selection. Suggested guidelines relative to RAP content in a recycled mix are as follows: 15% RAP or less: binder grade is the same as that used in a virgin mix; 15-25% RAP: binder grade should be one grade lower on both high and low temperature end, i.e., PG 58-22 rather than PG 64-16; higher than 25% RAP: perform tests to determine the percentage of RAP and ensure the quality of the blend. RAP will give environmental benefits by reducing the amount of new oil, construction wastes and also recycling so that natural resources will be conserved. Recycling money, costs of energy, costs of new material and transportation will be decreased from economical perspective. The need for virgin aggregate and bitumen will be reduced, resistance of cracking, rutting and also stiffness of the pavement will be improved by using RAP (Mrugacz, 2019).

A study concludes that high-RAP mixes containing more than 25% RAP have been used with success primarily in dense graded mixes both in the wearing course as well as the binder course. High RAP mixes performed well over the whole range of traffic levels, from residential streets to highways and interstates. Projects where rutting is a concern may benefit most from the relative increase in stiffness cause by the addition of RAP (Kitch, 2013).

A study determined the binder properties using conventional and Superpave methods. Increasing the amount of RAP binder in blend increases the stiffness, viscosity and critical temperature, increases the stiffness of the binder, the creep stiffness (S value) increases, but decrease with the increase in temperature (Arshad Hussaina et. al., 2013).

A study was carried out for RAP material percentages (10%, 20%, 30% & 40%) to check the performance of bituminous mixes. The Marshall Stability value has been on the decreasing trend with increasing RAP bitumen this may be attributed to the fact that the Virgin bitumen may fail to rejuvenate the RAP binder as its percentage increases, The Tensile strength ratio of recycled and virgin mixes can be observed that recycled mix as lower TSR when compared to virgin mix but if fulfils the minimum criteria (80%), about 20% and 30% of the cost of the wearing courses or binder courses can be effectively reduced with all the other liabilities. Conducting performance tests like rutting and fatigue cracking would have been helpful to fulfill the objective of the study (Sunil S, 2014).

Rutting resistance has been evaluated on mixes with 20% RAP; the result showed that mixes with RAP exhibited lower rutting depths than virgin mixes. Thus, the addition of RAP improved the rutting resistance of an asphalt mix, since mixes with RAP become stronger and stiffer when compared to virgin mixes leading to better resistance to permanent deformation. If there were more trial percentages for the RAP material it would be helpful to give a better conclusion for the effect of RAP on rutting resistance (Ahmad et. al., 2016).

Investigation has been held with Marshall Method. It’s concluded that Marshall Stability increased with the increase in RAP with good linearity, reaching twice the stability for mixes with 100% RAP when compared to the control mix. Furthermore, they argued that using RAP in design even up to 30% will help in preserving natural resources, reduction in costs, and performance improvement (Ahmad et. al., 2016).

Many studies had been conducted to evaluate the effect of RAP on the performance of asphalt pavements and showed that RAP increases the stiffness of asphalt mixes, due to the aged asphalt binder. The result shows an improvement of rutting resistance and better performance at high temperature. On the other hand, results were not consistent when it came to fatigue and thermal cracking. Few studies argued that there were no effects of RAP on these distresses, where other studies showed a reduction in fatigue and thermal cracking resistance leading to a poor performance of these mixes (Ahmad et. al., 2016).

Many studies have been conducted to evaluate the effect of RAP on the performance of asphalt pavements and showed that RAP increases the stiffness of asphalt mixes, due to the aged asphalt binder and also results in improvement of rutting resistance and better performance at high temperature.

From the Marshall test result of a study, the OBC for control mix is 5.34%, RAP 15 is 5.22%, RAP25 is 5.10% and RAP35 is 4.88%. The OBC for mixes containing RAP reduced as the amount of RAP increased, possibly due to the influence of the existing binder in the RAP. It can be concluded that the use of high percentages of RAP could influence the properties of the Marshall mix design (Arshad et. al., 2017).

The Hamburg wheel tracking test showed that the rutting resistance also decreased when the RAP content increased. The control mix sample shows the highest rutting resistance, followed with RAP15, RAP25 and RAP35. However, the difference in rut depth between the control sample and RAP mixes is minimal, indicating that the mixes with RAP have comparable rut resistance compared to control mix. There are significant effects on the Marshall properties with the inclusion of RAP in the asphalt mixes. Marshall Test results showed that the Marshall flow, VFA and Bulk SG increased as the RAP content increased. However, Marshall stability value and air voids in mix showed a decreasing trend with increasing RAP content (Arshad et. al., 2017).

Mixes with RAP, especially at 50% to 100%, when properly designed showed better performance compared to those of virgin mixes. Mixes with RAP showed improvement in the indirect tensile strength where the highest value was achieved at 50% RAP content exhibited a 106% increment when compared to control mixes. Additionally, the increase in RAP content enhanced the resilient modulus, absorbed energy, and rutting by about 216%, 194% and 70% respectively. A study showed that the increment of Rap usage increases marshal stability. As RAP percentage increased air voids, tensile strength ratio (TSR) and the resistance to moisture damage increased, whereas values of flow, unit weight, Voids in mineral aggregate and voids filled with binder inclined with the rising of RAP levels (Abu El-Maaty et al., 2015).

A study reported that asphalt mixes containing 50% RAP can be environmentally and economically beneficial and exhibit good performances (Ajideh et. al., 2013).

It was found that mix with the addition of RAP showed improvement in the fatigue life. The addition of 20% RAP, increased fatigue life by 67.2% compared to a virgin mix (Pradyumna, 2013)

ERA (2013) Flexible Pavement Design Manual, recommended that an unbound material containing RAP meets the specification for grading, density and CBR which are normally applied to fresh materials then it should be acceptable to use the RAP as road base.

Based on the results from a complete CBR results the bearing resistance of materials which have a blend equal and lower than 50% of RAP content are sufficient enough to use as a granular base course material. But from the five types of blending percentages tested in this study; the better strength achieved in blend of 25% RAP and 75% virgin aggregates, so it is highly recommendable to use this amount in weight. ((Fisha, 2019))

The experimental and theoretical results presented in this thesis prove that the asphalt binder course mixtures can be successfully produced using RAP material. Moreover, it was found that Asphalt binder course mixture containing RAP exhibits advantage in terms of cost compared to the conventional HMA. ((GIDIRSA, 2020)

2.2 Molasses studies

Molasses is the dark, a sweet, syrupy outcome made in the midst of the extraction of sugars from sugarcane and sugar beets. Molasses can change in shading, sweetness, and nutritional content dependent upon the variety or how much sugar has been isolated.

A study investigates the effect of molasses with different moisture contents on the property of HMA. Bitumen binders containing 5%, 10%, 15%, and 20% molasses were investigated as molasses modified binders. Molasses with 24.9% and 5.02% by weight of water were used to investigate the effect of moisture on the molasses modified binders. On this experimental investigation the rheological properties of molasses modified bitumen; the penetration resistance decreases with an increase in the content of molasses, the softening temperature of the binders increased with the reduction in the water content of molasses and the ductility of the binders increased with the reduction in the water content of molasses. Generally, the study revealed that low moisture content molasses could be used as a partial replacement for bitumen to enhance the rheological properties of the bitumen (Werku et. al., 2020).

A study evaluates the viability of molasses on penetration grade of bitumen and bituminous mix design using marshal method. It was observed that stability value shows increment up to 12% and then decrease. The flow value of the mix decreases on the addition of molasses. By addition of molasses in bitumen it was found that up to 10% the value of penetration is within the penetration range of 60/70, but when the percentage of molasses exceeds from 10% to 12% and above it showing drastic change in the penetration value of VG30 grade of bitumen corresponding to 80/100 penetration grade which is used as a penetration grade of VG10. Usage of molasses improved the pavement characteristics such as road safety, defects, long life of flexible pavements, stability, recycling of sugarcane waste and most important environment (Sharma, 2017).

An investigation has been made to evaluate the basic properties of bitumen and coarse aggregate using stone mastic asphalt samples using marshal compaction pedestal by varying the binder content as 5.5, 6.0, 6.5 and 7.0 percent by weight of aggregates and to find the optimum percentage of molasses content by replacing 5 to 15 % with 1 % increment by weight of OBC. VFB and flow value increased with increasing of bitumen content. Stability value initially increases and then decreases as bitumen content increase. With addition of molasses modifies samples at OBC; VFB and flow values increase with increment of molasses and stability shows increment up to 13% and then decreases. Volumetric Properties are improved for Molasses modified SMA Mix but drain down increases (G. Mounika, 2020).

The comparison of results between conventional bitumen and bitumen containing molasses has been conducted using laboratory tests. Penetration, ductility, softening point, Marshall stability tests were performed. On this research three percentages of bitumen (4%, 6% & 8%) and five percentages of molasses by weight of bitumen (4%, 8%, 10%, 12% & 16%) had been used. It concludes that the partial replacement of bitumen with molasses improves the Marshall characteristics, and also the strength and stability increase at 6% bitumen content and 8% molasses content. Modified bitumen increases penetration and softening point. The specific gravity remains the same but ductility decreases. Release of carbon dioxide reduces as the amount of the bitumen reduces. Overall, the research concludes that the optimum value of modified bitumen is 8% which is feasible to partial replace bitumen with molasses (Chaudhary et. al., 2019).

A study has been conducted by comparing normal asphalt binder with asphalt binder modified by 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 on five different percentages of molasses by weight of asphalt binder (3%, 6%, 9%, 12% and 15%). On this study softening point and ductility value decreases as molasses percentage increase and vice versa for penetration value. 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 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 (Abdulahi, 2017).

Research investigates the effect of cane molasses on performance of the base bitumen. Mixture modification using 0.10%, 0.15%, 0.20% molasses in binder content improves the Marshall Stability of the mixture and thus increasing its rutting resistance and load carrying capability. The addition of molasses as an additive with VG10 (80/100) grade bitumen shows there is decrease in penetration value. The softening point increases with the increment of molasses percentage (K.M. Padmapriya et. al., 2019).

Investigates has been held on the effect of cane molasses on performance of the base bitumen. The study revealed that as percentage of molasses-A, molasses-B and molasses-C increases from 0 to 20%, 0 to 10% and 0 to 5%, the PG was improved by 28.12%, 15.79% and 8.57% respectively. The PG decreases by 36.87%, 28.38% and 12.76% and similarly, the ductility decreases by 21.36%, 6.79% and 5.83% for 15% molasses-A, 10%molasses-B and 10% molasses-C mixtures respectively. The cost analysis also signifies that, the cost of base bitumen improved by 17.4%, 8.93% and 2.35% for using molasses-A, molasses-B and molasses-C respectively. From this study, it was concluded that as per DSR performance testing machine, 20% molasses-A, 10% Molasses-B and 5% Molasses-C improves the performance of original bitumen with different rate (Gemechu et. al., 2018).

A study of the bitumen samples is partially replaced with 5%, 10%, 15% and 20% of sugarcane molasses and are compared by adding 21% of quarry dust. The conventional and mechanical properties of bitumen samples were investigated by laboratory method such as penetration, viscosity, softening, ductility and also the performance of modified bitumen is tested by Marshall stability test. Test results showed that the increase in the sugarcane molasses results in the improvement of softening point, ductility of the modified samples, which is greater than that of the unmodified samples. It is found that the addition of Sugarcane molasses increases the ductility, but the addition of quarry dust decreases the ductility value. Marshall Stability is increased to a maximum value as the sugarcane molasses and quarry dust (A. Rangaraj et. al., 2020).

Literature Summary

Even though standards allow up to 30% RAP, the average RAP percentage in hot mix in the United States is only 10–20%. RAP is most commonly mixed with new or "virgin" aggregates and plain asphalt binder in hot asphalt mixes. According to a study, high-RAP mixes comprising more than 25% RAP have been employed successfully in dense graded mixtures. When compared to the control mix, stability improved with the rise of RAP with strong linearity, reaching double the stability for mixes with 100 percent RAP.

Using RAP in design up to 30% will help in the preservation of natural resources, cost savings, and performance improvement. The addition of RAP to asphalt mixes has a considerable impact on the Marshall characteristics. With increased RAP levels, however, the Marshall Stability value and air holes in mix decreased. When properly developed, RAP mixes outperformed virgin mixes, especially at 50 percent to 100 percent. When compared to a virgin mix, adding 20% RAP increased fatigue life by 67.2 percent.

To improve the rheological qualities of bitumen, molasses can be utilized as a partial substitute. Molasses use for increased road safety, flaws, the life of flexible pavements, stability, and sugarcane waste recycling, and, most importantly, the environment. Modified bitumen has an optimal value of 8%, making it possible to partially replace bitumen with molasses. At high temperatures, partial replacement of molasses improves the stiffness and rutting resistance of binders. It has little effect on the HMA mixture, but all blends are highly moisture susceptible. The influence of cane molasses on the performance of the base bitumen was investigated.

According to the literature, RAP usage increases in most regions, even if moisture resistance and rutting resistance diminish as RAP % increased. The use of molasses as a binder improved the behavior of the binder as compared to virgin material, even if the moisture susceptibility is affected. More research is needed to provide a more thorough picture of the molasses content, and most studies only look at the effect of utilizing the molasses modified binder without any modifiers or other replacement elements. So, utilizing modified binder, the gaps weaknesses that have been recognized from the use of RAP outlined in the researches will be investigated in this research.

Chapter 3: Methodology

3.1 Material selection

As asphalt concrete consists of different components like aggregate, binder and modifiers (if needed). The materials binder, aggregate, filler and RAP used for this research were taken from CCCC Research and development center asphalt plant. The molasses used for this research was taken from WONJI sugar factory. It's important to check the physical properties of the component material of hot mix asphalt if they meet all the requirements to ensure the good performance of the mixture.

3.1.1 Mineral Aggregates

Aggregates are one of the major components of hot mix asphalt as they are about 85% of the volume or around 95% in mass of dense graded HMA. Aggregates affects the behavior and performances of the HMA so they should be checked to fulfill the requirements to ensure their strength, hardness, toughness, durability, adhesion with bitumen binder.

Aggregates in HMA can be divided into three types according to their size: coarse aggregates, fine aggregates, and mineral filler. Coarse aggregates are generally defined as those retained on the 2.36- mm sieve. Fine aggregates are those that pass through the 2.36-mm sieve and are retained on the 0.075-mm sieve. Mineral filler is defined as that portion of the aggregate passing the 0.075-mm sieve. Mineral filler is a very fine material with the consistency of flour and is also referred to as mineral dust or rock dust.

Various tests were conducted to investigate the physical properties of the aggregates and their suitability in road construction, and the results are shown below.

Table 3. 1 Aggregate Test Results

Types of tests	**Test Method**	**Specification (ASTM)**	**Result**
LAA (%)	ASTM C131 / AASHTO T96	<40	16
Flakiness and Elongation particles (%)	ASTM D4791-10	<10%	7
Soundness loss by NaSO4 (%)	ASTM C88 / AASHTO T104	<12	7
Sand equivalent	ASTM D2419-14 / AASHTO T176	<50	29
Coarse material			
Bulk specific gravity	ASTM C127-15 / AASHTO T85	2.4 – 3	2.68
Water Absorption		<3%	2.1
Soundness loss by NaSO4 (%)	ASTM C88 / AASHTO T 104	<12	6
Fine material			
Bulk specific gravity	ASTM C128/ AASHTO T84	2.4 – 3	2.39
Water Absorption		1 - 2%	2
Soundness loss by NaSO4 (%)	ASTM C88 / AASHTO T 104	<12	7

After checking the quality of the aggregate trial gradation was prepared by using gradation requirements for the mix design.

Table 3. 2 Aggregate Gradation

SIEVE SIZE	14--20mm	6--14mm	0--3mm	Filler	Blending gradation	Upper Limit	Lower Limit
25	100	100	100	100	100	100	100
19	100	100	100	100	100	100	100
12.5	57	100	100	100	93	100	90
9.5	0	98	100	100	82	90	76
4.75	0	4	100	100	51	74	44
2.36	0	0	67	100	34	58	28
1.18	0	0	51	100	26	40	15
0.6	0	0	39	100	20	29	10
0.3	0	0	26	100	13	21	5
0.15	0	0	20	99	10	15	4
0.075	0	0	18	86	9	10	2

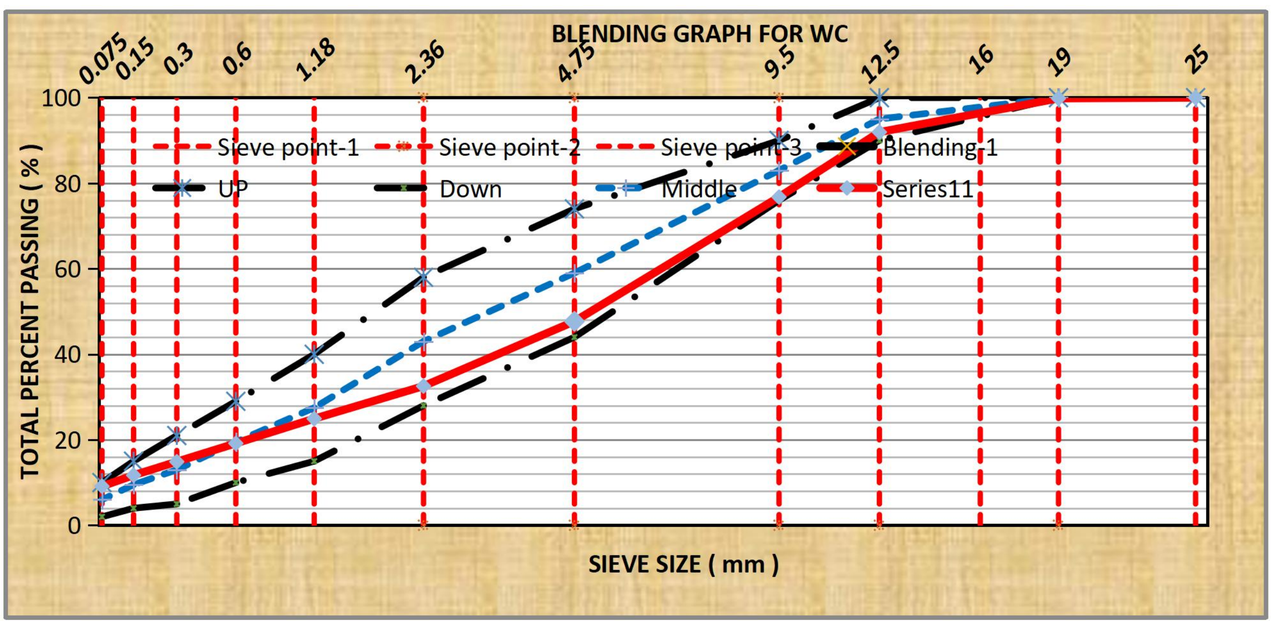


Figure 3. 1 Aggregate gradation Chart for ASTM specification

3.1.2 Asphalt binder

Asphalt binders are an essential component of asphalt concrete. They are the cement that holds the aggregates together. Asphalt also known as bitumen is a mixture of organic liquids that are highly viscous, black and sticky material. It is the black glue that binds more than 90% of highway together. It is found in naturally as well as artificially. Naturally occurring or crude bitumen is a sticky, tar like form of petroleum which is so thick and heavy that it must be heated or diluted before it will flow.

In marshal mix design method asphalt bitumen can be graded by penetration or viscosity. An asphalt binder of grade 60 / 70 penetration was used in the preparation of the trial mixes. A series of tests including penetration, specific gravity, softening point, flash point, and ductility had been conducted to check the suitability of the bitumen sample.

Table 3. 3 Binder Test Results

Types of tests	**Test Method**	**Result**	**Specification (ASTM D496)**
Penetration	ASTM D5 / AASHTO T49	60	60 - 70
Ductility	ASTM D113 / AASHTO T51-09	1113	>100
Softening Point	ASTM D36-DM36-14 / AASHTOT53-09	49	46 °C
Flash and Fire point	ASTM D92 /AASHTO T48	230	230 °C
Specific gravity	ASTM D70-97 /AASHTO T228	0.99	0.97 - 1.02

3.1.3 Mineral Fillers

Mineral fillers are the part of mineral aggregates, they fill voids formed in the mix which helps to reduce the formation of cracks and also tends to increase the viscosity of bitumen by making it dense. so, it will provide contact points between larger aggregates particles and thereby strengthen the mixture and lead to longer life of bitumen wearing coarse. Magnesium sulfate was used and filler was not controlled for this research. Sieve analysis was conducted and the results displayed on the below.

Table 3. 4 Filler Sieve Analysis

Sieve Size	Passing %
1.18	100
0.6	100
0.3	100
0.15	99
0.075	86

3.1.4 Reclaimed Asphalt Pavement (RAP)

The reclaimed asphalt pavement sample used for this research was taken from one of Addis Ababa city roads that is Tuludimtu – Gelan - Sefera road which was a rehabilitation project.

The reclaimed asphalt pavement (RAP) samples were subjected to bitumen extraction and sieve analysis tests. Four types of RAP percentage were used. These percentages were 10%, 20%, 30% and 40%. The gradation of reclaimed asphalt pavement is described on the next table

Table 3.5 RAP Gradation

Sieve Size	RAP (% passing)
5/8" (16mm)	100
1/2" 12.5	96.3
3/8" 9.5	87.0
#4 4.75	61.7
#8 2.36	42.5
#16 1.18	29.5
#30 0.6	20.5
#50 0.3	15.3
#100 0.15	12.8
#200 0.075	11.1
Pan	0.0

3.1.5 Molasses

Molasses is the dark, sweet, syrupy by-product of sugar refining industry. When no more sugar can be crystallized from the raw crop, the residual product is molasses. Molasses is used in a diverse range of industries due to its excellent non-pollutant binding properties as it is easier, safer and more efficient for handling. The molasses sample were taken from Wonji sugar factory. The property of the sample is described in the following table.

Table 3. 5 Molasses quality test result

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

Different literatures and studies were revised to select molasses content which was going to be used for this study. Maximum and minimum molasses contents were selected for more detailed study. The two selected trial percentages were minimum 3 (Timaj Abdulahi, 2017) and a maximum 10 % (Arpan Chaudhary et. Al., 2019) of molasses by optimum binder content. The Marshal stability and flow tests were conducted in a specimens prepared for the two molasses contents to select the appropriate percentage. Due to the cost and time limitations of this research, a single molasses content was used. The results for the test shown below.

Table 3. 6 Molasses percentage Trial mix result

Mixes	**Bitumen content**	**B. density**	**VMA**	**VFA**	**Air void**	**Stability**	**Flow**
3% Molasses	4.95	2.457	13.5	69.73	4.091	19.78	2.94
10% Molasses	4.82	2.444	13.845	64.597	4.903	21.365	2.255

On 3% molasses mixes VFA and air void values are around the middle range of the requirements and also stability was small compared with the other mix. As stability value increases the durability will be affected. RAP has better resistance for rutting than fatigue cracking so minimum molasses percentage which is 3% was selected as final study molasses content.

3.2 Sample preparation / HMA compaction

Marshal Mix design method prepares different binder content with 0.5 percent increments typically five by relying on local experience or procedure for the proposed gradation with at least 3 samples for each trial a total of 15 specimens will be prepared. In this study six specimens were prepared for each combination of virgin aggregates and virgin binder content.

Dry aggregates to constant weight at 105°C to 110°C and separate the aggregates by dry sieving into the desired size fractions. The mixing bowl was also heated for the appropriate mix temperature. The specimen mold assembly cleaned and heated to a temperature between 95 and 150°C. The mixture was weighted normally 1.2 kg into separate pans for each test specimen the amount of each aggregate size fraction required to produce the desired gradation and a batch that will result in a compacted specimen 63.5 ± 1.27 mm in height.

It is generally desirable to prepare a trial specimen prior to preparing the aggregate batches. If the trial specimen height falls outside the height limits, the amount of aggregate used for the specimen should be adjusted using the following formula (MS-2 Asphalt Mix Design Methods, 2014):

$$\text{Adjusted mass of aggregate} = \frac{63.5 \times (\text{mass of aggregate used})}{\text{Specimen height (mm) obtained}}$$

Also, in this study as the recommendation, trial sample was prepared to check the expected specimen height and the other sample weights had been adjusted based on the trial result. A filter or nonabsorbent paper cut to bottom size of the mould and placed before placing the sample to the mold. Test specimens are compacted with the marshal compaction hammer using a free fall of 457 mm (18 in.) by applying 50 or 75 numbers of blows per side as specified according to the expected design traffic category. In this project heavy traffic load was assumed.

After conducting quality tests and proving that it will fulfill the requirements needed to be used for asphalt mix design, blending was performed to have one aggregate gradation based on the required specification. For a single selected aggregate gradation, five different asphalt contents were prepared and tested for various volumetric and strength criteria to select the optimum binder content.

Based on the prepared aggregate gradation samples were prepared for five different binder content then volumetric property, stability and flow tests were conducted.

There are two ways to select the final binder content the first one is NAPA: corresponds to the specifications median air void content (typically this is 4 percent) and the other is Asphalt Institute Method: the average of asphalt contents at max stability, density, and mid-point of specified air void. For this research the Asphalt Institute method was selected.

3.3 Data Collection

Three different test data were collected for this research. Stability and flow tests conducted as the study used marshal mix design method. In addition, moisture susceptibility and rutting tests were also conducted in a laboratory prepared sample. Moisture susceptibility test by AASHTO: T 283 Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. The rutting test were conducted by Chinese standard T 0719—1993 Rutting test of bituminous mixtures. A minimum of four specimens were used for each test in order to have representative average result for each test.

3.3.1 Stability and flow

The performance of a paving mixture will be tested by stability and flow test values in marshal mix design method.

The compacted asphalt mixture specimen with a diameter of 101.6 mm and 63.5 ± 1.27 mm in height were immersed in water bath at 60°C ± 1°C (140°F ± 1.8°F) for 30 to 40 minutes. Then tested for the maximum load supported by the test specimen at a loading rate of 50.8 mm/minute (2 inches/minute). An automatic recording device were used to record the values, the load starts to decrease after it reached maximum. At the same time of loading the attached dial gauge measured the specimen’s plastic flow as a result of the loading.

3.3.2 Volumetric properties

Bulk specific gravity, Gmb

This is important property because it helps in improving the service life of the pavement. The ratio of the mass in air of a unit volume of a permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to the mass in air (of equal density) of an equal volume of gas-free distilled water at a stated temperature. This value is used to determine weight per unit volume of the compacted mixture.

The bulk specific gravity of an asphalt concrete mixture can be determined using either laboratory compacted specimens or cores or slabs cut from a pavement. The standard procedure for determining the bulk specific gravity of compacted asphalt concrete involves weighing the specimen in air and in water. The following formula is used for calculating bulk specific gravity of a saturated surface-dry specimen:

$$Gmb = \frac{A}{(B - C)}$$

Where Gmb = bulk specific gravity of compacted specimen

A = mass of the dry specimen in air, g

B = mass of the saturated surface-dry specimen in air, g, and

C = mass of the specimen in water, g

Total void in the mix (Va)

Air voids are the air found between aggregate particles that are coated by binder in a compacted paving mixture. It’s expressed as a percent of the bulk volume of the compacted paving mixture. The amount of air voids in a mixture is extremely important and closely related to stability and durability. In Marshall Mix design method of HMA, the allowable range for air void content in laboratory mix designs is range between 3.0 to 5.0% to allow for a slight amount of compaction under traffic and a slight amount of asphalt expansion due to temperature increases. The in-place air void is expected to be higher. Air void content is calculated from the mixture bulk and theoretical maximum specific gravity:

$$Va = 100[1 - \frac{Gmb}{Gmm}]$$

Where Va = Air void content, volume %

Gmb = Bulk specific gravity of compacted mixture

Gmm = Theoretical maximum specific gravity of loose mixture

Voids in mineral aggregate, VMA

The inter-granular void space between aggregate particles in a compacted paving mixture is called voids in mineral aggregate. It consists both air voids and voids filled with asphalt. Stability will decrease if VMA is high and when its low, there is not enough room in the mixture to add sufficient asphalt binder to adequately coat the individual aggregate particles. Binder type, binder quantity, sample temperature and Aggregate shape, strength and texture affects VMA. Mostly minimum VMA is specified. VMA requirements are specified by the nominal maximum particle size (mm). It's calculated by the following formula:

$$VMA = 100\ (1 - \frac{Gmb(1 - Pb)}{Gsb})$$

Where VMA = Voids in the mineral aggregate, % by total mixture volume

Gmb = Bulk specific gravity of compacted mixture

Pb = total binder, percentage by mass of mix

Gsb = bulk (dry) specific gravity of the aggregate

Voids filled with asphalt, VFA

Voids filled with asphalt (VFA) is the percentage of inter-granular void space between the aggregate particles (VMA) that contains or is filled with asphalt. VFA is used to ensure that the effective asphalt part of the VMA in a mix is not too little (dry, poor durability) or too great (wet, unstable). As the mix becomes finer and gains more total aggregate surface area VFA increases.

$VFA = 100\ (\frac{VMA - Va}{VMA})$

Where VMA = Voids in mineral aggregate

Va = volume of voids in compacted mixture

3.3.3 Moisture susceptibility

This test used to measure the change of diametral tensile strength resulting from the effects of water saturation and accelerated water conditioning, with a freeze–thaw cycle, of compacted asphalt mixtures. Two subsets of samples were prepared with the same sizes of marshal samples. One subset tested dry and the other was preconditioned before tested. The first group (dry samples) were covered with plastic and placed in a 25 °C (77 °F) for a minimum of 2 hours. The 2nd subset specimens were placed in the vacuum container by spacer and fill it with water then a vacuum of 13 – 67 kPa absolute pressure were applied from 5 – 10 minutes and soaked for 5 – 10 minutes. Then placed in a freezer at -18 ± 3 °C (0 ± 5 °F) for a minimum of 16 hours. After removal from the freezer, its placed immediately in to 60 ± 1 °C (140 ± 1.8 °F) water bath for 24 ± 1 hours. Then the specimens were removed and placed in a 25 ± 0.5 °C (77 ± 1 °F) for 2 ± 1 hours. The dry and conditioned specimens were placed between the two bearing plates in the testing machine. The load by a constant rate of movement of the testing machine head of 50mm (2 in.) per minute was applied and the indirect tensile strength at 25 °C (77 °F) was determined. The maximum compressive load will be recorded.

3.3.4 Rutting

This test used to measure the high-temperature anti-rutting capacity of bituminous mixtures. A test specimen that’s prepared in the laboratory with standard dimension of 300mm*300mm*50mm were used. The specimens were left at room temperature for at least 12 hours. Then the samples were insulated for 5 hours in a chamber with a 60 C temperature. Then tested at test temperature of 60 C and the wheel pressure is 0.7 MPa. The rut depth at 45, 60 min and dynamic stability were calculated and displayed or the dynamic stability can also be calculated by using the following formula.

$$DS = \frac{(t2 - t1) * N}{d2 - d1} * C1 * C2$$

Where: DS——Dynamic stability of bituminous mixtures, deformations per mm;

d1-Amount of deformation corresponding to time t 1, mm;

d2 - Amount of deformation corresponding to time t 2, mm;

C1 - Correction coefficient for types of testing machine, which is 1.0 of the movement with variable speed of test piece activated by crank connecting link, and is 1.5 of the movement with constant speed of test piece activated by chain;

C2 - Coefficient of test piece, which is 1.0 as for the test piece prepared in laboratory with width of 300mm, and is 0.8 as for the test piece cut from the pavement with width of 150mm;

N - The rolling velocity of test wheel in reciprocation, which is 42 per min

Figure 3. 2 Chinese Rutting Test Machine

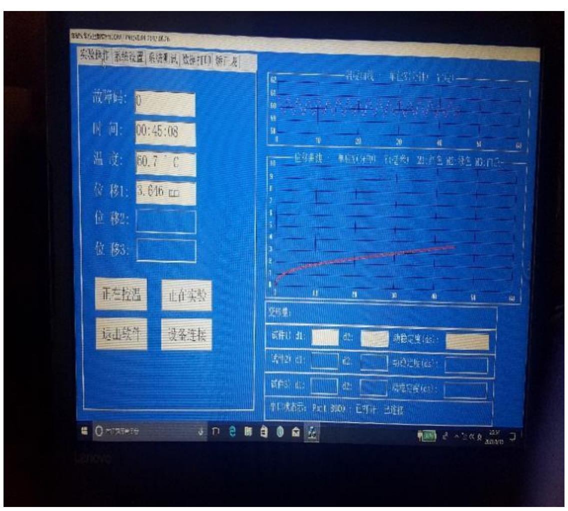


Figure 3. 3 Chinese Rutting Test Displaying Format

Figure 3. 4 Rutting Test Specimen

Asphalt Pavement Analyzer (APA) in AASHTO T 340 uses three rectangular slab or beam specimens or six cylindrical specimens can be tested at the same time using Gyratory, Marshall, or vibratory beam samples molded in the laboratory or field cores cut from the existing pavement. In a single pass, five or more measurements can be collected on a beam specimen and three or more on a cylindrical specimen. This extremely accurate system calculates the data to 0.00001mm. A PLC-based system with new Gen 5 Software controls operation and collects data on a PC where measurements are plotted and displayed in graphical/numerical format. The drive system operates the wheel tracking assembly from 0 to 60 cycles (120 passes) per minute. Both speed and stroke are adjustable for Hamburg Testing.

The Asphalt Pavement Analyzer comes fully equipped to run many loaded wheel tests. Concave wheels to perform rut and moisture testing, solid wheels for fatigue, and Hamburg testing are all included in sets of three each. Four sets of High-Density Polyethylene Molds for the rut, moisture, fatigue, and Hamburg testing are included, each as a set of three. Three 3/4in (19mm) high-pressure rubber hoses are used in conjunction with Concave Wheels for the AASHTO T 340 Rut Test and with the high-pressure loading feature for airport runway and taxiway design. A source of clean, dry compressed air at 120psi (8.3bar) and 8CFM (226LPM) is required.

Due to the availability of the APA machine, Chinese standard machine was used for this research.

Chapter 4: Result and discussion

In this section the results of tests will be discussed in detail for each test of every condition.

4.1 Hot Mix Asphalt mix design

For this study hot mix asphalt was designed by using marshal mix design method for the virgin aggregate and virgin binder materials. The asphalt binder and aggregate materials were tested for the appropriate quality tests before starting the mix design process as the hot mix asphalt contained these components its behavior will be mainly affected by their quality. Both materials fulfilled the requirements needed for the design.

Five different binder content were used to do the five mix trials to find the optimum binder content. The MS-2 suggestion for optimum bitumen content with nominal aggregate size led to the trial mix starting at 4% binder content. The following table shows the results of volumetric properties, stability and flow for the different binder contents.

Table 4. 1 Results of the five binder content mixes

Asphalt Ratio		Sample Size		Bulk Gravity	Abs	VV	VMA	VFA	Stability	Flow value
		Diameter	Height							
No.	AAR	Average	Average	——	(%)	(%)	(%)	(%)	(KN)	(mm)
1	4.0	101.6	64.3	2.346	2.2	9.1	15.0	39.3	13.6	1.9
2	4.5	101.6	63.7	2.358	1.2	7.8	15.0	48.0	14.1	2.2
3	5.0	101.6	63.3	2.384	0.4	6.1	14.5	58.0	14.7	2.4
4	5.5	101.6	63.3	2.417	0.4	3.2	14.0	77.4	12.3	2.4
5	6.0	101.6	62.8	2.403	0.2	3.0	14.7	79.4	12.2	2.3

Having the results binder content versus specific gravity, air void, voids in mineral aggregate, voids filled with asphalt, stability and flow charts had been prepared. The charts are shown below.

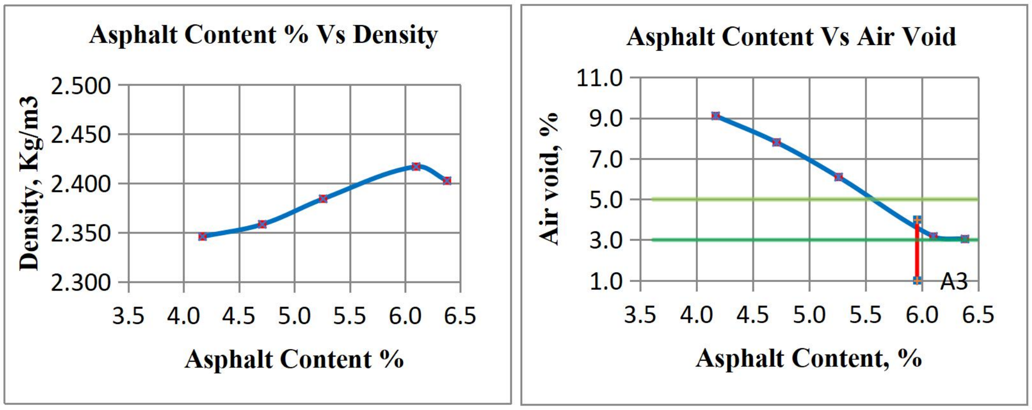


Figure 4. 1 Asphalt Content, % Vs Density, Air void

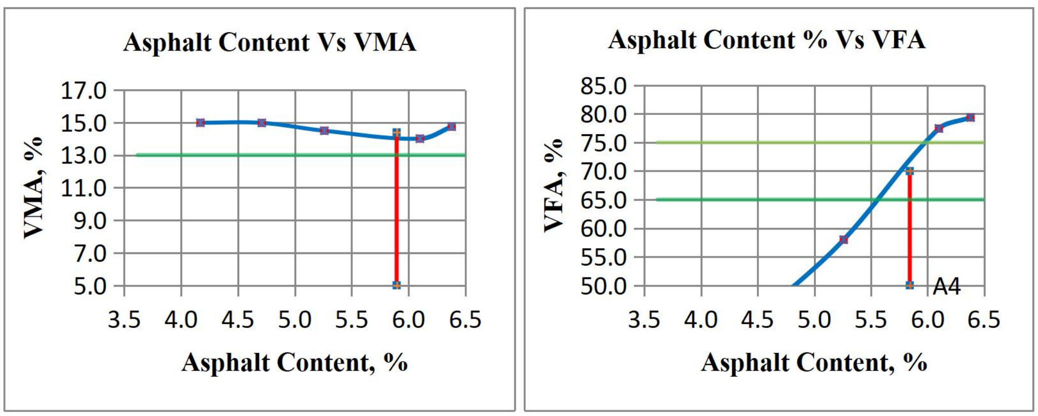


Figure 4. 2 Asphalt Content, % Vs VMA, VFA

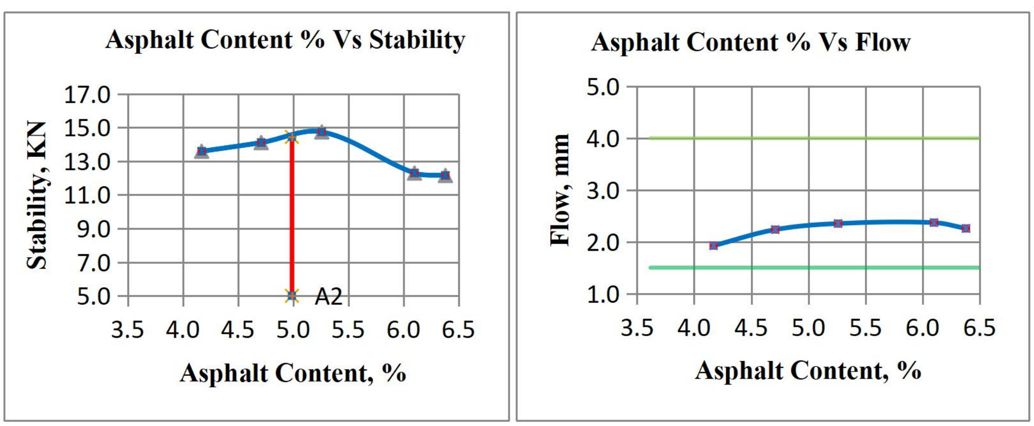


Figure 4. 3 Asphalt Content, % Vs Stability, Flow

Asphalt Institute Method was used and the Asphalt content at maximum stability, maximum density and specified air void range were determined. The average of these asphalt contents, 5.45 was used to determine the stability, flow, air void, VMA and VFA values from the plotted curves.

Those values were compared to the values that Marshal method given as criteria. The values are listed below.

Table 4. 2 OMC criteria Result

Criteria	Results	Specification
Stability	14000 N	8006 N (min)
Flow	2.35	2 - 3.5
Air void	4	3 – 5
VMA	14.1	14 (min)
VFA	70	65 – 75

As it's shown above all the criteria's fulfilled the requirements so, we can take the binder content as optimum. Therefore, 5.45 was decided as the optimum bitumen content.

4.2 Analysis of Compacted HMA Physical properties

Stability

The internal friction between aggregates and viscosity of bitumen depends the stability performance of asphalt mixtures. Any material which is able to increase these properties will be able to increase the stability of asphalt mixture. Stability was compared for mixes that contain four different RAP contents, molasses and RAP + molasses with control mix or mixes with no additives. The results will be discussed below.

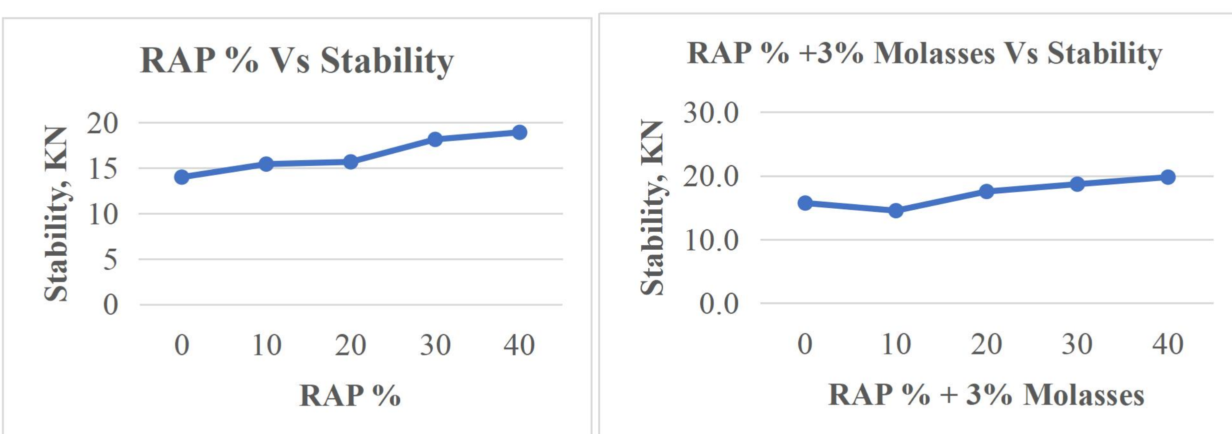


Figure 4. 4 Stability Comparison of Control with RAP and molasses modified mixes

The control mix stability values compared with mixes that contains four different RAP percentages. As the chart shows the stability value of the control mix is less than the mixes that contain different RAP contents. Figure 4.4 showed 10%, 12%, 30%, & 35% increment of stability with the addition of 10, 20, 30 & 40% RAP increment respectively. This is expected since the RAP adds stiffness to the mix due to the aging effect of the RAP material. A study by sunil et. Al, also showed that the increment of RAP percentages showed increased stability value on the mix as it is compared with the control or virgin mix.

The addition of molasses on the control mix shows 12% increment on the stability value when compared with the control mix. This indicate that effect of molasses on virgin mix is negeligiable but instead it will create the foaming effect which eventually evaporate creating a stiffer mix.

The addition of 10, 20, 30 & 40 % RAP on molasses modified mixes showed 8% decrease in the 10% RAP content but, increased 12, 19 and 26 % as compared with the molasses modified samples. As these mixes compared with the control mix, they showed 4%, 25%, 34%, and 41% increment with increasing trend. Which is expected as the percentage of RAP increases the softening effect of molasses decrease. In addition most of the stability property is attained from the aggregate and the binder effect may not cause significant difference, therefore the finesses of RAP material may also be the factor for this result.

Both mixes that contain the four different RAP contents with and without molasses showed increment on stability value as the percentage increased but, the mixes with the addition of molasses showed more stability value than the mixes without the molasses. Which is an indicator that the molasses act as softner or rejuvenator.

In this study the combination of both RAP and molasses increased the stability of asphalt mixture. We can understand that RAP material increased the friction between the inter particles interaction and also the molasses also increased the brittle resistance of the binder. The increment of stability affects the durability of the mixture so, here its better to conduct tests to check the durability performance of the mixtures.

Flow

Flow value is one of the major criteria's in designing a mix in marshal method. High flow values indicate a mix that will experience permanent deformation under traffic, whereas low flow values may indicate a mix with higher-than-normal voids and insufficient asphalt for durability and one that may experience premature cracking due to mixture brittleness during the life of the pavement. The following chart shows the results of flow values as different RAP percentages added to the control mix.

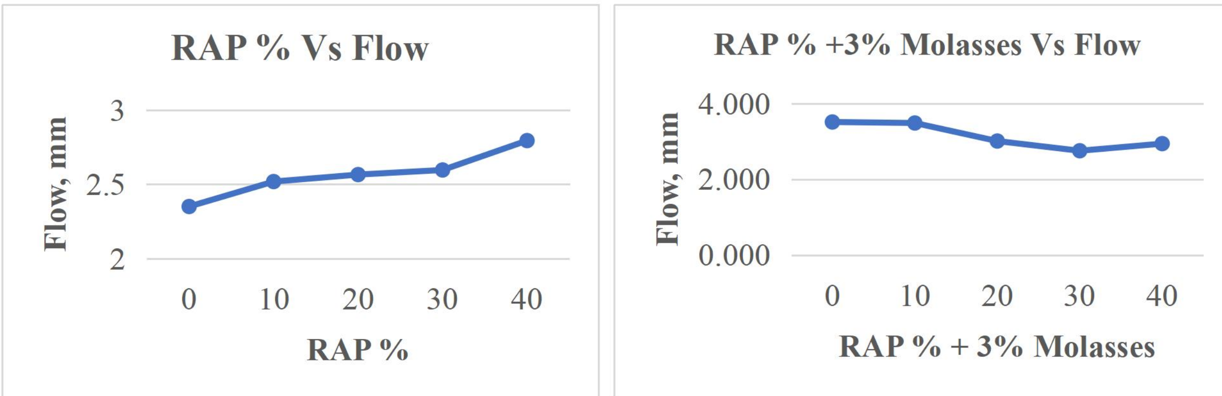


Figure 4. 5 Flow Comparison of Control with RAP and molasses modified mixes

The chart showed flow value increment of the other mixes as they compared with the control mix and with the addition of RAP, and also direct relation has been showed with the increment of RAP percentages. The addition of 10, 20, 30 & 40% RAP showed 7, 9, 11 and 19 % increment on flow value as compared with the control mix. This shows that the RAP didn't showed significant effect in flow the result is also somehow unexpected normally we expect decrease in flow due to the relatively high fine effect of RAP on the mix since the filler content isn't controlled manually for this research similar trend is also observed by other researchers (Sunil.et.al). A study by sunil et. Al, also showed that the increment of RAP percentages showed decreased flow value on the mix as it is compared with the control or virgin mix.

The addition of the molasses increased the flow value of the mix by 49% than the control mix. The addition of 10, 20 & 30 % RAP on molasses modified mixes showed 48, 28 & 17% increment respectively with decreasing trend but, starts increasing at 40% RAP by 25%. The flow value of all the mixes with molasses that contain RAP decreased with respect to the mix with molasses only. The molasses modified mixes with RAP decreases by 1, 14, 22 & 17% with the addition 10, 20, 30 & 40 % RAP as compared with molasses modified mix. This is expected as the molasses act rejuvenator the flow value of mix with RAP and molasses is higher than molasses only.

Bulk specific gravity, Gmb

Density relates with asphalt content; density decreases as asphalt content increases until the added asphalt content produces thicker films around the individual aggregates, thereby pushing the aggregate particles further apart. If the in-place air void decreases by any means it will cause an increase in density.

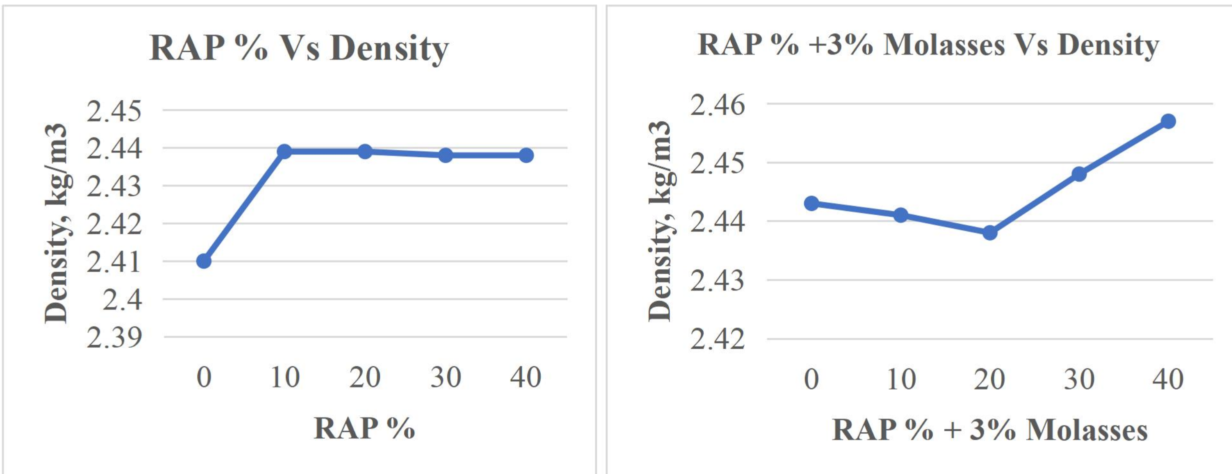


Figure 4. 6 Density Comparison of Control with RAP and molasses modified mixes

As we saw from the chart the bulk specific gravity of the control mix is less than the values from RAP modified mixes. The variation of the density with the increment of RAP percentages doesn't show much variations. The addition of molasses on the control mix showed 0.08% addition on the value, and up to 20 % RAP the values showed decreasing trend then continues to increase up to 40% RAP.

A study by sunil et. Al, also showed that the increment of RAP percentages showed decreased bulk density value on the mix as it is compared with the control or virgin mix. In this study RAP modified mixes showed not much variations on the addition and increment with respect to RAP + molasses modified mixes. As RAP and molasses modified mixes showed decreasing behavior up to 20 % RAP then increased.

Total void in the mix (Va)

Total air void is the space between coated aggregate which is expressed as percentage by volume of the mix. As air void increases the pavement will be exposed for further compaction due to traffic which becomes causes for failures. So appropriate amount should be left so as the road will be able to handle the additional compaction from the traffic.

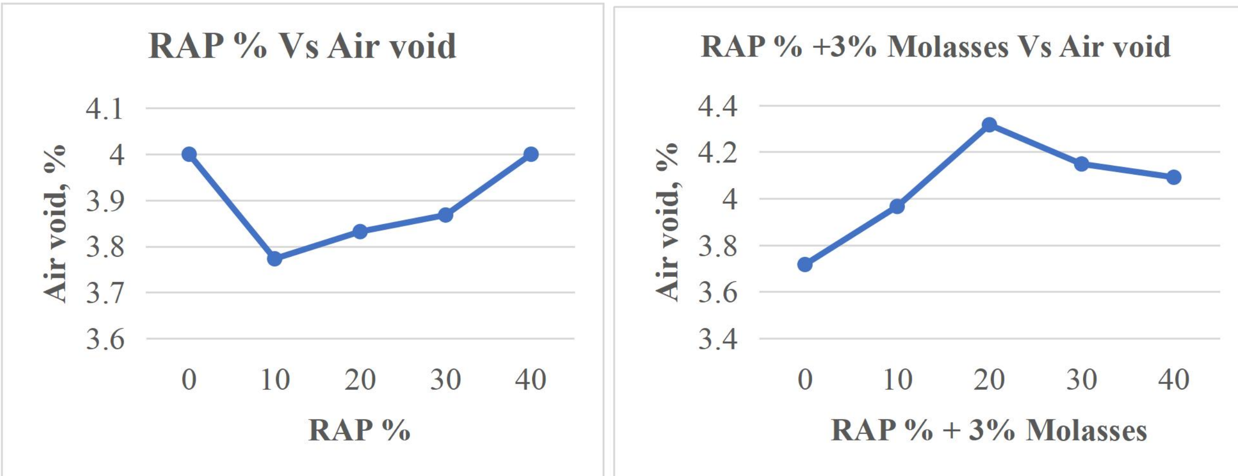


Figure 4. 7 Air void Comparison of Control with RAP and molasses modified mixes

The addition of 10% RAP material decreases the air void of the mix with respect to the control mix but, as the RAP percentage increases the air void also increase and reached the same value with the control mix at the final increment. The addition of molasses decreases the air void of the control mix by 7%, with the addition of RAP the air void increases up to 20 % then decreases. The addition of RAP on molasses modified mixes showed air void increment but, as the RAP percentages passes 20% it started to drop. But the addition of RAP on the control mix and RAP percentage increment was followed by air void increment.

A study by sunil et. Al, also showed that the increment of RAP percentages showed increased air void content on the mix as it is compared with the control or virgin mix. In this study also the increment of RAP content decreased the void content of the mix. Even with the addition of molasses on RAP mix showed higher air void content on the mix. This results showed that the addition of molasses and RAP increased the void content this may be due to as its showed earlier the addition of those materials didn’t sbrought visible difference on the density of the mixture so that the airvoid content was affected.

Voids in mineral aggregate, VMA

VMA is the total volume of voids with in the mass of compacted aggregate. VMA should be maintained well as it causes durability problems if it's too small, and if it's too large, the mix may show stability problems and be uneconomical to produce.

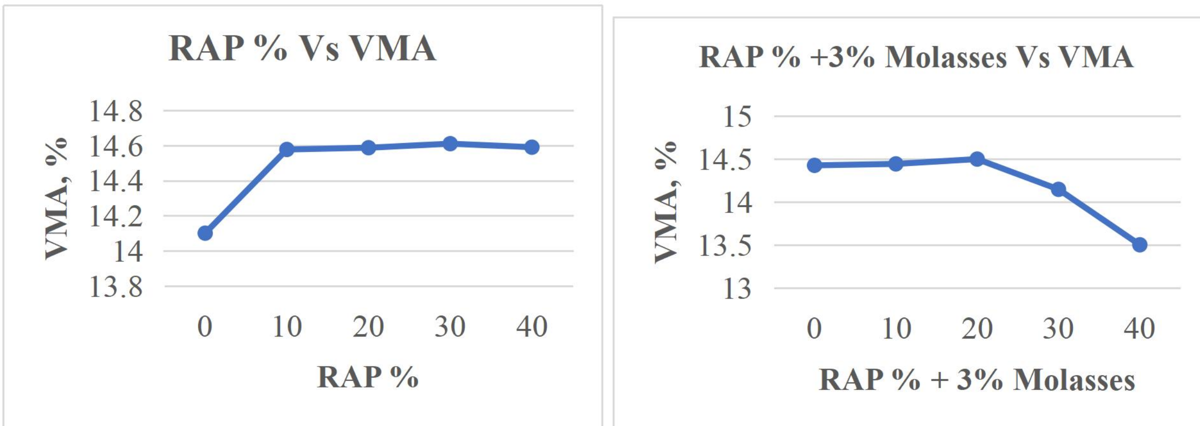


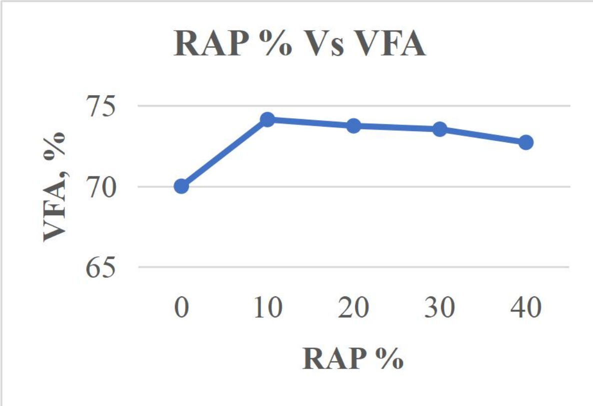
Figure 4. 8 VMA Comparison of Control with RAP and molasses modified mixes

The values of VMA of the control mix increases with the addition of RAP. The addition of 10, 20, 30 & 40% RAP doesn't show increment which is not significantly different from 4% at all percentages. The addition of molasses increased the VMA of the control mix by 2% then decreases when the RAP percentages exceed 20.

A study by sunil et. Al, also showed that the increment of RAP percentages showed increased VMA on the mix as it is compared with the control or virgin mix. In this study the increment of RAP percentages doesn't show significant difference on VMA results but when the mix include molasses the addition of RAP decreases the VMA from 20% RAP addition.

Voids filled with asphalt, VFA

VFA is the percentage of inter-granular void space between the aggregate particles (VMA) that contains or is filled with asphalt. VFA is used to ensure proper asphalt film thickness in the mix and it depends on both VMA and Va. Too low VFA may show a mix with poor durability and if its too high it shows unstable mix.



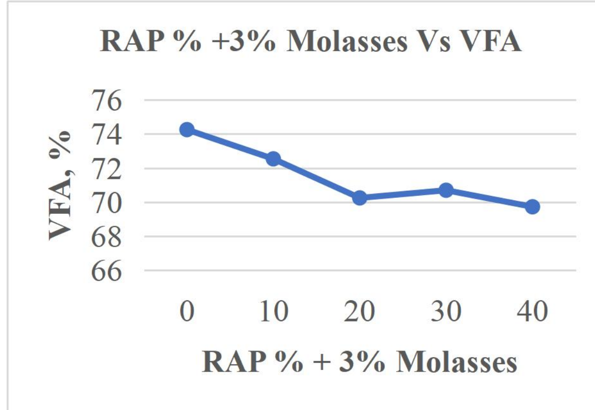


Figure 4. 9 VFA Comparison of Control with RAP and molasses modified mixes

The addition of 10% RAP shows 6% increment on the VFA value of the control mix. As the RAP percentage increases to 20, 30 & 40% the VFA value increases 6, 5 & 4% with decreasing trend but, still greater than the control mix. The addition of molasses on the control mix showed 6% increment on the VFA value but, this value showed decreasing trend with the addition and increment of RAP percentages.

A study by sunil et. Al, also showed that the increment of RAP percentages showed increased air void content on the mix as it is compared with the control or virgin mix. In this study molasses modified mix showed decreasing behavior due to the addition of 10%, 20% and 40 % RAP. The mixes of RAP added without molasses showed decreasing trend even if the values do vary significantly.

4.3 Analysis of Moisture susceptibility test results

Two subsets of specimens were prepared for two conditions, the first were dry and the second were wet by freeze-thaw cycle and then tested for tensile strength. The values for the tensile strength of the two conditioned sample have different values for control, Rap and molasses modified mix specimens. The values of tensile strength had two results for conditioned and unconditioned cases on each scenario.

Tensile strength of the samples from the control mix were 1437 Kpa at unconditioned state and decreased to 1323 Kpa after being conditioned. 10% RAP material was added on the control mix and the tensile strength of the mix increased to 1496 Kpa from 1437 Kpa at unconditioned state and increased to 1349 Kpa from 1323 Kpa when conditioned. The increment of RAP content by

10%, decreased the tensile strength of the mix to 1433 Kpa for unconditioned and 1274 Kpa for conditioned state. Increasing the RAP percentages to 30 % and 40% decreased the tensile strength to 1311 Kpa and 1308 Kpa for unconditioned and 1138 and 1075 for conditioned state.

This results showed that even if the addition of 10% RAP increased the tensile strength at both conditions the increment of its percentages decreased the tensile strength at both states. The higher % of the RAP material decreased the tensile strength at both conditioned and unconditioned states. The increase in susceptibility could be due to the inclusion of RAP material, which increases the stiffness of the mix as the RAP percentage is increased, making the mix unable to resist the freeze-thaw process since it is susceptible to cracking.

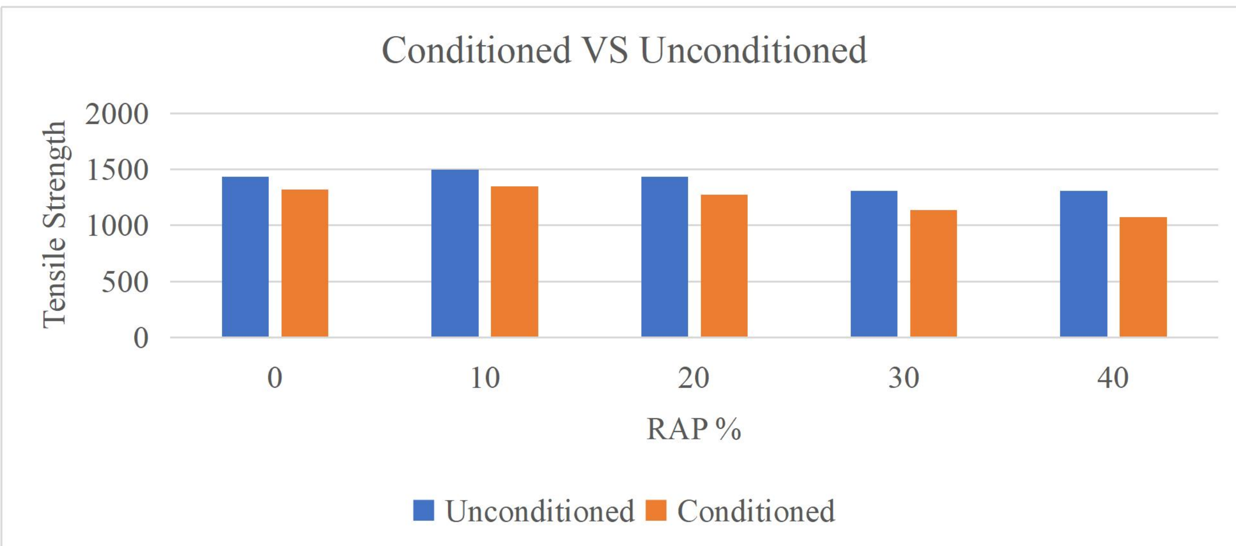


Figure 4. 10 Tensile Strength comparison between conditioned and unconditioned specimens

The molasses was added to the binder material to improve its behavior as it also reacted with RAP material bitumen. The effect was molasses was tested with respect to the control mix. Figure 4.11 showed that the addition of molasses increased the tensile strength of the control mix from 1437 Kpa to 1650 Kpa for unconditioned state and from 1323 Kpa to 1484 Kpa for conditioned state. The results showed that the addition of molasses brought improvement for both conditioned and unconditioned strengths by 15 and 12% respectively this may be due to the addition of molasses to the binder increased the adhesion property of the binder so that it increased the mixture resistance to moisture.

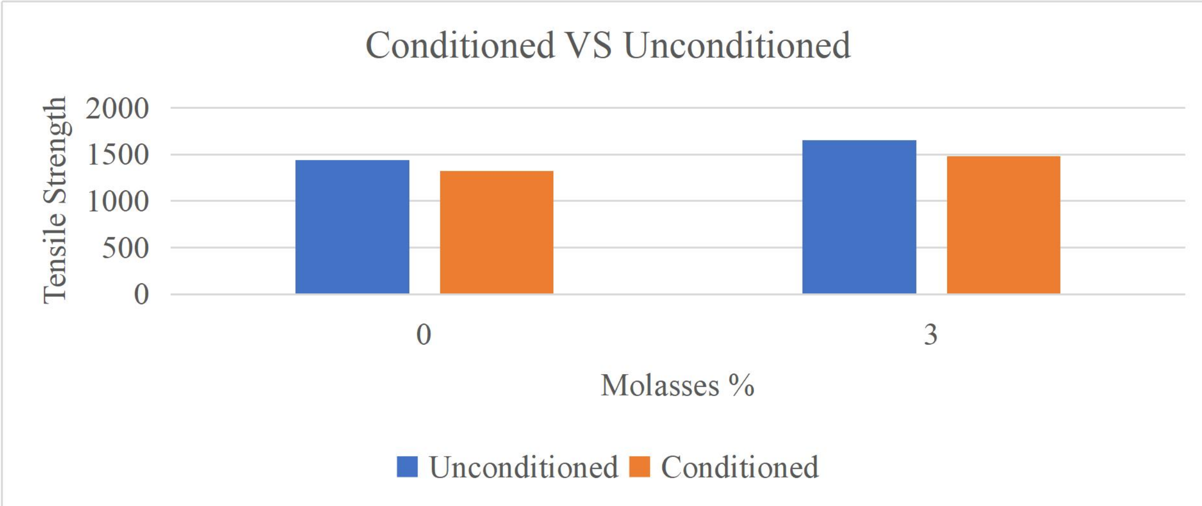


Figure 4. 11 Tensile Strength comparison between conditioned and unconditioned RAP modified specimens with control specimens

The effect of molasses on the weakness of adding RAP material was studied, so RAP material and molasses modified binder had been combined to their effect on moisture resisting capacity of the mixture and passed through a freeze-thaw cycle. With the addition of 10% RAP the tensile strength of the mixture was 1496 Kpa for unconditioned and 1349 Kpa for conditioned state after molasses was added to the binder the tensile strength goes to 1654 Kpa for unconditioned and 1463 Kpa for conditioned state. As described above, the addition of RAP material percentage decreased the tensile strength of the mixture, but as molasses was present in the mixture the increment of RAP percentage showed increment on the tensile strength. The 10% increment of RAP increased the unconditioned tensile strength reaches to 1555 Kpa from 1433 Kpa and 1351 Kpa from 1274 Kpa at conditioned state. When the RAP content reaches 30% and 40% the tensile strength ratio became 1457 Kpa and 1375 Kpa for unconditioned while 1219 Kpa and 1103 Kpa for conditioned state. Even if the addition of molasses increased the tensile strength ratio. RAP material was added in the mix with molasses with four different percentages. The results in figure 4. 12 showed that tensile strength of the molasses modified mix with 10%, 20% RAP increased 15 & 8% on unconditioned and 11 & 2% for conditioned state as compared with control mix respectively. But on the addition of 30% RAP the conditioned value will be less than the control mix and also on 40% addition it will fail to reach the control mixes tensile strength on both cases.

When the RAP percentage increased to the maximum limits the tensile strength ratio decreased even less than the control mix. This showed that the presence of higher amount of the RAP material increased the moisture sensitivity of a mixture, it may be due to RAP material increased the stiffness of the asphalt mixture.

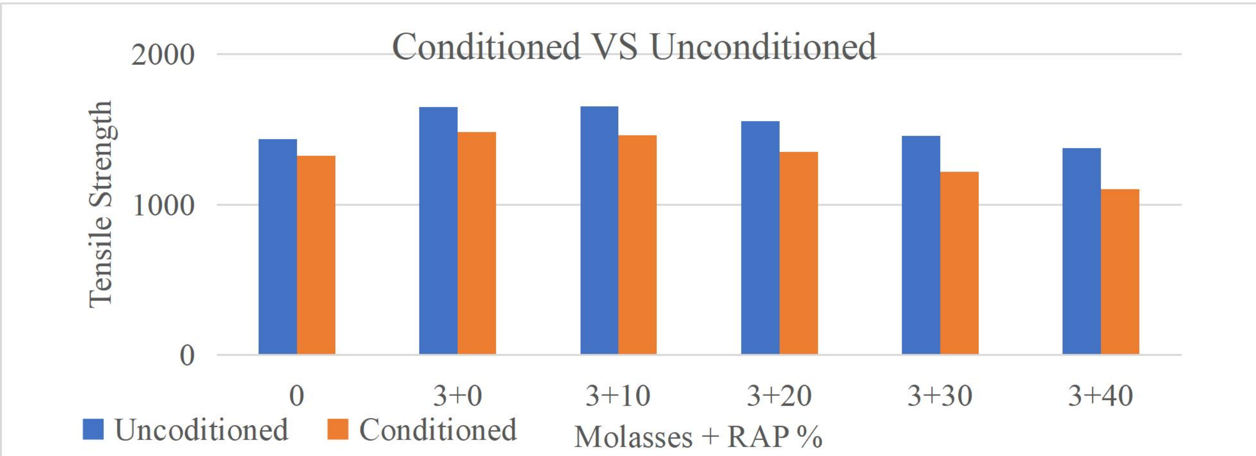


Figure 4. 12 Tensile Strength comparison between conditioned and unconditioned RAP and molasses modified specimens with control specimens

The mixes that contain molasses showed improvement on tensile strength due to the addition of RAP when compared with mixes contain RAP material only. But both mixes showed that due to the increment of RAP percentage, decreasing trend were followed for their tensile strength.

The tensile strength ratio was compared for all cases this research concluded. Figure 4. 13 showed the tensile strength ratio between the control mix and mixes that contain four different percentages. As the figure showed the addition of RAP percentages decreased the tensile strength ratio and as the RAP percentages increased the tensile strength ratio decreased. But we can understand that even if the values decreased from the control mix as the RAP percentages increased the value still fulfill the requirement.

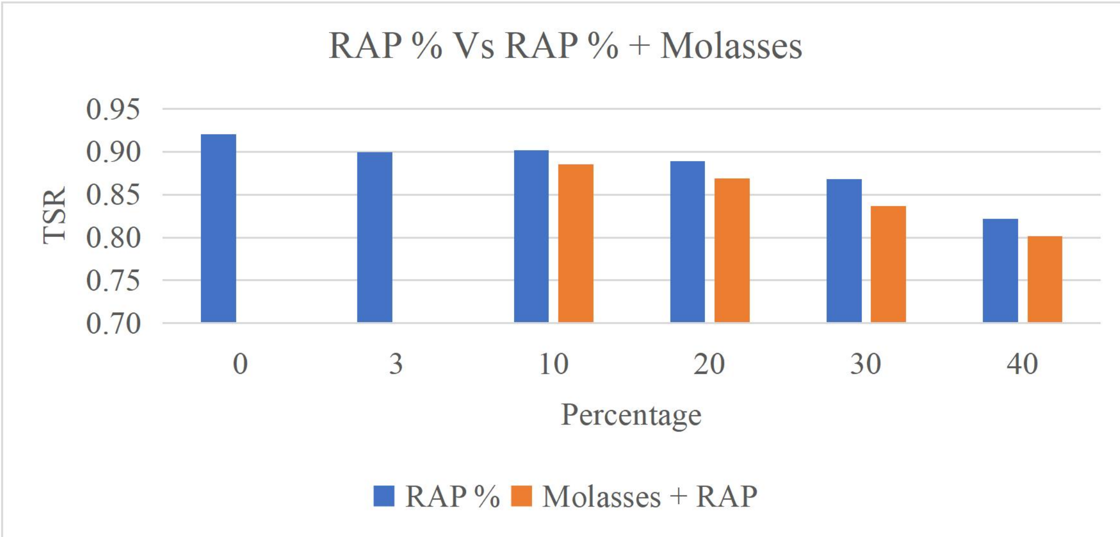


Figure 4. 13 TSR comparison between conditioned and unconditioned RAP and molasses modified specimens with control specimens

The addition of molasses on the control mix decreased the tensile strength ratio. The mix that contains molasses has the highest tensile strength ratio (TSR) than the mixes with the addition of RAP.

A research by susnil which studies on four different RAP percentages on common mix type and showed that the increament of RAP percentage decreased the tensile strength ratio of the material. The same as the metsioned study in this study also the addition of RAP percentages increased on the mix that contains molasses it followed decreasing trend on the TSR value and also failed to fulfil the requirements at 40% RAP.

The mixes that contain RAP only shows greater tensile strength ratio than the mixes that contain molasses in addition to the RAP.

4.4 Rutting

The rutting test results were described by two depths. The first and second depths was recorded at the 45^{th} and 60^{th} minute after the test was started. Dynamic stability was also recorded when the test was done. Dynamic stability is a character that describes the number of passes that cause deformation in a wheel tracking test. As the test took one hour to be completed and the depths at 45 and 60 min were recorded with calculated DS or the dynamic stability (DS) can also be calculated by formula.

When the control mix rut depth compared with the mixes that contain RAP, the addition of RAP decreased the rut depth of the mixes. The results showed that the mixes without any additives had the highest depth value. The addition of all the four RAP percentages showed decreased rut depth as compared to the control mix. When the final depth at the control mix was 8.552 but the addition of 10% RAP decreased the rut depth to 8.112 and the 10% increment of RAP percentage decreased the rut depth from 8.112 to 7.793 mm. the addition of 30% and 40 % RAP showed 13 and 15 % deduction on the rut depth as compared with the control mix. The results showed that rut depth decreases as the RAP percentages increased.

The study by A K Arshad et al, 2017 has been made on the effect of different RAP percentages on rutting behavior and found that the addition of RAP percentage decreased the rut depth which means that the addition of RAP showed lower resistance to rutting. But with this research the RAP percentage showed better resistance to the rutting behavior. This decrease in rut depth with the addition and increment of RAP percentages may be due to the RAP materials binder behavior as it helps to resist the deformation of the mix.

Table 4. 3 Rutting Test result for mixes with RAP

Mixes	d1	d2	DS
Control	8.345	8.552	3034
RAP 10%	7.840	8.112	2316
RAP 20%	7.506	7.793	2198
RAP 30%	7.172	7.472	2098
RAP 40%	6.963	7.287	1946

In addition to improving the control mix with RAP material, the effect of molasses was also compared with the control mix. The rut depth of the control mix were 8.552 when 3% molasses was added it decreased to 8.317. The bitumen was modified with molasses and it may improve the bitumen property which increased the stiffness of the mix so that it improved the resistance of the deformation of the mixture with respect to the control mix.

The control mix compared with the mixes that was modified with the combination of molasses with RAP. The mix with molasses had rut depth of 8.317 and decreased to 7.942 by 10% RAP addition. RAP reached 20% with rut depths 7.559, followed by 30% RAP and 40% RAP with 7.156 and 6.888 rut depths respectively.

The addition of 10% RAP on molasses modified mixes decreased the 8.552 mm rut depth of the control mix to 7.942. The addition of RAP percentages to 20% will decrease the rut depth to 7.559, following the increment of RAP to 30% and 40% decreased the rut depth to 7.156 and 6.888 respectively.

The addition of RAP on molasses modified mixes showed decreased rut depths at 60 min by 5, 9, 14 & 17% as compared with molasses modified mix and as it compared with the control mix it showed 7, 12, 16 & 19% as RAP percentages goes from 10, 20, 30 to 40%. This results showed the addition of RAP materials as the binder was also modified with bitumen showed better resistance to deformation as the molasses may increases the viscosity of the bitumen and RAP materials may also improve the stiffness of the mixture.

Table 4. 4 Rutting test result for mixes with RAP and Molasses

Mixes	d1	d2	DS
3% Molasses	8.076	8.317	2614
3% Molasses + 10% RAP	7.668	7.942	2302
3% Molasses + 20% RAP	7.265	7.559	2140
3% Molasses + 30% RAP	6.826	7.156	1909
3% Molasses + 40% RAP	6.529	6.888	1753
RAP 40%	6.963	7.287	1946

Chapter 5: Conclusions and Recommendations

5.1 Conclusion

Reclaimed Asphalt pavement material was studied in this research at four different percentages. The results of this research revealed that adding RAP increased stability and flow when the RAP percentages were raised. With the addition of RAP, the density of a mixture increased, but as the percentages grew, the density decreased. The void content of the mixtures increased when the RAP % was raised. RAP enhanced a mixture's VMA and VFA, but the percentages increased with little variance in their values. The inclusion of RAP material raised the tensile strength of a mixture by 10% in both the conditioned and unconditioned stages. When compared to the control mix, the inclusion and increment of RAP reduced rut depths.

For this study, a single molasses % was used. The addition of molasses to the control mix improved the stability of the mixture. The addition of RAP to the molasses mixture increased the mixture's stability and flow. In comparison to the control mix, molasses modified mixtures enhanced density, VMA, and VFA. Control mixes have a higher air void than molasses modified mixes. The tensile strength of molasses modified mixes in both conditioned and unconditioned states was greater than the tensile strength of controlled mixes in both conditions. When compared to the control mix, the molasses modified mix had a lower rut depth.

The four reclaimed asphalt pavement material (RAP) were added on the modified mixes by the single molasses content. In comparison between mixes that were modified by RAP and modified by both molasses and RAP, mixes modified by molasses and RAP showed increased stability, flow, density and air void than RAP only modified mixes, but RAP modified mixes showed increased values on VMA and VFA. Increased tensile strength had been showed at 10 and 20 % RAP for both conditioned and unconditioned states. Lower rut depths were showed for a mixture modified by both molasses and RAP as compared with the control and the other mixes.

In this study, control mixes were compared to RAP, Molasses, and both RAP and Molasses mixtures. When compared to the control mix, all of the modified mixes performed better in the tests undertaken for this study. When compared to other RAP and molasses-modified mixes, the RAP and molasses-modified mixes had better moisture resistance and lower rut depth. The RAP and molasses modified mixes performed better in terms of stability, flow, and volumetric qualities when compared to the other mixes, however because the RAP percentages utilized were 10%, 20%, 30%, and 40%, these attributes improved on the higher RAP (30 & 40) percentages.

Based on specification the following mixes are recommended for better performance mixing

- Mixes with RAP
- Mixes with Molasses
- Mixes with RAP plus Molasses

5.2 Recommendation

1. Further investigation can be carried out for more than 40% of the RAP materials and all the test can be evaluated
2. Further investigation needs to be carried out for more molasses content and also the combination of molasses and RAP materials.
3. Additional performance-based test methods can be carried out which is not covered in this research to provide accurate and realistic relationship.
4. The effect of RAP should also be carried out by considering not only the cost but also environmental and other factors.

LIMITATIONS

For this study availability modifier materials influenced the course and scope of this research study. The time especially cost limitations depend the number of samples to be used for the proposed tests.

References

a. Rangaraj et. Al., 2020. *Experimental investigation on partial replacement of bitumen with sugarcane molasses and quarry dust.* S.l.:S.n.

Abdulahi, t., 2017. Partial replacement of asphalt bitumen with sugarcane molasses.

Abu el-maaty et al., 2015. *Evaluation of hot asphalt mixtures containing reclaimed asphalt pavements.* S.l.:S.n.

Ahmad et. Al., 2016. *Utilizing rap in new pavement.* S.l.:S.n.

Ajideh et. Al., 2013. *Evaluation of fatigue life of asphalt mixture with high rap content utilizing innovative scanning method.* S.l.:S.n.

Ana e. Hidalgo, f. M.-n. *. R. T. A. M. C. R.-g., 2020. The influence of reclaimed asphalt pavement on the mechanical performance of bituminous mixtures. An analysis at the mortar scale.

Anon., 2018. *A laboratory study of bituminous mixes using sisal fiber.* S.l., s.n.

Anon., n.d. *Gilson company, inc..* [online]
available at: Https://www.globalgilson.com/asphalt-pavement-analyzer-apa

Arshad et. Al., 2017. *Marshall properties and rutting resistance of hot mix asphalt with variable reclaimed asphalt pavement (rap) content.* S.l.:S.n.

Arshad hussaina et. Al., 2013. *Effect of reclaimed asphalt pavement on the properties of asphalt binders.* S.l.:S.n.

Asphalt, c. O. R., 2020. Rheological properties and application of molasses modified bitumen in hot mix asphalt (hma).

Basim h. Al-humeidawi, 2001. *Asphalt institute sp-2.* S.l.:S.n.

Berg, a., 2016. *Cracking and rutting performances of field and laboratory hma mix designs.* S.l.:S.n.

Chaudhary et. Al., 2019. *Partial replacement of bitumen with molasses.* S.l.:S.n.

F. L. Roberts et. Al., 1991. *, "hot mix asphalt materialsmixture design and construction," First edition, napa education foundation,.* Lanham, maryland: S.n.

Fisha, t., 2019. Utilization of reclaimed asphalt as an effective unbound base course material, a case in addis ababa.

G. Mounika et. Al., 2020. *Study on percentage replacement of bitumen with molasses in stone matrix asphalt.* S.l.:S.n.

Gemechu et. Al., 2018. *Investigating the effect of cane molasses on the performance of base bitumen.* S.l.:S.n.

Gidirsa, t. K., 2020. Evaluation of asphalt road pavement containing recycled aspahlt pavement as a partial material in asphalt binder course mix in laboratory (case study: Ayertena – alem bank – yeshi debele road project).

Gidirsa, t. K., 2020. Evaluation of asphalt road pavement containing recycled aspahlt pavement as a partial material in asphalt binder course mix in laboratory (case study: Ayertena – alem bank – yeshi debele road project), 2020.

K.m. Padmapriya et. Al., 2019. *Experimental investigation on bitumen with partial replacement of sugarcane waste molasses.* S.l.:S.n.

Kitch, w. A., 2013. *Review of high percentage rap usage in asphalt concrete.* S.l.:S.n.

Kitch, w. A., 2013. Review of high percentage rap usage in asphalt concrete.

Mrugacz, j., 2019. *Recycled asphalt learn the benefits and process of recycling pavement.* S.l.:S.n.

Mrugacz, j., 2019. Uses of recycling asphalt (recycled asphalt: Learn the benefits and.

Onyebuchi nwabueze mogbo, m. T. T. E. C. D., 2020. Recycled asphalt pavement: A systematic literature review article.

Pradyumna, t. A. M. A. P. J., 2013. *Characterization of reclaimed asphalt pavement (rap) for use in bituminous road construction.* S.l.:S.n.

Pradyumna, t. A. M. A. P. J., 2013. Characterization of reclaimed asphalt characterization of reclaimed asphalt.

Sharma, s., 2017. *Evaluating the viability of molasses on penetration grade of bitumen and bituminous mix design.* S.l.:S.n.

Sharma, s., 2017. Evaluating the viability of molasses on penetration grade of bitumen and bituminous mix design.

Simeneh, a., 2013. *The effect of hydrated lime additives on moisture susceptibility and overall performance of hot mix asphalt mixtures.* S.l.:S.n.

Sunil s, k.m. Mallesh & t. Chandrasekaraiah, , 2014. *Experimental investigations on the performance of bituminous mixes with reclaimed asphalt pavement (rap) materials (case study tumkur to chitradurga-nh4).* S.l.:S.n.

Sunil s, k. M. &. T. C., 2014. Experimental investigations on the performance of bituminous mixes with reclaimed asphalt pavement (rap) materials (case study tumkur to chitradurga-nh4).

Teklu, w., 2015. *Effect of gradation of aggregates on the rutting performance of hot mix asphalt.* S.l.:S.n.

Timaj abdulahi, 2017. *Partial replacement of asphalt bitumen with sugarcane molasses.* S.l.:S.n.

Towhidul islam et. Al., 2020. *Development of improved asphalt mixture for the city of st, john's,a literature review on asphalt binder additives and modifiers.* S.l.:S.n.

Towhidul islam et. Al., 2020. *Development of improved asphalt mixture for the city of st, john's: A literature review on asphalt binder additives and modifiers,.* S.l.:S.n.

Us army corps of engineers, july 31, 1991. *Hot mix asphalt paving handbook.* S.l.:S.n.

Werku et. Al., 2020. *Rheological properties and application of molasses modified bitumen in hot mix asphalt (hma).* S.l.:S.n.