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Production of high performance paving material by improving the properties of stone mastic asphalt, using rubber and micro silica modifiers

A Thesis Submitted :

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بسم الله الرحمن الرحيم

{قَالُوا سُبْحَانَكَ لَا عِلْمَ لَنَا إِلَّا مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ}

صدق الله العلي العظيم

سورة البقرة : الآية (23)

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I certify that this thesis entitled **“Production of high performance paving material by improving the properties of stone mastic asphalt, using rubber and micro silica modifiers”**, which is prepared by **"Haneen Fadhil Kadhim "**, is under my supervision at Babylon University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Civil Engineering/ Transportation Engineering).

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Examining Committee Certificate

We certify that we have read this thesis entitled (**Production of high performance paving material by improving the properties of stone mastic asphalt, using rubber and micro silica modifiers**) and as an examining see examined that student (**Haneen Fadhil Kadhim Khadir**) in its content and that in our opinion it meets a standard of thesis for the degree of master in engineering \ Civil engineering\ Transportation .

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Dedication

This thesis is dedicated to

My Family especial My Father and My Mother for their love and continuous prayer

My husband Eng. Ameer for his endless help and continuous support

My children (Jana and Ayham)

For their pure prayers, smiles, and love that give me energy to work

To my supervisor Dr. Harith K K Ajam

I am grateful and deeply indebted to him for his ongoing support and encouragement. Without him, it would not have been possible to complete this research.

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ABSTRACT

The growing demand for high-quality pavements has encourage researchers to develop a new design procedure to improve the performance and prolong the lifespan of asphalt pavements, also the rise in maintenance costs is proportional to the rise in traffic volumes, necessitating the construction of better, more durable, and more efficient roads that prevent or reduce bituminous pavement issues. There are find a good choice for that problem is Stone Matrix Asphalt.

On other hand, use the waste material in asphalt provides an excellent opportunity to manage waste sustainably. Cost reduction, environmental protection, and energy consumption reduction. Accordingly, this research aims to investigate the impact of some local waste materials on the performance of the SMA asphalt mixture also to reduce the drainage to improve the performance of the mixture .

In this research, Stone mastic asphalt specimens have been prepared with aggregate, nominal maximum size (12.5) mm, filler type (1.5% cement and 8% hydrated limestone), asphalt cement sources (Durah) and two types of available additives is Crumb rubber and Micro silica, one percentages for Crumb rubber is 15% by weight of asphalt cement and three Percentage of Micro silica (2,4,6,)% by weight of asphalt cement. Use wet process to mix the additives with asphalt cement by using shear mixer .

The tests used in this research, physical properties for modified asphalt binder including penetration, softening point, ductility, penetration index, and rotational viscosity. The testing plan also included volumetric properties (e.g., bulk density, air void, void in the mineral aggregate, a void filled with asphalt, and drain down), mechanical properties (e.g., Marshall stability and flow, Indirect Tensile Strength, Cantabria abrasion loss, Skid Resistance, and Wheel tracking), and durability (Cantabria abrasion loss after ageing, and tensile strength ratio) to determine the impact of using these materials on SMA mixture characteristics. The result of the laboratory tests showed, the physical properties of the asphalt binder are greatly improved. The penetration, ductility, and sensitivity to the temperature of bitumen are decreased, while asphalt's softening point and viscosity are increased. In addition, the use of Micro Silica resulted in the improvement of nearly all stated characteristics, with 6% demonstrating a significant improvement in comparison to other low ratios, except 2%, where demonstrated a significant improvement in the tensile strength ratio, where the percent of increase was 11 %. The results showed when adding Micro silica at a rate of 6% to improve the properties of stone mastic asphalt , with a rate of 6% it gave the best performance for the drain down, reaching 0.013% and 0.067% at 160°C and 175°C, respectively. Skid resistance was reduction to 23%, wheel track was reduction of 58% compared to the control mixture, and the addition of 6% providing the best results in improving the indirect tensile strength where the resistance of the mixture to cracking that by approximately 33%. The study concluded that using Micro silica as using asphalt modifiers can enhance the performance of SMA mixtures especial at percentage 6% it is consider the optimum percentage .

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ABBREVIATIONS AND SYMBOL

AASHTO	American Association of State Highway and Transportation Officials
AV	Air Voids
B0	Neat Binder
BD	Bulk Density
BPN	British Pendulum Number
CO	Control mixture
CR	Crumb Rubber
DGA	Dense-graded asphalt
DRC	Dry Rodded
GR	Grading selection
HL	Hydrated Lime
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
MAS	Maximum Aggregate Size
MB	Modified Binder
MF	Marshall Flow
MMS	Modified Mixtures
MS	Micro Silica
NAPA	National Asphalt Pavement Association
NMAS	Nominal Maximum Aggregate Size
OAC	Optimum Asphalt Content
Pb	Percent of Asphalt Content by Total Weight of Mixture
PCA	Percent Coarse Aggregate in Total mixture

PG	Performance Grade
SBS	Styrene–butadiene–styrene
SEBS	Styrene–ethylene/butylene–styrene
SHRP	Strategic Highway Research Program
SMA	Stone Mastic Asphalt
SP	Softening Point
TSR	Tensile Strength Ratio
VCADRC	Voids of Coarse Aggregate in Dry Rodded Condition
VCA mix	Voids of Coarse Aggregate in Compacted Mixture
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
WTT	Wheel Tracking Test

Chapter One :
Introduction

1.1 Background

The mobility of citizens and goods is recognized as a critical issue for the economic development of countries and territories. A great deal of that mobility is ensured by the road networks, whose pavements must guarantee a good ride quality. Additionally, as the economy grows more and more trips are generated and demand for transport infrastructures rises. Increased use of heavy vehicles accelerates pavement degradation, necessitating the development of better road materials to meet growing demands. Over the past 50–60 years, various technologies for asphalt pavements have been developed due to these circumstances Stone matrix asphalt is well recommended for roads that need to be durable (Picado-Santos, Capitão and Neves, 2020). Dr. Zeicher introduced the Stone Matrix Asphalt (SMA), also known as an asphalt mastic mixture, to Germany in the 1960s (Razahi and Chopra, 2020).

Stone matrix asphalt (SMA) is a strong, resilient, and damp-resistant mixture that relies on rock-to-stone contact and a robust mortar adhesive to maintain durability. Stone matrix asphalt (SMA) is more expensive than conventional dense mixes by about 20 to 25%. SMA has the advantages of increasing durability and decreasing rutting, as well as reducing surface noise, which drives up the price of this type of asphalt. The mineral filler, fibers (natural or synthetic), modified binders, and asphalt components all contribute to stone matrix asphalt's higher cost (Kiran Kumar and Ravitheja, 2019).

The mastic contains higher asphalt content, filler and stabilizing agent. The higher asphalt content provides a durable pavement layer than the dense-graded mixtures. (Júnior, Filho and Bernucci, 2004) has found that SMA mixtures require

1.0% - 1.5% more bitumen than the conventional dense-graded mixture and that forms a thick film of asphalt coating around the aggregates, which reduces the friction and increases the fluidity of the mastic material. Therefore, such mixtures require a stabilizing agent to balance the fluidity and drain down of the mastic material from the mixture (Devulapalli, Sarang and Kothandaraman, 2022). The higher coarse aggregate content forms into skeleton structure and delivers stone-on-stone contact and the same provides superior tire grip and rut resistance (Sarang, Lekha and Shankar, 2014). In SMA mixtures, traffic and shear loads are carried out by coarse aggregate (Brown, 1993).

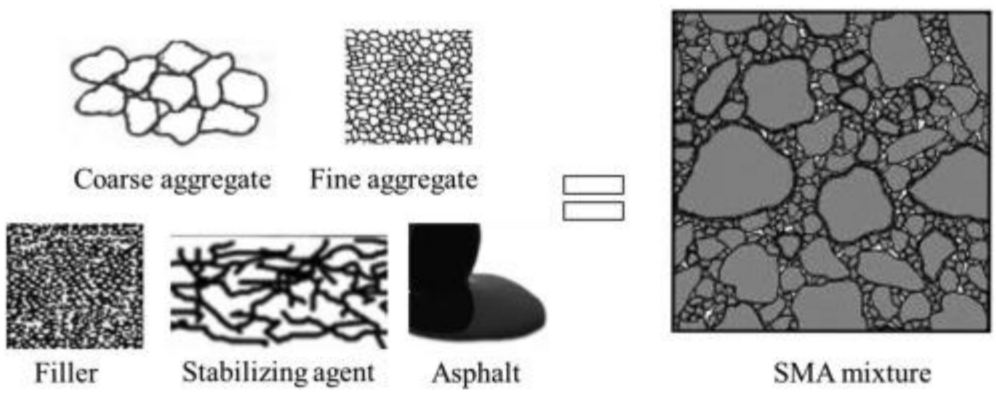

Figure 1- 1 Major components of SMA mixture (Devulapalli, Sarang and Kothandaraman, 2022)

Recognized for their resistance to rutting, gap graded SMA mixes are used mainly for surface courses subjected to heavy traffic, used in surface mixtures because of the high stresses near the surface and because SMA is a premium mix that costs significantly more than conventional dense graded HMA. SMA's inherent stability is due to the framework formed by the large proportion of durable, coarse aggregate particles present in the mix (Sharma and Goyal, 2006) Figure 1-2 show advantage of SMA .

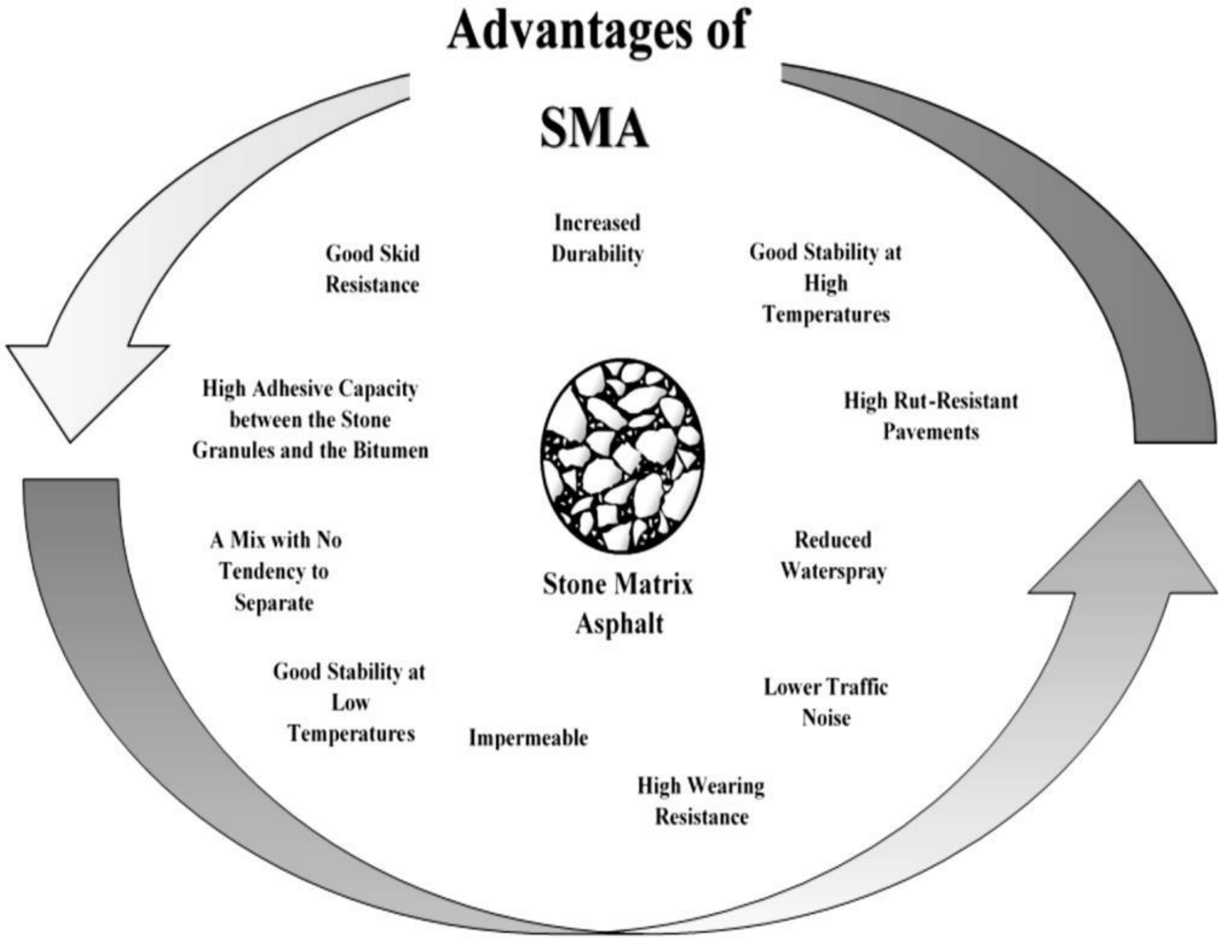

Figure 1- 2 Advantages of SMA (Limón-Covarrubias et al., 2019)

Experiments have shown that surface-modified asphalt (SMA) has greater rutting resistance, higher durability, and improved resistance to reflective cracking in comparison to dense graded asphalt (DGA) (Cooley and Brown, 2003 ,Mahrez and Karim, 2010). This is because the structure's composition is comprised of three parts: a coarse aggregate skeleton, a mastic, and air voids (Figure 1-3). Stone-on-stone contact is made possible because of the coarse aggregate skeleton, which contributes to the material's great resilience to deformation. The mastic is made up of fine aggregates, filler, and a sizeable portion (about 6–7% of the binder's mass).

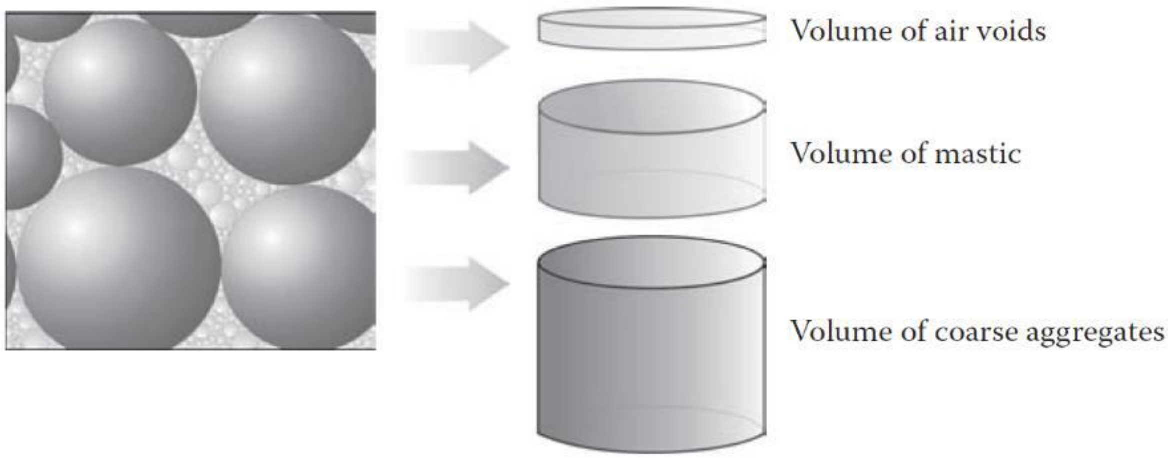

Figure 1- 3 Division of SMA into basic components (Blazejowski, 2016).

The higher binder content of SMA generates a bitumen layer that is more resistant to wear and strain in comparison to DGA; however, this also increases the danger of binder drain-off during the manufacturing process, as well as during shipping and installation. Stabilizers and drainage inhibitors are often present in the form of cellulose fibers and polymers (Mojabi, Abdi kordani and Mirbaha, 2020). According to Xue et al. (2013), various modifications have been made to the construction procedures, as well as the selection of materials and the mix design, to enhance the performance of SMA and minimize the amount of excessive binder drainage. These improvements were made to improve the performance of SMA and reduce the amount of excessive binder drainage. According to Bala et al. (2017), asphalt binder is prone to failure in several processes, including manufacture, storage, laying, and compaction. This binder may have several different additives added to it to increase the strength of asphalt pavements. Asphalt has been altered in recent times by the addition of fillers, items made from recovered rubber, catalysts, fibers, polymers (both natural and manufactured), and extenders (Tai Nguyen and Nhan Tran, 2018). (Arabi et al., 2017c) have been inspired to look for alternatives to bitumen pavement for a variety of reasons, some of which include environmental concerns, economic issues, and the need to save energy. According to Arabi et al., 2017c, waste materials, including recovered aggregates, waste masonry, glass, seashells, reclaimed asphalt pavement, and waste tires, have been effectively included in asphalt mixes as aggregate, filler, and asphalt modifier.

Fibers such as polyester fibers, mineral fibers, and cellulose fibers are added to asphalt mixes to enhance the dynamic modulus, tensile strength, moisture susceptibility, creep compliance, skid resistance, and fatigue life. Additionally, these fibers are added to limit discharge and modify the viscoelasticity of the asphalt. (Sheng et al., 2017) When fibers are included in asphalt mixes, a higher amount of bitumen is required. This results in an increase in the asphalt's durability, stability, and resistance to the effects of ageing under a variety of situations. When there is a rise in the amount of bitumen, there is also an increase in the membrane thickness of the aggregates. This results in a delay in the bitumen's ability to harden. To put it another way, the time it takes for denser bituminous coatings to harden and become rigid is longer. However, when the amount of bitumen grows, the inter granular vacuum space reduces or dissipates. This prevents air and water from entering the structure, which in turn prevents oxidation and the disintegration of the mixture. (Mojabi et al., 2020). On the other hand, the polymer is widely used in asphalt mixes to improve mechanical qualities while simultaneously reducing binder drawdown. To achieve the necessary mixing qualities, a variety of polymers, such as styrene–butadiene–styrene (SBS), ethylene–vinyl–acetate (EVA), polyethylene, or polypropylene, may be used, depending on the designer's goal. (Punith et al., 2007, Arabani et al., 2017c).

Polymers are a kind of substance that may be utilized to enhance the performance of asphalt. The resistance of a polymer-based pavement to thermal fracture and rutting is raised, but its resistance to fatigue failure, flaking, and temperature sensitivity is diminished. In high-stress sites, such as airports, vehicle weigh stations, and racetracks, polymer-modified binders have been used. Other examples are junctions of high-traffic streets with heavy vehicle traffic. (Yildirim et al., 2007, Arabani et al., 2017c) Among the numerous improved qualities of polymer-modified binders are a higher softening point, a better elastic recovery, a higher cohesive strength, more ductility, and a larger viscosity. These are only some of the benefits.

1.2 Problem statement

The durability of asphalt pavements after highway use is already a major concern. Because of the severity of the failure phenomena, the pavement must be repaired on a regular basis, resulting in mounting economic losses and negative consequences. As a result, improving asphalt pavement performance and extending pavement service life are critical issues facing the asphalt pavement design field. As a result, modern traffic has pushed expressway asphalt pavement standards higher. Experiments have shown that SMA has greater rutting resistance, higher durability, and improved resistance to cracking. the higher binder content provides a long-lasting asphalt layer that increases the risk of binder drain-off during production, transport, and laydown. To compensate for this, a SMA blend contains stabilizers or drainage inhibitors, so improving SMA characteristics is essential approach to gain its advantages. Furthermore, concern for environmental aspects is required nowadays for any proposed approach, so the use of waste materials can offer both economic and environmental benefits; however, there is no point in introducing an alternative that lacks these two characteristics in addition to the development of volumetric, mechanical, and durability properties.

1.3 Aim and Objectives of the Research

This study aims to improve the properties of SMA asphalt mixtures using a waste material in order to increase the service life of the SMA mixture and achieve the best resistance to pavement rutting, cracking, and wet weather skid resistance. This can be accomplished by pursuing the following objectives:

1. Modify the asphalt binder by using the local material Crumb Rubber (CR) and Micro Silica.
2. Producing modified binders by using different percent of additives materials.
3. Evaluating the consistency of unmodified and modified binders in terms of penetration, softening point, viscosity, and ductility
4. Identifying the characteristics of unmodified and modified SMA mixtures in terms of:
    a. Volumetric properties (bulk density, voids in mineral aggregate, voids filled with asphalt, air voids, and drain down).
    b. Mechanical examinations: (Marshall stability, Marshall flow, Indirect tensile strength, Cantabria abrasion loss, wheel track, and skid resistance).
    c. Durability tests: (Cantabria abrasion loss after aging and Tensile strength ratio).
5. Comparing the volumetric, mechanical, and durability properties of the newly developed SMA mixture to those of traditional SMA mixture to ensure that the development is feasible.

1.4 Scope of work

The scope of this research is summarized below for the wide range of materials, design methods, and testing methods:

1. All of the materials used in this study were sourced locally. One asphalt type (40-50), one aggregate gradation and type, and two filler types.

2. The mixtures' mechanical, volumetric, and durability properties were evaluated in the lab, and no field tests were conducted.

3. All tests were conducted at the University of Kerbela's and AL-Mustaqbale's highway transportation lab.

4. Some testing devices were produced locally, such as a shear mixer for mixing additives (CR and MS), and indirect tensile strength test. These manufactured devices were built following industry standards. Devices were used local programming and computerization with the assistance of an experienced programmer.

1.5 Thesis structure

This thesis is divided into five chapters, each of which demonstrates the study work outcomes as listed below:

Chapter 1 the background of the research, its statement of the problem, its aim and objectives, the scope of the research work, and finally the thesis structure are all presented.

Chapter 2 describes a review of SMA mixtures, their properties, performance, and SMA resistance to failure.

Chapter 3 discussion material, testing, and methodology: displays characterize used for raw materials, SMA mixture design, experimental plan, and finally research methodology.

Chapter 4 summarizes the laboratory test results, as well as the necessary analysis and interpretation of these results for both unmodified and modified binders and SMA mixtures

Chapter 5 presents the main conclusions and recommendations for future work.

Chapter Two:
Literature Review

2.1 Introduction

The asphalt industry recognizes the critical need for pavements that resist rutting, crack, and other pavement distresses caused by heavy traffic and studded tires. To meet this demand, roadway pavement contractors created a mix known as stone mastic asphalt (SMA); it was suggested in Germany for the first time. This mix is a gap graded mix with a high concentration of coarse aggregate (>70%), which maximizes stone to stone contact and provides a good network for load distribution.

This chapter reviews the literature on SMA. Moreover, it describes the characteristics of SMA, the application, conventional materials used in mix design, as well as waste materials used in asphalt binder modification. It also discusses the performance indices by SMA mixture, and finally, SMA resistance to various types of failure.

2.2 Pavement mixture technologies

Flexible pavement is a common type of pavement. According to statistics, flexible pavement covers 95 % of the world's highways. Asphalt concrete pavement or hot mix asphalt pavement is the surface course bound layers of a flexible pavement structure. The most common type of flexible pavement surfacing is a bituminous premix material known as Hot Mix Asphalt (HMA). As the name implies, HMA is mixed, placed, and compacted at a high temperature. HMA is usually applied in layers, with the lower layers supporting the top layer, also known as the surface course or friction course (Aziz et al., 2015, Rahman et al., 2020a). Dense-graded HMA has a large range of particle sizes, allowing it to spread easily through the asphalt concrete mix. Moreover, dense-graded HMA is the most commonly used form of asphalt concrete in the world and is appropriate for all traffic conditions. While Open-graded HMA is commonly used in drainage layers due to its relatively high void ratio, which allows the mix to be more permeable. (Guide et al., 2001, Grant et al.). Stone mastic asphalt, on the other hand, is a gap-graded HMA that is widely used in Europe. Due to the superior physical and mechanical properties required for the stone-to-stone contact structure, the aggregates used in SMA mixes are frequently of higher quality than the aggregates used in standard HMA mixes.. The high coarse aggregate content of SMA creates high rutting resistance and increases the structure's longevity (MS-2 ASPHALT MIX DESIGN METHODS, 2009, Blazejowski, 2019). Figure (2-1) shows a comparison of skeleton among different mixtures.

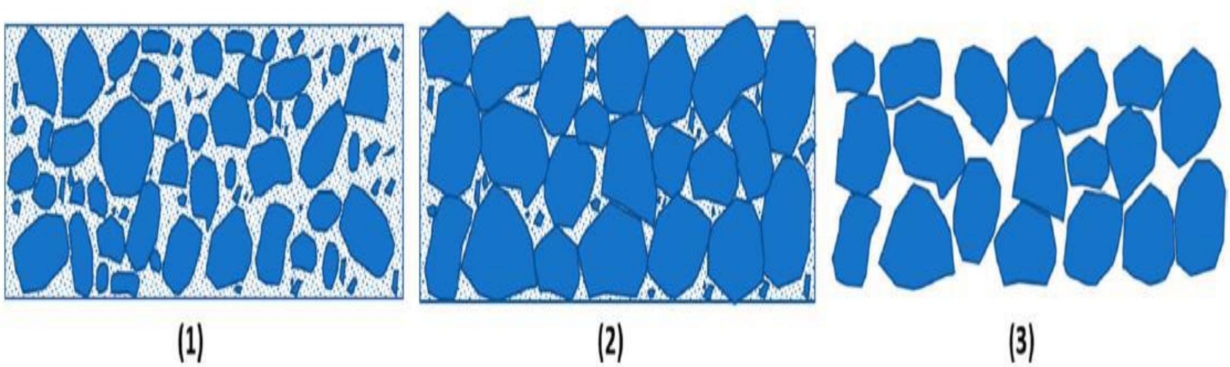

Figure 2- 1 Illustrative figure for the mixture skeleton of (1) DGA, (2) SMA, and (3) OGFC (Jamieson and White, 2020a)

2.3 Overview of stone mastic asphalt (SMA)

Since 1991, combinations of stone mastic asphalt (also known as SMA) have been used in the United States. Stone matrix asphalt (SMA) is a gap-graded asphalt mixture designed to increase rutting resistance and durability (Devulapalli et al., 2019). When compared to conventional mixtures, stone matrix asphalt contains a higher proportion of coarse aggregates and binder mortar. According to

(Liu *et al.*, 2017), the usual composition of SMA includes 70–80% coarse aggregate, 8–12% filler material, and 6–8% binder. A stone-on-stone contact structure must be present in the aggregate skeleton of the mixture. Stone-on-stone contact provides SMA with the internal strength that enables it to be tough, stable, and resistant to the formation of ruts. Mineral filler, fibers for stabilization, and binder are the three components that make up the rich binder mortar. According to MS-2 ASPHALT MIX DESIGN METHODS (2009), the mortar's job is to prevent the asphalt binder from draining down and partly fill the spaces in the coarse aggregate skeleton (MS-2 ASPHALT MIX DESIGN METHODS, 2009). It is anticipated that the stone-on-stone contact of the aggregates in the roadway would significantly cut down on rutting. This is due to the fact that aggregates do not shrink as much as asphalt binder does when loaded. By interlocking a gap-graded aggregate of excellent quality, the strength of the pavement may be increased. As can be observed in Figure (2-2), the gradation only comprises a tiny fraction of aggregate particles that fall within the midsize range. This results in more space being made available for the mortar, which is composed of fine aggregate and polymer-modified binder (Myers and Newman, 2007). The completed shape of the SMA surface is shown in Plate (2-1).

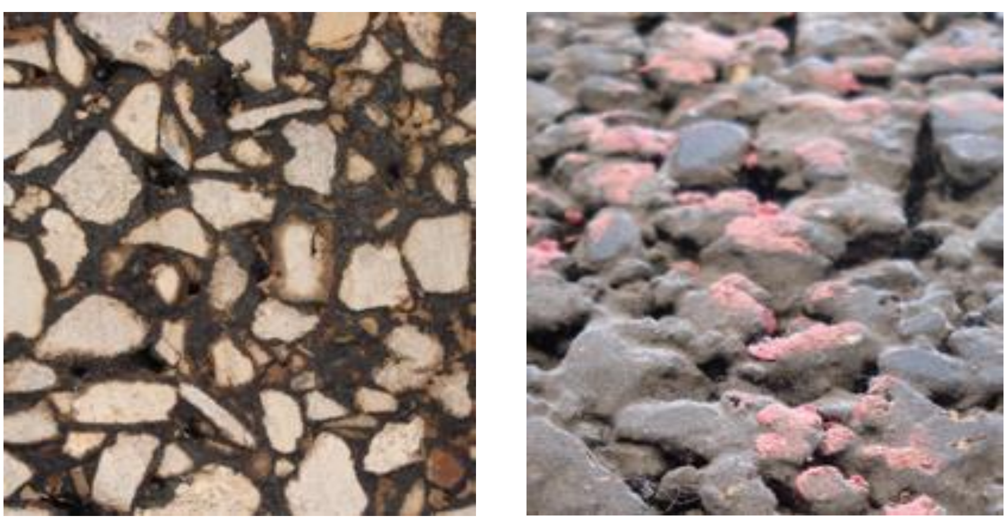

Plate 2- 1 SMA profile(on the left), SMA surface (on the right) (Cui et al., 2019)

There is high stone-to-stone contact between the aggregate particles forming the coarse aggregate skeleton, which improves the mixture's strength and rut resistance. In comparison to dense-graded mixtures, the coarse aggregate skeleton contributes to the shear strength and effective loading distribution pattern of vehicles, allowing them to withstand heavier traffic loads (Tashman and Pearson, 2012). Because of the higher binder and filler content, the rich binder mortar consists of fine aggregates, a bituminous binder, mineral filler, and generally a stabilizing additive. Stabilizing additives are used to control drain down, which is a common occurrence in gap-graded mixtures due to the higher bitumen and filler content. That occurs during the elevated temperatures of production, transport, laying, and compaction, as a portion of the bitumen and fines may be separated and flow down from the mixture (Stergiopoulos *et al.*, 2015). In terms of rut resistance, stability, and durability, SMA mixtures offer significant advantages. SMA has emerged as one of the most important asphalt mixtures over the years as a result of its advantages. (Kumar, Dhingra and Daniell, 2004, Selimović *et al.*, 2012, Devulapalli, Kothandaraman and Sarang, 2020). Both the structure and the composition of SMA combinations are shown in the Figures (2-2).

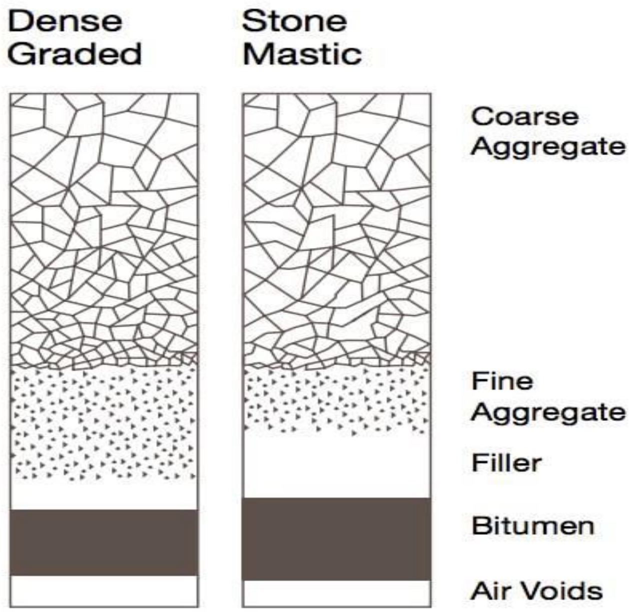

Figure 2- 2 SMA and DG composition (Oliver, 2020).

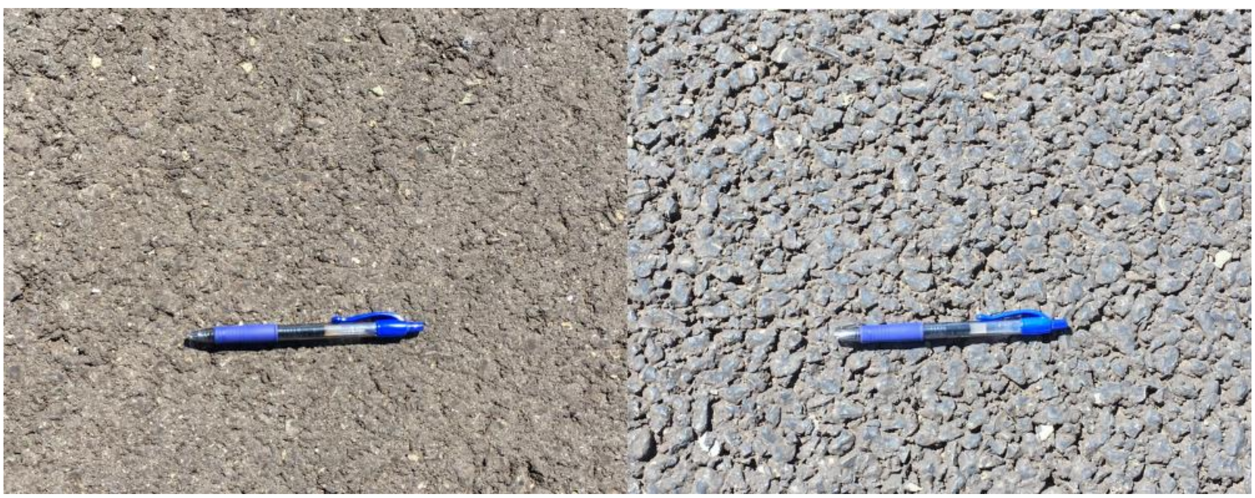

Plate 2- 2 Comparison of DGA (left) and SMA (right) (Oliver, 2020)

2.4 Composition of SMA Mixtures

2.4.1 Aggregate

The word "aggregate" may be used to refer to any mineral substance that is hard and inert. The American Society for Testing and Materials (ASTM) D (8) describes aggregate as a "granular material of mineral composition used as a construction material, meeting the requirements of road and paving applications such as sand, gravel, shell, slag, or crushed stone..." In asphalt mixes, the aggregates should have features such as the appropriate particle size and grading, strength and toughness, angularity and form, and low absorption. Other desirable properties include suitable particle size. According to ASTM D 8 (2018), the surface of the aggregate should be both rough and clean, and it should also have an affinity for asphalt. Because they make up around 85 percent of the entire volume of the HMA mixture, aggregates have a substantial influence on pavement load transmission. According to (Dannalie and Nataadmadja, 2021), aggregates are essential to the process of strengthening SMA mixes since they contribute more to the mixture. SMA has between 70 and 80 percent of its total stone content composed of coarse aggregate. Because of the higher proportion of coarse aggregate in the mixture, a skeleton-type structure is formed. This structure allows for better stone-on-stone contact between the coarse aggregate particles, which leads to improved shear strength, high resistance to rutting, resistance to cracking, and efficient loading patterns for vehicles to withstand heavy traffic loads (Liu, Hao and Xu, 2017).

Both the strength and rut resistance of SMA is mostly determined by the aggregate mix, specifically whether or not it is 100% crushed, has a nice form (cubical), and meets certain strength standards for abrasion resistance and crushing strength. According to (Ka Patel, Gupte and Parmar, 2016), crushing the sand is necessary because the internal friction adds to the overall strength of the material.

According to previous research works, the properties of the shape of coarse aggregates in SMA, such as flatness ratio, sphericity, angularity, texture, and elongation ratio, are the most important factors influencing the mechanical performance of SMA mixtures (.P and Adiseshu, 2013, Wang et al., 2016). Specifically, the flatness ratio of the coarse aggregates in SMA is the most important factor. Cubic particles, also known as polyhedral particles, contribute positively to the internal friction qualities of the aggregate and boost their resistance to permanent deformation. According to Huang et al.'s research from 2009, flat and elongated aggregates have the effect of reducing the interlock between aggregate particles and the breakdown, which in turn affects the mechanical characteristics of the aggregate structure. As a result, the aggregate with the greatest angularity is the most common kind of aggregate used in the process of formulating asphalt mixes because of its capacity to produce aggregate particle interlock. Mixtures of asphalt that include angular aggregates have greater shear resistance than those that do not contain these particles. Rougher aggregate surfaces improve particle-to-asphalt binder interface connection, which helps overcome or decrease difficulties related to the workability and fatigue defects of asphalt mixes (Bessa *et al.*, 2015). This connection helps overcome or minimize problems related to workability and fatigue defects of asphalt mixtures. In addition, from the perspective of comparison between sharp-angular and flat-elongated aggregates, (Kogbara *et al.*, 2016)stated that the sharp and angular aggregates particles are the better ones because they can help in offering better interlock and surface texture in contrast to the elongated and flat aggregates that are presenting a lower texture depths. This is because the sharp and angular aggregate particles can help in offering better interlock and surface texture.

According to (Cao, Liu and Feng, 2013) and (Mu *et al.*, 2020), the aggregates that are employed in SMA mixes should have the following characteristics.

a very cubic form with a rough surface that is resistant to movement and rutting.

b. A brittleness that is capable of withstanding large traffic loads without breaking.

b. a very high degree of resistance to polishing

d. Very high resistance to abrasion

In addition, the gradation of the aggregate is yet another significant aspect that plays a role in determining the performance of an asphalt mixture. Not only is the gradation of the aggregate significant for volumetric attributes, but it is also a critical aspect in deciding how well an asphalt mixture will function. Aggregate gradation is known to affect the stiffness, stability, durability, permeability, workability, fatigue resistance, skid resistance, and moisture sensitivity of asphalt mixtures (Al-Khateeb, Ghuzlan and Al-Barqawi, 2017). Because it is a complicated estimation process that is dependent on the characteristics of the mix, material properties, loading, and environmental conditions, as well as the section of pavement where it will be laid (Kalaitzaki, Kollaros and Athanasopoulou, 2015), the best gradation is difficult to define. This is because it is dependent on all of these factors, as well as the section of pavement where it will be laid.

2.4.2 Mineral fillers

The aggregate in the asphalt mixture that passes through sieve No. 200 includes mineral filler or dust. The properties of SMA mixtures are significantly influenced by mineral fillers. Mineral fillers make the asphalt mortar matrix more rigid. Mineral fillers influence the workability, moisture resistance, and aging properties of HMA mixtures. Mineral fillers also help decrease drain down in the mix throughout building projects, that also enhances the mix's durability by retaining the original amount of asphalt used in the mix. (Muniandy, Aburkaba and Taha, 2013). Many different types of fillers can be used in asphalt mixtures (conventional filler, ordinary Portland cement, quick lime, hydrated lime, fine sand, carbon black, and fly ash). Surface area, particle size distribution, porosity, chemical compositions, and other physical properties are some of the basic factors that distinguish different types of fillers. As a result, the asphalt mixture's performance varies depending on the type of filler used in the mixture (Likitlersuang et al., 2016).

Mineral fillers can be added in two ways. The first is as part of the aggregate, where it fills voids and forms contact points between aggregate particles, increasing the strength of the mixture structure. The second method is to combine it with the asphalt binder, which in this case is known as mastic and works to strengthen bonding between larger aggregate particles. Mastics have piqued the interest of asphalt producers due to their influence on the properties of the asphalt mixture. Mastic strength and cohesion are affected by a variety of factors, including interactions between asphalt and filler, filler particle size, temperature, and loading time. Strategic Highway Research Program researchers (SHRP), developed a simplified method for controlling the amount of filler to asphalt binder by setting the factor dust/asphalt (D/A) ratio, which has been specified to be between (0.6–1.2) (Chen et al., 2008a). In HMA mixtures, fly ash was used as a filler rather than a secondary aggregate, resulting in a 7.8 % decrease in resilient modulus.as stated by Rahman et al. (2020a). In addition, the resulting mixture was softer and denser than the control sample.

(Muniandy et al., 2012). assessed the effects of filler type and particle size on the permanent deformation properties of SMA mixtures containing four different fillers (limestone as control, ceramic waste, coal fly ash, and steel slag). The results and analysis of the fundamental parameters of permanent deformation and resilient modulus have indicated that laboratory blended and proprietary SMA mixtures incorporating ceramic waste and steel slag fillers with medium size particles (50/50) proportion) have improved stiffness and potential benefits in terms of high temperature rutting (increased stiffness and elastic response) in comparison to the control mixture. The mixtures of coal fly ash are the least prone to permanent deformation, as can be seen in Figure (2-8).

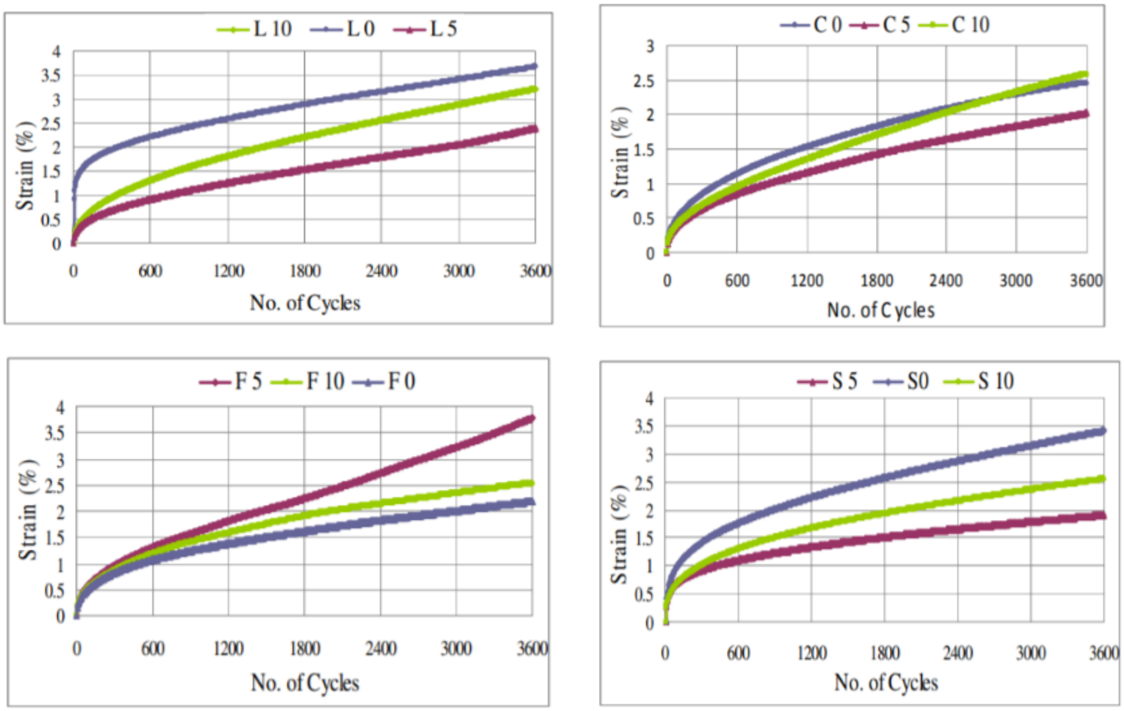

Figure 2- 3 Axial strain versus number of load cycles for SMA Mix with limestone as control, ceramic waste, coal fly ash, and steel slag (Muniandy et al., 2012).

Hydrated lime (HL) is commonly used to limit moisture-induced bitumen damage and chemical aging. Furthermore, it stiffens the mastic better than standard mineral filler; however, this is only noticeable above room temperature, which influences the mechanical properties of the asphalt mixture. The HL content in HMA is always 1–1.5 % based on dry aggregate. To achieve the desired results, some mixtures may require lime contents as high as 2.5%, while it was discovered by others that the most effective hydrated lime ratio was 2% of aggregate weight (Lesueur et al., 2013). Because it improves fatigue resistance and moisture resistance, HL is an effective filler in asphalt mixtures. The reaction between HL and asphalt mixtures can be described as a physicochemical reaction. This material has a dual function: physically, it acts as an inactive filler, filling voids in asphalt mixtures and lowering the volumetric optimum asphalt content. It can also improve the stability and resistance to fatigue cracking by dispersing fine particles throughout the mixture, which helps to reduce cracks. Chemically, it acts as an active filler due to its importance in reducing aging hardening and increasing the mixture's resistance to moisture damage (Lee et al., 2011, Yilmaz et al. (2015) investigated the effects of styrene–butadiene–styrene (SBS), American gilsonite (AG), and Iranian gilsonite (IG) in bitumen modification, as well as hydrated lime used as a filler in mixture modification, on the performance of HMAs. As shown in Figure (2-9), all of the mixtures exceeded the Superpave TSR criterion of 80%. The resistance of the mixtures to moisture-induced damage was improved by using hydrated lime as a filler and by using additives in bitumen modification.

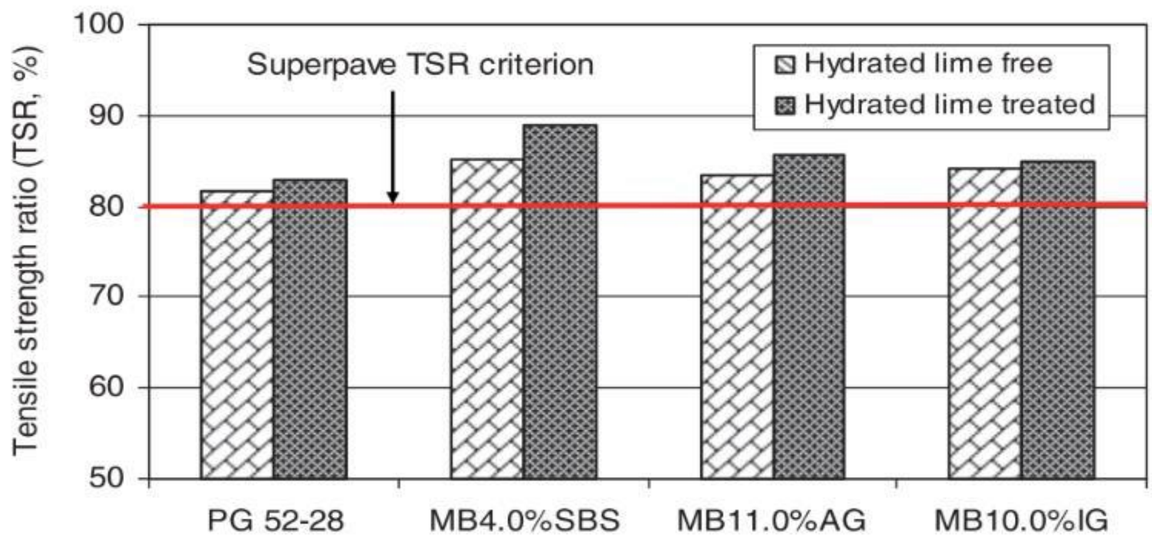

Figure 2- 4 Tensile strength ratio values of mixtures (Yilmaz and Yalcin, 2016)

2.4.3 Asphalt Binder

Asphalt Binder is a viscoelastic material that is the only deformable component of pavement and plays an important role in pavement performance. Because bitumen adheres and coheres well with aggregates, it has been used for paving (Kalantar, Karim and Mahrez, 2012 ,Taherkhani and Afroozi, 2017).

It is an organic mixture with various chemical components that has good visco-elastic properties and a nature that is a mix of polar and non-polar compositions. Asphalt binder is a colloidal system made up of two different molecular weight components: maltene and asphaltene. The maltene component contains low molecular weight hydrocarbons (saturates "paraffin," aromatics, and resins) and acts as a dispersant for the high molecular weight "asphaltene." Asphaltene is the polar component of asphalt and plays an important role in the chemical composition of asphalt, which is responsible for its rheological properties, as well as its stability. Asphaltene is a key component of the asphalt structure, and it is found in maltene and resins, forming an electrified body that begins in the center with high molecular weight compounds and progresses to the edges with low molecular weight compounds. Asphalt has two types of structures: "Sol and Gel" Figure (2-10) display a description of the asphalt structure and its formations (Read and Whiteoak, 2003, (Nejres, Mustafa and Aldewachi, 2022)**.**

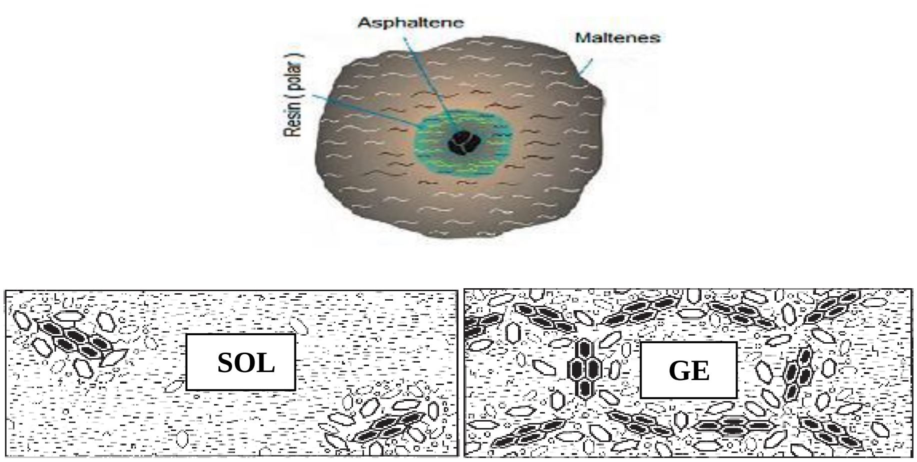

Figure 2- 5 Representation of the asphalt structure and its SOL and GEL forms (Read and Whiteoak, 2003, Nejres, Mustafa and Aldewachi, 2022).

In SMA mixtures, bitumen binding agent for aggregates, fines, and stabilizers. SMA mixes have a high concentration of mortar binder, which increases the durability of the mix. Temperature susceptibility, viscoelasticity, and aging are bitumen properties that influence the behavior of bituminous mixtures. The behavior of bitumen is affected by temperature as well as loading time. It is stiffer at lower temperatures and for shorter periods of loading. Because bitumen has both viscous and elastic properties at normal pavement temperatures, it must be treated as a viscoelastic material. Though it behaves like an elastic material at low temperatures and like a viscous fluid at high temperatures (Sobolev et al., 2014, Ameli et al., 2020). High asphalt contents are used in the design of SMA mixtures, sometimes reaching 8%. Because of the high asphalt content and coarse aggregate skeleton of such mixtures, the mixture is more susceptible to drain down problems (Sarang et al., 2015b, Devulapalli, Kothandaraman and Sarang, 2020). Besides that, due to the black color of asphalt increases its capacity to absorb solar radiation and raise the internal temperature, and the increase in traffic loading and volume nowadays causes asphalt pavements to suffer from various types of failures such as rutting, fatigue, and temperature susceptibility, in addition to aging problems, particularly when exposed to sunlight, heat, oxygen, or a combination of the three (Ameri and Nasr, 2016, Ma et al., 2018).

Therefore, upon these weaken points of asphalt; the researchers tend to use modifiers asphalt has an inherent property. Some modifiers and asphalt mix additives may have an impact. As a result, researchers frequently employ modifiers to improve the properties and performance of asphalt binder. As a result, the asphalt mixture performs better and has a longer service life (Lagos-Varas et al., 2022).. Polymers, fibers, and ashes are examples of additives.

Many factors influence the choice of the appropriate additive, including economic factors, geographical conditions, facilities in various countries, environmental issues, and modifier production (Camargo et al., 2021).

2.5 Characteristics of SMA asphalt mixtures

2.5.1 Safety

Wet pavement surfaces are well known to have a negative impact on road safety by causing splash and spray, in addition to the hydroplaning phenomena that cause reduced night visibility, Figure (2-3) and Plate (2-3) depict these. phenomena resulting in poor visibility for drivers. Other vehicles' splash and spray, particularly large trucks, cause visibility impact issues by creating clouds of spray and obscuring the view for drivers in adjacent vehicles. Water that has accumulated on the road surface, normally causes splash and spray, as a vehicle's tires roll down a slick road (Rungruangvirojn and Kanitpong, 2010a)**.**

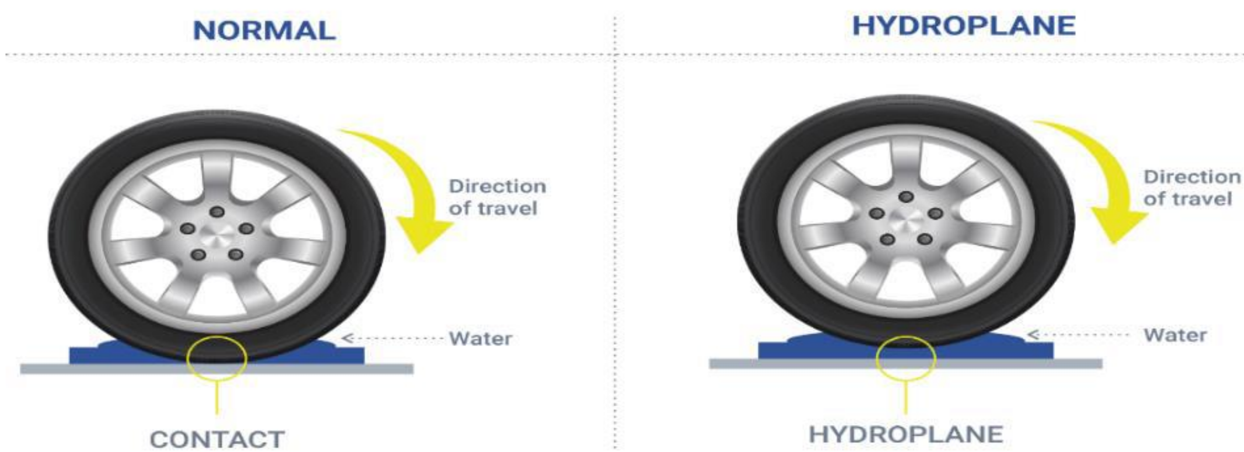

Figure 2 -6 Hydroplaning phenomena (Tyres-N-Services, 2021)

Speed tiers pick up water from the surface and eject it into the air as small droplets. The spray can cause problems for drivers by making it difficult to see through the clouds of water spray. To deal with the splash and spray phenomenon, many innovations in vehicle design, tyres, and lighting have been developed. A significant advancement in pavement materials has been proposed to reduce the problem of splash and spray. Stone mastic asphalt (SMA) pavements are specially designed asphalt pavements that provide surface drainage and have been shown to reduce splash and spray in wet weather conditions (Rungruangvirojn and Kanitpong, 2010b). When compared to dense-graded HMA, the rough surface texture of SMA means that more water can be held within the SMA rather than on the surface. This reduces glare at night from oncoming vehicle lights, increases the visibility of pavement markings, and reduces splash and spray (Di Angelantonio *et al.*, 2016).

Plate 2- 3 Spray and splash problem in SMA(Rungruangvirojn and Kanitpong, 2010b)

2.5.2 Environmental benefits

Traffic noise is a problem impacting society and the quality of life, it is well-known for a long time. However, in recent decades, there has been a shift, whereas noise has gotten more attention because it contributes to pollution and causes other environmental issues. Nowadays, traffic noise is recognized as one of the most serious environmental issues, as well as a growing challenge for national road authorities, according to (Sangiorgio, Uva and Fatiguso, 2018). Some noise-control measures include traffic management, the construction of noise barriers, and vehicle speed reduction (Vogiatzis and Remy, 2014; Gatta *et al.*, 2015).

However, the only solution that reduces noise without affecting service levels or having a visual impact, is pavement rehabilitation using new pavement with improved acoustic properties. According to research reports and engineering studies, the use of SMA bituminous mixtures can reduce the noise generated by tire/pavement interaction (functional performance) (Paje *et al.*, 2013, Paje, Vázquez, *et al.*, 2013).

The following are the main principles of texture optimization for SMA pavements based on their impact on tire/road noise reduction potential**,** (Descornet, 2005, Asphalt-StB, 2007).

1. To achieve a smooth surface and reduce tire vibrations, use a maximum aggregate of small size. The maximum aggregate size for reducing the noise produced by light vehicle tires is between 4 - 6 mm, whereas the maximum aggregate size for reducing the noise produced by heavy duty vehicle tires is between 6 - 10 mm.

2. Macro texture optimization:

• For light vehicles, high amplitudes in the 1–8 mm wavelength range and low amplitudes in the 10–50 mm wavelength range.

• For heavy-duty vehicles, high amplitudes in the 0.5–12 mm wavelength range and low amplitudes in the 16–50 mm wavelength range.

• Open and 'negative' texture, which is distinguished by a large number of narrow and small spaces between the particles, as opposed to 'positive' texture, which has a large number of irregularities.

3. To ensure that air pumping is reduced, the air void content should be around 5–6 percent. This could be accomplished by incorporating a low sand and filler content into the asphalt mixture.

4. Cubic shapes with sharp edges aggregate to ensure an even and smooth surface

2.5.3 Driver advantages

The friction force that keeps the tire from slipping on the pavement surface is referred to as skid resistance. It was demonstrated that when the skid resistance fell below a certain threshold value, the risk of a traffic accident increases, significantly. As a result, pavement skid resistance is an important design parameter affecting driving safety (Flöstrand and Ström, 2006). Adhesion and hysteresis contribute to skid resistance/friction force, which is primarily determined by the pavement's surface texture. Plate (2-4) illustrates the mechanisms ofpavement friction. Pavement friction is caused by two mechanisms: hysteresis and adhesion. The amount of energy lost when a vehicle tire deforms while in motion is represented by hysteresis. While adhesion is generated by the interfaces bond in areas where high pressure is released (Kogbara *et al.*, 2016).

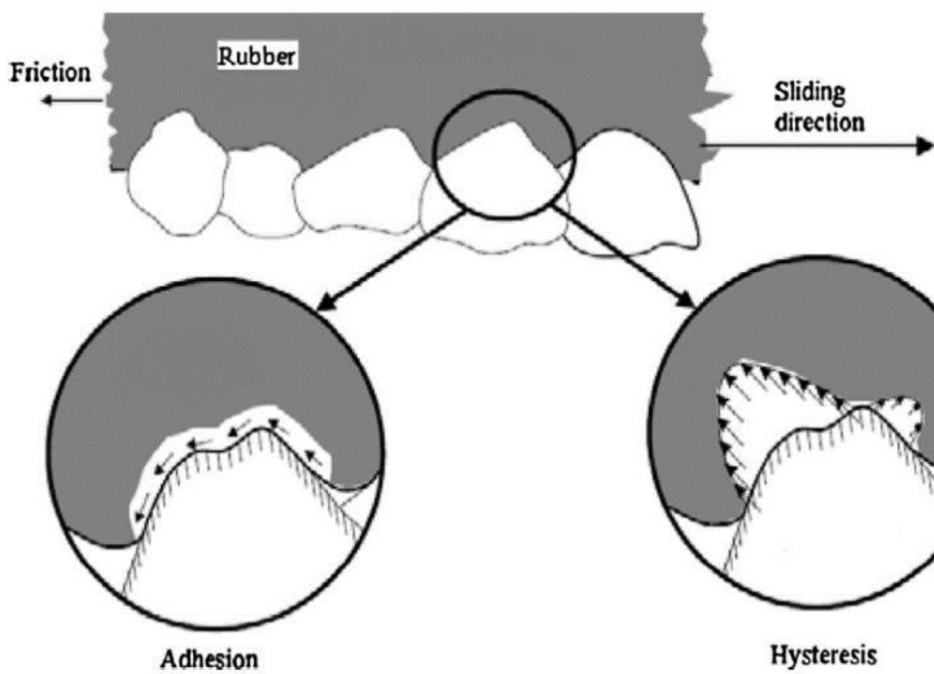

Plate 2- 4 Key mechanisms of tire-pavement friction (Kogbara et al., 2016a)

Surface texture is classified based on wavelengths, with microtexture (0–0.5 mm), macrotexture (0.5–50 mm), and megatexture (50–500 mm) being the most common. The small-scale texture of the pavement aggregate component (which controls contact between the tire rubber and the pavement) is referred to as microtexture. As a result, the coarse aggregate is used to create the pavement surface. The large-scale texture of the pavement as a whole caused by the aggregate particle arrangement is referred to as macro texture (which regulates the escape of water beneath the tire and, as a result, the loss of skid resistance at high speeds (Batayneh, Marie and Asi, 2007). Plate (2-5) shows the difference between the macro and micro texture.

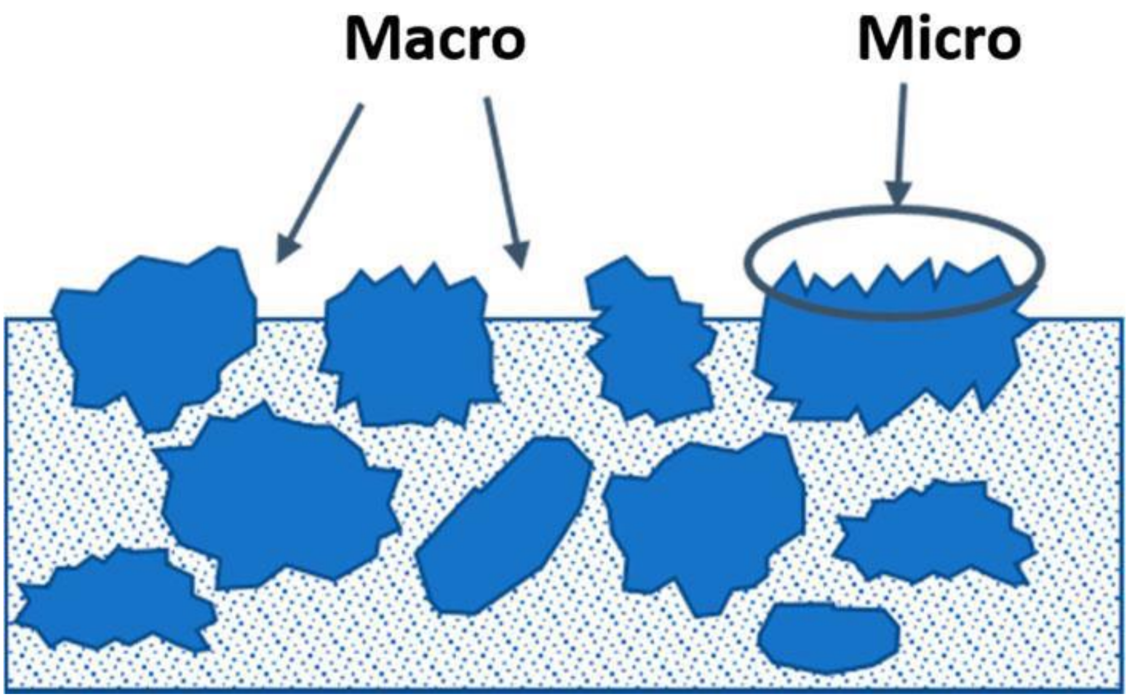

Plate 2- 5 Difference between macro-texture and micro-texture (Jamieson and White, 2020a)

Skid resistance is an important pavement evaluation parameter because: inadequate skid resistance leads to an increase in the number of skid-related accidents.

• Most agencies are required to provide users with a ‘‘reasonably" safe roadway.

• Skid resistance measures may be used to evaluate a variety of construction practices and materials.

SMA has a rougher surface texture than dense-graded asphalt as represented by Plate (2-5), which ensures good skid resistance. As a result, SMA surfaces have high frictional resistance, which improves safety for motorists traveling on wet pavements (Di Angelantonio *et al*., 2016)**.**

Plate 2- 6 SMA Pavement Surface https://pavementinteractive.org/wp-content/uploads/2009/06/SMA_Surface11.jpg.

(Wan *et al.*, 2019) investigated the effect of mixture design parameters on the slip resistance of SMA pavement. Three parameters have recognized to have a critical impact on improving the skid resistance of the pavement, namely, percentage of aggregates passing the maximum size (PNMSA), passing the control sieve Size (PCS) and asphalt content (AC). Among them, PNMSA found to be the greatest impact on skid resistance, followed by AC, while the PCS appears to have the smallest impact on skid resistance. Figure (2-4) shows a comparison of the variation of skid resistance with respect to PNMSA, PCS and AC parameters, through different types of SMA mixtures.

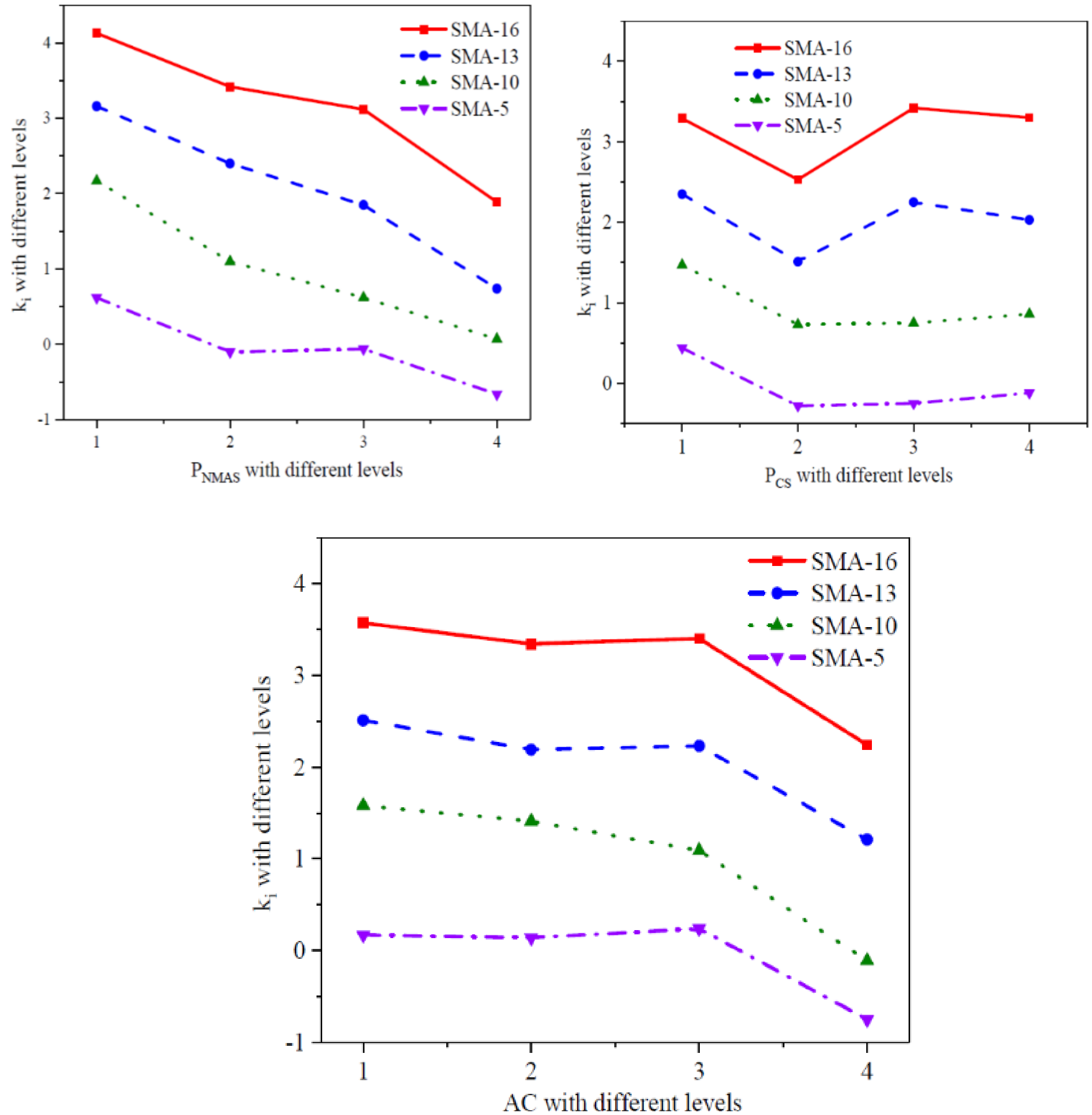

Figure 2- 7 Relationship between skid resistance and (a) PNMAS, (b) PCS, and (c) AC of SMA pavement (Yang et al., 2019)

2.6 Applications of stone matrix asphalt mixtures

SMA mixture is suitable for the following uses (NAPA-QIP122, 2002):

1. SMA is adaptable to high traffic densities, and SMA overlays on autobahns are a popular alternative to dense-graded HMA.

2. SMA can be used in a variety of thicknesses, ranging from 2.5 to 5 time the maximum particle size, depending on the application. The cost effectiveness of using thin layers of SMA to renew skid resistance on thick layers of dense-graded HMA.

3. Versatile SMA has also been used as the initial protective layer on bridge decks.

4. SMA can also be used in high-load situations.

5. SMA was used as a runway surface, Figure (2-5).

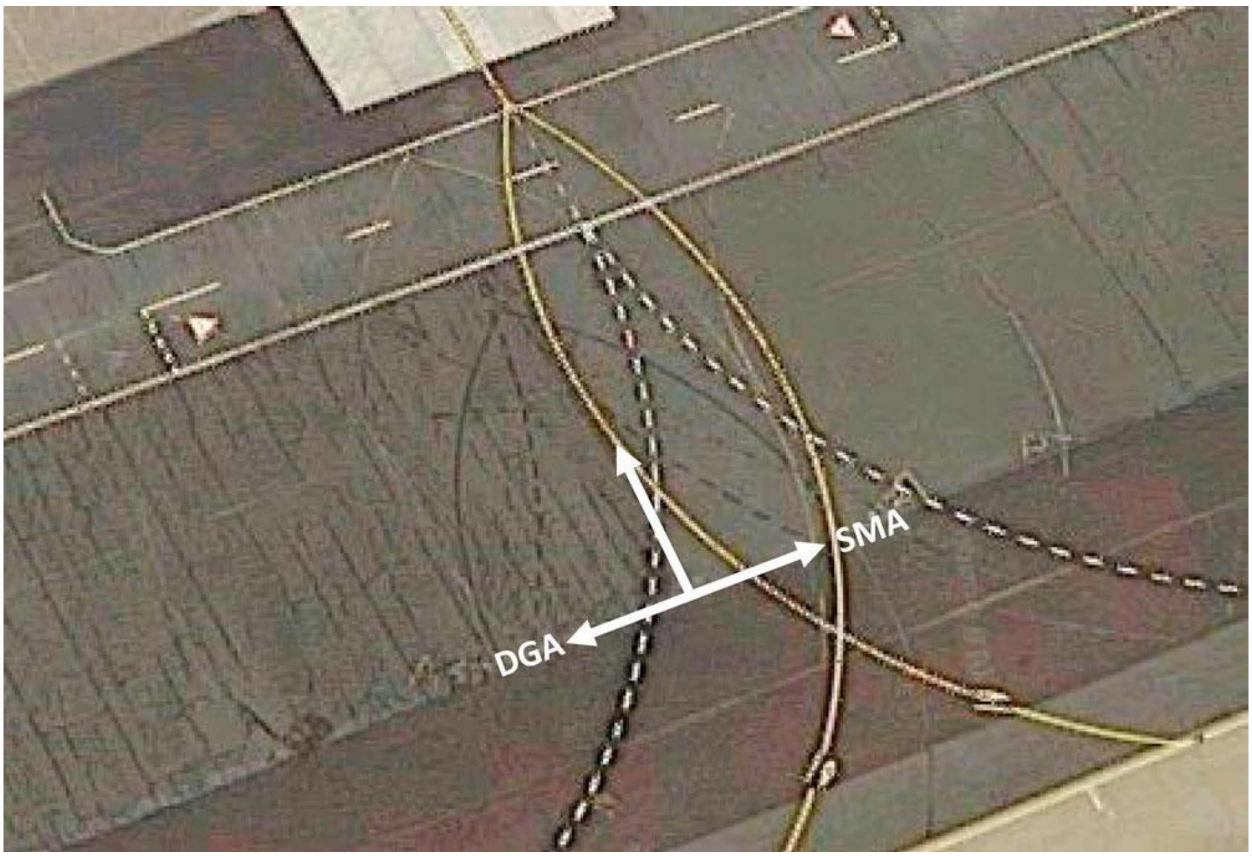

Figure 2- 8 Aerial image of Cairns airport–SMA Bay 19 compared to DGA (Jamieson and White, 2020b)

2.7 Strengths and Weakness of SMA

SMA's rapid and widespread growth can be attributed to several undeniable advantages, including the following (Blazejowski, 2016 ,Rahman and Mohajerani, 2020).

1. A long working life (service life).
2. High deformation resistance due to high coarse aggregate content and strong skeleton of interlocked aggregate particles.
3. Increased fatigue life as a result of higher binder content.
4. Good layer surface macro texture and reduced water spray generated by traffic on wet surfaces.
5. Excellent noise-canceling properties.
6. Increased in-service traffic wears resistance due to the existence of hard coarse aggregate grains.

However, despite its advantages, the following disadvantages exist:

1. High cost of the mix compared to conventional asphalt concrete (initial costs can be increased by 10–20 % due to a higher binder, filler, and stabilizer contents, but the pavement's extended service life can result in lower life cycle costs)
2. The possibility of various types of fat spots appearing on the surface as a result of errors or variability during SMA design, production, or construction.

2.8 Advantages and Disadvantages of Stone Matrix Asphalt Mixtures

Stone matrix asphalt offers a variety of benefits that are not available with traditional thick-graded asphalt. The following are some examples of these:

1. Resistance to permanent deformation or rutting (30-40%) less permanent deformation than dense graded asphalt. (Van de Ven et al,. 2013) also suggests that the stone to stone contact of an aggregate skeleton should prevent the mix from becoming temperature sensitive and thus susceptible to permanent deformation at high temperatures.

2. The mechanical properties of SMA rely on the stone to stone contact so they are less sensitive to binder variations than the conventional mixes (Suaryana, 2016).
3. Good durability due to high binder content (slow ageing), resulting in longer service life (up to 20%) over conventional mixes (Campbell, 1999).
4. Good flexibility and resistance to fatigue (3-5 times increased fatigue life).
5. Good low temperature performance..
6. Good wear resistance.
7. Good surface texture.
8. Wide range of applications.
9. SMA can be produced and compacted with the same plant and equipment available for dense grade asphalt.
10. More economical in the long term (Fernandes, Silva and Oliveira, 2019).

Perceived disadvantages of SMA include:

1. Increased cost associated with higher binder and filler content, and fiber additive.
2. High filler content in SMA may result in reduced productivity. This
1. may be overcome by suitable plant, modifications.
2. Possible delays in opening to traffic as SMA mix should be cooled to
3. 40°C to prevent flushing of the binder surface.
4. Initial skid resistance may be low until the thick binder film is worn off the top of the surface by traffic. (Fernandes, Silva and Oliveira, 2019).

Apart from good stability and durability that ensures a long service life other advantages are claimed for SMA including:

1. It can be laid over a rutted or uneven surface because it compresses very little during compaction. This also helps to produce good longitudinal and transverse

evenness (Nunn, 1994). There is no harm to the final evenness of the surface even when applied in different mat thicknesses.

2. If the pavement lacks stiffness, such that a dense graded asphalt with conventional binder may suffer premature fatigue induced cracking ,then it may be beneficial to place SMA because of its improved fatigue resistance properties (Ghasemi and Marandi, 2011).
3. An anticipated secondary benefit of SMA is the retardation of reflection cracks from the underlying pavement (Hainin, Reshi and Niroumand, 2012).An indication of the relative performance of SMA in comparison to conventional dense graded asphalt (DGA) has been provided by Nordic asphalt technologists.

2.9 Performance of SMA mixtures

(Brown et al., 1997) analyzed the data from their research of 86 SMA projects in the United States based on several performance indicators, including rutting, cracking, ravelling, and other issues. The data showed that 90% of SMA projects had only 4 mm of rutting, stronger thermal and reflecting fracture resistance than a dense-graded mixture, and no indication of ravelling. In addition, the reflected crack resistance was larger than that of a dense-graded mixture. (Asi, 2006) investigated the performance of SMA in the laboratory particularly for very hot temperatures, and they concluded that SMA mixes had greater resilience and rutting resistance. According to the findings of (Kamaraj, 2015), who carried out field research. According to (Stuart, 1991), the large percentage of coarse aggregate that is included in SMA mixes is what contributes to the material's superior resilience to cracking when compared to dense-graded mixtures. Researchers have shown that adding stabilizing chemicals to a material may increase its resistance to rutting and make it less likely to undergo plastic deformation. According to (Brown and Manglorkar, 1993), the resilience modulus of the SMA mixes that included granite aggregate was comparable to that of the conventional dense-graded mixtures. deformations were seen more often in mixes that had been formulated with 3%–4% air spaces. Because of this, maintaining air spaces within safe limits is of the utmost importance (Drews, 2008b). According to the tensile strength ratio and the diametric modulus (Stuart, 1991), the dense-graded mixture poses a greater risk of moisture damage than the SMA does. This is the case when comparing the SMA to the dense-graded mixture. According to the findings of a study that was conducted in 1997 by Brown et al., SMA blends on high-traffic highways performed very well. (Woodward et al. 2016) conducted a wear test, and the results showed that SMA blends had better performance and durability.to withstand high temperatures and dampness (Brown and Manglorkar, 1993), (Behnood and Ameri, 2012), and (Kamaraj, 2015)are only a few of the studies that support this idea. According to the findings of a study that was conducted in 1991 by Brown, Haddock, and Crawford, the addition of stabilizing agents increased the SMA mixes' resistance to fatigue and thermal cracking at intermediate and low temperatures. According to (Boscaino, Praticò and Vaiana, 2005), the surface of the coarse aggregate skeleton has a rough texture, which contributes to the material's high skid resistance. SMA mixes, on the other hand, have a lower initial skid resistance than other types of mixtures due to the accumulation of a thin layer of mastic material on the surface. To avoid this from happening, fine aggregate gratings or chips are put on top of the SMA mixes (Błazejowski, 2016; Brown et al. 1997; Brown, 1993). According to research done by Brown et al. in 1997, once the mastic has been worn away by traffic stress and ageing, SMA blends give superior skid resistance. And although SMA mixtures are durable and have superior performance than dense-graded mixes Because SMA mixes are required to conform to gap gradation, and the aggregate skeleton structure is what defines the overall strength of the mixture, this structure must be appropriately maintained throughout the whole of the mix design process. SMA combinations need a significant amount of asphalt, which creates a challenge for water to drain away. Many design standards, such as the qualities of materials, gradation, and volumetric parameters, need verification, adjustment, or the formulation of new requirements depending on the climate, geography, and traffic patterns of the location. The initial construction cost of a pavement is somewhat greater than the cost of constructing a thick graded mix as normal. As a consequence of this, researchers are hard at work to find solutions to these problems and create a more comprehensive SMA combination (Devulapalli, Sarang and Kothandaraman, 2022).

2.9.1 Drain-down Test:

The drain-down value evaluates the sensitivity of the SMA mixture at elevated temperatures. Therefore, it is important to determine the drain down and appropriate measures must be taken to reduce the same to control the drain. The modification in- includes the usage of CRMB, polymer-modified binder (PMB), ground rubber tire (GTR) modified binder, etc. A few re- searchers showed that SMA mixtures prepared with GTR-modified binder controlled the drain down within the specification limit Similarly evaluating the drain down of the SMA mixture with CRM results showed negligible drain down also reported that CRMB limited the drain down within the specification limit (Devulapalli, Sarang and Kothandaraman, 2022). The results of the drain-down test for bitumen bleeding showed that only the fiber-free base mixture had more than 0.3% drain down, and the rest of the mixtures were within the allowable range. Also, by increasing the amount of CRP the bitumen bleeding decreased. As can be seen, cellulose fibers prevented the bitumen bleeding of the mixtures, which indicates the high ability of cellulose fibers to increase the bitumen resistance against draining down in SMA mixtures (Duan *et al.*, 2021). Putman and Amirkhanian found The mixture without fibers reached 0.3% drain down at 6.53% binder (by weight of mix). The tire and carpet fibers, obtained from waste streams, were effective in preventing excessive drain down of the SMA mixtures (Putman and Amirkhanian, 2004).

2.9.2 Rutting

A pavement structure may be inadequate for several reasons. The pavement may subject to a greater number of ESAL (equivalent number of 80-kN (18,000-lb.) single-axle load applications) than the pavement isdesigned for. This may happen as planned, since pavements are typically designed for a finite number of ESAL anticipated over a specific design period typically, 20 years. In some cases, the traffic loading (especially heavy trucks (increased beyond what was projected, causing structural distress to occur more rapidly than anticipated. Rutting is caused by deformation in the underlying aggregate base or subgrade (Asphalt Institute, 1983, Pouranian, Imaninasab and Shishehbor, 2020).Figure (2-6) shows the rutting due to weak subgrade or underlying layer.

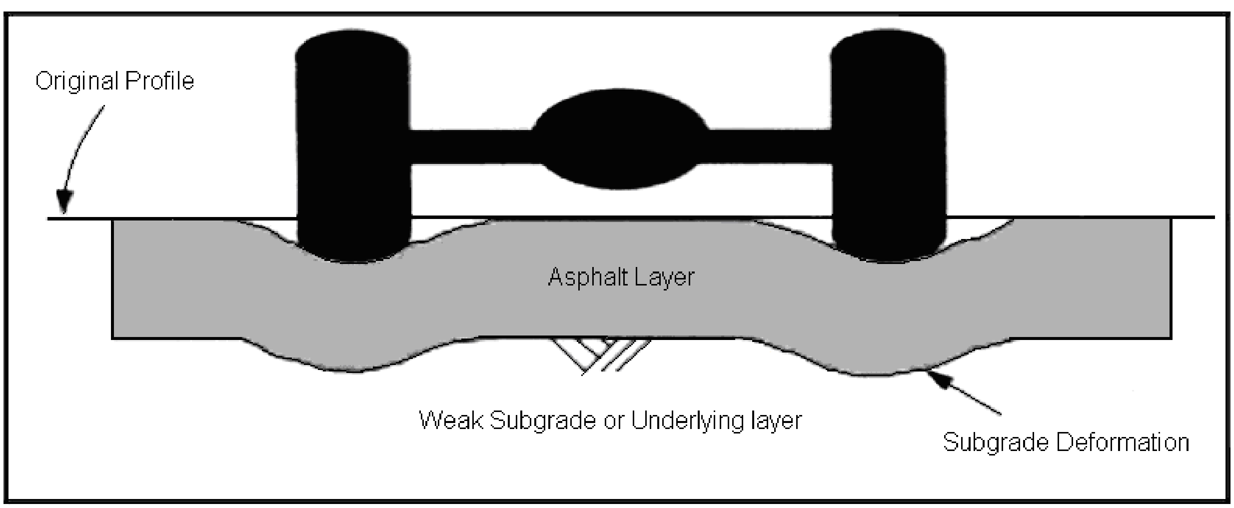

Figure 2- 9 Rutting from Weak Subgrade, (Asphalt Institute 2014)

Asphalt pavement distresses may also result from deficiencies in the hot mix asphalt, where mixtures were not properly designed, produced, or placed. Excessive permanent deformation can occur within one or more asphalt layers by moisture damage, low air voids, poor quality aggregate and poor construction practices (Ismael, Fattah and Jasim, 2022). in Figure (2-7) shows rutting from weak mixture.

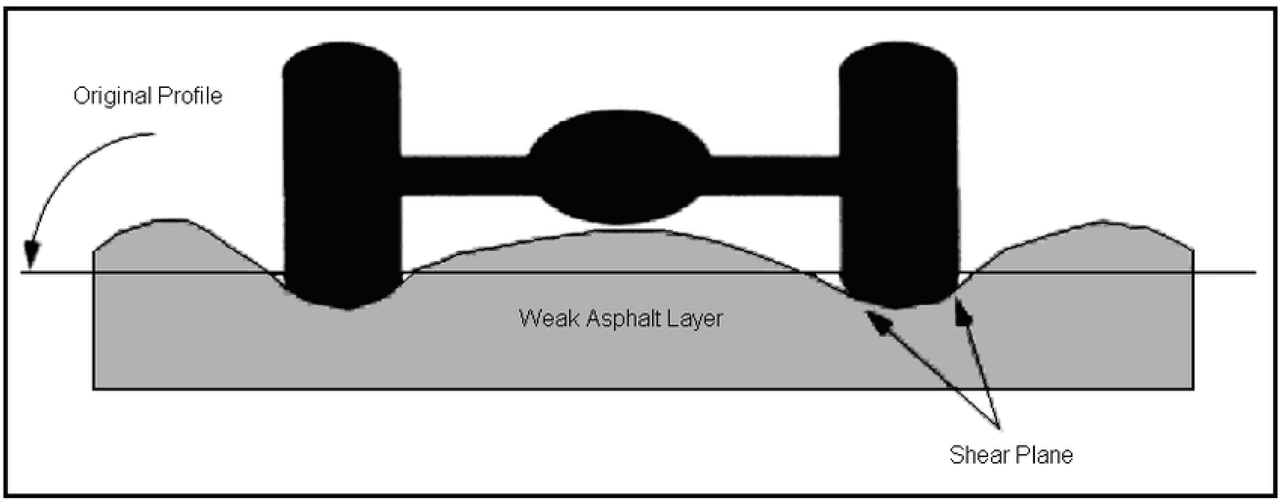

Figure 2- 10 Rutting from Weak Mixture, (Asphalt Institute 2014)

Mixtures may also be unstable because of excessive asphalt, poor aggregate interlock, insufficient voids-in-the-mineral-aggregate (VMA) or using too much rounded gravel or natural sand. When a mixture becomes unstable, plastic deformation is normally the result According to research published in 1983 by the Asphalt Institute.

Gap-graded SMA mixtures with stone-on-stone contact have a highly rut-resistant structure. This is due to its resistance to compressive stresses, which is supported by its stone matrix (Nejad et al., 2010). SMA has been used as the premier surface mixture to combat rutting by many transportation agencies in the United States since 1994. SMA has since become a common high-volume surface mix in a number of states. In 1997, the National Center for Asphalt Technology

(NCAT) tend to evaluate the performance of pavements in the United States by selecting a more than 140 pavements (Brown et al., 1997). They intended to collect the data related to the mixture design, plant production, placement, and performance for all the selected pavements to fulfill the study requirements. They found that, in terms of performance, more than 90% of the SMA pavements show rut depths of equal and lower than 4 mm Excluding six of them offered a rut depth greater than 6 mm caused by the SMA layer (Smit et al., 2011). According to Watson et al. (2014) SMA mixes are designed for stone-on-stone contact to overcome the rutting problems and have a rich mortar to provide long-term durability. They are more expensive than standard dense mixtures, but they are extremely cost-effective because the mixes can last for more than 20 years without being resurfaced. (Chen et al. 2017) stated that the SMA pavement showed a better field of view in the long run higher performance than HMA control pavement in terms of crack and rut resistance.

It has been shown by (Ismael, Fattah and Jasim, 2022) that the rutting resistance of asphalt paving mixes may be improved by the inclusion of crumb rubber and SBR. According to the findings of the laboratory investigation, the CR-modified and SBR-modified asphalt mixes exhibited greater stiffness when heated to 60 degrees Celsius in comparison to the modified mixtures. In the Loaded Wheel tests, the asphalt mixes that had been adjusted resulted in greater gyratory shear strengths and smaller rut depths than the mixtures that had not been amended.

(Chiu and Lu, 2007) researched to determine whether or not it would be possible to use asphalt rubber (AR), which is created by combining ground tire rubber (GTR) with asphalt, as a binder for stone matrix asphalt (SMA). The GTRs that were utilized were of two different sizes and were built in Taiwan. In addition to this, the potential performance of combinations of AR and SMA was assessed.

According to the findings of this research, it is not possible to make an appropriate SMA combination by combining an AC-20 with 30% coarse GTR that has a maximum size of 0.85 mm. This is the conclusion that can be drawn from the findings of this study. On the other hand, SMA mixes that are capable of satisfying the conventional volumetric criteria for SMA might be formed by utilizing an asphalt rubber that contains 20% of a fine GTR that has a maximum size of 0.6 mm. When this asphalt rubber was used, the usage of fiber was not required to avoid drain-down. According to the findings of the wheel tracking tests conducted at a temperature of 60 degrees Celsius, the rutting resistance of the AR–SMA combinations was superior to that of the traditional SMA mixtures. The rate of rutting that various mixtures experienced during the wheel tracking test is shown in Figures 2-10.

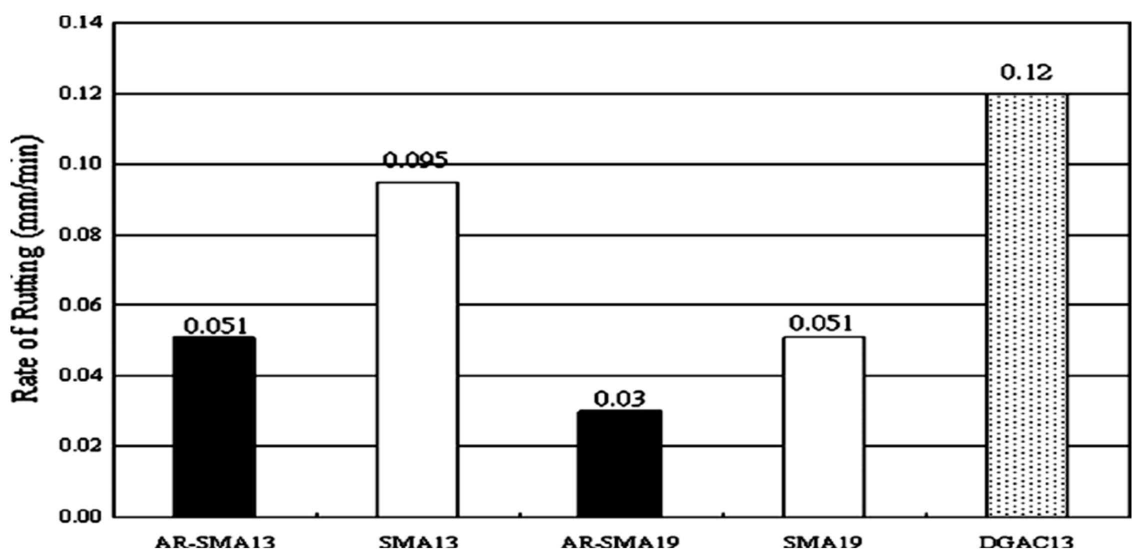

Figure 2- 11 Rate of rutting of different mixes evaluated in wheel tracking test (Chiu and Lu, 2007)

2.9.3 Moisture Susceptibility of Stone Mastic Asphalt Mixtures

Moisture susceptibility is generally the cause of poor mixture durability. It may be caused by the loss of cohesive bond between binder and aggregate, usually due to moisture intrusion. This is called stripping, and it often starts at the top of the pavement and progresses downward, resulting in raveling. Moisture susceptibility can be evaluated in the laboratory by performing stability, resilient modulus, or tensile strength testing on unconditioned and moisture conditioned samples. A number of researchers are certain of that SMA Mix is further sensitive to moisture-damage than dense HMA. Actually, they indication that in SMA mixes, water could transfer easily across the mix structure, and therefore the asphalt covering of aggregate is further exposed to moisture than with dense HMA, this could lead to improved moisture-sensitivity (Behnood and Ameri, 2012). According to (West et al.'s 2001) research, gap-graded asphalt has a little larger percentage of voids in the mineral aggregate and a poorer tensile strength than the more densely graded mix types. In the study done by (Sarang, Mehnaz and Shankar, 2014), studied, two aggregate gradations, with nominal maximum aggregate sizes (NMAS) 16 and 13 mm were adopted to prepare SMA mixtures and their laboratory performances were compared. Polymer modified bitumen (PMB) was used as the binder material and no stabilize additive was used. For SMA 1 mixtures, tensile strength was 28 %–31 higher than the other mix and moisture resistance was also slightly better . The results TSR test are given in Table (2-1).

Table 2- 1 TSR test results (Sarang et al., 2015).

SMA Mix	**ITS Unconditioned (Mpa)**	**ITS Conditioned (Mpa)**	**TSR (%)**
SMA1	1.110	1.013	91.26
SMA2	0.867	0.773	89.16

(Haghshenas *et al.*, 2015) compared the moisture resistance of two types of mixtures (dense HMA) and (SMA), and test the effect of gradation and asphalt binder content on the stripping potential of SMA and dense HMA using modified Lottman test procedure. The results showed that SMA mixes exhibit better moisture resistance than dense HMA mixes. In dense HMA mixtures, decreasing the aggregate size and the con sequential increase in the mastic will result in a mix that is more susceptible to stripping, while the similar situation in the SMA will really decrease its moisture resistance. An improper amount of binder content could cause a reduction in moisture resistance of mixtures. However, this effect was greater in dense HMA mixtures.

2.9.4 Cracks

The following were the most common types of cracks: Fatigue (Alligator) Cracking, fatigue cracking the ability of an asphalt mix to withstand repeated bending without fracture. Alligator or exhaustion Cracking is a series of interconnected cracks caused by fatigue failure of the asphalt surface or stabilized base under repeated traffic loading. Cracking is thought to begin at the bottom of the surface layer or stabilized base, where the tensile stress is greatest. The cracks begin as one or more longitudinal or transverse cracks that spread to the surface. Finally, these cracks connect to form many-sided, sharp-angled pieces that form a pattern resembling alligator skin. Fatigue cracking is regarded as a significant structural hazard (Castell et al., 2000). The following are some of the primary causes of asphalt pavement deterioration(Miller et al., 2003) :

- Traffic congestion
- Climate or the environment
- Inadequate drainage
- Material issues
- Defects in construction
- External factors (such as utility cuts)

The pavement becomes more prone to cracking as its ages because stiffens due to oxidation, which hardens the asphalt binder. Some factors, in addition to age hardening, can cause a crack, and age hardening alone can cause a crack. Age cracking is defined as large rectangular blocks that are interconnected and separated by cracks. This is known as block cracking. The asphalt binder in these pavements will lose its flexibility to resist contraction and expansion forces as temperatures fluctuate, causing cracks to form in a consistent pattern. In newer pavements, however, the same cracking can occur if the asphalt binder is too stiff (NAPA, 2002).

The SMA mixture is more resistant to fatigue and thermal cracking from bottom to top and top to bottom cracking than the HMA mixture. Most likely as a result of the thickening of the asphalt layer caused by the SMA mixture. So, when properly designed and built, the SMA berth can be a viable solution for extending the life of the pavement (Wu et al., 2017). SMA is intended to reduce cracking in asphalt overlays while still providing adequate rut resistance. SMA was used to delay cracking in several rehabilitation projects where traditional HMA overlays had failed prematurely due to reflective cracks (Chen et al., 2015, Wu et al., 2017). Watson (2003) demonstrated that reflective cracking propagation rate may be significantly reduced by SMA mixes, as one of the SMA projects in Wisconsin records. That project was 8 years old, and the SMA sections had approximately 40% less reflective cracking than the conventional mix sections.

2.10 Modified Asphalt Binder

Many asphalt researchers over the last four decades have advised combining a variety of asphalt modifiers with asphalt binders to enhance the characteristics and performance of asphalt. According to (Dehouche, Kaci and Mokhtar, 2012), asphalt binder is a delicate substance that can be identified by its viscoelastic characteristics, sensitivity to ageing, and mechanical reaction that is based on the amount of loading time as well as the temperature.

Because of the growing number of vehicles, bigger automobiles and trucks, and a rising percentage of vehicles that are carrying more passengers than they should, there has recently been a surge in the need for roads of a higher grade. Standard asphalt made from oil has a few problems that need to be addressed. The primary one is that it cannot tolerate very high temperatures. Because it contains so much paraffin, it will be able to flow when the temperature is high but will remain solid when the temperature is low. As a direct consequence of this, the asphalt will be broken up, lubricated, and marred by wheel ruts. According to the findings of (Behnood and Gharehveran, 2019), oil asphalt is unable to fulfill the standards that are in place at this time, which is why more researchers are focusing on developing ways to change standard asphalt oil.

According to (Mashaan et al., 2011) research, the following are some other elements that contribute to this modification:

1. High-quality bitumen can only be produced with massive amounts of oil, which are in short supply.
2. There aren't many effective control activities that can be used throughout the refining process.
3. The need of obtaining a greater number of economic rewards

The use of additives in asphalt mixes results in a significant improvement to the service life of the mixture as well as an increase in its resistance to irreversible deformations. This may be accomplished in two different methods. One option is to alter the equilibrium between the elastic and viscous strain response components by boosting the contribution of the elastic component while simultaneously decreasing the contribution of the viscous component. The second strategy is to improve the stiffness of the bitumen, which will result in the mixture being stiffer. This will result in less strain for a given weight. According to (de Sá et al., 2013), the perfect modified bitumen has an appropriate viscosity with a small temperature dependency at the temperatures that are typical for pavement service. In conclusion, the most important purpose for using these fillers and other types of modifiers is to enhance the performance of the paving mixture to fulfill criteria despite the circumstances that are currently in place. During the early stage of modification, a combination of asphalts of varying grades was used, which resulted in improved performance.

To prevent or cure the following types of damage that might occur to pavements, asphalt binders have been modified using various additives.

1. Defects on the surface (including ravelling and stripping).
2. Deformation of the surface, including rusting, shoving, and distortion.
3. The formation of cracks (fatigue cracks and thermal cracks).

Over time, a wide variety of various kinds of substances have been suggested for use as additions in bituminous mixtures

2.10.1 Polymer

According to (Yan, Xu and You, 2015), conventional bituminous cannot fulfill the standards for high-grade asphalt roads (highways), hence the material must undergo further modification. Polymers are a common kind of asphalt modification that is used in the industry to a large extent. According to (Zhu and Kringos, 2015), the primary way for altering the qualities of virgin asphalt is to combine the virgin asphalt with a synthetic polymer. Polymer modification is regarded to be one of the primary remedies for the problems of thermal cracking and rutting, as well as a rise in the fatigue life of asphalt road pavement.

The origin of the term polymer may be traced back to the combination of two Greek words, "polys" and "meros," which together imply "many parts." Because "polys" denotes a large number of occurrences and "meros" refers to a component, "polymers" are compounds consisting of a large number of individual components. Polymers are lengthy chemical chains that are formed by the joining together of several monomers, which are smaller molecules. According to (Yusoff et al., 2014), a polymer is defined as a big molecule that is made up of one or more repeating units that are connected by covalent connections.

The addition of polymer to asphalt has a wide variety of beneficial effects. The primary objective is to improve the pavement's performance and the mechanical features it has. Since the binder suffered a drop in its effective glass transition temperature, the second one is to reduce sensitivity to high temperature and boost resistance to low-temperature cracking. This is because the binder underwent a decrease in its effective glass transition temperature. Last but not least, there was an increase in the material's resistance to deformation (Fang et al., 2012).

2.10.2 Types of Polymers

The commercial modifiers may be broken down into three distinct types. The first category consists of components that are found in nature. The second category is comprised of waste materials, while the third is made up of engineered items. Reclaimed rubber, fillers, fibers, catalysts, extenders, and polymers (both natural and manufactured) are a few examples of the types of items that fall under these categories (Yusoff et al., 2014).

According to the Asphalt Institute (2015), beginning in the middle of the 1960s, the following polymers were most often utilized to alter bitumen and improve its qualities.

1. Polymers found in nature, such as lignin
2. Thermoplastics, such as polypropylene, polyethylene, and ethylene vinyl acetate to name a few examples

3. Elastomers, such as natural rubber, synthetic rubber, polybutadiene, and butyl rubber, among other examples
4. Thermoplastic Elastomers (such as polyolefin blends, thermoplastic polyurethane, and styrene block copolymers, for example)
5. Rubber from Ground Tyres (also known as recycled waste tires). Polymers have the potential to function as modifiers in asphalt mixes.

The nature of the individual molecular units that make up a polymer, the amount of those molecular units that make up each chain of the polymer, and the mixture of those molecular types with others determine the polymer's physical and chemical characteristics. In applications using modified bitumen, there are typically two primary kinds of polymers used: i)elastomers, ii) plastomers

1. Elastomers, Thermoplastic materials soften and become plastic-like when heated, but revert to their rigid condition once they have cooled. Elastomers are a kind of thermoplastic material. Such as Styrene butadiene Styrene (SBS), Styrene butadiene rubber (SBR) .
2. Plastomers, also known as thermosetting materials, are those that can flow under stress when heated, but after they have cooled, they are unable to be re-softened by heat. For example, polyethylene (PE) and polypropylene (PP), may have either a low or a high density.

Although the use of polymer-modified bitumen to prevent damage caused by moisture is not widely used, there is some evidence that some polymers may function as anti-stripping agents.

Additively made of crumb rubber (CR), Highway authorities in several regions of the globe are using crumb rubber asphalt pavement to extend the life of pavement, save money, and preserve the environment. However, because of the usage of these materials, it is important to evaluate the effects of moisture degradation on rubberized asphalt concrete (RAC) compositions that comprise

RAP. Although the addition of crumb rubber had a somewhat negative impact, the findings showed that, in general, the addition of RAP was useful in improving the ITS values and lowering the moisture susceptibility of the mixture. However, the results revealed that the addition of RAP was beneficial in improving the ITS values. (Moreno, Rubio and Martinez-Echevarria, 2012) the addition of crumb rubber may cause an asphalt rubber binder to have a higher viscosity. This is because the addition of crumb rubber causes an increase in the volume of rubber particles, which is caused by the light oil absorption properties of rubber. Because of this, the capacity of the modified binder to effectively coat the surface of the aggregate is probably hindered by the reduction in oil. As a result, there is a possibility that the bonds between the rubber, the binder, and the aggregate will be broken.

The production of silicon and ferrosilicon alloys produces micro silica, which is an amorphous (non-crystalline) polymorph of silicon dioxide. Micro silica is a waste product of these industries. It is created in electric arc furnaces by the process of reducing high-purity quartz or silicon metal into silicon dioxide. The ensuing vapors are collected and processed to produce micro silica, which is subsequently filtered to eliminate any impurities and guarantee a quality that is uniform throughout the product (Nishchal *et al.*, 2016). Micro silica is made up of highly reactive and very small particles. These particles generally have a size of around 0.1 micrometers on average. Micro silica is a viable ingredient for asphalt mixes because it contains very small particles, each of which has its own set of distinctive qualities. The pozzolanic nature of micro silica is one of the most striking characteristics that it has. Pozzolanic materials, such as micro silica, have the potential to react with calcium hydroxide, a waste product produced during the hydration of cement, to produce extra calcium silicate hydrate (CSH) gel. This reaction helps to densify and reinforce the binder matrix in asphalt mixes, which is a result of how asphalt is made. Because the small particles of micro silica fill the spaces between bigger aggregate particles, the packing density of the asphalt is enhanced, and the number of voids in the asphalt is decreased. Due to these qualities, micro silica is an appealing modifier for improving the mechanical properties and overall performance of SMA mixes (Kai *et al.*, 2018).

It has been shown that improving numerous important aspects of SMA mixes with the addition of micro silica. The strengthening of rutting resistance is a key advantage that may be gained. Asphalt pavements often experience distress known as "rutting," which is produced by the persistent deformation of the surface due to the combined effects of high temperatures and strong traffic loads. Because the asphalt binder has increased stiffness and viscosity as a result of the integration of micro silica, this material is less likely to undergo irreversible deformation. This enhanced rutting resistance is especially significant for highly used roads and highways, which are exposed to heavy repeated stress. This is because the pavement in these areas is prone to developing ruts. Micro silica has the potential to improve the fracture resistance of SMA mixes, in addition to the rutting resistance it provides. (Ding *et al.*, 2017)the pozzolanic reaction that takes place when micro silica and calcium hydroxide are combined serves to generate a binder matrix that is more linked and long-lasting, which effectively stops cracks from spreading. This quality is very necessary for areas where temperature swings and the introduction of new moisture into asphalt pavements play a role in the development and spread of cracks in the paving material. Micro silica's higher fracture resistance makes it possible to greatly prolong the service life of SMA pavements, which in turn reduces the frequency with which they need maintenance and rehabilitation (Al-taher et al., 2018).

In addition, the resistance of SMA mixes to damage caused by moisture may be improved by the addition of micro silica. Because of the tight packing that is produced when micro silica is included, the permeability of the asphalt binder is reduced, which in turn minimizes the amount of moisture that can seep into the mixture. Because it serves to limit the adverse effects of moisture on the structural integrity of the pavement, this quality is especially helpful in regions that experience excessive rainfall or frequent freeze-thaw cycles. This is because these types of climates experience regular cycles of freezing and thawing. Micro silica has the potential to contribute to the long-term durability and performance of SMA pavements by lessening the damage caused by moisture. The use of micro silica in SMA mixes presents several obstacles, although it has a great number of benefits. The large specific surface area of the asphalt is a key cause for worry since it might result in an increased requirement for an asphalt binder. When incorporating micro silica, it is necessary to give careful thought to the ideal dose to guarantee that the right interaction between the binder and the aggregate occurs and to keep the mixed qualities that are desired. In addition, the large surface area of micro silica particles might result in problems with workability during the manufacturing of mixtures and placement of said mixtures. To respond appropriately and successfully to these issues, appropriate steps need to be made to optimize the mixing and compacting processes (Fakhri, 2016).

2.11 Summary

The review of the literature gives an integral view of the stone matrix asphalt mixtures. The SMA materials, and also their concentration and correlating test methods, were chosen for the present study while helping to keep the main points of the research in mind. The performance of SMA mixtures is primarily determined by the coarse aggregate skeleton's stone-on-stone contact; bituminous binders have an effect on the mix's strength. However, previous research has found that using stiffer binders in the mixture improves the mix properties. From the literature review that has been accomplished in this chapter, as related to the modification of asphalt binder by polymers the following points can be highlighted:

• In spite of the increase in the cost of modified asphalt binder compared to the conventional (neat) asphalt binder, use the additives in Stone Mastic Asphalt Mixture is very important to reduce the drain down, modified asphalt mixtures that are used in pavements with the objective of obtaining environmental, frictional and safety benefits. But it is very important to note that waste polymers are significantly low-cost compared to the original polymers.

• It became apparent that there are different polymers types, such as rubber, fiber, polymers, etc. to improve the current properties of SMA mixture with the durability approach.

• In this research work, it was proposed using polymer modified binder to improve SMA suitability (Mechanical and volumetric properties) and durability for highway network. More details for such procedure will be explained in the next chapters.

The researchers concentrated on the use of crumb rubber and other substances as an additives to improve the properties of asphalt mixture, where many researchers focused on knowing its effect on the asphalt binder as well as its effect on the conventional mixture this also applies to micro silica, as there are no studies using micro silica as an additives for Stone Mastic Asphalt. Therefore, these two additives were chosen to find out their effect on the performance of SMA.

Chapter Three :
Material, Testing, and Methodology

3.1 Introduction

This chapter describes the researcher experimental work, as it's classified into three parts. The first part includes the properties of the SMA mixture's materials (e.g., aggregate gradation, bitumen grade, and modifiers). While the second part deals with the implementation of mixture tests that are required to understand the behavior of SMA before and after modification. In the third, and the chapter offers the whole methodology followed in this research

3.2 Materials

The materials in terms of aggregate, bitumen and modifiers that are required to fulfill the design requirements of SMA in this research were supplied from local quarries and factories. The following sections display the whole properties of these materials.

3.2.1 Asphalt Binder

The asphalt binder used in this research was procured from the Al-Dura facility. The asphalt had a grade of 40/50 penetration, which is commonly adopted in Iraq for dense graded HMA. The ASTM requirements were adhered to conduct the laboratory tests that are shown in Table (3-1)

Table 3- 1 Properties of Asphalt Binder

Property	**ASTM designation**	**Test results**	**SCRB requirements**
Penetration,100gm., 25°C, 5 sec (1/10 mm)	D 5 (ASTM International, 2020)	48	40-50
Specific Gravity, 25°C, (gm/cm^3)	D70 (ASTM- D70-2018, 2018)	1.03	-
Ductility, 25°C, 5 cm/min (cm)	(ASTM D113 − 17, 2008)	117	>100
Flashpoint,°C	D92(ASTM, 2007)	310	>232
The softening point,°C	D 36 (ASTM- D70-) (2018, 2018	51	-
Rotational Viscosity @135 °C, Cp *	D4402 (Materials, 2006)	610	≤ 3000 centistokes

* In Highway Lab at the University of Karbala has conducted this test.

3.2.1.1 Rotational Viscosity Test

By ASTM D4402 (ASTM, 2016), a rotating viscometer instrument known as a Brookfield rheometer was used to assess the asphalt binder's level of viscosity. The results of this test were utilized to determine the temperature range that is optimal for mixing and compacting unmodified asphalt binder. According to ASTM D6926 (American Society for Testing and Materials, 1999), the viscosity of the material during mixing should be 170±20°C, and the viscosity during compaction should be 280±30°C. The mixing and compaction temperatures for unmodified asphalt binders are shown in Table (3-2) and Figure (3-1), respectively.

Table 3- 2 Mixing Temperature and Compaction Temperature for Asphalt binder

property	**Asphalt binder**
Mixing temperature, °C.	160
compaction temperature, °C.	154

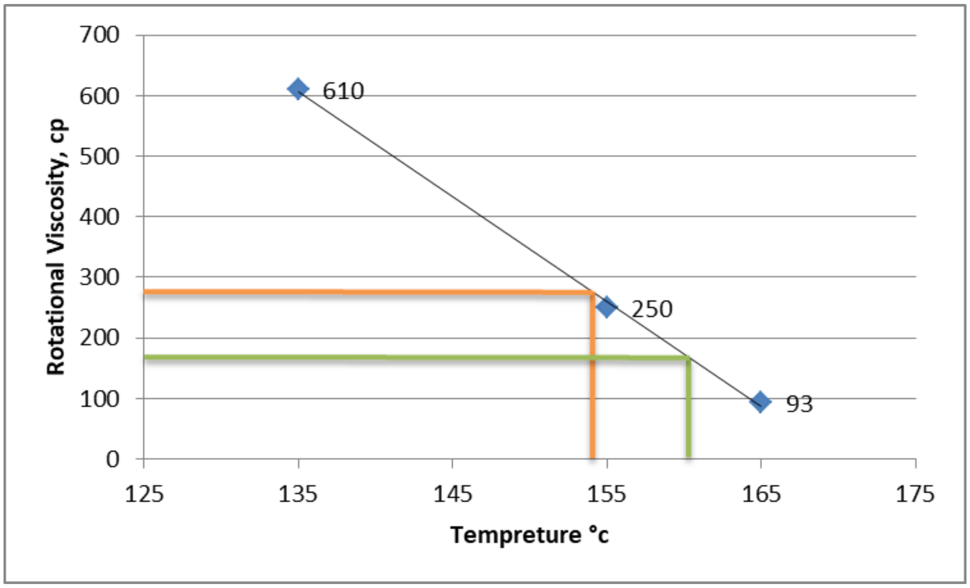

Figure 3- 1 Temperature –Viscosity Relationship for Neat Asphalt Binder

3.2.2 Aggregate:

Crushed aggregates were used, which obtained from Al-Nibaie quarry, north of Baghdad. This type of aggregates are characterized by their widely use in the asphalt paving industry, both nationally and locally. The selection of a better aggregate type depends mainly on the physical properties, chemical properties and gradation of the used one. These factors play an important role in obtaining a successful asphalt mixture. The physical properties of coarse and fine aggregates were determined by performing routine tests at the University of Al-Mustaqbal laboratories. The test results for both aggregates are shown in Table (3-3).

Table 3- 3 Physical properties of course and fine aggregates.

Property	ASTM designation	Test results		SCRB requirement	
		coarse	fine	coarse	fine
coarse aggregate bulk specific gravity (gm/cm3)	C127**(American Society for Testing and Materials, 2013)**	2.67		_	
Fine aggregate bulk specific gravity (gm/cm3)	C128 **(ASTM C128, 2022)**		2.641		_
coarse aggregate water absorption (%)	C127 **(American Society for Testing and Materials, 2013)**	0.48		2 Max	
Fine aggregate water absorption (%)	C128 **(ASTM C128, 2022)**		2.41		_
Los Angeles abrasion value (%)	C131**(American Society for Testing and Materials, 2014)**	14.22		30Max	
percentage of broken particles on one side, %.	D5821 **(Drews, 2008a)**	97		100	
percentage of broken particles on both sides.	D5821 **(Drews, 2008a)**	95		90	

3.2.3 Mineral Filler:

In this study, two types of mineral fillers have been used: ordinary Portland cement and hydrated lime passing from sieve No.200 (0.075mm), hydrated lime obtained from a local factory in Holly Karbala Governorate was used in this work, ordinary Portland cement from Hilla, the percentage of filler is (1.5 % OPC and 8% HL), The physical properties of filler are presented Table (3-4).

Table 3- 4 The physical properties of OPC and OPC fillers (Mahdi and Aboalmaali, 2015).

Physical properties	Filler type	
	HL	OPC
Specific gravity	2.44	3.14
Fineness (cm2/gm)	3850	3050
% Passing sieve No. 200	100	100

3.2.4 Selection of Aggregate Gradation

This aggregate gradation provides a large space for the air voids volume in the asphalt-aggregate mixture, while simultaneously achieving the design air voids desired to permit the thermal expansion of the asphalt within the mixture during hot weather. Gradation is illustrated in Table (3-5) and Figure (3-2). The aggregate selecting NMAS of 12.5 mm was adopted here according to the limits suggested by AASHTO M325 (AASHTO, 2018). It is important to point out that in order to achieve the desired volumetric qualities, a gradation that was finer than the mid limits was used.

Table 3- 5 Gradation of SMA mixture as recommended by AASHTO M325(AASHTO, 2018)

Size(in)	Sieve(mm)	% Passing by weight	% Passing (Average)
[3⁄4 in.]	19	100	100
[1⁄2 in.]	12.5	90-100	95
[3⁄8 in.]	9.5	50-80	65
[No. 4]	4.75	20-35	27.5
[No. 8]	2.36	16-24	20
[No.200]	0.075	8-11	9.5

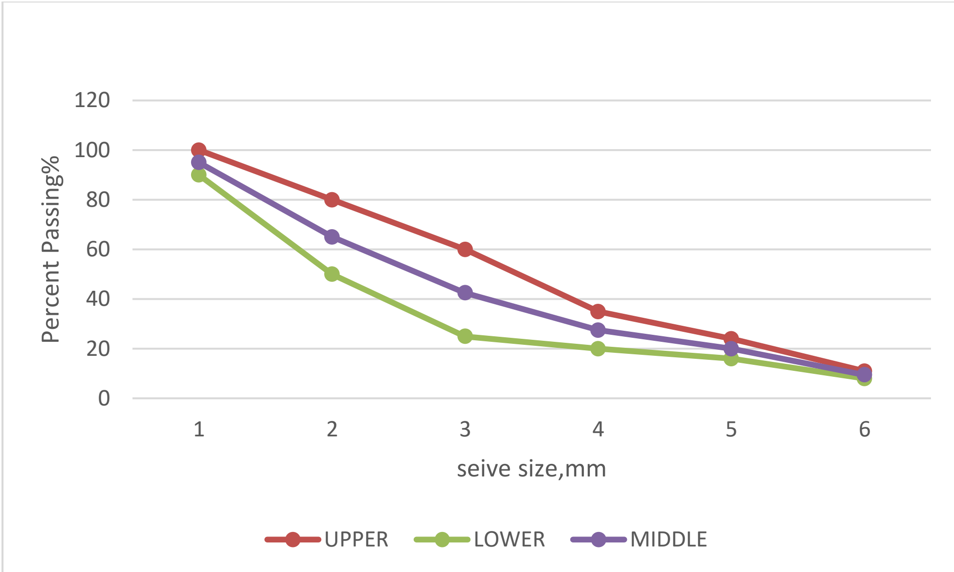

Figure 3- 2 Aggregate gradation limits suggested by AASHTO M325 (AASHTO, 2018)

3.2.5 Additives:

To evaluate the effect of the physical properties of additives on the performance of asphalt mixtures two types of additives are used there are:

3.2.5.1 Crumb Rubber (CR):

Rubber was used in asphalt mixes as additives. The paving industry grew interested in rubber in the 1960 due to its elasticity property, which had the potential to increase the skid resistance and longevity of asphalt mixes (Hassan *et al.*, 2014). In the asphalt mixtures, different types of additives have been used, and among these additives is rubber, and a number of tests were conducted to know the performance of the road. The crumb rubber (CR) used in the research with one particle size (CR passing sieve No.50) (250-micron size or less) with one percentage of the polymer was investigated with (15%) by weight of asphalt. This crumb rubber was obtained from AL- the Najaf factory. Table (3-6) shows the physical properties and material specifications of the crumb rubber.

Table 3- 6 Physical Properties and Materials Specification of Crumb Rubber (Al-Essawi, 2017)

Property	Unit	Requirement or Value
Tensile Strength (σt)	MPa	40 - 70
Specific gravity	----	1.13
Elongation at Break	%	25 - 50
Density	Kg\ m³	1320
Young's Modulus (E)	MPa	2600 – 2900
Rubber Hydrocarbon	%	48min
Carbon Black	%	25 - 35
Acetone Extract	%	10 - 20
Ash at 550	%	8.0 min
Metal Content	%	0.03 max

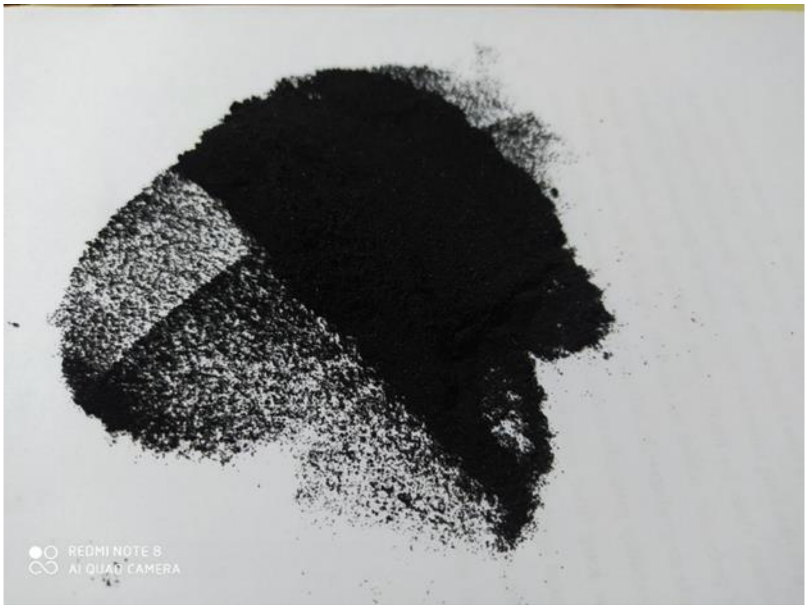

Plate 3- 1 Particles of Crumb Rubber

3.2.5.2 Micro silica (MS):

Micro Silica (MS) is an amorphous (non crystalline) polymorph of silicon oxide. It has its forms also i.e., silica fume (SF). It is ultrafine powder with an average particle size of 0.1 to 0.5 µ. Micro Silica is pozzolanic material and is available in different forms (Nishchal *et al.*, 2016). It has the advantages of chemical corrosion resistance; good thermal stability and dimensional stability, excellent mechanical and electrical properties, and reinforcement. Micro Silica (MS) is widely used in building, chemical, metallurgical, and other industries. For example, it can be used as replacement cement admixture or add as polymer for asphalt directly to improve the performance of mixture. It has been well used in harbor wharfs, highways, airport runways, tunnels, and other fields, because it has high strength, wear resistance, erosion resistance, corrosion resistance, permeability resistance, frost resistance and early strength (Zheng ; Xu ; Feng; Kai Cao, 2020). The micro silica used in this research from company (CONMIX, UAE). The percentages of (MS) used in research are (2%, 4%, and 6%). Table (3-

7) and Table (3-8) demonstrate the chemical and physical properties of micro silica, respectively.

Table 3- 7 shows the chemical Properties of Micro Silica (Zghair, Joni and hassan, 2020)

Oxides	**content, %**	**Limits of specification [25]**
Al2O3	0.71	<1%
SiO2	91.51	> 85%
Fe2O3	0.44	< 2.5%
K2O + Na20	1.38	<3%
L.O. I.	4.38	Max. 6%
SO3	0.95	<1%
Cao	0.89	<1%

Table 3- 8 shows the physical properties of Micro Silica (Zghair, Joni and hassan, 2020.)

Feature	**Results**	**Limits of specification [25]**
Specific surface area	17	≥ 15 m2/g
Size	0.15 ~	0.15 µm
Specific gravity, kg/m³	2.21	---
Color	Grey	---
Moisture	---	< 2%

Plate 3- 2 Particle of Micro Silica

3.2.6 Preparation of modified bitumen:

During this research, two different asphalt binders were prepared: the first and second by combining asphalt cement with MS or CR, separately. by using wet process of mixing additives with asphalt cement. To make the modified binder, a shear mixer rotating at a rate of 2000 revolutions per minute was employed for 30 minutes. Three percent of MS, are used 0.2%, 0.4%, and 0.6% by total weight of asphalt cement, at temperature 140°C were adopted as suggested by previous research study such as (Zghair, Joni and hassan, 2020), (Zghair, Joni and Hassan, 2019), (Karthikeyan Bindhu K PG Student Associate Professor, 2018). While for CR one percent 15% by total weight of asphalt cement was used, because it has been remarked as the better percent by other researchers and According to the Standard Specification for Asphalt-Rubber Binder ASTM D 6114 (ASTM, 2009), (Mahdi and Aboalmaali, 2015), (Kashesh *et al.*, 2023).

To begin the process of preparation, the asphalt is first heated in an oven at 165 degrees Celsius for the amount of time that is necessary to make it fluid enough for mixing. To achieve a homogeneous asphalt-modified blend, a particular experimental technique was used. The fluid asphalt was then put into the shear mixer seen in Plate (3-3), and the additive was slowly added to the heated asphalt cement while the mixing continued at a constant speed rate to prevent the modifiers from agglomerating. This process was repeated with each additive substance until all forms of the modified binder were done, as suggested by previous studies, (Mohammed, Parry and Grenfell, 2018), (Jun, Yuxia and Yuzhen, 2008), and Table (3-9) presented all of the information relevant to the modification process

Plate 3- 3 Shear mixer device

Table 3- 9 Information of modification materials

Material	***Abbrev.***	***Percent by weight of asphalt, %***	***Mixing temperature used, °C***	***Mixing velocity (rpm)***	***Mixing time (min)***
Crumb Rubber	*CR*	*15*	*180*	*2000*	*30*
Micro Silica	*MS*	*2*	*140*		
		4			
		6			

3.2.7 Physical tests of modified asphalt:

The physical characteristics of modified asphalt are described by the set of characteristics listed in Table (3-10). See Chapter 4

Table 3- 10 Physical Proberties of Asphalt cement.

Property	***ASTM designation***	***Test results***	***SCRB requirements***
Penetration,100gm., 25°C, 5 sec (1/10 mm)	*D 5 (ASTM International, 2020)*	*48*	-
Ductility, 25 °C, 5 cm/min (cm)	*(ASTM D113 − 17, 2008)*	*117*	-
The softening point, °C	*D 36 (ASTM- D70-2018,) (2018*	*51*	-
Rotational Viscosity @135 °C, Cp	*D4402 (Materials, 2006)*	*610*	-

3.3 Preparation of SMA mixture:

SMA asphalt mixtures, including the control mixture (CM) and Modified Mixtures (MMs) were prepared. Moreover, to achieve the goal of this research, the mixtures were designed using two different types of specimens through two stages. The first stage involved the preparation of unmodified mixtures, using four different concentrations of neat asphalt, ranging from 6% to 7.5%, with a 0.5% increase for each level. In order to complete the requirements of determination the SMA-Control mixture with Optimum Asphalt Content (OAC) as outlined in AASHTO R46 (American Association of State Highway and Transportation Official, 2017). Using Marshall specimens with a height of 63.5±2.5 mm (2.5±0.2 in) and a diameter of 100 mm (4 in) as shown in Plate (3-4), were prepared using 75 blows of the Marshall hammer on each face, as recommended in AASHTO T245 (AASHTO, 2004c) to achieve the required limit of air voids. All unmodified mixtures are characterized in terms of air voids, voids in the coarse aggregate, drain down, and tensile strength ratio tests as mentioned by AASHTO M325 (AASHTO, 2012). Then, the output results were used to specify the mixture with

OAC that represents the CM in the whole research. The second stage deals with the preparation of the MMs of SMA using the additive contents described earlier, (see section 3.2.5). After that, the specimens were used to characterize the mixture in terms of volumetric, mechanical, and functional properties.

The other type of samples that were used in this study are slab samples with dimensions of 300×165×40 mm that are specified for wheel track and skid resistance tests. The compaction procedure of these samples was done as recommended by BS EN 12697-32:2003 code (BSI, 2003b), for more information, see (see section 3.4.2.4).

Plate 3- 4 Marshall specimen

3.4 Mixture testing methods:

In this study, numerous testing procedures were carried out to evaluate the performance of SMA mixtures by studying the volumetric, mechanical, and durability properties. The experimental program used to identify these properties is summarized in Table (3-11).

Table 3- 11 test program

property	***Volumetric properties***	***Mechanical properties***	***Durability properties***
Test Method	*Bulk Density*	*Marshall test and flow*	*Cantabria Abrasion Loss*
	V.M.A	*Indirect Tensile strength*	
	V.F.B	*Skid resistance test*	
	V.C.A	*Wheel track test*	*Moisture damage*
	Drain down	*Unaged Cantabria Abrasion Loss*	
Standard	*AASHTO R46(American Association of State Highway and Transportation Official, 2017)* *AASHTO T166 (Maximum et al., 2022)*	*D 6927(Statements, 2015)*	*ASTM D7064M(ASTM D 7064-08, 2013)*
		D6931 (ASTM D6931, 2017)	
		ASTM E303 (ASTM, 2013c)	*AASHTO T283 (AASHTO-T283, 2003)*
		EN BS 12697-22 (European Standard, 2020)	
	AASHTO M 325-8 (AASHTO, 2018)	*ASTM D7064M (ASTM D 7064-08, 2013)*	
Importance of test	*Providing indications that help to evaluate the level of compaction, aging, bleeding, etc.*	*Evaluating the resistance to plastic permanent deformation*	*Evaluating aging*
		Evaluating the potential of cracking	
		Evaluating resistance to slipping	
		Evaluating resistance to rutting	*Evaluating the resistance to moisture damage*
		Evaluating surface abrasion	

3.4.1 Volumetric Properties:

Important factors to consider for the long-term performance and longevity of any compacted pavement mixture. The volume or quantity of asphalt binder used in asphalt mixes is very important to the longevity of the mixture. It is expected that there would be a sufficient quantity of asphalt to provide a suitable covering for the aggregates. The gradation of the aggregate is what defines the aggregate surface area, and together with the asphalt content and absorption, it is also what dictates the quantity of free asphalt that is available to coat the aggregates, (Qiu, 2007). Volumetric properties of HMA, including asphalt content, voids in the total mix (VTM), voids in the mineral aggregate (VMA), voids in the coarse aggregate (VCA), and the voids filled with asphalt (VFA), Volumetric properties are determined using the mass and/ or volume measurements of a mixture and its constituent components (binder, aggregate, air) as shown in plate (3-5) . Laboratory asphalt mixture testing is primarily conducted to determine two fundamental asphalt mix properties, the bulk specific gravity of the mixture (Gmb) and the theoretical maximum specific gravity of the mix (Gmm). These values are utilized in calculating volumetric properties which are specified requirements for most asphalt mix design procedures (Mahdi and Aboalmaali 2015).

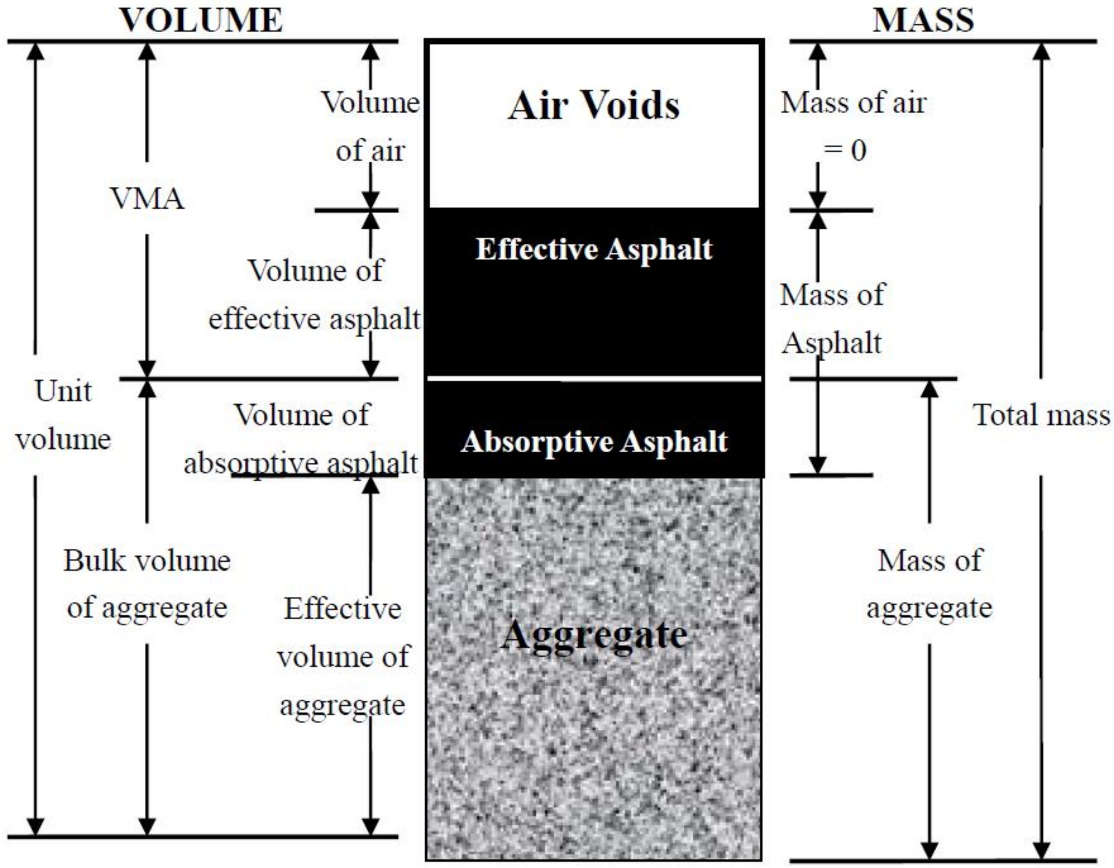

Plate 3- 5 Component Diagram of Compacted SMA Sample (Qiu, 2007)

3.4.1.1 Determination of the ratio of voids in coarse aggregate (VCA)

The voids in coarse aggregates (VCA) determination are used to evaluate the stone-on-stone contact property of the aggregate gradation used in the design of the SMA mixture. The recommendations in AASHTO R46-08 (American Association of State Highway and Transportation Official, 2017) were followed to ensure the best of SMA mixture performance. The determination of stone-on-stone contact depends on specifying the coarse aggregates that actually contribute to this criterion, (Fakhri, Kheiry and Mirghasemi, 2012), (Alvarez, Mora and Espinosa, 2018).

They showed that depending on a comparison done between the volumetric and Discrete Element Method-Image Analysis (DEM-IA); the breaking sieve size may be either 4.75 mm or 2.36 mm.

In this study, for the aggregate gradation used, the sieve of 2.36 mm was used as the breaking sieve. According to AASHTO R46-08 (American Association of State Highway and Transportation Official, 2017), the percentage of voids in coarse aggregate in the compacted mixture (VCA mix) must be less than VCA in the dry rodded condition (VCADRC). The test procedure suggested by AASHTO T 19M/T 19-14(AASHTO T 19M/T 19-14, 2015). was followed here, and Equations (3-1, 2 and 3) were used to calculate the VCADRC, VCAMIX ,and PCA, respectively, AASHTO T85 (AASHTO, 2004b), was used to determine the bulk specific gravity of coarse aggregate, whereas the bulk specific gravity of the SMA compacted mixture was determined using the dimensional analysis procedure specified in AASHTO T166 (Maximum et al., 2022).

$$VCADRC=\frac{GCA\gamma W-\gamma S}{GCA\gamma W}\times 100$$ *Equation 3- 1*

$$VCAMIX=100-\left(\frac{Gmb}{GCA}\times PCA\right)$$ *Equation 3- 2*

$$PCA=\left(\frac{\%RBS}{100}\right)\times\left(1-\frac{\%\mathrm{Pb}}{100}\right)$$ *Equation 3- 3*

Where:

GCA: bulk specific gravity of the coarse aggregate,

γs: bulk density of the coarse aggregate fraction in the dry-rodded condition (Kg/m3),

γw: density of water 998 Kg/m3 (62.3 Ib/ft3),

PCA: percent coarse aggregate in the total mixture,

Gmb: bulk specific gravity of the compacted mixture,

% RBS: percent of aggregate retained on the breaking sieve, and

% Pb: percent of asphalt content by total weight of the mixture.

3.4.1.2 Drain down test (DRT)

Drain down test gives an indication of the ability of asphalt binder to separate itself from the aggregates during production, transport, placing and compacting. Because it has a greater percentage of bitumen and filler content than dense graded mixtures, the drain-down test is one of the most essential tests that has been addressed during the design of SMA asphalt mixtures, According to (Devulapalli, Kothandaraman and Sarang, 2020). As a result, the potential drain down of SMA mixtures must be investigated. AASHTO M325-08 (AASHTO, 2012) recommends that the maximum acceptable level of drain down is 0.3%. This test was carried out using a set of four samples, each of them was tested at a different temperature: anticipated plant production temperature and anticipated plant production +15○C, as recommended by AASHTO T305-03 (AASHTO, 2001a). As shown in Plate (3-6), the test is carried out on a loose mixture placed in a standard basket with 6.3 mm mesh and placed over a known weight pan. The drain down sample will then be conditioned for 1 hour ± 5 minutes in a force draft oven, as shown in Plate (3-7), as recommended by AASHTO T305 (AASHTO, 2001a). After conditioning is completed, the basket containing the sample and pan are removed from the oven and allowed to cool to room temperature. The weight of the separated asphalt and filler in the pan is then calculated. The drain down amount is calculated using Equation (3-4), and the test requirements are summarized in Table (3-12).

$$draindown\ (percent) = \frac{(D-C)}{(B-A)} \times 100 \qquad \textit{Equation (3-4)}$$

where:

A: mass of the empty wire basket,

B: mass of the wire basket and sample,

C: mass of the empty catch plate or container, and

D: mass of the catch plate or container plus drained material.

Plate 3- 6 Drain down the test basket and sample

Plate 3- 7 Force draft oven used

Table 3- 12 Standard limits of drain down test and used test conditions according to ASTM D6390 (ASTM D 6390, 1997)

Parameters	***Standard***	***Test condition***
No. of samples required	4	4
Anticipated plant production temperature	(120-175) ○C	160 ○C
Anticipated plant production temperature +15	+15	175 ○C
Time required to complete the test	1 h ± 5 min	1 h ± 5 min
Mass of samples, gram	1200 ± 200	1200
Basket length, mm	165±16.5	165
Length of bottom basket, mm	25±2.5	25
Basket diameter, mm	108±10.8	108
Diameter of basket mesh, mm	6.3	6.3

3.4.2 Testing of mechanical properties

The mechanical property of a material is the relationship between load (stress) and displacement (strain). Fundamental material properties are those that are based on fundamental units and are independent of testing dimensions or specimen geometry (Jabbar, 2021) In this study, several tests were performed to evaluate the mechanical properties of SMA. Sections below briefly provide an integrated idea about these tests.

3.4.2.1 Marshall stability (MS) and flow (MF)

ASTM D6927 (ASTM, 2015a), describes the procedure for preparing and testing the specimens to determine Marshall stability (MS) and Marshall flow (MF). The method was used to assess the resistance of the mixture to plastic deformation. All test conditions reported in ASTM D6927 (ASTM, 2015a), are shown in Table (3-13). It is worth noting that the Marshall test was carried out using a loading frame connected to a load cell and a linear variable differential transducer (LVDT) to record the MS and MF.

Table 3- 12 Marshall Test Conditions According to ASTM D6927.

Parameter		***Test standard***	***Used value for testing***
Number of specimens		3	3
Mix temperature, °C		130-180	160
The temperature of aggregate, °C		170	170
Asphalt temperature, °C		150-165	160
Accuracy of measuring devices		Min. 0.01 N	0.01 N
The load rate, mm/min		50 ± 5	50
Test temperature, °C		60 ± 1	60 ± 1
Duration of conditioning before a test, min	*In bath water*	30-40	30 min in bath water
	In oven	120-130	
Specimen compaction		*75blows each face*	*75 blows each face*
Specimen thickness, mm		63.5 ± 2.5	63.5
Specimen diameters, mm		101.6-101.7	101.6-
Curing, hr.		24hr at Lab temperature	24hr at Lab temperature

3.4.2.2 Indirect tensile strength test (ITS)

This test was conducted to assess the tensile strength for HMA by determining the Indirect Tensile (ITS) Strength. The tensile properties of bituminous mixtures are of interest to pavement engineers because of the problems associated with cracking. The ITS strength of bituminous mixtures is conducted by loading a constant rate of compressive load on a cylindrical specimen across its vertical diametric plane at a specified rate of deformation and test temperature. The ITS strength values can be used to examine the relative quality of HMA mixtures in combination with laboratory mix design testing, and for probable cracking to be estimated. The test follows the procedure of ASTM D6931-12(ASTM D6931-12, 2007), whereas test conditions are shown in Table (3-13).

Table 3-13 Indirect tensile strength Test Conditions According to ASTM D6931

Item	Standard	Used condition
No. of specimens	3	3
Rate of loading, mm/min	50 ± 5	50
Accuracy of device	Min. 0.01 N	0.01 N
Test temperature, ºC	25 ± 2	25 ± 2
Curing	Placed in a water bath for a minimum of 2 hours at testing temperature	Placed in a water bath for a minimum of 2 hours at testing temperature

The specimen was centered on the vertical diametrical plan between the two parallel loading strips (19.05 mm) in width, Steel loading strips with a concave surface having a radius of curvature equal to the nominal radius of the test specimen. The length of the loading strips shall exceed the thickness of the specimen. Compressive vertical load by testing machine was applied up to the maximum load resistance reached by dial gage reading and this value was recorded. plate (3-8) illustrates the indirect tensile test device.

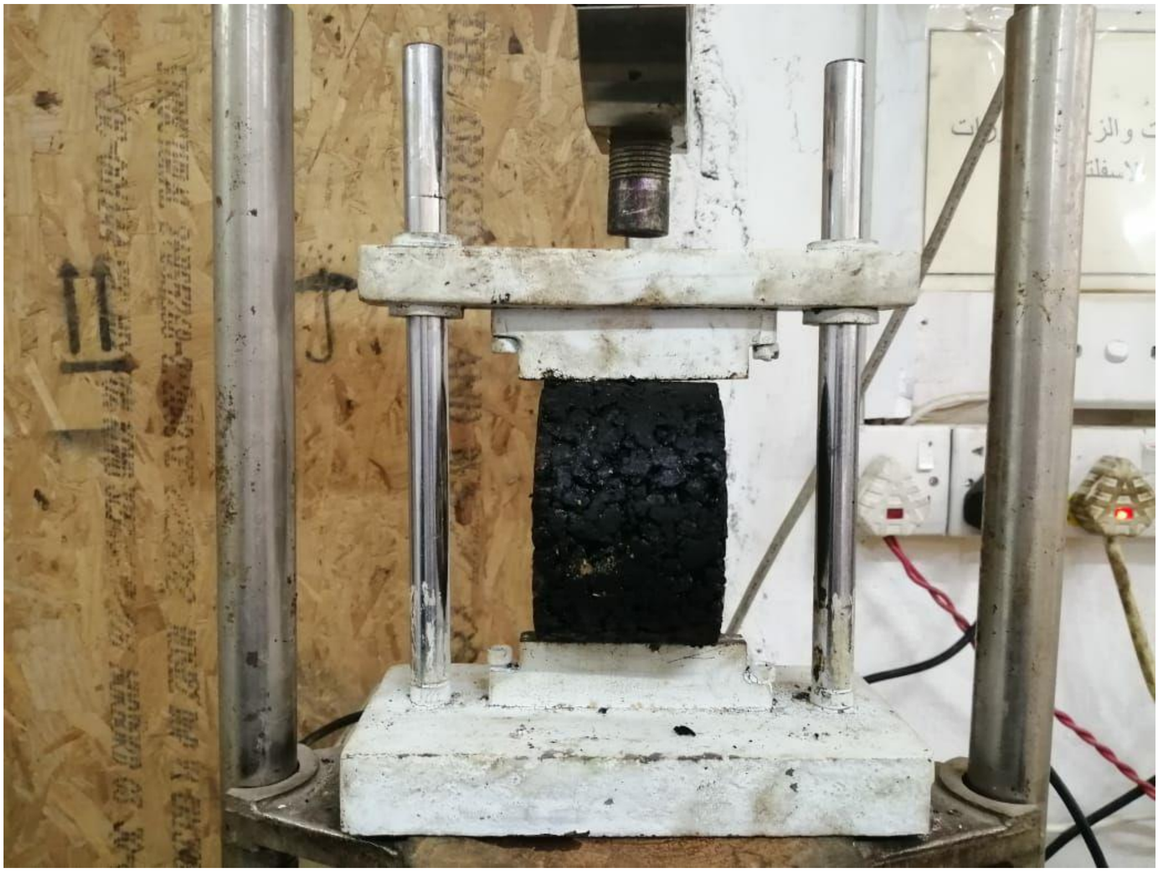

Plate 3- 8 illustrates the indirect tensile test device

According to the following equation, the indirect tensile strength is calculated according to (ASTM D6931-12, 2007)

$$ITS = \frac{2000\,P}{\pi\,D\,t} \qquad \text{Equation (3-5)}$$

Where:

ITS: Indirect tensile strength, kPa.

P: maximum load, N.

D: specimen diameter, mm.

t: specimen height immediately before test, mm.

The ITS test results can also be used to decide the probable field pavement moisture damage when results are obtained on both unconditioned and moisture-conditioned specimens.

3.4.2.3 skid resistance test

The resistance of asphalt pavement surface to sliding vehicle tires is indicated by skid resistance. It is a relationship between the horizontal and vertical forces generated when the tire slips on the road surface.

The British Pendulum Tester Device was used to evaluate the skid resistance of SMA mixtures according to the ASTM E303 (ASTM, 2013b) in terms of British Pendulum Number (BPN), shown in Plate (3-7). The procedure of this test was carried out using wheel track slab samples with dimensions of 300×165×40 mm. The test was performed for both dry and wet surface conditions in order to determine the friction characteristics of asphalt mixtures. The BPN was measured when the rubberized slider passed a standard distance specified on the slab surface between 124 mm and 127 mm. For each sample and condition, four readings were taken, and the average of these readings is calculated to represent the skid resistance of the tested mixture.

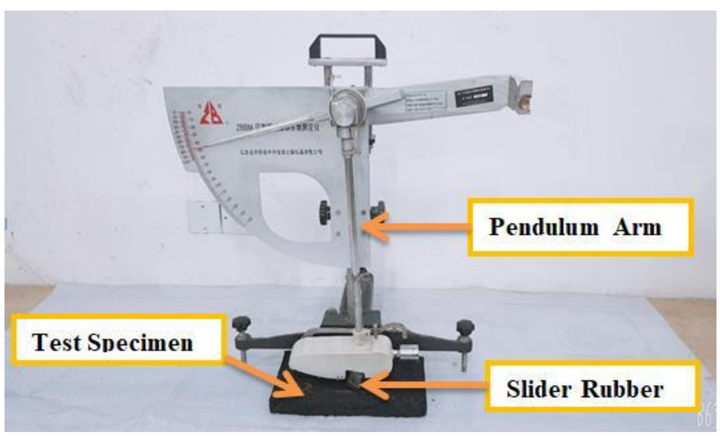

Plate 3- 9 British Pendulum Device in Highway Lab at the University of Karbala

3.4.2.4 Wheel Track Test

Wheel track test simulates the behavior of asphalt mixtures under repeated wheel loads in service. The test procedure was carried out in accordance with the BS EN 12697-22:2003 code(European Standard, 2020). The rut depth of SMA mixtures was determined using an average of two small slab samples. The used slabs had a dimension of 300×165×40 mm and had a minimum air voids content of about 7±0.5%. This resulted from conducting a several of trials using vibratory compaction procedure, Plate (3-10) shows an example of the used samples. As well. Before conducting the test, each sample was conditioned at 60 °C for two hours to simulate the critical performance requirements in order to understand the ability of the SMA mixture to resist the permanent deformation under repeated load and at high service temperature. The test description is represented in Table (3-14).

Plate 3- 10 Wheel track specimen

Table 3-14 Limitations of the wheel-track test according to BS EN 12697-22:2003 code (European Standard, 2020)

Parameter	***Standard limits***	***Test condition***
No. of required specimens	2	2
Diameter of wheel, mm	200-205	200
Wheel width, mm	50 ± 5	50
No. of wheel passes per min.	50 ± 5	52
Speed of wheel, cycle/min	26.5 ± 1	26
Load on the wheel, N	700 ±10	700
Specimen thickness, mm	25 - 80	40
Air voids content specimens, %	4 or 7%	7
Test temperature, ºC	40± 2 to 60 ± 2	60
Specimen's type	Slab/beam or Cylinder	Slab
Specimen dimensions, mm	300 × 260	300 × 165
Compaction effort to air void 7%, min	Depended on the required air void 7%	Depended on the required air void 7%

3.4.3Testing of durability properties

The ability of the construction material to withstand the applied stress for an extended time without significant deterioration is referred to as durability. The main factors influencing the durability of asphalt paving materials are age hardening and moisture damage. The material properties change over time as the mixture stiffens due to the hardening of the asphalt binder. The durability tests followed here will be highlighted in the next sections.

3.4.3.1 Cantabria abrasion loss test

The Cantabria test procedure was carried out in accordance with ASTM D7064/D7064M (ASTM D 7064-08, 2013) The test indicates the resistance of asphalt mixtures to degradation (resistance to raveling). A set of six samples was prepared to complete the requirements of this test. Three of them were used for unaged Cantabria loss. The cylindrical specimens were fabricated using Marshall hammer with 75 blows on each face. Before performing the test, the specimens should be placed in an oven at (25± 5) °C for four hours. Following that, samples are placed in an abrasion machine shown in Plate (3-11) without steel balls and run for 10 minutes at a speed of (30-33) revolutions per minute to achieve a total number of 300 revolutions. Thereafter, by using Equation (3-6), the loss percentage of the specimen's weight is calculated; the percentage represents the resistance of the asphalt mixture to raveling. While for the aged condition, the remaining three samples should be conditioned initially for 7 days (168 hours) in a force draft oven at 60℃ as suggested by ASTM 7064/ 7064M (ASTM D 7064-08, 2013). After that, samples shall be extracted and leave it in the air for a while to cool down, then placed in a 25 ℃ force draft oven for four hours. Finally, the abrasion process was conducted as mentioned earlier and the abrasion loss was determined from Equation (3-6) as well.

$$P= \frac{(P1-P2)}{P1} \times 100 \qquad \textit{Equation (3- 6)}$$

Where:

P: abrasion loss percentage,

P1: specimen weight before abrasion test, and

P2: specimen weight after abrasion test.

ASTM D7064/D7064M (ASTM D 7064-08, 2013) recommends that the percentage of weight loss of the gap graded friction coarse specimen must be no more than 20% for unaged condition and 30% for aged condition, the same value adopted here for the SMA. Table (3-15) summarizes the characteristics of this test.

Table 3- 15 Cantabria test characteristics according to ASTM D7064/D7064M

parameter	***Standard limits***	***Test condition***
No. of samples required	*3*	*3*
Specimens' diameter, mm	*101.5-101.7*	*100*
Specimen's thickness, mm	*63.5 ±2.5*	*63.5*
Compaction effort, Marshall hammer	*75×2*	*75×2*
Time of preparing specimen before conducting the test	*4hours*	*4hours*
Test temperature	*(25 ± 5) ○C* *(77 ± 10) ○F*	*(25 ± 5) ○C* *(77 ± 10) ○F*
No. of revolutions	*300*	*300*
Operating speed, revolution/min	*30-33*	*30-33*

Plate 3- 11 Los Angeles abrasion machine

3.4.3.2 Tensile Strength Ratio (TSR)

Moisture damage in bituminous mixes refers to the loss of serviceability due to the presence of moisture. The extent of moisture damage is called the moisture sensitivity. The ITS test a performance test which often used to evaluate the moisture sensitivity of a bituminous mixture. Tensile strength ratio (TSR) (AASHTO-T283, 2003) was 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) (as show in section 3.4.2.2) which is expressed as a percentage. All specimens were compacted at 7±1% air voids The examined HMA were prepared in accordance with standard Marshall design method with different number of blows for adopting the required percent air voice (about 7%) to evaluate the moisture sensitivity of related tests, this test includes preparation of six specimens and divided into two subsets unconditioned (tested in dry state) and conditioned (tested in saturated state). The conditioned samples as shown in table (3-16) were saturated with water to between (70-80%) by applying a vacuum of (13-67 KPa absolute pressure). After that, the conditioned samples are freeze for 16 hr. at -18oC. Then they are immersed for 24 (hrs.) in water at 60°C, which seemingly decreases the tensile strength. The tensile strength ratio is calculating to two decimal places as follows:

Tensile strength ratio (TSR) $= \frac{S2}{S1} \geq 80\%$ *Equation (3-7)*

Where:

S1 = average tensile strength of the dry subset, KPa (psi); and

S2 = average tensile strength of the conditioned subset, KPa (psi).

Table 3- 16 Preparation condition of Indirect Strength Ratio Test Specimens

parameter	***Standard limits***	***Test condition***
No. of specimens	*6*	*6*
Rate of loading, mm/min	*50 ± 5*	*50*
Accuracy of device Min.	*0.01 N*	*0.01 N*
Test temperature, ºC	*25 ± 2*	*25 ± 2*
Specimen diameters, mm	*63.5±2*	*63.5*
Compaction effort, Marshall hammer	*50×2*	*50×2*
Specimen conditioning before the test	*subjected to vacuum saturation followed by a freeze cycle followed by a 24-hour thaw cycle then,2 hr. at 25°C*	*subjected to vacuum saturation followed by a freeze cycle followed by a 24-hour thaw cycle then,2 hr. at 25°C*

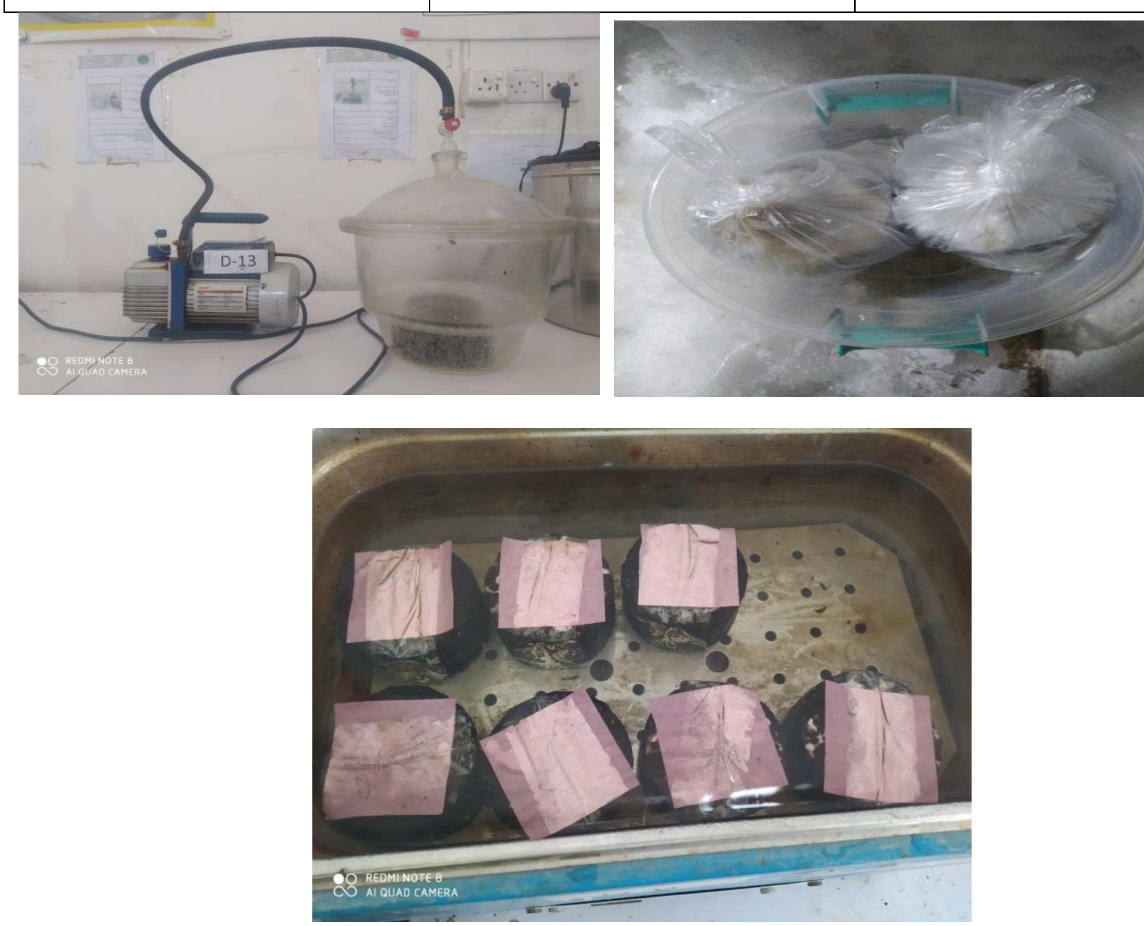

Plate 3- 12 specimen tensile strength ratio

3.5 Methodology

To achieve the primary goal of this study, various types of SMA asphalt mixtures were prepared and then characterized using a set of volumetric and mechanical properties. The matrix of mixture types and the tests performed are shown in Tables (3-17). While the flowchart in Figure (3-1) summarizes the stages of this research, which included:

1. Making the SMA Control mixture in order to determine the volumetric and mechanical properties of this mixture.
2. Adding the sustainable modifiers to asphalt binder, such as CR and MS, at different percentages individually. This stage entails identifying the modified asphalt characteristics, as well as varying the percentages of the additives.
3. Investigating the volumetric, mechanical and durability properties of modified asphalt mixtures using the previously developed asphalt binder.

Table 3- 17 Matrix of the experimental plan

property		**Identifying OAC**	**Characterizing the control mix with 6.7% OAC**	**Modifying asphalt mix with CR %**	**Modifying asphalt mix with MS%**		
				15	**0.2**	**0.4**	**0.6**
Volumetric Properties	**BD**	√	√	√	√	√	√
	AV	√	√	√	√	√	√
	VCA	√					
	VMA	√	√	√	√	√	√
	VFA	√	√	√	√	√	√
	DRT	√	√	√	√	√	√
Mechanical properties	**MS**		√	√	√	√	√
	MF		√	√	√	√	√
	ITS		√	√	√	√	√
	SR		√	√	√	√	√
	WTT		√	√	√	√	√
Durability properties	**CAL**		√	√	√	√	√
	TSR	√	√	√	√	√	√

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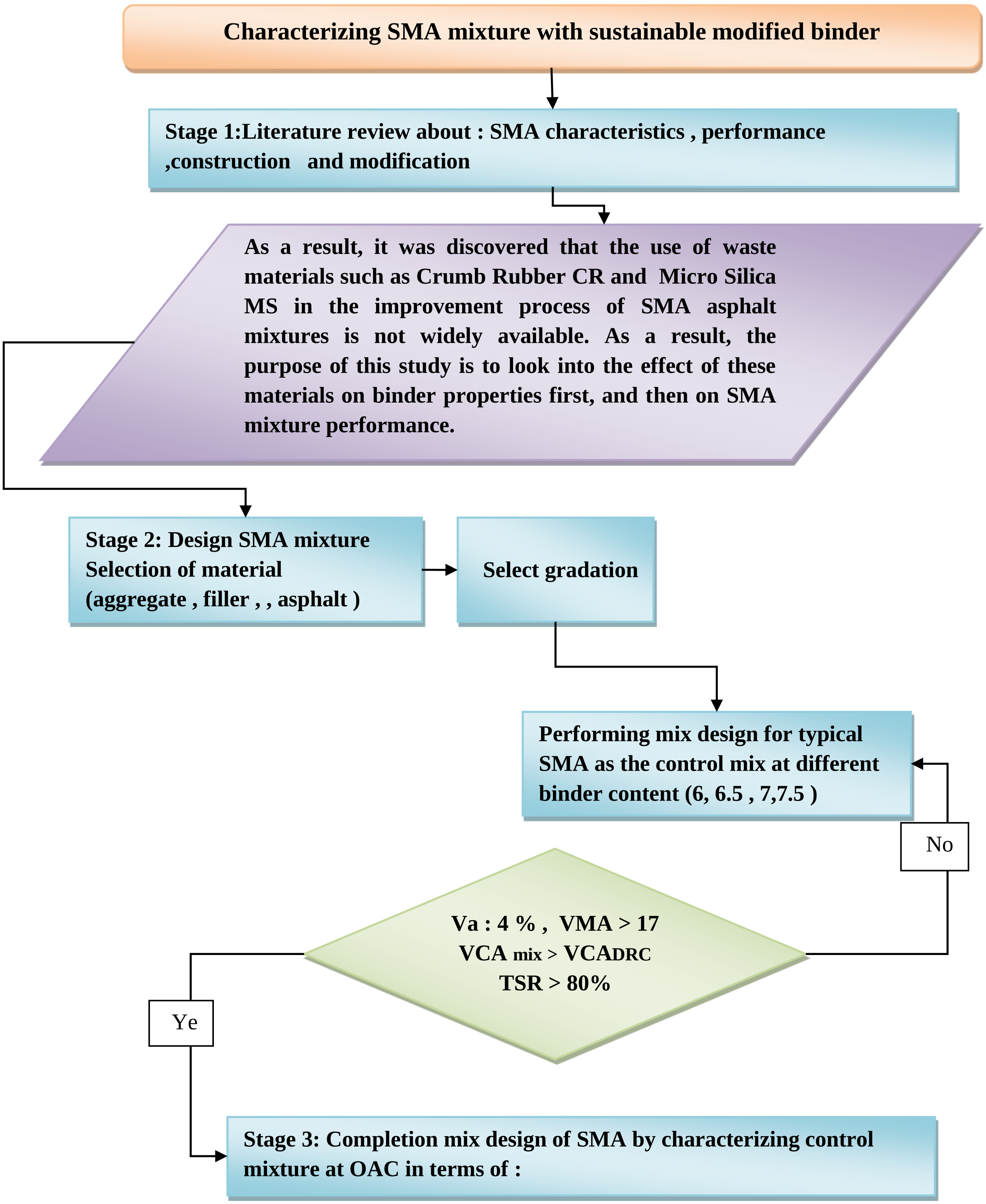

Characterizing SMA mixture with sustainable modified binder
Stage 1:Literature review about : SMA characteristics , performance ,construction and modification
As a result, it was discovered that the use of waste materials such as Crumb Rubber CR and Micro Silica MS in the improvement process of SMA asphalt mixtures is not widely available. As a result, the purpose of this study is to look into the effect of these materials on binder properties first, and then on SMA mixture performance.
Stage 2: Design SMA mixture Selection of material (aggregate , filler , , asphalt)
Select gradation
Performing mix design for typical SMA as the control mix at different binder content (6, 6.5 , 7,7.5)
No
Va : 4 % , VMA > 17
VCA mix > VCADRC
TSR > 80%
Ye
Stage 3: Completion mix design of SMA by characterizing control mixture at OAC in terms of :

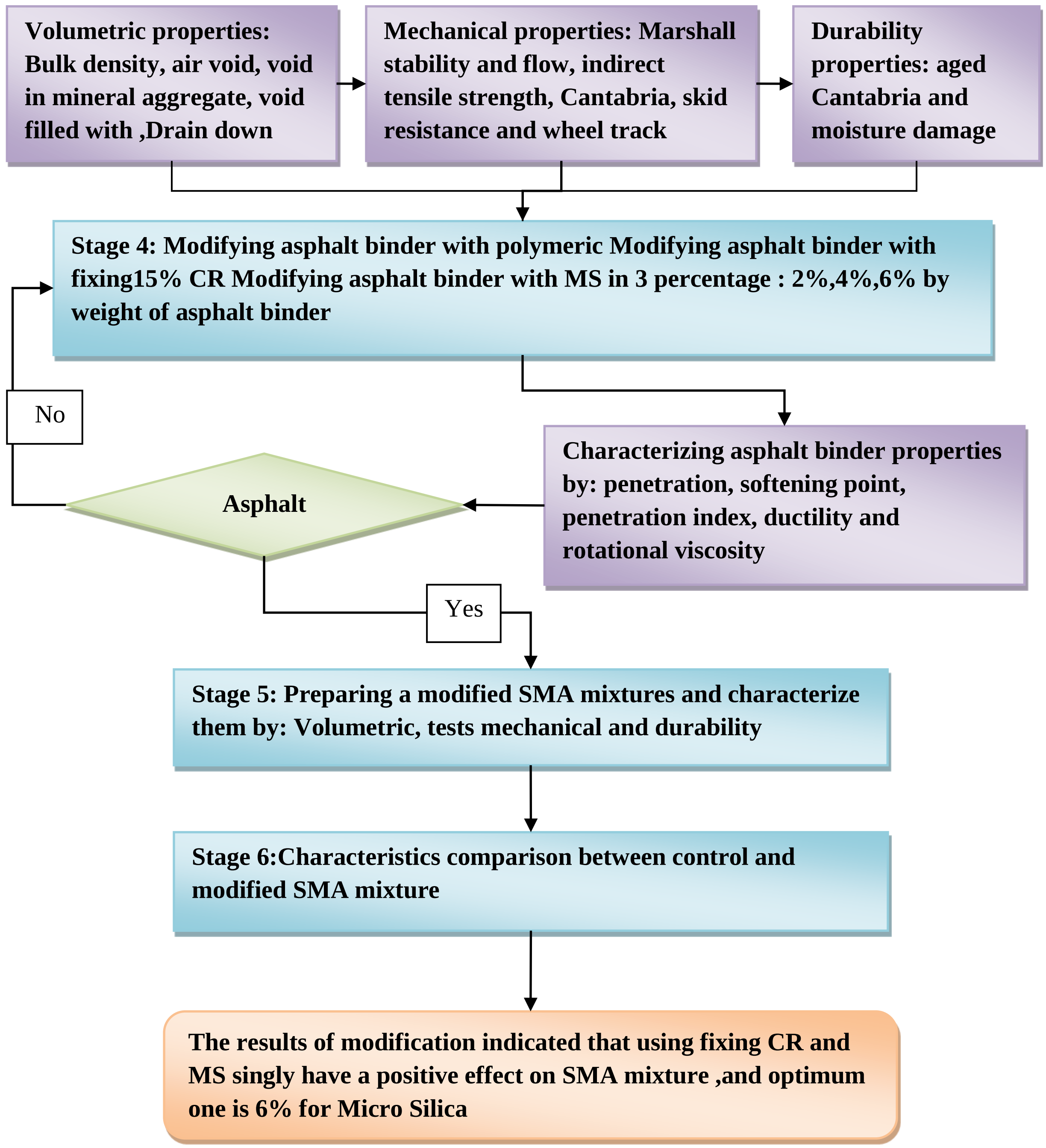


Figure 3- 3 Methodology flowchart

Chapter Four :
Results and Discussion

4.1 Introduction

This chapter discusses analyzing and interpreting the results of the bitumen modification procedure. This factor affected the volumetric, functional, and mechanical properties of compacted Marshall specimens, slab specimens, and dispersed mixtures in addition to the properties of bitumen itself. In addition, the chapter compares the results of SMA compounds with and without modifications.

4.2 Characterization of unmodified SMA asphalt mixture

The unmodified SMA mixture was created by combining AC, which had a penetrability grade of (40-50), virgin coarse and fine aggregates, and two different kinds of filler: OPC and H.L. The aggregate gradation that had an NMAS of 12.5 mm was the one that was used. To make the unmodified SMA mixes, I employed Four different asphalt contents: 6, 6.5, , 7, and 7.5 percent. This was done by the recommendations made by AASHTO R46. SMA mixes were tested by AASHTO M325 to determine the amount of air voids present, void in the coarse aggregate, voids in mineral aggregates, drain down, and tensile strength ratio. In this study, the mixture with optimum asphalt content was used as a control mixture (CO), and it is remarked as a reference for demonstrating the effect of the modification process on the behavior of the SMA mixture. The following sections describe the details of the obtained result.

4.2.1 Characterization of volumetric properties for unmodified SMA mixture

The structure of the SMA is based, initially and fundamentally, on the volumetric characteristics of the mixture. NMAS with four AC. (that is, 6.0%, 6.5%, 7.0%, and 7.5%) as was described before. In the end, the NMAS was used with the aforementioned AC to build the SMA combinations necessary to estimate the OAC. These mixtures were designed based on the results of a series of experiments that are discussed further down in this paragraph.

4.2.1.1 Density of unmodified SMA mixtures

According to (Fernandes, Silva and Oliveira, 2018), the strong association that exists between air void limits and density level has a substantial impact on the final mixture design. The relationship between the variation in asphalt content (AC) and the change in bulk density (BD) of compacted SMA mixes is shown in (Figure 4-1). Density gradually increases as AC increases until it reaches its maximum value at 6.5% AC. This is a potential behavior because the increment in asphalt content gives the mixture more lubricity, which simplifies the specimen compaction process. It is also a result of decreasing air voids as asphalt fills voids as AC rising. This, in turn, reduces the volume and increases the weight of the mixture, resulting in an increase in density, MS2 confirms this finding (Institute, 2014a). After then, the Density started to decrease gradually at 7%, and then to 7.5% owing to two different factors. The first was the increase of the binder film that led to disperse the closed aggregate particles. While the second was the expelled-out of the binder during the compaction of the specimens due to low viscosity of the binder mastic as low fines materials are existed in SMA. It is noteworthy saying that SMA mixture with high neat binder showed very low stability and ability to withstand, because increasing the asphalt content leads to increase the bonding of mix composition to a certain limit.

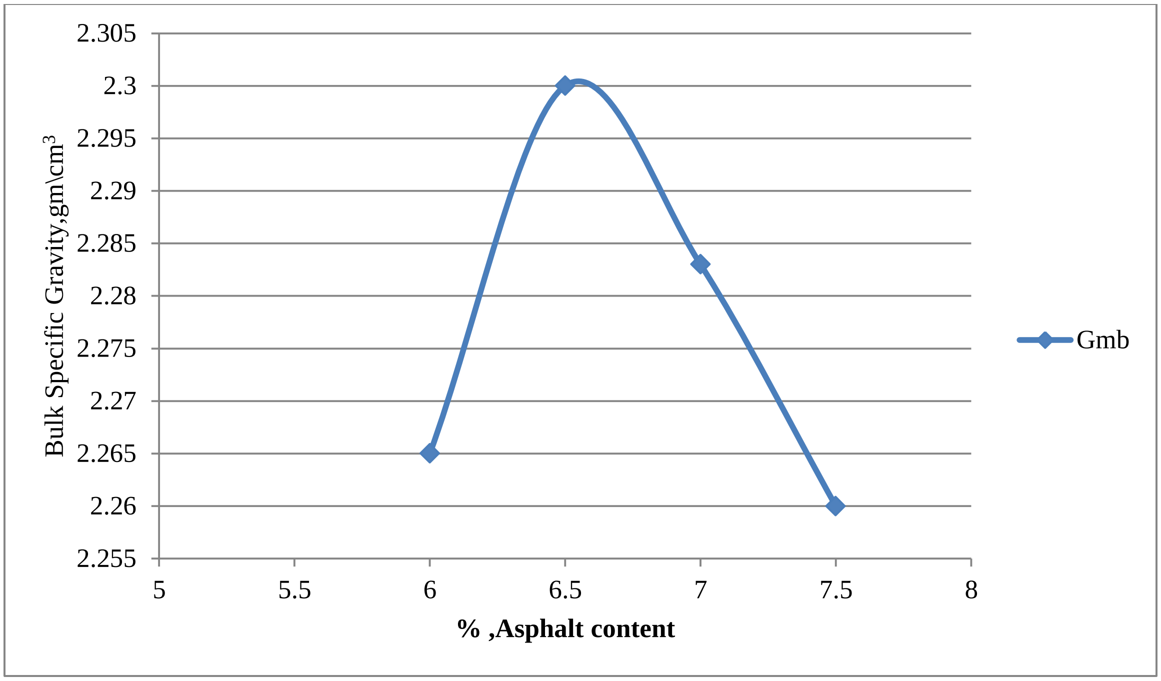


Figure 4- 1 Bulk density of unmodified SMA asphalt mixtures

4.2.1.2 Determination of VCA of unmodified SMA mixtures

The VCA indicates the availability of stone-on-stone contact within the aggregate gradation, which is a factor that affects the resistance to rutting and the durability of the surface. It is calculated as Its evaluated as a ratio between the voids in coarse aggregate of the compacted mixture (VCA_{MIX}) and the voids in coarse aggregate in dry rodded condition (VCA_{DRC}). Stone-on-stone contact is determined to exist in a combination when this ratio is either equal to one or less than one (Sarang *et al.*, 2015); (Devulapalli, Kothandaraman and Sarang, 2020). Table (4-1) Its evaluated as a ratio between the voids in coarse aggregate of the compacted mixture (VCA_{MIX}) and the voids in coarse aggregate in dry rodded condition (VCA_{DRC}). Thus, it remains constant as can be seen in Table (4-1), where it achieves a percentage equal to 37.61%. the results show that there is a slight reduction in VCA_{MIX} with increase in asphalt content then tend to increase again after 6.5% AC. The reason attributed to that increase in AC leads to increase the asphalt film thickness that coating aggregate. On the other hand, Table (4-1) shows that the ratio of (VCA_{MIX}/ VCA_{DRC}) achieves closer values near to 1, this means that stone-on-stone contact property realized by the aggregate gradation of SMA mixture used in this research.

Table 4- 1 Voids in coarse aggregate information of unmodified SMA mixtures

AC, %	***GCA***	***PCA***	***GMB***	***AV***	***VCA_{DRC}***	***VCA_{MIX}***	***VCA_{MIX}/ VCADRC***
6	2.600	75.2	2.265	6.3	37.61	34.48	0.916
6.5	2.600	74.8	2.3	4.5	37.61	33.83	0.899
7	2.600	74.4	2.283	3.42	37.61	34.6	0.919
7.5	2.600	74	2.26	3.25	37.61	35.6	0.946

4.2.1.3 Air voids of unmodified SMA mixture

One of the most important factors influencing the performance of asphalt pavements during their service life is the percentage of the air voids in the mixture. The amount of voids in the mixture can be controlled by adjusting the asphalt content, construction compaction effort, and traffic load compaction. High air voids increase the water and air permeability, which in turn results in the appearance of various types of distresses on the pavement such as oxidation, water damage, cracking, and raveling. Low air voids, on the other hand, cause the rutting and shoving of asphalt pavements (Brown, 1990), Figure (4-2) displays that as the AC raised, the air voids decrease, until reached to 3.25% at 7.5% AC. This is related to that asphalt binder tend to fill the gaps between the aggregates, then work on reducing the level of air voids.

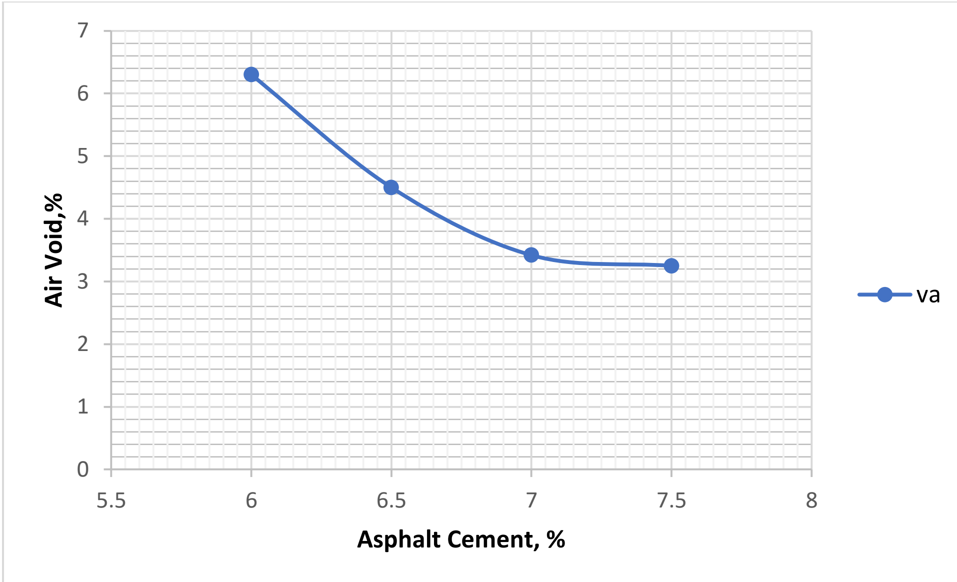


Figure 4 -2Air voids of unmodified SMA mixture

4.2.1.4 Voids in mineral aggregates (VMA) of unmodified SMA mixture

Voids in the mineral aggregate (VMA) is the spaces in the compacted asphalt mixture between the aggregates, which includes the air voids in addition to the spaces filled with asphalt that are not absorbed by the aggregates particles. These voids have a great effect on the durability of asphalt mixtures. Where, the high VMA referred to that the asphalt film thickness coating aggregate is thick, and this meaning high durability and vice versa. Therefore, the VMA should be designed well to the properties of the specified mixture (Ahmadinia *et al.*, 2011; Institute, 2014a). Figure (4-3) represents how the percentage of VMA changes as the AC changes. The percentage of VMA starts to rise after reaching its lowest point at 6.5% AC and continues to do so until it reaches its maximum of 20.4% at 7.5% AC. This is attributed to that mixture becomes more compressible as the asphalt content increases, resulting in more weight per unit volume, which leads to an increment in the BD and a decrement in the VMA. The increase in VMA with increasing asphalt binder content can be explained by increasing the asphalt binder film, which increases the spacing between aggregate particles. Similar finding was disclosed by (Sarang *et al.*, 2015).

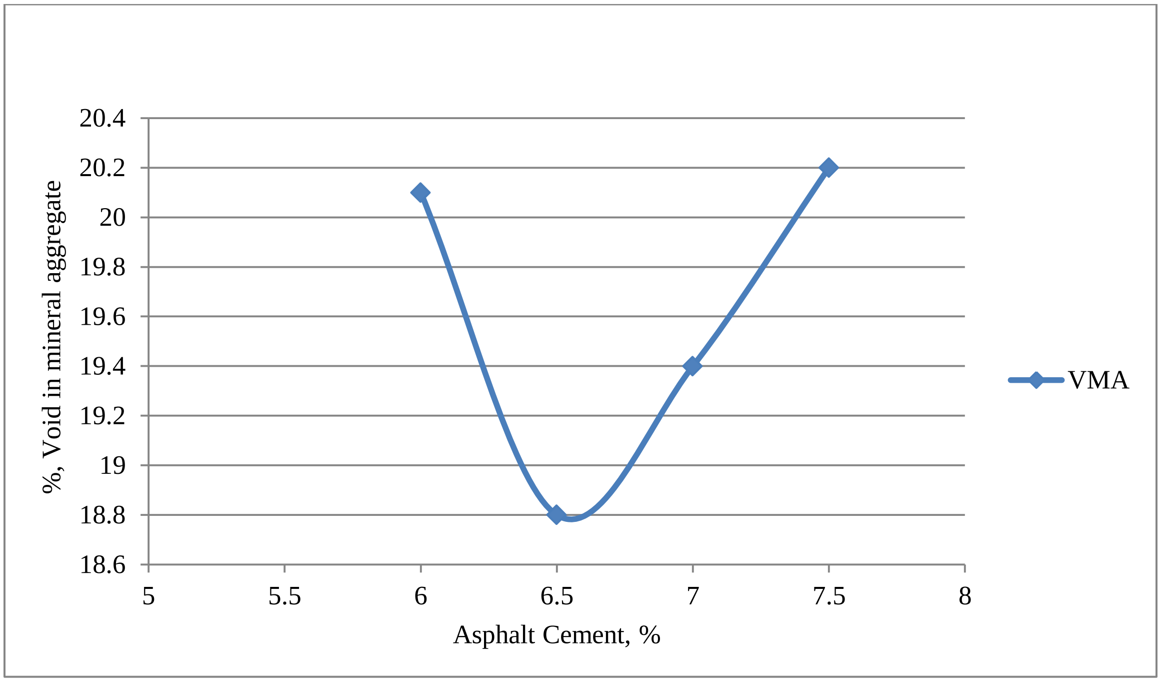


Figure 4- 3 VMA of unmodified SMA mixtures

4.2.1.5 Voids filled with asphalt (VFA) of unmodified SMA mixture

The air spaces that are occupied with asphalt in the compacted mixture are referred to as the void filled with asphalt (VFA), it is the ratio by volume of the VMA that is occupied with the effective binder. VFA limits referred to the proper asphalt film thickness coating aggregates, also, it gives an indication about the mixture durability. The mix will become unstable if it is set too low, and it will do the reverse if it is set too high; this can be seen in Figure (4-4) demonstrates the relationship between AC and VFA. As the amount of asphalt raises, the amount of VFA rises consequently until it reaches 84% at 7.5% AC. The results show that the VFA increases with increasing asphalt binder due to the reduction in air voids caused by filling them with asphalt.

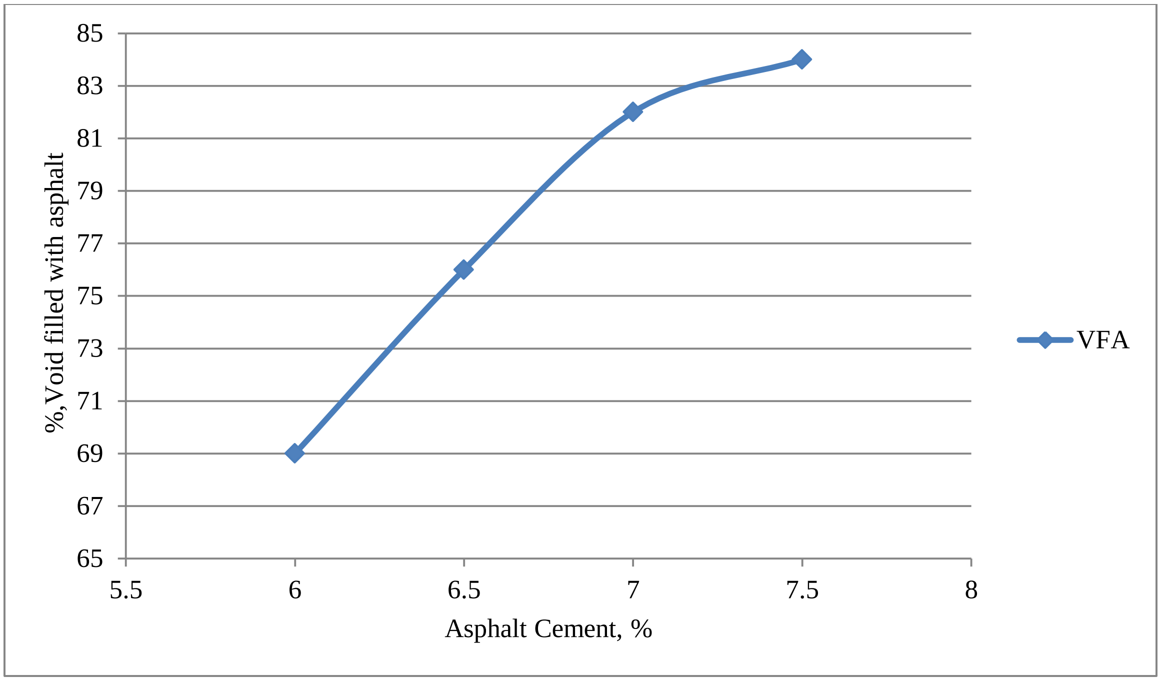


Figure 4- 4 VFA of unmodified SMA mixtures

4.2.1.6 Drain down characteristics of unmodified SMA mixture

Due to the high amounts of asphalt binder and filler materials used in the design of SMA mixture, therefore making it suffer from exposures to the separated of these materials from the SMA mixture. Especially, during design, hauling, placing and compaction besides the elevated work temperature. The amount of drain down in SMA mixtures should not exceed 0.3 % (Devulapalli, Kothandaraman and Sarang, 2020). The results of drain down at two temperatures with the variation in AC are shown in Figure (4-5). It can be seen that drain down levels appear higher than the recommended level at all AC and both temperatures (anticipated and anticipated+15). Where the amounts of increment reach approximately 2.52% and 3.31% at 160°C and 175°C, respectively, when using 7.5% AC, this could be attributed to the higher asphalt content and coarse aggregate gradation of the SMA mixture. In addition, the lower viscosity of neat asphalt causes a portion of asphalt with small amounts of fillers to separate from the mixture, then lead to an increase in the amount of drain down Furthermore, Figure (4-5) also demonstrates that the bond between drain down and AC at both 160℃ and 175℃ temperatures goes up as an exponential mode for drain down at both temperatures as AC increases. The relationships, on the other hand, show that 175°C temperature has a greater effect on SMA mixture drain down than 160°C temperature.

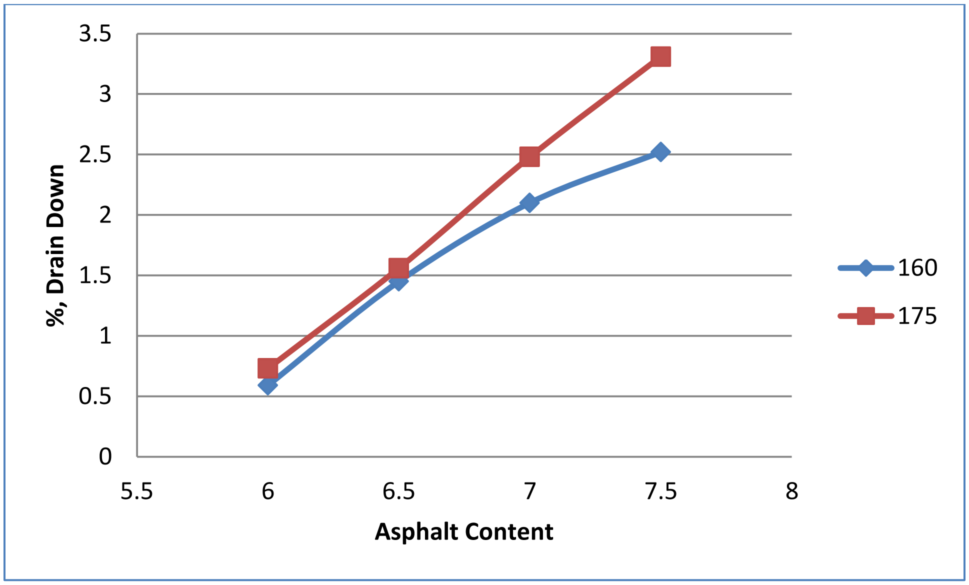


Figure 4- 5 Drain down of unmodified SMA mixture

4.2.2 Characterization of mechanical properties of unmodified SMA mixtures

4.2.2.1 Tensile strength ratio characteristics of unmodified SMA mixture

Tensile strength ratio (TSR) is a moisture sensitivity forecasting formula. According to AASHTO T-283 (AASHTO-T283, 2003) the recommended limit of TSR is 0.8 at a minimum. Moisture damage is a common cause of asphalt pavement failure, particularly surface layer failure. Asphalt pavement moisture susceptibility is an important reference index for evaluating the performance of the SMA pavement structure body (Xue *et al.*, 2013), Figure (4-6) displays the results of the TSR with the variation into AC, where the percentage gradually decreases as AC increases until it reached 0.69 at 7.5% AC. This was related to that the rising into AC lead to de-bonding between the aggregate particles and asphalt binder, then works on weaken the resistance of mixture against water.

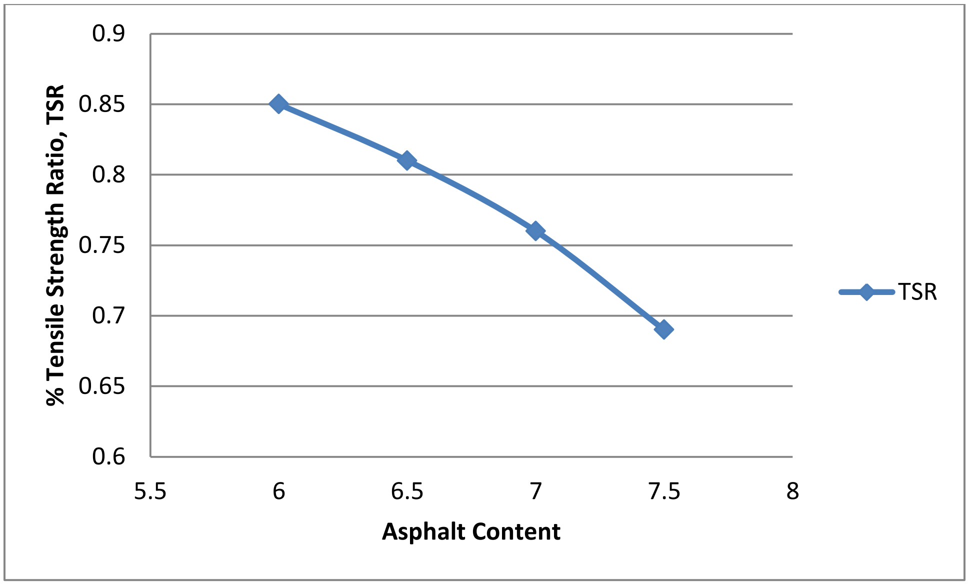


Figure 4- 6 Tensile strength ratio of unmodified mixtures

4.2.3 Characteristics of Control SMA Mixture with OAC

The data allow for the inference to be made that 6.7% of the asphalt satisfies the best limits of the air voids, drain down, and tensile strength ratio tests, in addition to the characteristics of VMA and VFA. This is the conclusion that can be formed from the findings. The fact that the results were seen lends credence to the idea that this is the case. To carry out the procedure that will lead to an improvement, a control combination (CM) will be used, and the SMA mixture and the OAC mixture will both be employed as components of this CM. However, the results of the study show that the use of B0 resulted in a drop in the SMA combination strength, particularly in drain down and moisture sensitivity. This was the case as a result of the findings. Therefore, there is a strong argument for creating asphalt cement in addition to the SMA combination, with the end goal of generating a mixture that has increased strength. This can be accomplished by producing a mixture that has enhanced strength. As a result of this, the following sections will provide some concise information on the many ways in which the bitumen and the mixture may be changed.

4.3 Characterization of the physical properties of modified binder

This section will be offering a detailed discussion about the physical behavior of both neat and modified asphalt; achieved through sections 4.3.1 to 4.3.5, depending on the results observed from the laboratory tests. Moreover, it will be displayed a summary for the finally results obtained, given by the Table (4-2).

Table 4- 2 Summary of results of neat and modified asphalt binders

Asphalt type	Modifier type	Penetration at 25 °C (0.1 mm)	Softening point (R&B °C)	Ductility at 25 °C (cm)	Penetration index	Viscosity at 135°C
Asphalt Cement	AC	48	51	117	-1.015	610
Modified Asphalt	15% C.R.	31	56	22	-0.851	3690
	MS 2%	38	52	93	-1.312	3335
	MS 4%	32	54	81	-1. 209	3600
	MS 6%	26	59	75	-0.595	3925

4.3.1 Penetration test properties

The consistency of the bitumen as well as its level of stiffness may be determined by the penetration test. According to (Palit, Reddy and Pandey, 2004), a reduction in penetration values is indicative of high bitumen stiffness and, as a result, an increase in the mechanical strength of bitumen against damage. Figure

(4-7) displays the findings of the penetration depth at 25 °C for all varieties of modified asphalt (CR and MS). The results demonstrate that adding modification materials to asphalt, such as C.R. and MS, helps to lower the penetration depth of asphalt mastic; This is the overall conclusion that can be drawn from the findings. The findings indicate that increasing the percent while utilizing CR and MS causes a reduction in the penetration depth.

The use of CR to modify asphalt cement results in a significant reduction in penetration values. Adding 15% CR reduced penetration by about 35% compared to Asphalt Cement (AC). This could indicate that the asphalt cement after being exposed to a process mixing with the CRM leads to an increase in hardness due to the stiffening of asphalt because of the absorption of some asphalt oils by rubber (due to swelling phenomena), which increases the viscosity of asphalt due to it is possible to consider penetration point test as an indirect measuring instrument of the viscosity of the asphalt binder material at 25ºC. However, a multiphase system forms when blended asphalt binder with a CRM containing rich asphaltenes. The rubber particles cannot absorb those asphaltenes. The reduction in penetration of the mix because of the formation of an internal structure is more complex. A good dispersion can be accomplished due to the small size of CRM particles. Furthermore, the size of CRM particles used is very small (250 microns or less), which will lead to a large surface area per unit mass of polymer; this will result in the completion of more rapid dissolution due to swelling of the CRM and penetration of the binder is facilitated.

While for the utilization of MS, the results indicate that penetration values decrease noticeably as the MS content increase, where at 6% MS, the reduction ratio reached 45 % compared to AC This behavior can be attributed to the chemical composition of MS, which contains SiO2. In addition, the asphaltene component of the binder is also increased by the micro silica's absorption of the maltene phase. Additionally, tiny silica particles are more rigid than asphalt. Based on the findings, it was possible to conclude that micro silica significantly impacted the stiffness characteristics of the investigated binder.

All the mentioned factors work combined, resulting in stiffer asphalt mastic. As a result, the binder's resistance to mechanical damage was improved (Arabani, Tahami and Hamedi, 2018., Chew *et al.*, 2020).

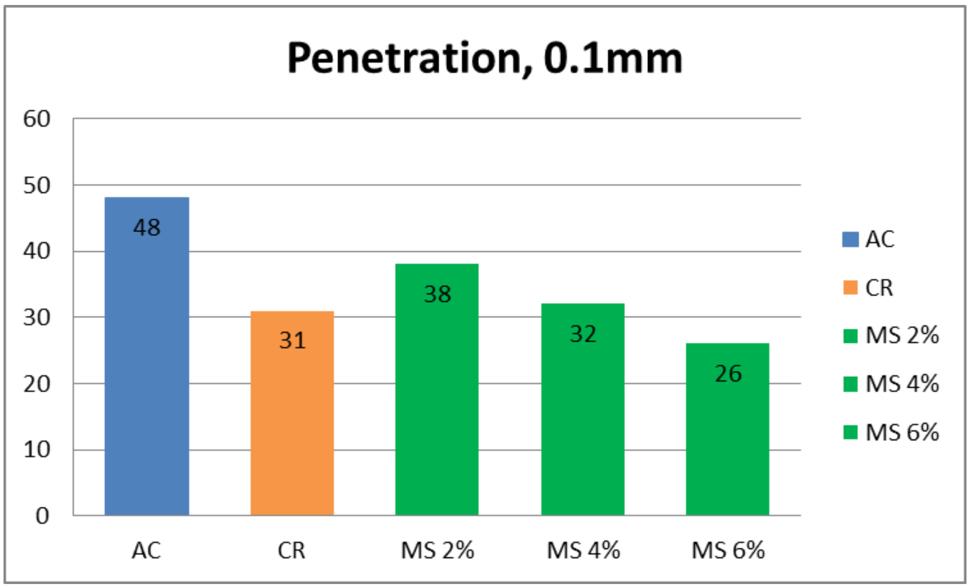


Figure 4- 7 The penetration depth of neat and modified asphalt binder

4.3.2 Softening point (S.P.) test

Another test for determining the consistency of asphalt binder is the softening point (SP). Figure (4-8) shows the softening point of unmodified and modified asphalt binders with varying percentages of modifiers. It can be seen that the softening point values increased as the modifier content increased. When comparing the results of asphalt modified with CR with AC, the increase in SP reached 10%. This increase in softening point is as a result of the internal structure formed by CRM which seemed to be thermodynamically unstable and thus has affected the softening point of virgin asphalt. This can be an indicative the good performance to permanent deformation. Also, it should be noted that the addition of CRM usually accompanied with the decrease in penetration while softening point is usually increased that means an inverse relationship between two empirical tests.

Figure (4-8) demonstrates that adding MS into asphalt lead to increase SP to 13.5% at 6% MS as compared with AC. Due to the presence of SiO2 particles in the chemical composition of MS which provides the asphalt with some stiffness. In addition, the increased surface area of MS allows it to absorb a greater quantity of lightweight bitumen. In addition to this, the asphaltene component of the binder is elevated as a direct result of the micro silica's capacity to absorb the maltene phase. Given the data, it was possible to conclude that micro silica influenced the stiffness properties of the binder being tested. The asphalt binder stiffness is increased as a result of all of these variables, which also leads to an increase in the levels of SP Increasing the softness point is desirable because bitumen with a greater softening point is less sensitive to temperature, and asphalt mixtures are more resistant to permanent deformation and rutting at high temperatures. In general, the use of CRM and MS results in an increase in the elasticity of HMA. As a result, it is feasible to enhance the cracking resistance of SMA mixtures.

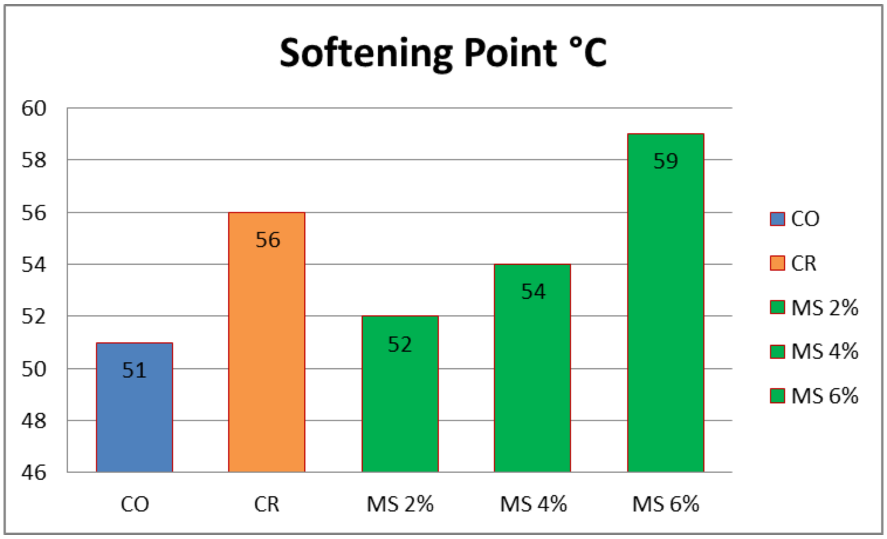


Figure 4- 8 Softening point of neat and modified asphalt binder, ℃

4.3.3 Penetration Index (P.I.)

Temperature susceptibility is defined as the change in stiffness, consistency, and viscosity as a function of temperature (Read and Whiteoak, 2003, Lagos-Varas *et al.*, 2022). A technique for calculating asphalt behavior in terms of divergence from Newtonian to non-Newtonian is temperature susceptibility. The Penetration Index for Asphalt for road building ranges from +1 to -1. The typical method for describing the rheological behavior of asphalt materials is to utilize penetration index values. It is one of the most well-known tools for characterizing asphalt cement's sensitivity to temperature changes. According to the index of penetration, the results of the asphalt binder's temperature sensitivity were assessed, as shown in Figure (4- 9). Results generally show that modifiers increase the asphalt's sensitivity to temperature; this indicates that the asphalt's resistance to rutting and low-temperature cracking increases, as shown by (Yan, Xu and You, 2015, Duan et al., 2019) . When CR was added to asphalt cement, the temperature susceptibility was significantly reduced, where the reduction difference is about 1.809, this returns to the increase in the elastic behavior of the asphalt binder after the addition of CR due to the formation of the polymer network. This means modified bitumen would be less sensitive to temperature than virgin asphalt, resulting in less cracking in low temperatures and less rutting in hot temperatures.

Figure (4-9) shows that as the amount of MS increased, the value of PI decreased and the amount of reduction difference reached 1.566 with 6% MS. This is due to the chemical composition of MS, which contains SiO2 particles, as well as, the other effects mentioned in the previous sections ,which help in increasing binder flexibility and decreasing binder sensitivity.

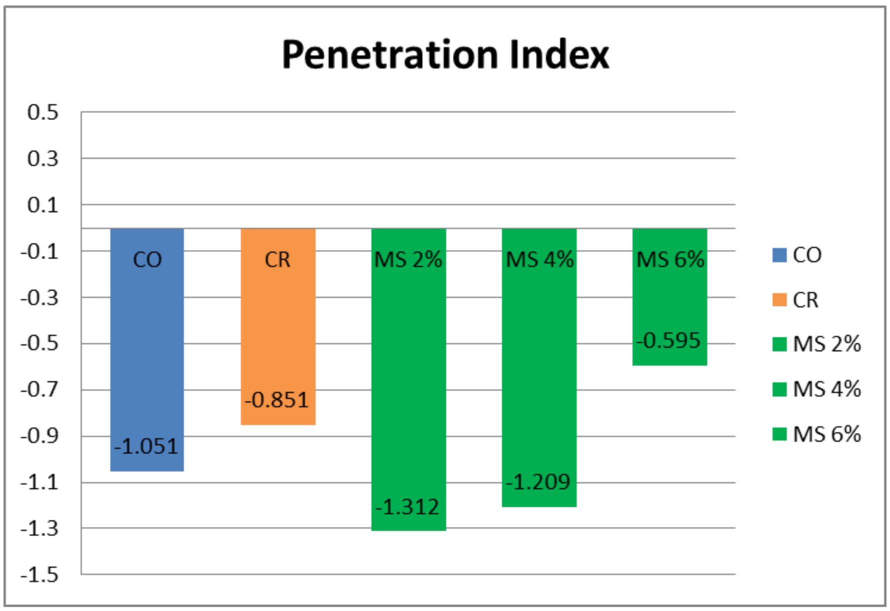


Figure 4- 9 Penetration index of neat and modified asphalt binder, ℃.

4.3.4 Ductility test

The constancy and homogeneity properties of bituminous materials are measured using ductility properties. Figure (4-10) illustrates the ductility results at 25°C. It is possible to see that the ductility of the asphalt binder decreases as the additive dosages increase. when 15% CR was utilized to modify asphalt, the ductility was decreased by 81%. This could be a result of swelling effect of the added CRM, the amount of free aromatics and other low molecular ingredient becomes fewer, thus making the asphalt less ductile, and the rubber particles are able to form interconnections, which makes the asphalt binder less stiff and yield increased ductility or the presence of CRM introduces more elasticity, consequently resulting in increased ductility. Figure (4-10) also shows that the of MS results in a reduction in ductility level to greater than 36% at 6 % MS. This is due to the presence of SiO2 particles in its chemical composition, as well as the other reasons mentioned in the preceding sections.

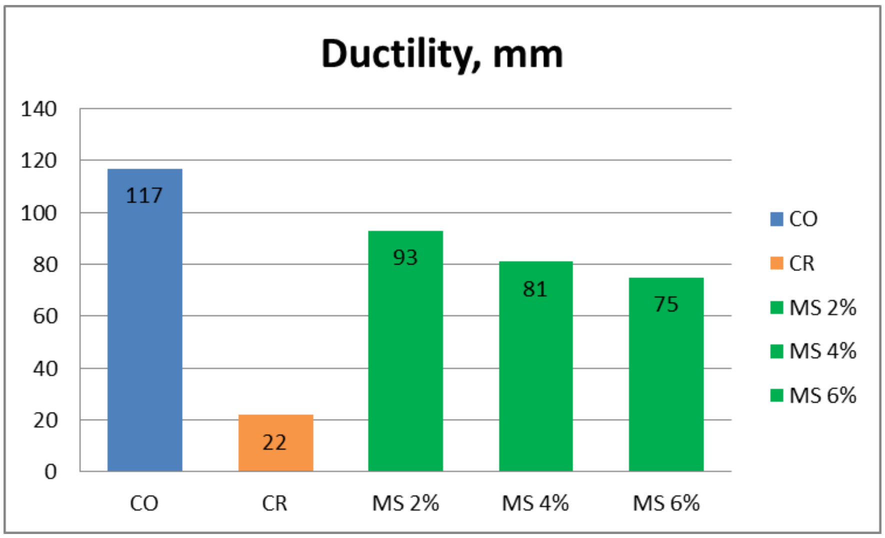


Figure 4- 10 Ductility of neat and modified asphalt binder, mm

4.3.5 Viscosity test

The viscosity properties of asphalt samples were determined by a rotational viscometer according to ASTMD-4402. The equipment was used to measure the viscosity characteristics of the virgin asphalt and modified asphalt with (CR, and MS). The test results of viscosity for modified asphalt binder show in Table (4-3).

Table 4- 3 Viscosity of Different Amounts of MS and Single CR

Asphalt Binder Type	% Additives	Viscosity, (Cp)		
		@ 135 ºC	@ 155 ºC	@ 165 ºC
AC		610	250	93
CR	15%	3690	1445	490
MS	2%	3335	860	320
MS	4%	3600	875	420
MS	6%	3925	895	455

The amount of viscosity affects the characteristics of bitumen at high temperatures. Figures (4- 11) and (4- 12) shows the results of the rotating viscosity test for all varieties of asphalt binders according to ASTMD-4402. RV values are at 135, 155, and 165 ºC for unmodified and modified asphalt. It is noticed that the percentage of increase in the viscosity is 83% and 81% when the asphalt binder content is 15% of CR as compared to asphalt cement for temp. test 135 ºC and 165 ºC. This increase in viscosity because of increased absorption of components with a small molecular weight, which increases the Density, increases the viscosity of rubberized asphalt.

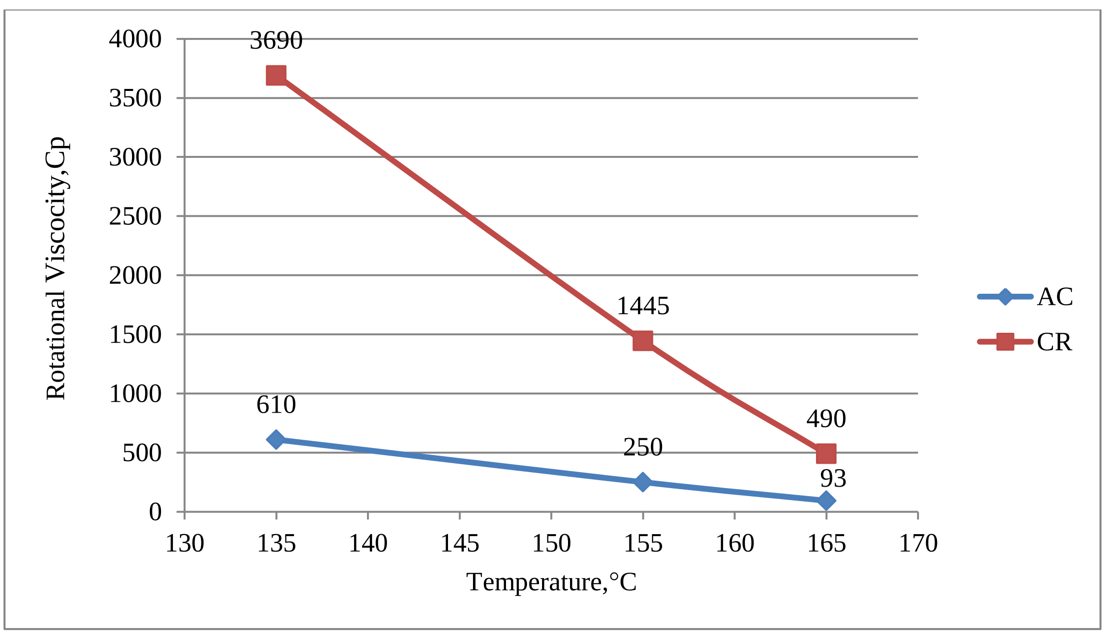


Figure 4- 11 the rotational viscosity of unmodified and modified asphalt binder with CR

Moreover, Figure (4-12) shows the result of asphalt binder modified MS .Its noticed that the percentage of increase in the viscosity is 82% and 70% when the MS content is 2%, then increases to 83% and 79% at MS content 4% and then increases to 83% and 77% at MS content 6%, respectively (as compared to control asphalt binder for temp. test 135 ºC and 165 ºC). Adding more micro silica increases the viscosity because the asphaltene component of bitumen is increased by the micro silica, which absorbs the maltene. Road construction in the summer and places with traffic is suited for asphalt mixtures manufactured with highly viscous bitumen. Absorption of substances with low molecular weights, which will raise the Density. The high viscosity of bitumen raised the temperatures required for mixing and compaction. However, because of the bitumen's high cohesiveness, the bitumen and aggregates adhered better to one another, improving the pavement performance (Meng *et al.*, 2022).

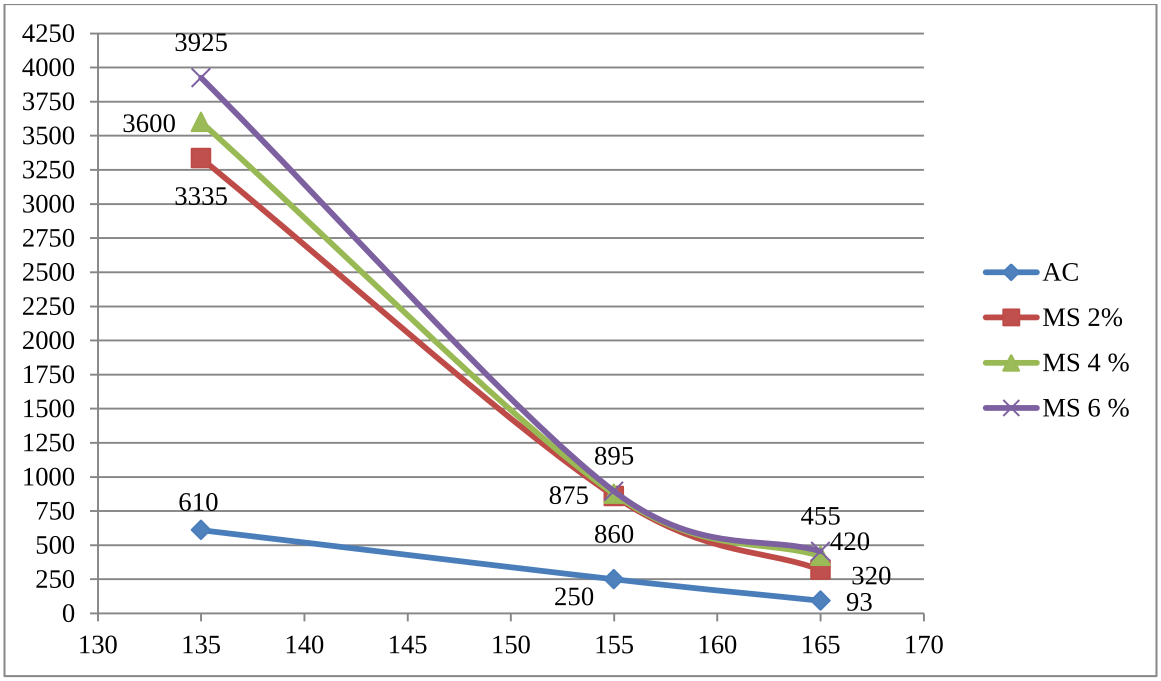


Figure 4- 12 shows the rotational viscosity of unmodified and modified asphalt binder with MS, Cp.

4.4 Characteristics of unmodified and modified SMA mixtures

Nowadays, the modified binders are widely used, whereas neat asphalt

binder exhibits some inferior properties and/ or superior properties are required.

As a result, extensive research has been conducted in order to improve asphalt binder by adding CR and MS, (see section 4.2). A comparison was conducted between the properties of CM and modified mixtures in terms of volumetric, mechanical and durability properties. The following sections describe the results observed from these tests.

4.4.1 Volumetric tests results

4.4.1.1 Bulk Density

The bulk density of the SMA mix varies based on the additives that are used and the quantity of those additives, as shown in Figures (4–13). These figures describe how this shift occurs. after compared to the CM, the density values of the modified asphalt have a lower value after it has been adding CR and MS. According to the results, a decrease in the density of asphalt mixtures occurs when the quantity of MS in asphalt mixtures is increased , where the mixture containing 15% CR had the lowest values. This behavior is related to the increment of viscosity level with respect to the MS and CR content. As the continuous increment will reduce the mixture lubricity and making it stiff ,then result in a decrease in the mixture density consequently .

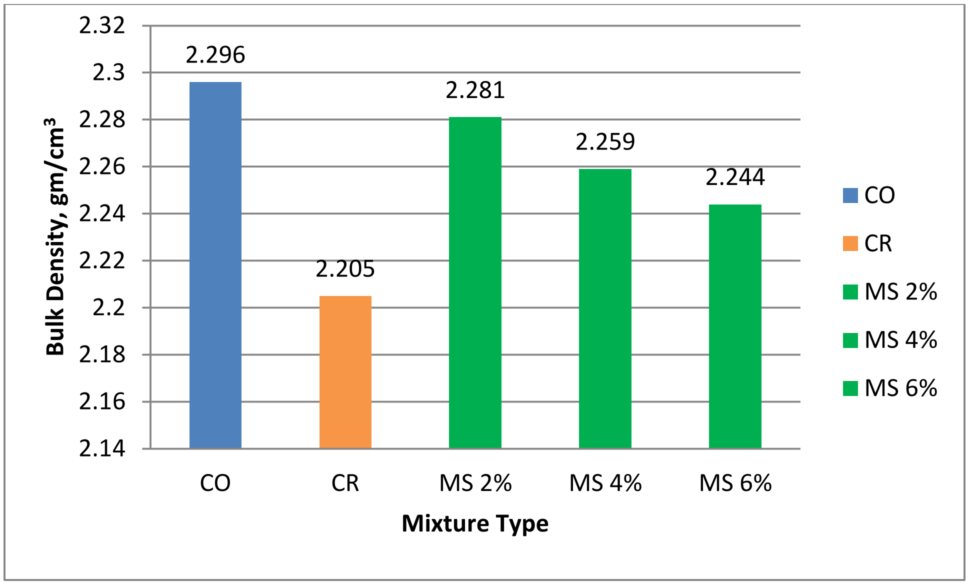


Figure 4- 13 Bulk densities of unmodified and modified SMA mixtures

4.4.1.2 Air Voids

When adding the MS for mixtures by (2, 4, and 6) % in addition of 15%CRM admixture the air voids increases as shown in Figure (4-14), as a result of increasing of thin film asphalt binder that coated the aggregate particles, the high increase of modified asphalt binder viscosity, and binder became more hard, so the volume of effective binder begins to increase. Therefore, it will push the coated aggregate particles and increase the air voids. The air void contents of the modified mixture are far from that of the non-modified mixture.

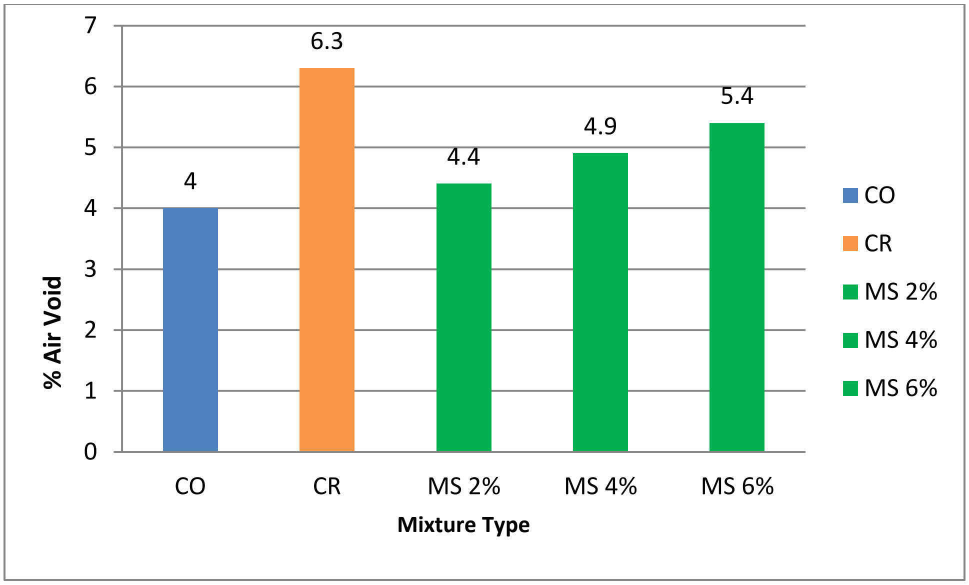


Figure 4- 14 Air voids of unmodified and modified SMA mixtures

4.4.1.3 Voids in the Mineral Aggregate

Figure (4–15) displays the influence that MS. and CR. have had on VMA. According to the results, the modified mixtures that had a higher VMA% when compared to the unmodified mixtures. It is essential to take note that the VMA increase when 15% of CRM is included when compared with the unmodified mixes, the percentage rise is about of 14.4%, and it achieves its greatest value when contrasted with the mixture that has been modify with MS. because the rubber particles at higher temperatures swelled in size as a result of absorption of the asphalt binder, that allows for increasing the liquid asphalt binders concentrations in mixtures. Consequently, increasing thin film of asphalt binder and creates a thicker film of the CRM asphalt cement which coats the aggregates in the presence of the rubber particles. When the percentage of MS. is raised to 6%, there is an approximately 10% increase in the VMA. This is because there is an increase in the asphalt film thickness that covers the aggregate.

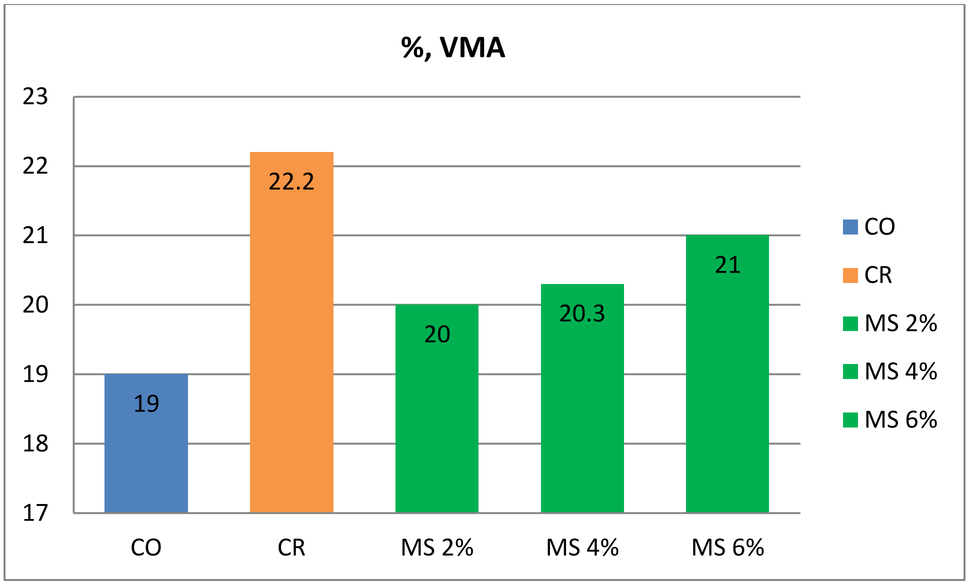


Figure 4- 15 Voids in mineral aggregate of unmodified and modified SMA mixtures

4.4.1.4 Voids Filled with Asphalt

The proportion of voids filled with asphalt (VFA) in SMA mixes with varied additives is shown in Figure (4-16), which may be found here. According to the results shown in Figure (4-19), the kinds and amounts of additives used have a discernible influence on VFA. When the C.R. and M.S. were added to the mixture, the results showed a steady decrease in the percentage of VFA by about 10% and 6% at C.R. and 6% M.S., respectively. The reduction in the amount of VFA is due to the addition of modifiers, which absorb a portion of the bitumen, increasing its viscosity, and finally reducing the VFA space.

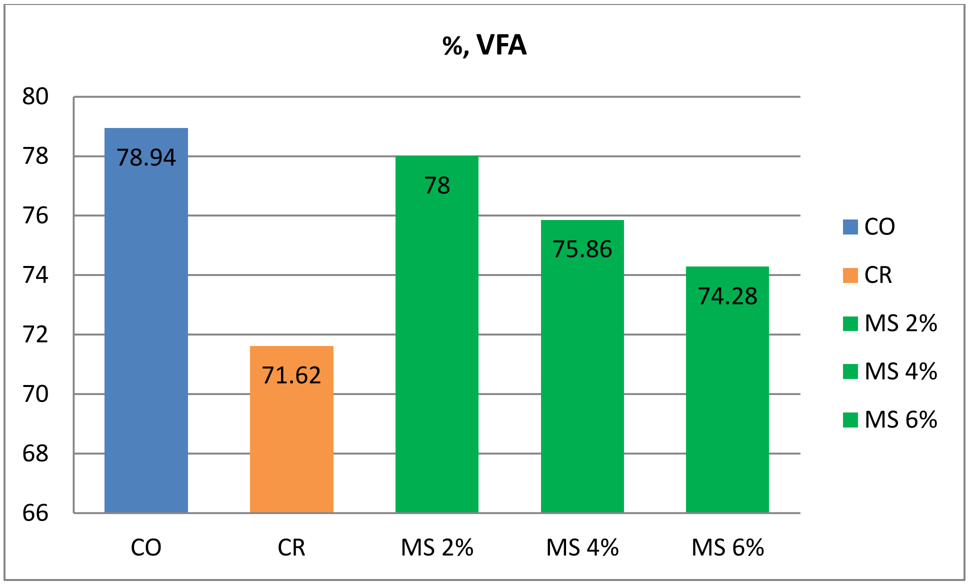


Figure 4- 16 Voids filled with asphalt of unmodified and modified SMA mixtures

4.4.1.5 Drain down

Figure (4-17) summarizes the results of the drain down test performed on different mixtures after one hour conditioning in a force draft oven, and Plates (4-1 and 2) show illustrative captures of the variation in drain down amounts for the various SMA mixtures. The rate of drain down in modified samples versus unmodified samples indicates the efficiency of modifiers to reduce the ability of the SMA mixture to segregate.. In the case of adding of CR, success in eliminating the amount of mixture drain down is achieved to 0.43 and 0.69% at 160℃ and 175℃, respectively. This is attributed to the polymer network that works to reinforce the asphalt binder, as well as, SMA mixture, as well, increasing the asphalt binder viscosity. Besides the enhancement of the adhesion between aggregate and asphalt, and the cohesion between asphalt ingredients themselves. These factors work combined in reducing the blending of binder from the mixture.

Results offer by Figure (4-17) also indicate that adding MS shows a similar pattern: as the amount of additives increase, the amount of bitumen drainage decreases. The sample containing 0.6 % MS has the least drain down of about 0.35% and 0.98% at both temperatures 160°C and 175°C, respectively. This could be due to the asphalt binder's high viscosity values with MS, as well as the presence of SiO2 compounds. Which promote adhesion bonding between asphalt binder and aggregates, significantly improving performance by acting as a reinforcing material, this led to decrease drain down.

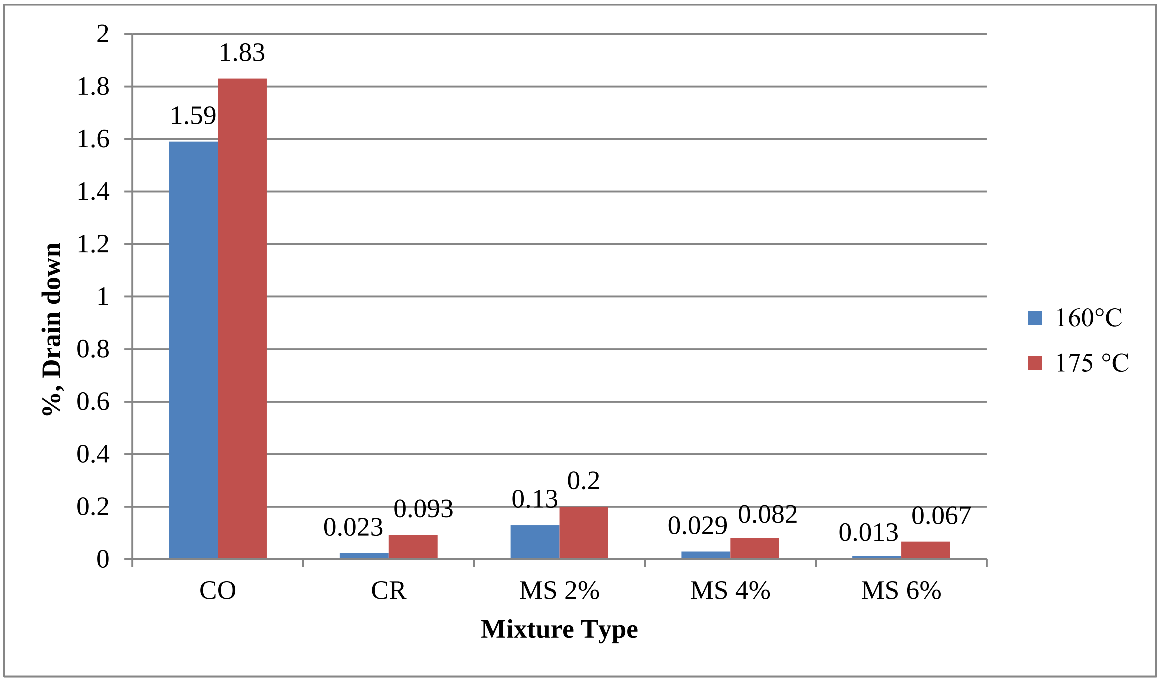
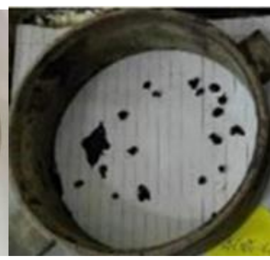


Figure 4- 17 Drain down amounts of unmodified and modified SMA at 160°C & 175 °C.

Control CR 15% MS 2% MS 4%

MS 6%

Plate 4- 1Drain down of unmodified and modified SMA at 160℃

Control CR 15% MS 2% MS 4%

MS 6%

Plate 4- 2 Drain down of unmodified and modified SMA at 175℃.

4.4.2 Mechanical Test Results

4.4.2.1 Marshall Stability and Flow

Stability is an important property for the performance of asphalt mixture in the surface course design. It shows the ability to resist shoving, rutting and give layer the adequate stiffness under traffic. The stability of modified asphalt mixtures regardless of modifier type and concentration is higher than the control asphalt mixtures. The stability is increased by increasing the density of polymers. The density of polymers has an effective impact on the stability, because the plastomers and elastomer polymers product mixtures with higher stability and stiffness that dependent on the molecular weight of polymers, it is related to increasing of density. The stability of modified mixtures varies according to the type, physical properties and concentration of modifier.

Figures (4-18 and 19) summarize the results of the Marshall Stability and flow tests, and Plate (4-3) shows an example of the tested samples. Generally, results show that Marshall Stability values of the modified SMA mixture appear higher when compared to the control mix. It can be seen that adding 15% CR results in an increment in Marshall Stability of about 31% compared to the CO mixture. This due to the enhancement in the adhesion characteristics between aggregate asphalt interface, also increases the cohesion between asphalt molecules as a result of the network reinforcement of polymer.

Moreover, results show that SMA mixtures containing MS given more stability. Where the maximum stability is achieved by adding 6% MS by about 41% in contrast with the CO mixture. This return to the increase of the adhesion properties between asphalt and aggregate due to the adhesive effect of SiO2 particles in the chemical composition of MS. Besides the higher viscosities of MS modified asphalt and the network properties of the mentioned modifier. These factors work on increase the asphalt film thickness coating aggregate and therefore making the stability of the mixture to be enhanced.

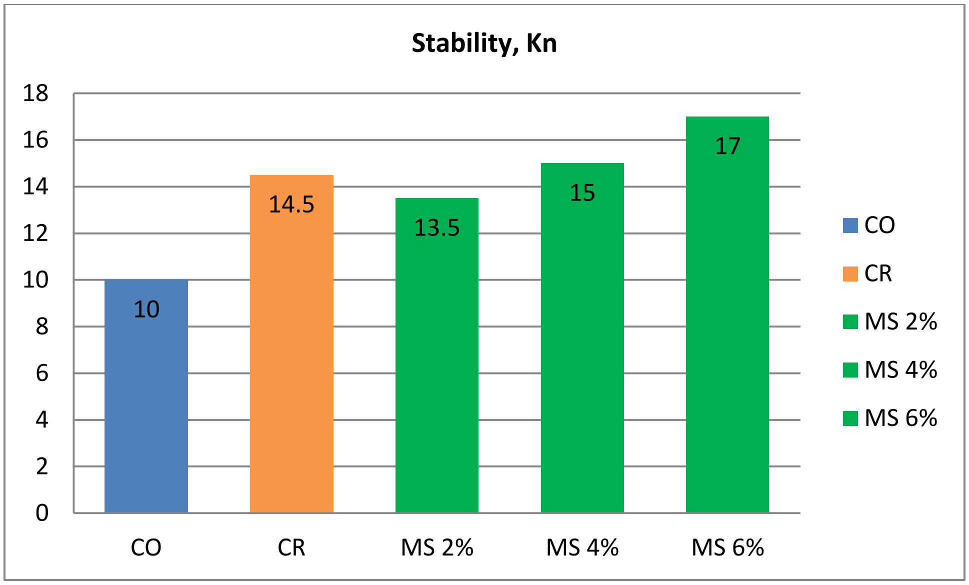


Figure 4- 18 Results of Marshall Stability Test for Control and Modified SMA Mixtures

Figure (4-19) illustrates the flow characteristics of asphalt in SMA mixes including a variety of additives. After the addition of CR, flow values showed a discernible drop of roughly 37%, which may be attributed to the increased hardness of the mixes. This observation is in line with what (Al-Hadidy and Tan, 2009) found. In addition, it can be shown in Figure (4-19) that lowering the MS causes the flow value to decease , reaching around 47% at 6% MS when compared to the CO combination. The findings presented here are consistent with those found by (Tai Nguyen and Nhan Tran, 2018).

This conclusion of MS and MF is well known, and the behavior described here is supported by further research carried out by (Milad, Ali and Yusoff, 2020) , and (Noura *et al.*, 2021).

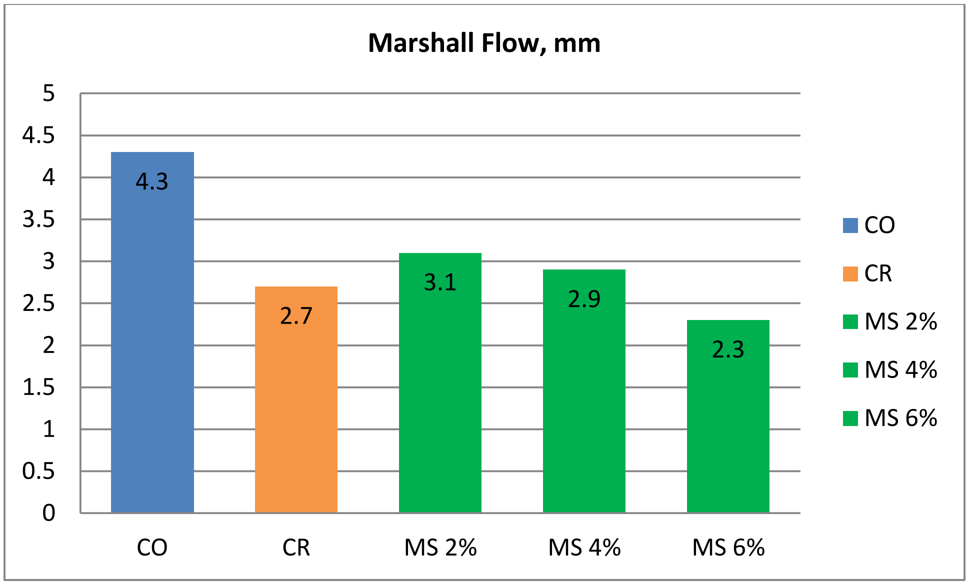


Figure 4- 19 Results of Flow for Control and Modified SMA Mixtures

Plate 4- 3 Marshall stability and flow samples of control and modified SMA mixture

4.4.2.2 Indirect Tensile Strength Test

The results of the control SMA and the modified mixes are compared to one another in Figure (4-20). According to the findings, the incorporation of MS led to an increase in the indirect tensile strength (ITS) of the SMA mixes. This means that MS has a positive effect on improving the tensile resistance of the asphalt mixture; which shows greater cracking resistance strength of modified mixes in terms of cohesion and improves the cohesion properties of asphalt binder. This has been supported by the findings of several studies (Lee, Mun and Kim, 2011); (Ameli *et al.*, 2021).

Because the related polymer networks operate to strengthen the binder on the one hand and extend a bonded load transformer between adjoining aggregate particles, it can also be noticed that the 6% MS combination exhibited the largest incensement in ITS, which was 33% greater than CO. On the other hand, a high dose may affect the binder cohesiveness qualities present in the binder component. A greater tensile strength leads to increased resistance to cracking as well as increased strain just before the breakdown of the pavement. In contrast, the addition of 15% CR brought the total ITS value down to 20%, which resulted in a decrease in ITS values when compared to the control mix. The CR may be responsible for this decrease. the increased brittleness of the mixes is due to the high concentration of CR, which absorbs malten and leaves the asphaltene, hence limiting the materials' capacity to be ductile. Additionally, since high viscosity increased asphalt hardness where less elasticity of asphalt was present, this led to a drop in ITS. The findings of (Mashaan *et al.*, 2013) are in line with these findings.

It is possible to conclude that the mixture that consists of asphalt binder that has been treated with 6% MS had the greatest resistance to cracking when the temperature was in the intermediate range. This means that mixes containing MS have higher values of tensile strength at failure, which demonstrates a greater cracking resistance strength of modified mixes in terms of adhesion. Improving the adhesion and cohesion properties of asphalt binder and preventing the stripping of binder from the surface of aggregate are the results of these changes .

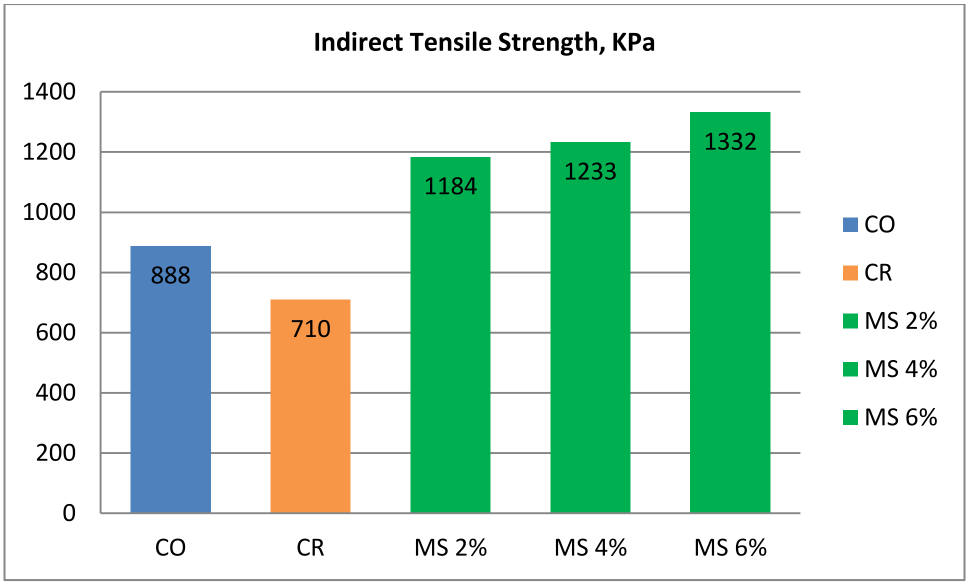


Figure 4- 20Indirect tensile strength for Control and Modified SMA Mixtures

4.4.2.3 Skid resistance

The degree of micro-roughness of the pavement surface is indicated by skid resistance. Both dry and wet conditions are shown in Figure (4-21), demonstrating how the addition of additives improves the skid resistance of the surface of the SMA mixture. Both modified SMA mixtures offered noticeable enhancement into the resistance of mixture surface to skid by about 22% and 29% when comprising 15% CR and 6% MS, respectively. This indicates an increment in the stiffness of the asphalt binder, and thus it works to restrict the aggregate and prevent it from slipping under traffic loads. In addition to improving the volumetric characteristics of the SMA surface's macro texture. Besides that, the addition of modifiers helps in the improvement of the micro-texture properties of the pavement surface, which contributes to the increment of the surface roughness properties. Furthermore, this can aid in increasing friction forces, by increasing the area of contact between the vehicle's tires and the pavement surface. (Sangiorgi *et al.*, 2018).

Results in Figure (4-21) also displays that the resistance of SMA mixture to skid was reduced in general at wet condition compared to the dry condition but remain higher than the CO mixture. Where the amount of reduction reached 21%, 24% when adding 15% CR and 6% MS, respectively. This is due to the reduction in the friction between the slider rubber of the British pendulum tester and the sample surface. As a result, the presence of water on the sample surface, where it works as a barrier between the sliding rubber and the sample surface. Then this leads to reduce the mixture resistance to skid slightly.

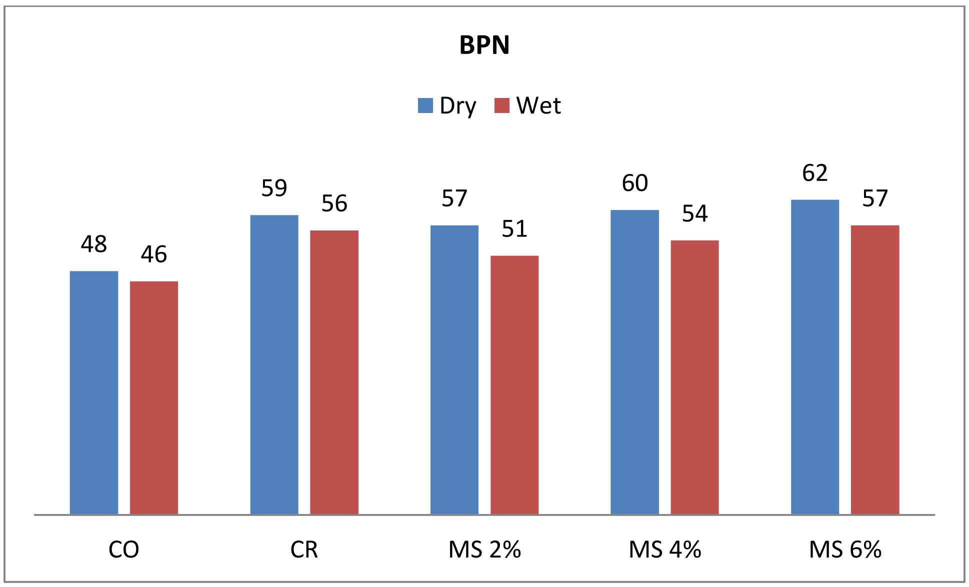


Figure 4- 21 Skid Resistance for Control and Modified SMA Mixtures

4.4.2.4 Wheel Track Test

Wheel tracking test is to simulate the application of the actual wheel loads into the road pavement. It directly estimates the internal resistance of asphalt mixtures in terms of rutting depth. The specimens were tested in accordance with BSI (EN 12697-22).

Rutting resistance of a paving asphalt mixture is one of the important considerations in asphalt mix design, as a large part of accumulated rutting in pavement structure occurs in the surface layer. Formation of ruts, having started in the initial stage of pavement operation, increases with the high of the flow high percentage of heavy vehicle traffic volume. There are several causes of such deformations. Some of them are high temperature, unsuitable mixture, and traffic loads. In general, rutting at higher temperatures occur due to pavement consolidation and/or HMA experiences lateral movement which is a shear failure.

Rutting or permanent deformation is a common problem in flexible pavements. As a result, the wheel track test simulates asphalt mixtures' resistance to permanent deformation. The rutting resistance of modified mixtures is affected by the type and physical properties of modifier and its concentration, the effects of physical properties of CR and MS on the rutting (permanent deformation) resistance for modified mixtures are shown in Figures (4-22, and 23) summarize the results of 10,000 wheel passes at 60°C temperature, and Plate (4-6) illustrates the form of samples after the test. Generally, results show that the depth of rut increases with respect to the number of passes. Where the presence of modification materials in the SMA mixture works as a base to absorb an amount of the applied stresses, The SMA modified mixture is then more resistant to permanent deformation than the CO mixture. Figure (4-22) display the effect of CR on rutting resistance in mixtures. After 10,000 cycle, the rut depth for the mixture with 15 % CR is enhanced by about 54% compare to the CO mixture. This is attributed to the enhancement of the mixture stiffness after the addition of CR polymer. It has high resistant to permanent deformation and that returned to significant interaction and bonded of softer particles with asphalt binder at blending process.

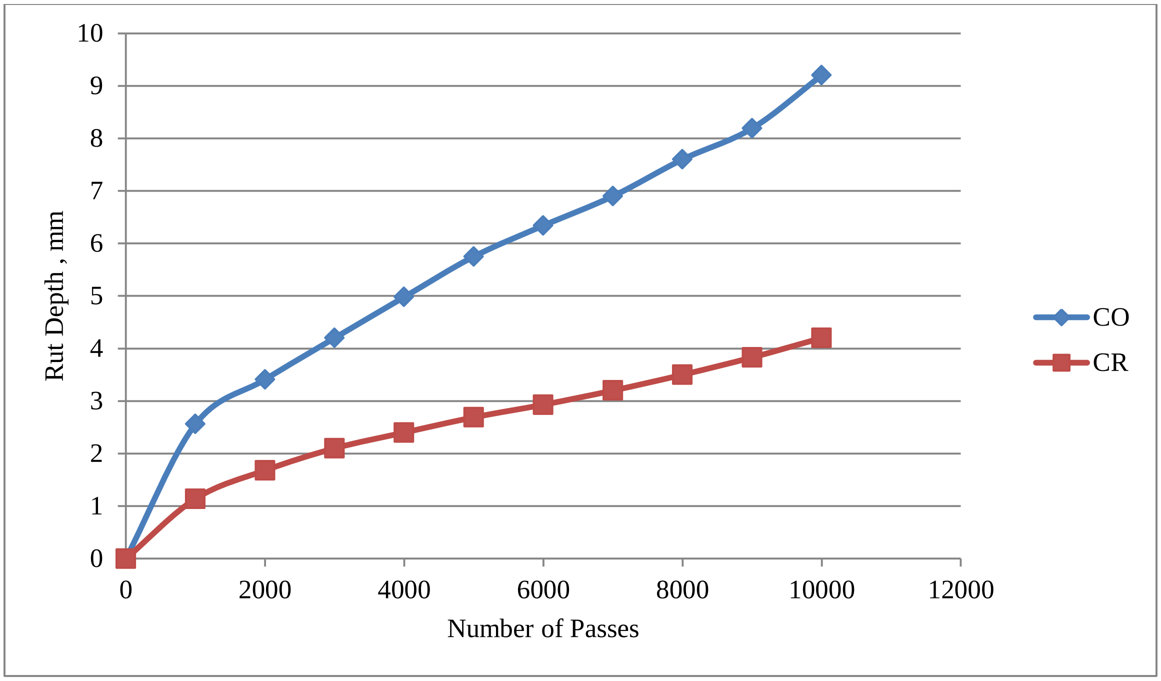


Figure 4- 22 Rut depth for Control and CR SMA Mixtures

The SMA mixtures with MS show a reduction in rut depth by approximately 57% at 6% MS in contrast with the CO mixture, as represented in Figure (4-23). This is related to the presence of SiO2 in the chemical composition of MS that gaining the mixture its rigidity properties, then causes a decrement in the depth of rut. In addition, to increase the asphaltene adhesive of MS, this may lead to increase cross-linking between aggregate and asphalt, resulting in a lower rut depth than the CO mixture.

The results that (Xue *et al.*, 2013) and (Dalhat *et al.*, 2020) achieved with this combination had a similar effect on the mixture's behavior.

the use of an asphalt modified by used CR and MS additives. The SMA become stiffer at the high testing temperature. It can be concluded that used polymers-modified binder made the polymers modified mixtures more stiff than control mixes with unmodified asphalt binder at high temperature. This is due to increase in viscosity of the film, increase in viscosity at high temperature leading to increase in binder stiffness. While using the soft binder will lubricate the aggregate particles to such an extent that mixture will lack internal friction (stone on stone contact) and become unstable.

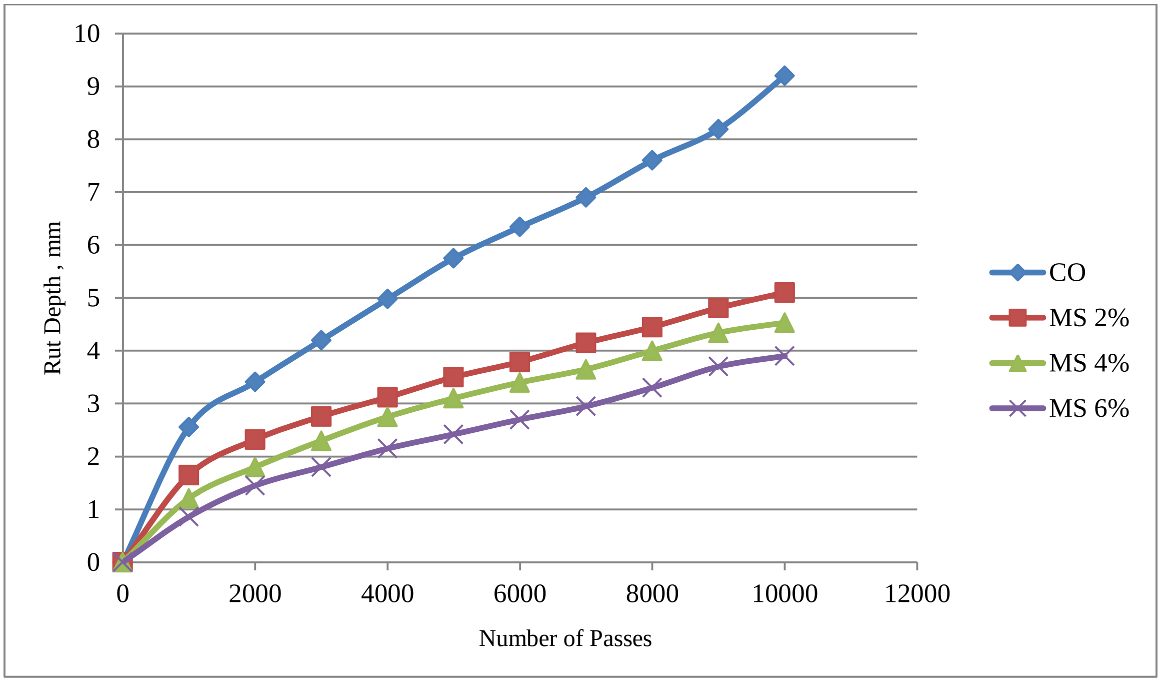


Figure 4- 23 Rut depth for Control and MS SMA Mixtures

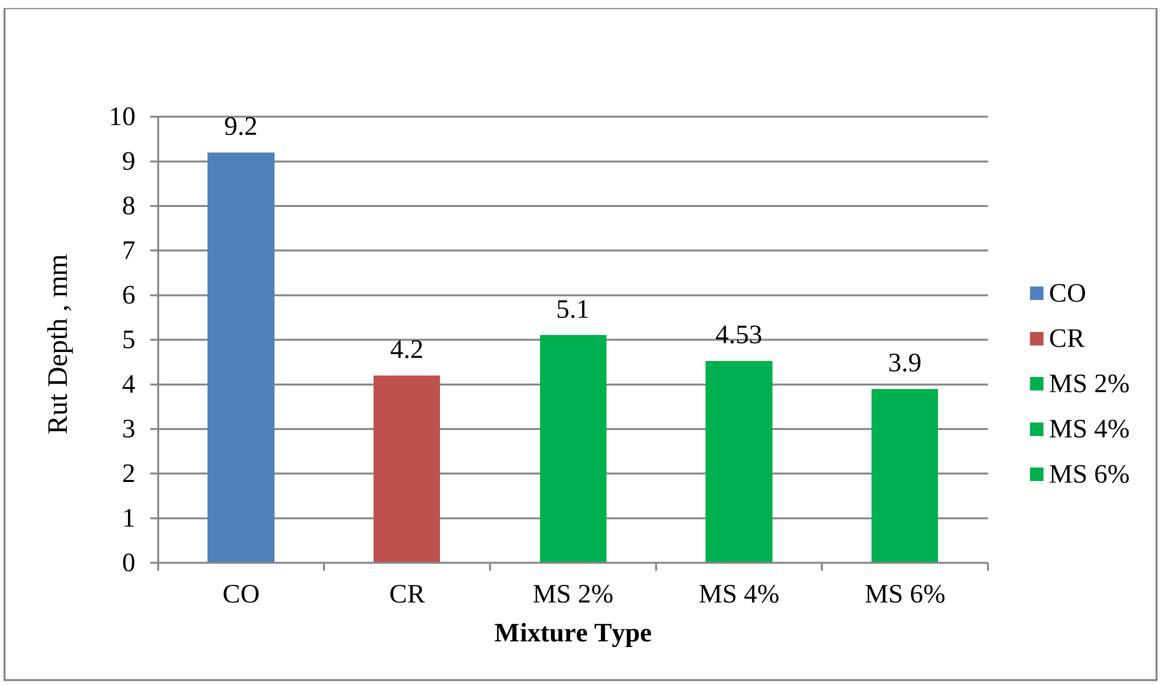


Figure 4- 24 Rut depth for Control and modified SMA Mixtures

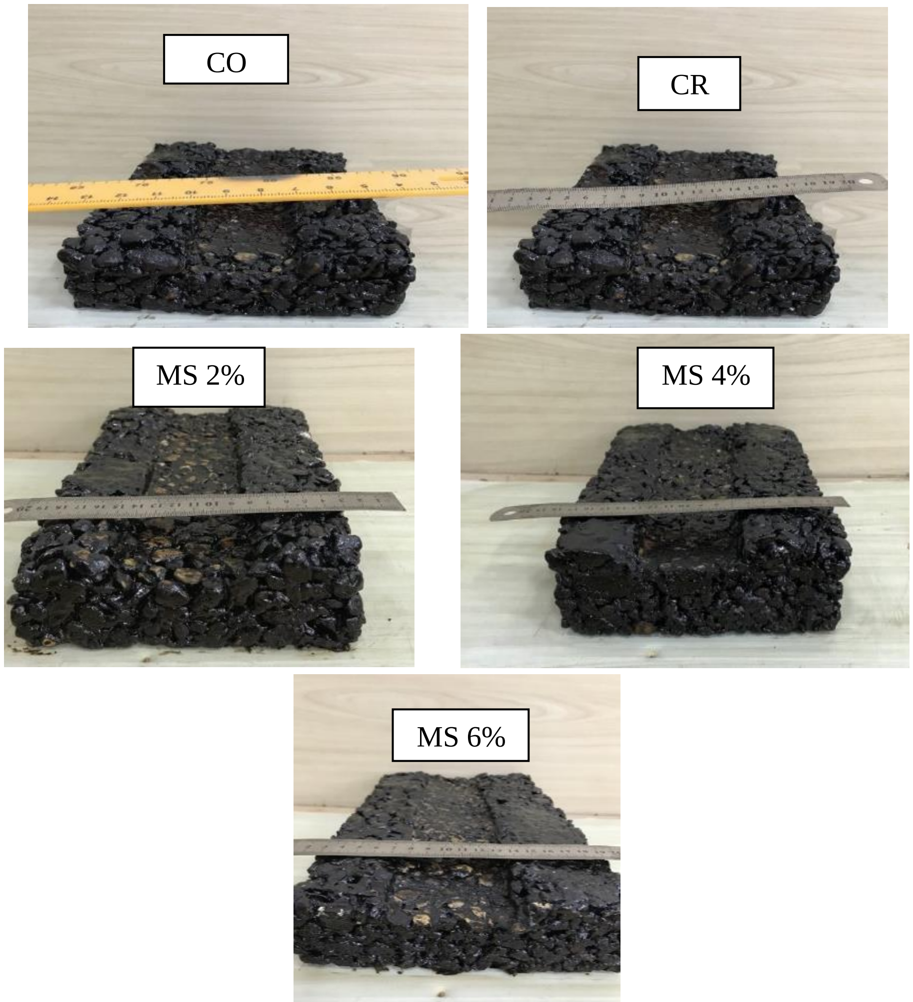


Plate 4- 4 Rut depth of control and unmodified SMA

4.4.2.5 Cantabria Abrasion Loss Test

The results of this test were included with the durability characteristics for comparing the results before and after aging.

4.4.3 Durability properties

4.4.3.1 Cantabria Abrasion Loss Test

The resistance of the SMA mixture to raveling is indicated by the abrasion ratio evaluation. Figure (4-24) demonstrates the Cantabria test results after 10 minutes in the Los Angeles abrasion machine for each type of SMA mixture, while Plate (4-7) displays the samples after abrasion. In general, results show that the abrasion loss of aged samples is greater than that of unaged samples. The amount of abrasion loss of mixture with CR appeared lower than CO mixture by about 30% and 35% for unaged and aged conditions, respectively. addition of CR the asphalt binder film around the aggregate particles becomes thicker and more durable, which increases mixture bonding. In addition, the polymer network increases the stiffness of the asphalt binder. Then, these parameters help in increasing the mixture resistance to abrasion.

The findings shown in Figure (4-24) reveal, in addition, that the usage of MS exhibited an increasing tendency, which brought a reduction in the amount of abrasion that was experienced with the MS content. In such cases, the largest increase in mixture resistance to abrasion occurs at 6% MS. Because of this, the inclusion of SiO_2 particles in the chemical composition of the MS, as was discussed before, causes an increase in the mixture's stiffness as well as its flexibility. In addition, the film that surrounds the aggregate particles becomes thicker and more durable when asphalt binder is added, which results in increased mixture bonding. In addition to this, the polymer network contributes to an increase in the asphalt binder's degree of stiffness. After that, these characteristics contribute to an increase in the abrasion resistance of the combination. (Arabani and Hamedi, 2011).

In addition, Moreover, the use of HL in the design of the SMA mixture also has a significant impact on increasing the polarity of aggregate. Then, help in forming a layer on the aggregate surface work on increase the boding of aggregate particles surface with asphalt. Therefore, this gained additional resistance to the mixture to withstand the impact of loss.

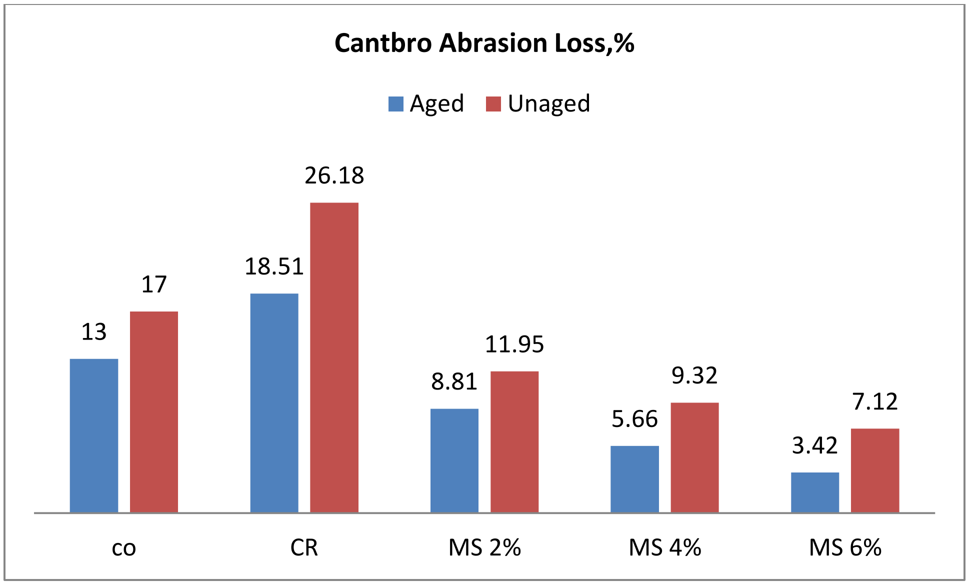


Figure 4- 25 Cantabria abrasion loss for control and modified SMA mixtures before and after Conditioning

Plate 4- 5 Unaged Cantabria with CR and MS after test

4.4.3.2 Tensile Strength Ratio

Figure (4-25) shows the difference between the of dry ITS and the wet ITS conditioned specimens. As usual, the unconditioned specimens have higher ITS values than conditioned specimens. The decrease in ITS for the conditioned samples can be explained by loss of the adhesion between the asphalt binder and aggregate, or loss of cohesion in the asphalt binder because of exposure to water for a long time.

The results of the TSR of the control with the modified mixes are shown in Figure (4-26). The level of tensile strength ratio decreases as the viscosity of the asphalt binder increases, which indicates that SMA mixtures containing MS would exhibit a good resistance to moisture damage at 2% and 4% because it has low air void in comparison to mixtures containing MS at 6% and the asphalt binder has strong adhesion powers due to high viscosity, which leads to decreased stripping; therefore, the MS at 2% and 4% mixture exhibits high resistance to moisture damage. The highest value of TSR is less affected when immersion in water. This improvement in TSR is due to the improvement in binder stiffness and resistance against stripping due to improvement in adhesively and cohesion. The findings of this study are consistent with those found by (Gong *et al.*, 2019, Tiwari *et al.*, 2023). With an increase in the percentage of MS reaching MS 6%, there is a drop in TSR. This is due to a decrease in the adhesion between the aggregate and the asphalt, which results in the mixture being stripped (Xue *et al.*, 2009).

The addition of 15% CR decrease the TSR because of a rise in the binder film and a reduction in the adhesion between the aggregate and the asphalt, both of which lead to stripping, several researches have shown that the addition of CR will lessen the damage caused by moisture. This is partly due to the increase in air void that will result from doing so. When compared to modified mixes including CR and MS, the modified mixture containing MS exhibited superior resistance to moisture damage. Following the completion of the test, the unconditioned and conditioned specimens are shown on plates (4-8).

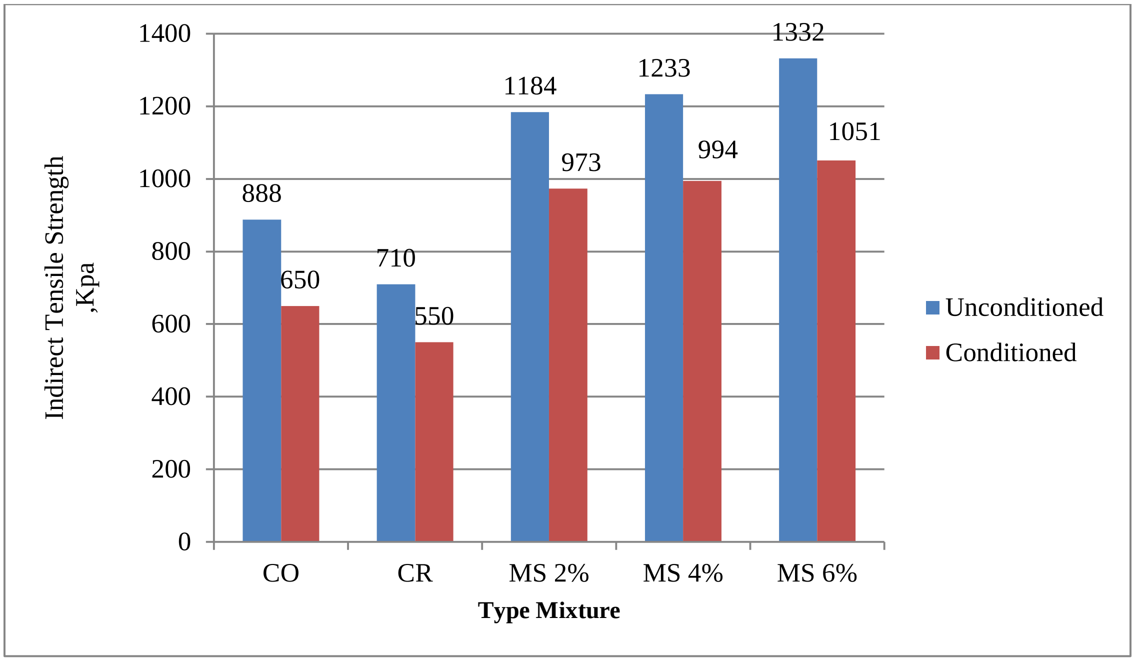


Figure 4- 26 ITS for Control and Modified SMA Mixture Before and After Condition

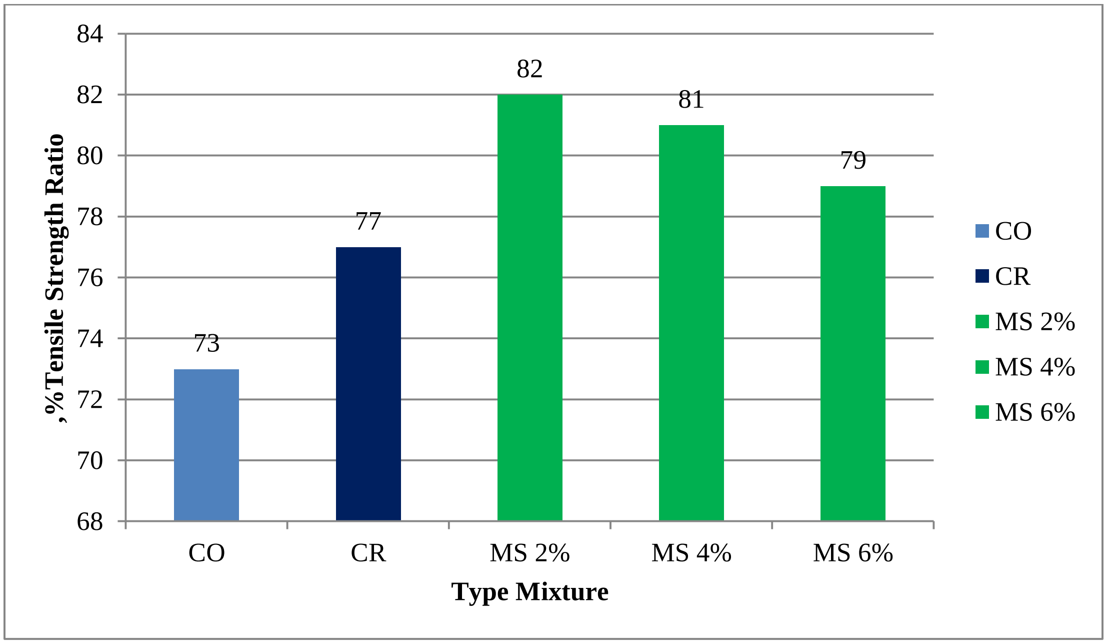


Figure 4- 27 Tensile Strength Ratio for Control and Modified SMA Mixture

4.5 Summary

This chapter included the results of testing for characterizing SMA using various materials. The main findings are summarized in the main statement as follows:

1. The first part of this chapter presents the results of tests carried out to specify the control mixture by determining the SMA mixture with OAC. Four asphalt contents were used to support these requirements, and four tests, voids in total mix, VCA, drain down limits, and tensile strength ratio, were performed.

2. The second section is about treating asphalt with two different types of additives.

3. The third section summarizes all results related to the modified SMA control mixtures, which include two modified binder types with varying percentage, and compares the modified mixtures to the unmodified control mixture. The comparison was carried out by characterizing SMA mixtures using a set of volumetric, durability, and mechanical properties.

Chapter Five :
Conclusion and Recommendation

5.1 Introduction

The purpose of this study was to improve the performance of SMA by using CR and MS. The volumetric, mechanical, and durability properties were investigated through numerous laboratory tests. The conclusions that follow are depending on the outcomes and conversations of exploratory studies on various SMA mixtures.

5.2 Conclusions

Based on the limitations of test results, the following conclusions could be drawn:

1. The use of an unmodified SMA mixture in paving works is ineffective. It does not meet the required volumetric and durability properties. For example, it has a drain-down rate of more than 3% and a tensile strength ratio of less than 80%.
2. The addition of modification materials improves the properties of the asphalt binder. The addition of CR and MS, changes the physical properties of asphalt significantly. Adding CR and MS to asphalt binder reduces penetration, temperature sensitivity, and ductility while increasing softening point and viscosity.

- The penetration reduces by 35% when the addition of 15% of CR as compared with the neat binder, and the percentages of reduction in penetration point are 20 %, 33%and 45% when the percentage of MS are 2%, 4%, and 6%, respectively.

- When CR and MS are mixed with asphalt cement, their ductility is reduced by 81% and 36%, respectively.
- When CR and MS are mixed with asphalt cement, their softening point is increased by 10% and 13%, respectively.
- The outcomes of the tests show that the viscosity of the modified asphalt binder mix increases by about 83% when 15% CRM is added, and that when utilizing the MS, the viscosity increases with an increase in the percentage of MS, reaching its maximum at 6% about 84%.

3. Modifying asphalt binder by CR and MS results in a significant change in the properties of the SMA mixture:

- Drain down decreases to 0.023, 0.029 when using CR and 0.013,0.067 when using 6% MS, at 160 and 175 °C, respectively.
- Marshall stability increases by 31% when 15 % CR, while it increases by 30 %, 33 %, and 41 % when 2 %, 4 %, and 6 % MS are included, respectively, while flow decreases by 37% when 15 % CR, while it decrees by 28 %, 33 %, and 47 % when 2 %, 4 %, and 6 % MS are included, respectively.
- The indirect tensile strength (ITS) decreases when CR is added in comparison to when control is used; the percentage of reduction is around 20%. However, when MS is added, the ITS increases by three percentage points and reaches its maximum of 6%, representing an increment of approximately 33%.
- Increasing the percentage of MS in SMA mixtures improves skid resistance significantly. Similarly, CR has a positive effect. The increase amounted is 29% and 22%.
- Rutting resistance increases with the presence of CR, as rut depth decreases by 55 %. The greatest increase in rutting resistance for SMA include MS is achieved with 6 % MS as rut depth decreases by 58 %. compare to the control mix

- By adding CR the abrasion resistance is decreased to 27 % and 35 %, respectively. Increase abrasion resistance concerning MS content, with 6% MS mixture showing a 74 % and 45 % decrease for unaged and aged.
- The use of CR leads to a reduction in tensile strength, which is then followed by increase when adding 6% MS.

5.3 Recommendations and Further Work

Several possible future studies can be recommended based on the laboratory work done during this research, which are listed below:

1. Because only one gradation was used here, a trial can be made to compare the various gradations proposed by various agencies.
2. To improve SMA performance, use MS at a high percentage of 6%, which is conceded as the optimum percentage.
3. To improve additives performance in SMA to reduce air void in the mixture after adding CR or MS to asphalt increase temperature mix.
4. Trying other waste or recycling waste additives to improve the physical properties of asphalt binder, as well as, SMA asphalt mixture for example: waste glass, steel slag, recycling waste such as LLDPE, HDPE, and other types of polypropylene polyvinyl chloride (PVC), polyethylene terephthalate (PET), cigarettes fiber, polyester fiber etc.
5. Examination of the high-temperature stability and cracking performance (load-induced, fatigue, top-down, etc.) of SMA mixtures with CR and MS.
6. It is possible to use chemical modification groups such as epoxy groups, maleic anhydride, and other similar compounds to improve the SMA mixture and increase compatibility between asphalt and polymer.
7. Use the dry process.

Reference

.P, G.N. and Adiseshu, S. (2013) ‘Influence of Coarse Aggregate Shape Factors on Bituminous Mixtures’, *International Journal of Engineering Research and Applications*, 1(4), pp. 2013–2024.

AASHTO-T283 (2003) ‘Resistance of compacted asphalt mixtures to moisture-induced damage’, *American Association of State Highway & Transportation Officials. Washington DC*, 2(25 mm), pp. 1–6.

AASHTO (2018) ‘Standard Specification for Stone Matrix Asphalt (SMA)’, 1(2012), pp. 1–5.

AASHTO T 19M/T 19-14 (2015) ‘Standard Method of Test for Bulk Density (“Unit Weight”) and Voids in Aggregate’, *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, pp. 2064–2072.

Ahmadinia, E. *et al.* (2011) ‘Using waste plastic bottles as additive for stone mastic asphalt’, *Materials & design*, 32(10), pp. 4844–4849.

Al-Khateeb, G.G., Ghuzlan, K.A. and Al-Barqawi, M.O. (2017) ‘Effect of Superpave restricted zone on volumetric and compaction properties of asphalt mixtures’, *International Journal of Pavement Research and Technology*, 10(6), pp. 488–496. Available at: https://doi.org/10.1016/j.ijprt.2017.03.004.

Al-taher, M.G. *et al.* (2018) ‘Comparative Study of Performance of Modified Asphalt Mixtures Using Different Traditional and Nano Additives’, (April).

Alvarez, A.E., Mora, J.C. and Espinosa, L. V. (2018) ‘Quantification of stone-on-stone contact in permeable friction course mixtures based on image analysis Allex’, *Construction and Building Materials*, 165, pp. 462–471. Available at: https://doi.org/10.1016/j.conbuildmat.2017.12.189.

Ameli, A. *et al.* (2021) ‘The effects of gilsonite and crumb rubber on moisture damage resistance of stone matrix asphalt mixtures’, *Construction and Building Materials*, 274, p. 122052.

American Association of State Highway and Transportation Official (2017) ‘Standard Practice for Designing Stone Matrix Asphalt (SMA)’, pp. 1–12. Available at: http://www.techstreet.com/products/1839074.

American Society for Testing and Materials (2013) ‘ASTM C127-15: Standard Test Method for Density , Relative Density (Specific Gravity), and Absorption of

Coarse Aggregate', *ASTM Standard Book*, (C), pp. 1–6.

American Society for Testing and Materials (2014) 'ASTM C131-14_Método de Prueba Estándar para Determinación de la Resistencia al Desgaste del Agregado Grueso de Tamaño Pequeño, por Abrasión e Impacto en la Máquina de Los Ángeles', i, pp. 1–5. Available at: https://doi.org/10.1520/C0131.

Di Angelantonio, E. *et al.* (2016) 'Body-mass index and all-cause mortality: individual-participant-data meta-analysis of 239 prospective studies in four continents', *The Lancet*, 388(10046), pp. 776–786.

Arabani, M. and Hamedi, G.H. (2011) 'Using the surface free energy method to evaluate the effects of polymeric aggregate treatment on moisture damage in hot-mix asphalt', *Journal of Materials in Civil Engineering*, 23(6), pp. 802–811.

Arabani, M., Tahami, S.A. and Hamedi, G.H. (2018) 'Performance evaluation of dry process crumb rubber-modified asphalt mixtures with nanomaterial', *Road Materials and Pavement Design*, 19(5), pp. 1241–1258.

Asphalt-StB, T.L. (2007) 'Technische Lieferbedingungen für Asphaltmischgut für den Bau von Verkehrsflächenbefestigungen', *Forschungs gesellschaft für Straßen- und Verkehrswesen, Köln* [Preprint].

ASTM- D70-2018 (2018) 'Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus) American Society for Testing and Materials. USAfile:///C:/Users/52A7~1/AppData/Local/Temp/Rar$DRa9624.18381/D/D 70 - 18.pdf', *ASTM International, West Conshohocken, PA*, 5, pp. 1–5. Available at: https://doi.org/10.1520/D0070-18.2.

ASTM (2007) 'Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester', *Annual Book of ASTM Standards*, i, pp. 1–10.

ASTM C128 (2022) 'ASTM C128: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate', *Annual Book of ASTM Standards*, i, pp. 2–7. Available at: https://doi.org/10.1520/C0128-15.2.

ASTM D 6390 (1997) 'Standard Method of Test For Determination of Draindown Characteristics In Un-compacted Asphalt Mixtures', *Annual Book of American Society for Testing materiasl ASTM Standards*, 11(Reapproved), pp. 6–8. Available at: https://doi.org/10.1520/D6390-11R17.2.

ASTM D 7064-08 (2013) 'mo', *ASTM International*, 08(Reapproved 2013), pp. 1–7. Available at: https://doi.org/10.1520/D7064.

ASTM D113 − 17 (2008) 'Standard Test Method for Ductility of Asphalt Materials', *Manual on Hydrocarbon Analysis, 6th Edition*, i, pp. 545-545–3. Available at: https://doi.org/10.1520/D0113-17.2.

ASTM D6931-12 (2007) 'Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures', *ASTM International*, (Fixed desination D6981), pp. 1–5. Available at: https://doi.org/10.1520/D6931-12.2.

ASTM D6931 (2017) 'Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures, ASTM International, West Conshohocken, PA.', p. 5. Available at: https://doi.org/10.1520/D6931-17.2.

ASTM International (2020) 'D5/D5M-20 Standard Test Method for Penetration of Bituminous Materials', *West Conshohocken, PA*, (May), pp. 5–8. Available at: https://doi.org/10.1520/D0005.

Batayneh, M., Marie, I. and Asi, I. (2007) 'Use of selected waste materials in concrete mixes', *Waste management*, 27(12), pp. 1870–1876.

Behnood, A. and Ameri, M. (2012) 'Experimental investigation of stone matrix asphalt mixtures containing steel slag A.', *Scientia Iranica*, 19(5), pp. 1214–1219. Available at: https://doi.org/10.1016/j.scient.2012.07.007.

Behnood, A. and Gharehveran, M.M. (2019) 'Morphology, rheology, and physical properties of polymer-modified asphalt binders', *European Polymer Journal*, 112, pp. 766–791.

Bessa, I.S. *et al.* (2015) 'Aggregate Shape Properties and Their Influence on the Behavior of Hot-Mix Asphalt', *Journal of Materials in Civil Engineering*, 27(7). Available at: https://doi.org/10.1061/(asce)mt.1943-5533.0001181.

Blazejowski, K. (2016) *Stone matrix asphalt: Theory and practice*. CRC Press.

Błazejowski, K. (2016) *Stone matrix asphalt: Theory and practice*, *Stone Matrix Asphalt: Theory and Practice*.

Boscaino, G., Praticò, F.G. and Vaiana, R. (2005) 'Tyre/road noise on different road pavements: Synergetic influence of acoustical absorbing coefficient and surface texture', *European Automobile Engineers Cooperation - 10th EAEC European Automotive Congress, EAEC 2005*, 2, pp. 633–644.

Brown, E. (1990) 'Density of asphalt concrete-how much is needed?'

Brown, E.R. and Manglorkar, H. (1993) 'Evaluation of Laboratory Properties of

SMA Mixtures’, *NCAT Report 93-05* [Preprint], (October).

Cao, W., Liu, S. and Feng, Z. (2013) ‘Comparison of performance of stone matrix asphalt mixtures using basalt and limestone aggregates’, *Construction and Building Materials*, 41, pp. 474–479. Available at: https://doi.org/10.1016/j.conbuildmat.2012.12.021.

Chew, J.-W. *et al.* (2020) ‘Microscopic analysis and mechanical properties of Recycled Paper Mill Sludge modified asphalt mixture using granite and limestone aggregates’, *Construction and Building Materials*, 243, p. 118172.

Chiu, C.-T. and Lu, L.-C. (2007) ‘A laboratory study on stone matrix asphalt using ground tire rubber’, *Construction and Building Materials*, 21(5), pp. 1027–1033.

Cooley, L.A. and Brown, E.R. (2003) ‘Potential of using stone matrix asphalt (SMA) for thin overlays’.

Dalhat, M.A. *et al.* (2020) ‘Chicken Feather fiber modified hot mix asphalt concrete: Rutting performance, durability, mechanical and volumetric properties’, *Construction and Building Materials*, 239, p. 117849.

Dannalie, E. and Nataadmadja, A.D. (2021) ‘The usage of recycled materials on hot mix asphalt’, *IOP Conference Series: Earth and Environmental Science*, 729(1), pp. 29–34. Available at: https://doi.org/10.1088/1755-1315/729/1/012045.

Dehouche, N., Kaci, M. and Mokhtar, K.A. (2012) ‘Influence of thermo-oxidative aging on chemical composition and physical properties of polymer modified bitumens’, *Construction and Building Materials*, 26(1), pp. 350–356. Available at: https://doi.org/10.1016/j.conbuildmat.2011.06.033.

Descornet, G. (2005) ‘Low-noise road surfaces: European state of the art’, *Journal of the Association of Asphalt Paving Technologists*, 74.

Devulapalli, L., Kothandaraman, S. and Sarang, G. (2020) ‘Effect of rejuvenating agents on stone matrix asphalt mixtures incorporating RAP’, *Construction and Building Materials*, 254, p. 119298. Available at: https://doi.org/10.1016/j.conbuildmat.2020.119298.

Devulapalli, L., Sarang, G. and Kothandaraman, S. (2022) ‘Characteristics of aggregate gradation, drain down and stabilizing agents in stone matrix asphalt mixtures: A state of art review’, *Journal of Traffic and Transportation Engineering (English Edition)*, 9(2), pp. 167–179. Available at: https://doi.org/10.1016/j.jtte.2021.10.007.

Ding, X. *et al.* (2017) ‘Experimental study of stable crumb rubber asphalt and asphalt mixture’, *Construction and Building Materials*, 157, pp. 975–981. Available at: https://doi.org/10.1016/j.conbuildmat.2017.09.164.

Drews, A. (2008a) ‘Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate1’, *Manual on Hydrocarbon Analysis, 6th Edition*, 13(Reapproved), pp. 545-545–3. Available at: https://doi.org/10.1520/mnl10913m.

Drews, A. (2008b) ‘Standard Test Method for Penetration of Bituminous Materials’, *Manual on Hydrocarbon Analysis, 6th Edition*, i, pp. 47-47–3. Available at: https://doi.org/10.1520/mnl10829m.

Duan, H. *et al.* (2021) ‘Effect of crumb rubber percentages and bitumen sources on high-temperature rheological properties of less smell crumb rubber modified bitumen’, *Construction and Building Materials*, 277, p. 122248. Available at: https://doi.org/10.1016/j.conbuildmat.2021.122248.

European Standard (2020) ‘BS EN 12697 - 19 : 2020 Bituminous mixtures — Test methods’, *British European Standard* [Preprint].

Fakhri, M. (2016) ‘The effect of waste rubber particles and silica fume on the mechanical properties of roller compacted concrete pavement’, *Journal of cleaner production*, 129, pp. 521–530.

Fakhri, M., Kheiry, P.T. and Mirghasemi, A.A. (2012) ‘Modeling of the permanent deformation characteristics of SMA mixtures using Discrete Element method’, *Road Materials and Pavement Design*, 13(1), pp. 67–84. Available at: https://doi.org/10.1080/14680629.2011.644080.

Fernandes, S., Silva, H.M.R.D. and Oliveira, J.R.M. (2019) ‘Mechanical, surface and environmental evaluation of stone mastic asphalt mixtures with advanced asphalt binders using waste materials’, *Road Materials and Pavement Design*, 20(2), pp. 316–333.

Fernandes, S.R.M., Silva, H.M.R.D. and Oliveira, J.R.M. (2018) ‘Recycled stone mastic asphalt mixtures incorporating high rates of waste materials’, *Construction and Building Materials*, 187, pp. 1–13. Available at: https://doi.org/10.1016/j.conbuildmat.2018.07.157.

Flöstrand, P. and Ström, N. (2006) ‘The valuation relevance of non-financial information’, *Management Research News*, 29(9), pp. 580–597.

Gatta, G. *et al.* (2015) ‘Prognoses and improvement for head and neck cancers diagnosed in Europe in early 2000s: The EUROCARE-5 population-based study', *European journal of cancer*, 51(15), pp. 2130–2143.

Ghasemi, M. and Marandi, S.M. (2011) 'Laboratory investigation of the properties of stone matrix asphalt mixtures modified with RGP-SBS', *Digest Journal of Nanomaterials and Biostructures*, 6(4), pp. 1823–1834.

Gong, F. *et al.* (2019) 'Strength and durability of dry-processed stone matrix asphalt containing cement pre-coated scrap tire rubber particles', *Construction and Building Materials*, 214, pp. 475–483. Available at: https://doi.org/10.1016/j.conbuildmat.2019.04.151.

Haghshenas, H.F. *et al.* (2015) 'Stripping Potential of HMA and SMA: A Study Using Statistical Approach', *Journal of Materials in Civil Engineering*, 27(11), pp. 1–6. Available at: https://doi.org/10.1061/(asce)mt.1943-5533.0001266.

Hassan, N.A. *et al.* (2014) 'A review of crumb rubber modification in dry mixed rubberised asphalt mixtures', *Jurnal Teknologi*, 70(4), pp. 127–134. Available at: https://doi.org/10.11113/jt.v70.3501.

Ismael, M., Fattah, M.Y. and Jasim, A.F. (2022) 'Permanent Deformation Characterization of Stone Matrix Asphalt Reinforced by Different Types of Fibers', *Journal of Engineering*, 28(2), pp. 99–116. Available at: https://doi.org/10.31026/j.eng.2022.02.07.

Jabbar, A.H. (2021) 'Characterizing Stone Mastic Asphalt Mixture (SMA) Incorporating Hybrid Fiber Modified Binder', (December).

Jun, L., Yuxia, Z. and Yuzhen, Z. (2008) 'The research of GMA-g-LDPE modified Qinhuangdao bitumen', *Construction and Building Materials*, 22(6), pp. 1067–1073. Available at: https://doi.org/10.1016/j.conbuildmat.2007.03.007.

Júnior, J.L.F., Filho, C.L.D.N. and Bernucci, L.L.B. (2004) 'Uso do ligante asfalto-borracha em misturas asfálticas SMA', in *Congresso Brasileiro de Ciência e Tecnologia em Resíduos e Desenvolvimento Sustentável, Florianópolis, 2004*.

Ka Patel, A., Gupte, S. and Parmar, N.B. (2016) 'Stone Matrix Asphalt (SMA) Mix Design Using Different Filler', 3(3), pp. 179–182.

Kai, C. *et al.* (2018) 'High- and Low-Temperature properties and thermal stability of silica Fume/SBS Composite-Modified asphalt mortar', *Advances in Materials Science and Engineering*, 2018. Available at: https://doi.org/10.1155/2018/1317436.

Kalaitzaki, E., Kollaros, G. and Athanasopoulou, A. (2015) ‘Influence of aggregate gradation on hma mixes stability’, *Romanian Journal of Transport Infrastructure*, 4(2), pp. 13–22. Available at: https://doi.org/10.1515/rjti-2015-0034.

Kalantar, Z.N., Karim, M.R. and Mahrez, A. (2012) ‘A review of using waste and virgin polymer in pavement’, *Construction and Building Materials*, 33, pp. 55–62. Available at: https://doi.org/10.1016/j.conbuildmat.2012.01.009.

Kamaraj, C. (2015) ‘DESIGN, CONSTRUCTION AND PERFORMANCE OF STONE MATRIX ASPHALT (SMA) - FIELD TEST SECTION C.KAMARAJ* Dr.P.K.JAIN** B.M.SHARMA** Dr.S.GANGOPADHYAY*** * Research Scholar, DnTE, Anna Un...’, (June 2013).

Karthikeyan Bindhu K PG Student Associate Professor, M.B. (2018) ‘Comparative Study on Bituminous Concrete Modified by Nano Silica and Micro Silica’, *IJSTE-International Journal of Science Technology & Engineering |*, 4(10), pp. 53–57. Available at: www.ijste.org.

Kashesh, G.J. *et al.* (2023) ‘Laboratory investigation on the performance of asphalt bitumen using recycled tyre rubber produced in Iraq’, *Materials Today: Proceedings* [Preprint].

Kiran Kumar, N.L.N. and Ravitheja, A. (2019) ‘Characteristics of stone matrix asphalt by using natural fibers as additives’, *Materials Today: Proceedings*, 19(June), pp. 397–402. Available at: https://doi.org/10.1016/j.matpr.2019.07.624.

Kogbara, R.B. *et al.* (2016) ‘A state-of-the-art review of parameters influencing measurement and modeling of skid resistance of asphalt pavements’, *Construction and Building Materials*, 114, pp. 602–617. Available at: https://doi.org/10.1016/j.conbuildmat.2016.04.002.

Kumar, S., Dhingra, A. and Daniell, H. (2004) ‘Stable transformation of the cotton plastid genome and maternal inheritance of transgenes’, *Plant molecular biology*, 56, pp. 203–216.

Lagos-Varas, M. *et al.* (2022) ‘Viscoelasticity modelling of asphalt mastics under permanent deformation through the use of fractional calculus’, *Construction and Building Materials*, 329(March). Available at: https://doi.org/10.1016/j.conbuildmat.2022.127102.

Lee, S., Mun, S. and Kim, Y.R. (2011) ‘Fatigue and rutting performance of lime-modified hot-mix asphalt mixtures’, *Construction and Building Materials*, 25(11), pp. 4202–4209.

Liu, H., Hao, P. and Xu, J. (2017) 'Effects of nominal maximum aggregate size on the performance of stone matrix asphalt', *Applied Sciences (Switzerland)*, 7(2), pp. 1–9. Available at: https://doi.org/10.3390/app7020126.

Liu, S. *et al.* (2017) 'Towards better analysis of machine learning models: A visual ', *Visual Informatics*, 1(1), pp. 48–56.analytics perspective

Mahdi, Y. and Aboalmaali, E. (2015) 'Performance of Modified Asphalt Mixture Suitable for Thin Overlay'.

Mahrez, A. and Karim, M.R. (2010) 'Fatigue characteristics of stone mastic asphalt mix reinforced with fiber glass', *International Journal of Physical Sciences*, 5(12), pp. 1840–1847.

Mashaan, N.S. *et al.* (2011) 'An overview of crumb rubber modified asphalt', (September). Available at: https://doi.org/10.5897/IJPSX11.007.

Mashaan, N.S. *et al.* (2013) 'Performance Evaluation of Crumb Rubber Modified Stone Mastic Asphalt Pavement in Malaysia', 2013.

Materials, A.S. for T. and (2006) 'ASTM D4402-06 Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer', *Annual Book of ASTM Standards*, i(C), pp. 1–4. Available at: https://doi.org/10.1520/D4402.

Maximum, T. *et al.* (2022) 'BULK SPECIFIC GRAVITY (Gmb) OF COMPACTED ASPHALT MIXTURES USING SATURATED SURFACE-DRY SPECIMENS FOP FOR AASHTO T 166', 209(October 2021), pp. 1–12.

Meng, Y. *et al.* (2022) 'Study on the performance and sustainability of modified waste crumb rubber and steel slag powder/SBS composite modified asphalt mastic', *Journal of Cleaner Production*, 338, p. 130563.

Milad, A.A., Ali, A.S.B. and Yusoff, N.I.M. (2020) 'A review of the utilisation of recycled waste material as an alternative modifier in asphalt mixtures', *Civil Engineering Journal*, 6, pp. 42–60.

Mohammed, M., Parry, T. and Grenfell, J. (J R.A.). (2018) 'Influence of fibres on rheological properties and toughness of bituminous binder', *Construction and Building Materials*, 163, pp. 901–911. Available at: https://doi.org/10.1016/j.conbuildmat.2017.12.146.

Mojabi, S.A., Abdi kordani, A. and Mirbaha, B. (2020) 'Laboratory investigation of stone matrix asphalt modified with SBS polymer and C25 fiber in using the semi-circular bend geometry (SCB) and moisture susceptibility', *Construction and Building Materials*, 261, p. 120511. Available at: https://doi.org/10.1016/j.conbuildmat.2020.120511.

MONTGOMERY, D.C. (1999) 'ASTM D113-99 - Ductility of bituminous materials', *American Association State Highway and Transportation Officials Standard*, 113(5), pp. 1–3.

Moreno, F., Rubio, M.C. and Martinez-Echevarria, M.J. (2012) 'The mechanical performance of dry-process crumb rubber modified hot bituminous mixes: The influence of digestion time and crumb rubber percentage', *Construction and Building Materials*, 26(1), pp. 466–474. Available at: https://doi.org/10.1016/j.conbuildmat.2011.06.046.

Mu, K. *et al.* (2020) 'Development of a microstructure-based numerical approach for analyzing heat transfer within the asphalt mixture', *Construction and Building Materials*, 260. Available at: https://doi.org/10.1016/j.conbuildmat.2020.119890.

Muniandy, R., Aburkaba, E. and Taha, R. (2013) 'Effect of Mineral Filler Type and Particle Size on Asphalt-Filler Mastic and Stone Mastic Asphalt Laboratory Measured Properties', *Australian Journal of Basic and Applied Sciences*, 7(11), pp. 475–487.

Myers, M.D. and Newman, M. (2007) 'The qualitative interview in IS research: Examining the craft', *Information and organization*, 17(1), pp. 2–26.

NAPA-QIP122 (2002) 'Designing and Constructing SMA Mixtures - State-of-the-Practice', *National Asphalt Pavement Association*, QIS 122.

Nejres, A.M., Mustafa, Y.F. and Aldewachi, H.S. (2022) 'Evaluation of natural asphalt properties treated with egg shell waste and low density polyethylene', *International Journal of Pavement Engineering*, 23(1), pp. 39–45. Available at: https://doi.org/10.1080/10298436.2020.1728534.

Nishchal, A. *et al.* (2016) 'Article ID: IJCIET_07_04_030 Cite this Article: Arun Nishchal Guleria and Sandeep Salhotra, Effects of Silica Fume (Micro Silica or Nano Silica) On Mechanical Properties of Concrete: A Review', *International Journal of Civil Engineering and Technology*, 7(4), pp. 345–357. Available at: http://www.iaeme.com/IJCIET/index.asp345http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4http://www.iaeme.com/IJCIET/index.asp346http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4.

Noura, S. *et al.* (2021) ‘Evaluation of measured and predicted resilient modulus of rubberized Stone Mastic Asphalt (SMA) modified with truck tire rubber powder’, *Case Studies in Construction Materials*, 15(February), p. e00633. Available at: https://doi.org/10.1016/j.cscm.2021.e00633.

Paje, S.E., Vázquez, V.F., *et al.* (2013) ‘Field performance evaluation of stone mastic asphalt with crumb rubber’, in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Institute of Noise Control Engineering, pp. 2440–2447.

Paje, S.E., Luong, J., *et al.* (2013) ‘Road pavement rehabilitation using a binder with a high content of crumb rubber: Influence on noise reduction’, *Construction and building materials*, 47, pp. 789–798.

Palit, S.K., Reddy, K.S. and Pandey, B.B. (2004) ‘Laboratory evaluation of crumb rubber modified asphalt mixes’, *Journal of materials in civil engineering*, 16(1), pp. 45–53.

Picado-Santos, L.G., Capitão, S.D. and Neves, J.M.C. (2020) ‘Crumbrubber asphalt mixtures: A literature review’, *Construction and Building Materials*, 247, p. 118577. Available at: https://doi.org/10.1016/j.conbuildmat.2020.118577.

Putman, B.J. and Amirkhanian, S.N. (2004) ‘Utilization of waste fibers in stone matrix asphalt mixtures’, 42, pp. 265–274. Available at: https://doi.org/10.1016/j.resconrec.2004.04.005.

Qiu, Y. (2007) ‘Design and performance of stone mastic asphalt in Singapore conditions’, p. 253. Available at: dr.ntu.edu.sg.

Rahman, M.T. and Mohajerani, A. (2020) ‘Use of bitumen encapsulated cigarette butts in stone mastic asphalt’, *Construction and Building Materials*, 261, p. 120530.

Razahi, M.M. and Chopra, A. (2020) ‘A review of using sisal fiber and coir fiber as additives in stone matrix asphalt’, *International Research Journal of Engineering and Technology (IRJET)*, 7(2), pp. 1692–1697.

Read, J. and Whiteoak, D. (2003) *The shell bitumen handbook*. Thomas Telford.

Rungruangvirojn, P. and Kanitpong, K. (2010a) ‘Measurement of visibility loss due to splash and spray: porous, SMA and conventional asphalt pavements’, *International Journal of Pavement Engineering*, 11(6), pp. 499–510.

Rungruangvirojn, P. and Kanitpong, K. (2010b) ‘Measurement of visibility loss due to splash and spray: Porous, SMA and conventional asphalt pavements', *International Journal of Pavement Engineering*, 11(6), pp. 499–510. Available at: https://doi.org/10.1080/10298430903578945.

de Sá, M. de F.A. *et al.* (2013) 'Weathering aging of modified asphalt binders', *Fuel Processing Technology*, 115, pp. 19–25.

Sangiorgi, C. *et al.* (2018) 'Stone mastic asphalt (SMA) with crumb rubber according to a new dry-hybrid technology: A laboratory and trial field evaluation', *Construction and Building Materials*, 182, pp. 200–209. Available at: https://doi.org/10.1016/j.conbuildmat.2018.06.128.

Sangiorgio, V., Uva, G. and Fatiguso, F. (2018) 'Optimized AHP to overcome limits in weight calculation: Building performance application', *Journal of Construction Engineering and Management*, 144(2), p. 4017101.

Sarang, G. *et al.* (2015) 'Laboratory performance of stone matrix asphalt mixtures with two aggregate gradations', *Journal of Modern Transportation*, 23(2), pp. 130–136. Available at: https://doi.org/10.1007/s40534-015-0071-5.

Sarang, G., Lekha, B.M. and Shankar, A.U.R. (2014) 'Stone matrix asphalt using aggregates modified with waste plastics', in *Pavement Materials, Structures, and Performance*, pp. 9–18.

Sarang, G., Mehnaz, E. and Shankar, A.U.R. (2014) 'Comparison of Stone Matrix Asphalt Mixtures Prepared in Marshall Compaction and Gyratory Compactor', 5(3), pp. 233–240.

Selimović, Š. *et al.* (2012) 'Microscale strategies for generating cell-encapsulating hydrogels', *Polymers*, 4(3), pp. 1554–1579.

Sharma, V. and Goyal, S. (2006) 'Comparative study of performance of natural fibres and crumb rubber modified stone matrix asphalt mixtures', *Canadian Journal of Civil Engineering*, 33(2), pp. 134–139.

Statements, B. (2015) 'Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures 1', i, pp. 1–7. Available at: https://doi.org/10.1520/D6927-15.2.

Stergiopoulos, V. *et al.* (2015) 'Effectiveness of housing first with intensive case management in an ethnically diverse sample of homeless adults with mental illness: A randomized controlled trial', *PLoS One*, 10(7), p. e0130281.

Stuart, D. (1991) 'Evaluation of Stone Matrix Asphalt Versus Dense-Graded Mixtures', pp. 58–65.

Suaryana, N. (2016) 'Performance evaluation of stone matrix asphalt using indonesian natural rock asphalt as stabilizer', *International Journal of Pavement Research and Technology*, 9(5), pp. 387–392. Available at: https://doi.org/10.1016/j.ijprt.2016.09.007.

Taherkhani, H. and Afroozi, S. (2017) 'Investigating the Performance Characteristics of Asphaltic Concrete Containing Nano-Silica', *Civil Engineering Infrastructures Journal*, 50(1), pp. 75–93. Available at: https://doi.org/10.7508/ceij.2017.01.005.

Tai Nguyen, H.T. and Nhan Tran, T. (2018) 'Effects of crumb rubber content and curing time on the properties of asphalt concrete and stone mastic asphalt using dry process', *International Journal of Pavement Research and Technology*, 11(3), pp. 236–244. Available at: https://doi.org/10.1016/j.ijprt.2017.09.014.

Tashman, L. and Pearson, B. (2012) 'Characterisation of stone matrix asphalt mixtures', *International Journal of Pavement Engineering*, 13(4), pp. 297–309. Available at: https://doi.org/10.1080/10298436.2011.595793.

Tiwari, N. *et al.* (2023) 'Experimental and Machine Learning Approach to Investigate the Mechanical Performance of Asphalt Mixtures with Silica Fume Filler', *Applied Sciences*, 13(11), p. 6664.

Vogiatzis, K. and Remy, N. (2014) 'From environmental noise abatement to soundscape creation through strategic noise mapping in medium urban agglomerations in South Europe', *Science of the Total Environment*, 482–483(1), pp. 420–431. Available at: https://doi.org/10.1016/j.scitotenv.2013.07.098.

Wan, Z. *et al.* (2019) 'Low resistance–integrated all-solid-state battery achieved by Li7La3Zr2O12 nanowire upgrading polyethylene oxide (PEO) composite electrolyte and PEO cathode binder', *Advanced Functional Materials*, 29(1), p. 1805301.

Xue, Q. *et al.* (2013) 'Evaluation of pavement straw composite fiber on SMA pavement performances', *Construction and Building Materials*, 41, pp. 834–843.

Xue, Y. *et al.* (2009) 'Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: Pavement performance and environmental impact', *Construction and Building Materials*, 23(2), pp. 989–996.

Yan, K., Xu, H. and You, L. (2015) 'Rheological properties of asphalts modified by waste tire rubber and reclaimed low density polyethylene', *Construction and Building Materials*, 83, pp. 143–149. Available at:

https://doi.org/10.1016/j.conbuildmat.2015.02.092.

Yusoff, N.I.M. *et al.* (2014) ‘The effects of moisture susceptibility and ageing conditions on nano-silica/polymer-modified asphalt mixtures’, *Construction and Building Materials*, 72, pp. 139–147. Available at: https://doi.org/10.1016/j.conbuildmat.2014.09.014.

Zghair, H., Joni, H. and hassan, maan s. (2020) ‘Evaluating The Effects of Micro and Nano Size of Silica Filler on Asphalt Cement Properties’, *Engineering and Technology Journal*, 38(12), pp. 1832–1841. Available at: https://doi.org/10.30684/etj.v38i12a.1565.

Zghair, H.H., Joni, H.H. and Hassan, M.S. (2019) ‘Evaluation of the Effect of Mixing Conditions of Micro-Silica Modified Asphalt Binder’, *IOP Conference Series: Materials Science and Engineering*, 518(2). Available at: https://doi.org/10.1088/1757-899X/518/2/022048.

Zheng ; Xu ; Feng; Kai Cao (2020) ‘High and Low Temperature Performance and Fatigue Properties of Silica Fume/SBS Compound Modified Asphalt Xuewen’, pp. 1–20.

Zhu, J. and Kringos, N. (2015) ‘Towards the development of a viscoelastic model for phase separation in polymer-modified bitumen’, *Road Materials and Pavement Design*, 16(August), pp. 39–49. Available at: https://doi.org/10.1080/14680629.2015.1030834.

الخلاصة

إن الطلب المتزايد على الطرق عالية الجودة شجع الباحثين على تطوير إجراءات تصميمية جديدة لتحسين الأداء وإطالة عمر الطرق الإسفلتية، كما أن ارتفاع تكاليف الصيانة يتناسب مع ارتفاع أحجام المرور، مما يستلزم إنشاء طرق أفضل، طرق أكثر متانة وأكثر كفاءة تمنع أو تقلل من مشاكل الطرق الاسفلتيه. هناك خيار جيد لهذه المشكلة وهو الإسفلت الماستكي الحجري .

ومن ناحية أخرى، فإن استخدام مواد النفايات في الأسفلت يوفر فرصة ممتازة لإدارة النفايات بشكل مستدام. خفض التكاليف وحماية البيئة وخفض استهلاك الطاقة. وعليه يهدف هذا البحث إلى معرفة تأثير بعض مواد المخلفات المحلية على أداء الخلطة الإسفلتية SMA وكذلك تقليل تصريف الاسفلت لتحسين أداء الخلطة.

في هذا البحث تم تحضير عينات من الخلطة الاسفلتية الساخنة باستخدام المقاس الركام (12.5 ملم) , المادة المالئة (1.5% اسمنت و 8% نورة مطفأة) , مصدر الاسفلت (مصفى الدورة) , نوعين من الاضافات المتوفرة هي المطاط , والميكرو سيليكا , بنسبة واحدة للمطاط هي 15% من وزن الإسفلت وثلاثة نسب من الميكرو سيليكا (2,4,6%) من وزن الاسفلت باستخدام العملية الرطبة لخلط المواد المضافة مع الإسفلت باستخدام الخلاط .

الفحوصات المستخدمة في هذا البحث عديده منها: فحص الخصائص الفيزيائية للإسفلت المعدل من هذه الفحوصات الفيزيائية: الاختراق، نقطة التليين، الاستطالة، مؤشر الاختراق، واللزوجة الدورانية. تضمنت خطة الاختبار أيضًا الخصائص الحجمية (على سبيل المثال، الكثافة الظاهرية، وفراغ الهواء، والفراغ في الركام المعدني، والفراغ المملوء بالإسفلت، وتصريف الاسفلت)، والخواص الميكانيكية (على سبيل المثال، ثباتيه مارشال و زحف مارشال، قوة الشد غير المباشرة، فقدان تآكل ، مقاومة الانزلاق، فحص حساب عمق التخدد)، فحوصات الديمومه (فقدان تآكل بعد التقادم، حساب مقدار الرطوبة) لتحديد تأثير استخدام هذه المواد على خصائص خليط SMA. أظهرت نتيجة الفحوصات التي اجريت في المختبر أن الخواص الفيزيائية لمادة الأسفلت قد تحسنت بشكل كبير بعد اضافة المضافات حيث تم تقليل الاختراق، الاستطالة،

والحساسية لدرجة حرارة الاسفلت، في حين يتم زيادة نقطة تليين الأسفلت واللزوجة. بالإضافة إلى ذلك، أدى استخدام مايكرو سيليكا إلى تحسين جميع الخصائص المذكورة اعلاه، حيث أظهرت 6% تحسنًا كبيرًا مقارنة بالنسب المنخفضة الأخرى، باستثناء 2%، حيث أظهرت نتائج جيده في فحص مقاومة الرطوبة، حيث كانت نسبة الزيادة 11%. نجد من خلال النتائج ان افضل نسبه لتحسين اداء الخلطة الاسفلتية عند اضافة 6% من المايكروسيليكا .حيث أعطت أفضل أداء لتصريف الخلطة الاسفلتية حيث بلغت 0.013% و 0.067% عند 160 درجة مئوية و 175 درجة مئوية، على التوالي. تم تخفيض مقاومة الانزلاق إلى 23%، كما تم تخفيض مقدار التخدد بنسبة 58% مقارنة بخلطة الاساسيه، كما أن إضافة 6% يوفر أفضل النتائج في تحسين قوة الشد غير المباشر حيث بلغت مقاومة الخليط للتشقق ذلك بنسبة 33% تقريباً. وتوصلت الدراسة إلى أن استخدام الميكرو سيليكا كمضاف للخلطه الإسفلتية يمكن أن يحسن أداء الخلطات SMA خاصة بنسبة 6% وهي تعتبر النسبة المثلى.

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية الهندسة
قسم الهندسة المدنية

انتاج مواد رصف عالية الأداء من خلال تحسين خصائص الأسفلت الماستكي الحجري ، باستخدام معدلات المطاط والسيليكا الدقيقة

رسالة مقدمة إلى

كلية الهندسة في جامعة بابل كجزء من متطلبات نيل درجة ماجستير في الهندسة /الهندسه المدنيه / مواصلات

من قبل

حنين فاضل كاظم خضير

بإشراف:

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