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Characterizing Stone Mastic Asphalt Mixture (SMA) Incorporating Hybrid Fiber Modified Binder

A Thesis Submitted to the Department of Civil Engineeringat the University of Kerbala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering.

By

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بسم الله الرحمن الرحيم

﴿وَأَنْ لَيْسَ لِلْإِنْسَانِ إِلَّا مَا سَعَى(٣٩) وَأَنَّ سَعْيَهُ
سَوْفَ يُرَى(٤٠) ثمَّ يجْزاه الجْزَاء الاوفى(٤١)﴾

صدق الله العلي العظيم

سورة النجم

Dedication

This thesis is dedicated to:

To the one who supported me with her prayers and supplications

To who stayed up the nights in order to light my path

To my first teacher, my dear mother

To the one who did not hesitate to provide the way of goodness and happiness for me, my father

To my supervisor Assist. Prof. Dr. Shakir Al-Busaltan

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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I would also like to express my sincere gratitude to the Head of the Civil Engineering Department Dr. Raid Almuhanna for their support and assistance.

Supervisor Certification

I certify that this thesis entitled “Characterizing Stone Mastic Asphalt Mixture (SMA) Incorporating Hybrid Fiber Modified Binder”, which is prepared by "Ayat Hameed Jabbar ", is under my supervision at University of Kerbala in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Civil Engineering/ Transportation Engineering).

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Abstract

Any national road network is critical to its economic development, social integration, and trade. The increase in maintenance costs corresponds to an increase in traffic volumes, necessitating the urgent need to build better, more durable, and more efficient roads that prevent or reduce bituminous pavement problems. The growing demand for high-quality pavements has encourage researchers to develop a new design procedure to improve the performance and prolong the life_span of asphalt pavements. Stone mastic asphalt (SMA) represents a technology used to improve the performance of asphalt mixtures. As well, these mixtures are characterized by their hardness, good stability and crack resistance that relies on the contact of rock stone for strength and the bond of a rich slurry for durability. The estimated cost increase of 20% to 25% is offset by an increase in the mix's life expectancy, primarily due to decreased cracks and increased durability. SMA is an excellent combination to use in areas with high traffic volumes, and where frequent maintenance is costly.

On other hand, nowadays the concept of sustainability is a necessity (not a wish) in many aspects of life, including the pavements industry. The incorporation of waste materials into asphalt mixtures provides an excellent opportunity to manage waste sustainably. Cost reduction, environmental protection, and energy consumption reduction, all are contributed to sustainability. Accordingly, this research aims to investigate the impact of some local waste materials on the performance of the SMA asphalt mixture. Therefore, for neat asphalt binder modification, two types of waste materials were suggested: Recycled Low-Density Polyethylene (R-LDPE) and Waste Paper Fiber (W-PF). SMA was then improved using developed asphalt binders via R-LDPE

at fixing dosages of (3%), and W-PF incorporated at three different dosages, namley0.3%, 0.5%, and 0.7% of binder weight, individually or collectively. Traditional tests such as penetration, softening point, ductility, penetration index, and rotational viscosity were used to characterize the modified asphalt binders. Moreover, the thin film oven test was used to verify the effect of aging. Furthermore, to determine the impact of using these materials on SMA mixture characteristics, the testing plan included volumetric properties (e.g., bulk density, air void, void in the mineral aggregate, void filled with asphalt, and draindown), mechanical properties (e.g., Marshall stability and flow, Creep Compliance, Indirect Tensile Strength, Cantabro abrasion loss, Skid Resistance and Wheel track), and durability (Cantabro abrasion loss after aging, and tensile strength ratio) properties.

Noticeably, the use of waste additives improves the physical properties of asphalt binder, i.e., the penetration, ductility, and temperature sensitivity of bitumen were reduced, while the softening point, viscosity, and aging resistance of bitumen were increased. Simultaneously, the incorporating of R-LDPE positively enhances the SMA mixture performance. Additionally, using W-PF individually, lead to enhance almost all stated characteristics, whereas 0.7% showed a significant improvement in comparison to other low ratios, except for 0.3 %, which showed a significant improvement in indirect tensile strength. Where the increase reached 33% and resistance to abrasion loss only where the increase in mixture resistance to abrasion reached 28% and 22% for unaged and aged conditions, respectively. The R-LDPE and W-PF blends resulted in additional SMA enhancement, with 3.7 % providing the best performance in the drain down, reaching 0.08 % and 0.15 % at 165°C and 180°C, respectively. Skid with a reduction of 28%, wheel track with a reduction of 28% Whereas the reduction in creep stiffness is greater than 60%, Where obtained that the higher enhancement reached 71 % in comparison to B0 mixture and the addition of 3.5 % providing the best results in improving the indirect tensile strength where the resistance of the mixture to cracking that by approximately 27 %. The study concluded that using local waste materials as modifiers for asphalt binder can improve sustainably the performance of SMA mixtures.

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ABBREVIATIONS AND SYMBOL

AASHTO	*American Association of State Highway and Transportation Officials*
AV	*Air Voids*
AG	*American Gilsonite*
B0	*Neat Binder*
BD	*Bulk Density*
BPN	*British Pendulum Number*
C25	*Composite Fiber*
CC	*Creep Compliance Test*
CMF	*Conventional Mineral Filler*
DGA	*dense-graded asphalt*
DRC	*Dry Rodded*
EBA	*ethylene–butyl acrylate*
EVA	*ethylene–vinyl acetate*
GR	*Grading selection*
HDPE	*High Density Polyethylene*
HL	*Hydrated Lime*
HMA	*Hot Mix Asphalt*
IG	*Iranian ilsonite*
ITS	*Indirect Tensile Strength*
ki	*Value Represents to Skid Resistance*
LDPE	*Low-Density Polyethylene*
LLDPE	*Linear Low-Density Polyethylene*
LVDT	*Linear Variable Differential Transducer*
MAS	*Maximum Aggregate Size*
MB	*Modified Binder*
MC	*Mix Collective Additives*
MF	*Marshall Flow*
MMS	*Modified Mixtures*
MS	*Marshall Stability*
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*
PP	*polypropylene*
PPC	*Pavement Profile Condition*
PRC	*Pavement Rutting Condition*
PRO	*Roctor*
PSC	*Pavement Structural Condition*
R-LDPE	*Recycled Low Density Polyethylene*
RO	*Roller*
SBS	*styrene–butadiene–styrene*
SEBS	*styrene–ethylene/butylene–styrene*
SEM	*Scan Electron Microscope*
SHRP	*Strategic Highway Research Program*
SIS	*styrene–isoprene–styrene*
SMA	*Stone Mastic Asphalt*
SP	*Softening Point*
SPI	*Softening Point Index*
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*
W-PF	*waste paper fiber*
WTT	*Wheel Track Test*
WSPMS	*Washington State Pavement Management System*

Chapter One

Introduction

1.1 Background

Over the last two decades, nearly all developing and developed countries have faced significant challenges in terms of economic competitiveness and productivity. Economic competitiveness, on the other hand, has resulted not only in an unprecedented increase in goods production but also in the development of the most efficient and safest transportation facilities used for product delivery. As a result, to maintain economic competitiveness in the delivery of goods across global markets, manufacturers have shifted to producing larger vehicles and containers with more axle load and higher tire pressure. As a result, the number of these heavy vehicles on existing roads has increased significantly see Figure 1-1 (Moghaddam et al., 2011, Ahmadinia et al., 2012a).

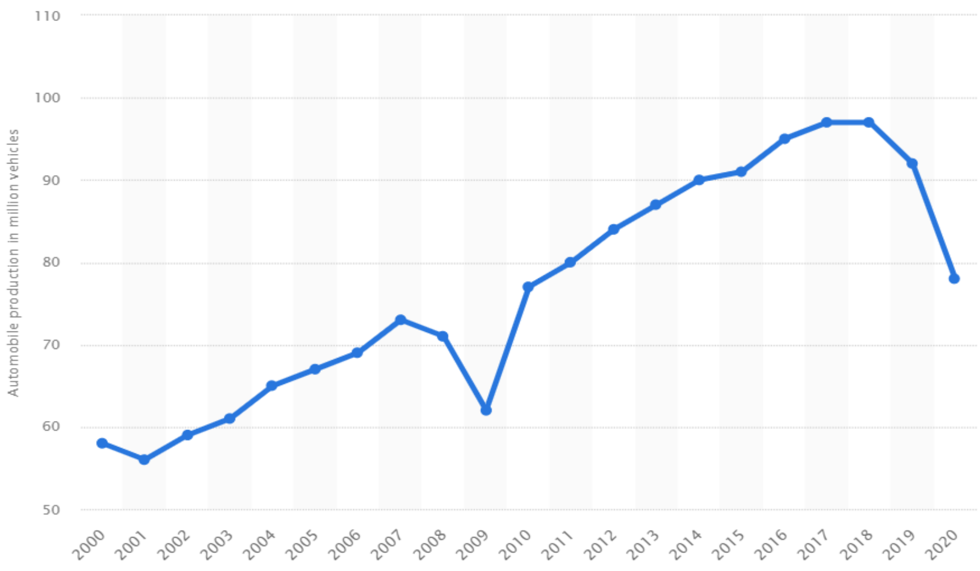

Figure 1- 1 Estimated worldwide automobile production from 2000 to 2020 (in million vehicles) (Department, 2021).

Asphalt pavements are deteriorating and decomposing faster than expected due to an unprecedented increase in the number and frequency of road traffic and axle loads. To counteract this process, improvements in roadway design, the use of higher and better-quality materials, the use of modifiers and additives for bitumen and asphalt mixtures, and the use of more effective road construction techniques are being implemented (Tortum et al., 2005, Tayfur et al., 2007, Moghaddam et al., 2011). The growing demand for higher-quality pavements, combined with the poor performance of some bituminous mixtures, has prompted researchers to develop new methods and designs to improve bituminous mixture performance and effective service life. Stone mastic asphalt (SMA) is a technique for improving the performance of asphalt pavements. Stone mastic asphalt (SMA) is a method of improving the performance of asphalt pavements (as shown in Figure 1-2) that has been supported by numerous research reports (Tayfur et al., 2007, Chiu et al., 2007). SMA mixtures were invented in Germany in the 1960s. Split mastic asphalt is also known as stone mastic asphalt in Europe and stone matrix asphalt in the United States. Originally intended to provide a mixture with the greatest resistance to studded tire wear (Manosalvas-Paredes et al., 2016a, Sheng et al., 2017, Jamieson et al., 2020).

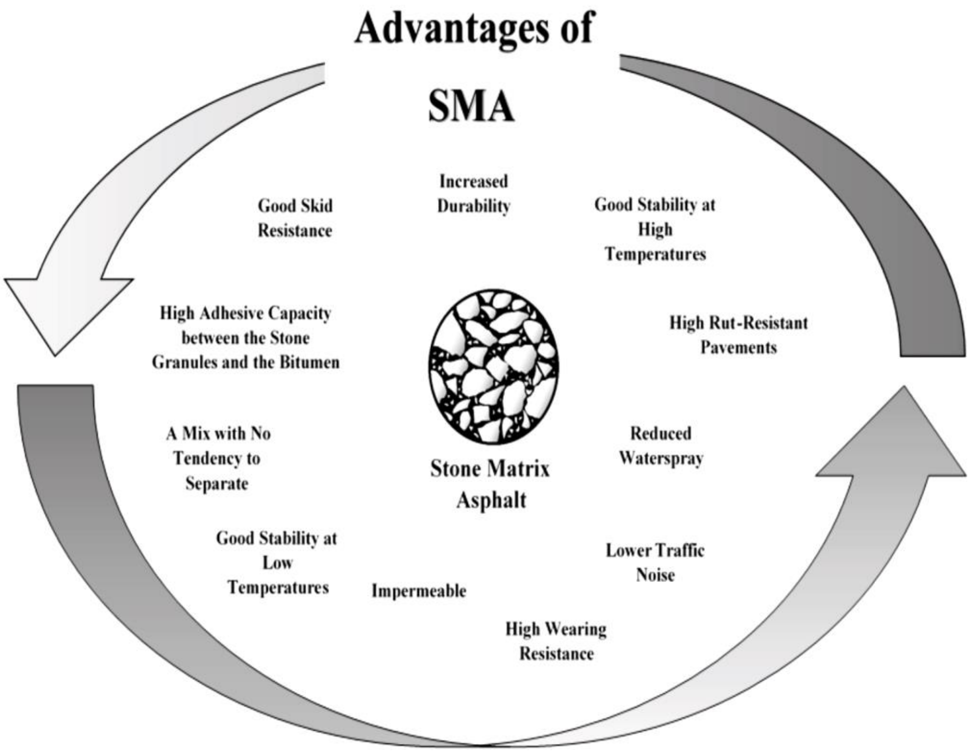

Figure 1- 2 Advantages of SMA (Limón-Covarrubias et al., 2019).

Experiments have shown that SMA has greater rutting resistance, higher durability, and improved resistance to reflective cracking when compared to dense graded asphalt (DGA) (Cooley Jr et al., 2004, Mahrez et al., 2010, Jamieson et al., 2020) because of the structure's composition, which consists of three parts: a coarse aggregate skeleton, a mastic, and air voids, as can be seen in Figure 1-3. Stone-on-stone contact is provided by the coarse aggregate skeleton, resulting in high deformation resistance. The mastic is made of fine aggregates, filler, and a significant amount of binder (approximately 6–7 % by mass).

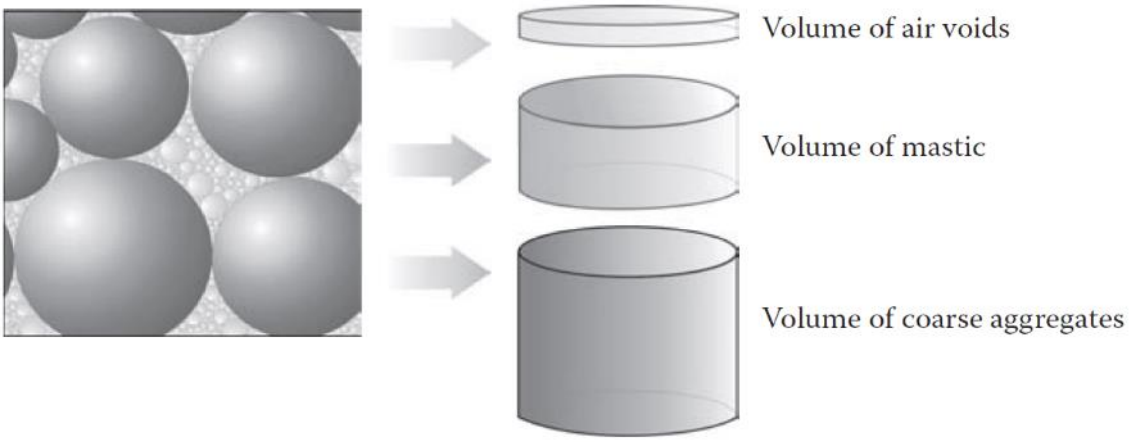

Figure 1- 3 Division of SMA into basic components (Blazejowski, 2019).

When compared to DGA, the higher binder content in SMA 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, both of which are commonly found in the form of cellulose fibers and polymers (Riccardi et al., 2016, Dalhat et al., 2020, Rahman et al., 2020c, Jamieson et al., 2020). Many improvements in the material selection, mix design, and construction methods have been made to improve SMA performance and prevent excess binder drainage (Xue et al., 2013). Asphalt binder is prone to failure at various stages, including production, storage, laying, and compaction of bituminous mixtures (Bala et al., 2017). This binder can be modified by a variety of additives to increase the strength of asphalt pavements. Fillers, reclaimed rubber products, catalysts, fibers, polymers (natural and synthetic), and extenders have all been used to modify asphalt in recent years (Arabani et al., 2017c). Many factors have led researchers to look for an alternative in the asphalt pavement industry, including environmental concerns, economic concerns, and energy conservation. Waste materials (e.g., recycled aggregates, waste brick, glass, seashells, reclaimed asphalt pavement, and waste tire) have been successfully used as aggregate, filler, and asphalt modifier in asphalt mixtures (Arabani et al., 2017c) .

To improve the dynamic modulus, tensile strength, moisture susceptibility, creep compliance, tear resistance, fatigue life and to reduce the amount of drainage and to change the viscoelasticity of the asphalt mixture, fibers such as polyester fibers, mineral fibers and cellulose fibers are added. (Sheng et al., 2017) The addition of fibers to asphalt mixtures necessitates a greater amount of bitumen, resulting in higher asphalt durability, stability, and aging prevention under various conditions. The thickness of the aggregates' membrane increases as the amount of bitumen increases, resulting in late hardening of the bitumen. In other words, thicker bituminous coatings take longer to harden and stiffen. However, as the amount of bitumen increases, the inter-granular void space decreases or disappears, preventing air and water from having entered the structure and oxidation and mixture breakdown. (Mojabi et al., 2020).

Polymer, on the other hand, is frequently used in asphalt mixtures to improve mechanical properties while decreasing binder drain down. To achieve the desired mixture properties, various polymers (such as styrene–butadiene–styrene (SBS), ethylene–vinyl–acetate (EVA), polyethylene, or polypropylene) may be used, depending on the designer's vision. (Punith et al., 2007, Arabani et al., 2017c). Polymers are materials used to enhance the performance of asphalt. Polymer-based pavement has a higher resistance to thermal cracking and rutting, as well as lower fatigue failure, stripping, and temperature susceptibility. Polymer modified binders have been used in high stress areas such as high-volume street intersections, airports, vehicle weigh stations and race tracks. Many improved properties of polymer modified binders include higher softening point, higher elastic recovery, higher cohesive strength, higher ductility, and higher viscosity (Yildirim et al., 2007, Arabani et al., 2017c).

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 sustainability 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 knowledge on properties (volumetric, mechanical, and durability) of SMA asphalt mixtures using a sustainable approach 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. To achieve the sustainability principle, the more readily available and low-cost local materials recycling-Low-density-polyethylene (R-LDPE) and waste paper fiber (W-PF) were chosen for asphalt binder modification.
2. Producing modified binders by using different sustainable materials composition ratios.
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 draindown).
    b. Mechanical examinations: (marshall stability, marshall flow, indirect tensile strength, creep compliance, cantabro abrasion loss, wheel track and skid resistance).
    c. Durability tests: Cantabro abrasion loss after aging.
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, two filler types.
2. The mechanical, volumetric, and durability properties of the mixtures were evaluated in the lab, and no field tests were conducted.
3. All tests were carried out at the University of Kerbela’s highway transportation lab.
4. Some testing devices were produced locally, such as a shear mixer for mixing polymer and fibers (W-PF and R-LDE), an indirect tensile strength test, and a creep compliance 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 discusion 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 highe 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 (Blazejowski, 2019). Figure (2-1) shows a comparison of skeleton among different mixtures.

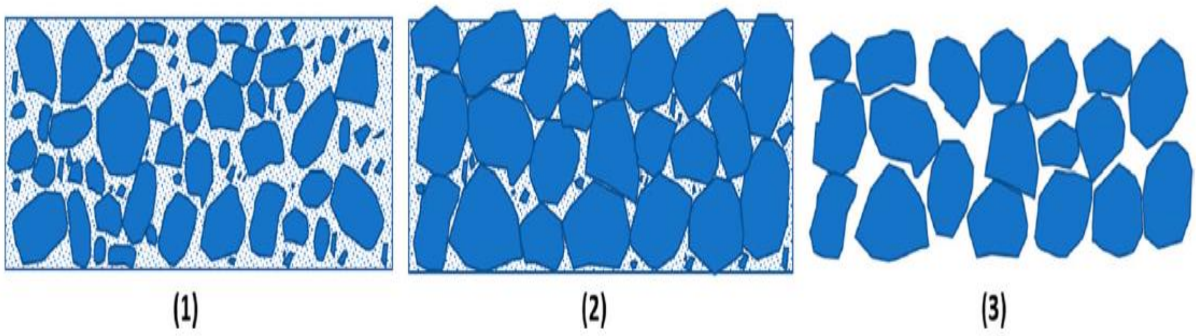

Figure 2- 1 Illustrative figure for the mixture skeleton of (1) DGA, (2) SMA, and (3) OGFC (Jamieson et al., 2020).

2.3 Overview of stone mastic asphalt (SMA)

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 highe proportion of coarse aggregates and binder mortar. SMA is typically composed of 70–80 % coarse aggregate, 8–12 %filler material, and 6–8 % binder. The coarse aggregate forms a skeleton structure, which provides strength and superior tire grip, while voids formed in the skeleton structure are filled with filler material (Liu et al., 2017). Plate (2-1) shows the final form of the SMA surface.

Plate 2- 1 SMA profile(on the left), SMA surface (on the right) (Yao 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 et al., 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 (Sarang et al., 2015a). 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 et al., 2004, Silva et al., 2012, Devulapalli et al., 2020). Figures (2-2 and 2-3) display the structure and composition of SMA mixtures.

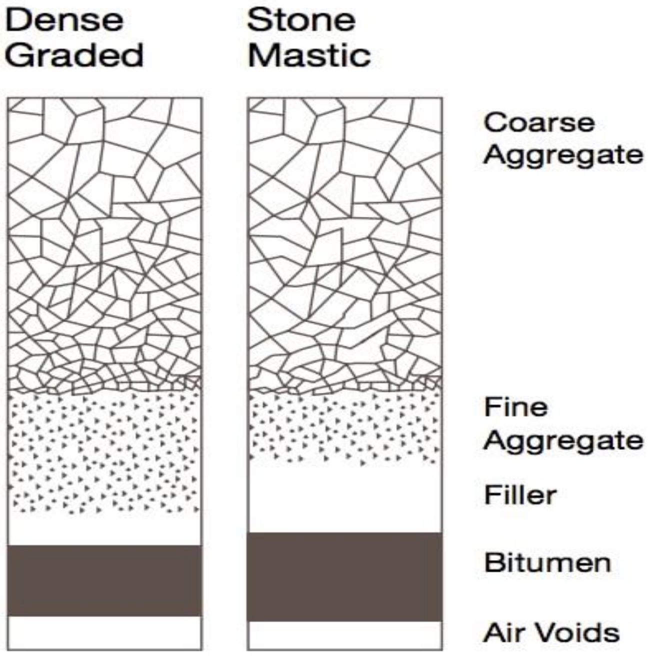

Figure 2- 2 SMA and DG composition (Oliver, 2020).

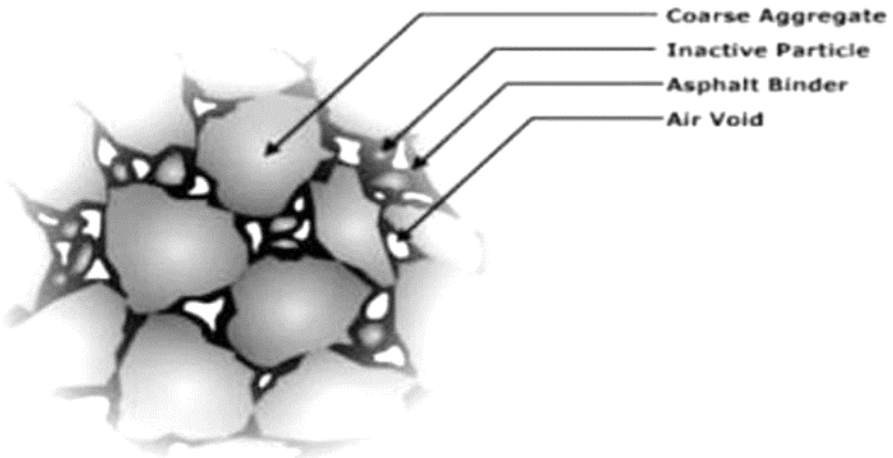

Figure 2- 3 SMA structure (Marathe, 2018).

2.4. Characteristics of SMA asphalt mixtures

2.4.1 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 (2-4) and Plate (2-2) 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 et al., 2010a).

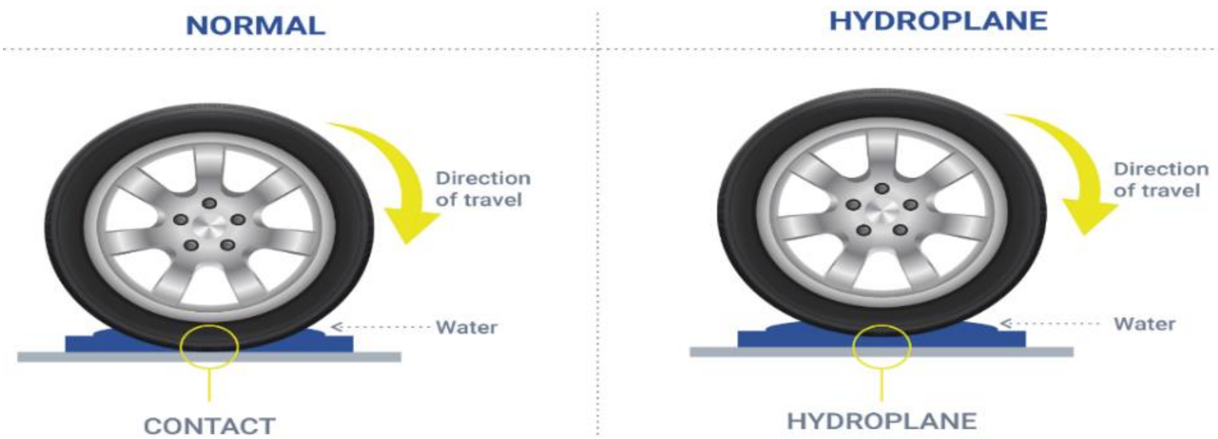

Figure 2- 4 Hydroplaning phenomena (Tyres-N-Services, 2021).

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 et al., 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 (Woodward et al., 2016).

Plate 2- 2 Spray and splash problem in SMA (Rungruangvirojn et al., 2010b).

2.4.2 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 (Sangiorgi et al., 2018). Some noise-control measures include traffic management, the construction of noise barriers, and vehicle speed reduction (Vogiatzis et al., 2014, Licitra 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., 2013a, Paje et al., 2013b).

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 light vehicle tire noise reduction is 4–6 mm, and the maximum aggregate size for heavy-duty vehicle tire noise reduction is 6–10 mm.
2. Macrotexture 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.

Figure (2-5) illustrates the effect of variation in wavelength on both safety and environmental factors.

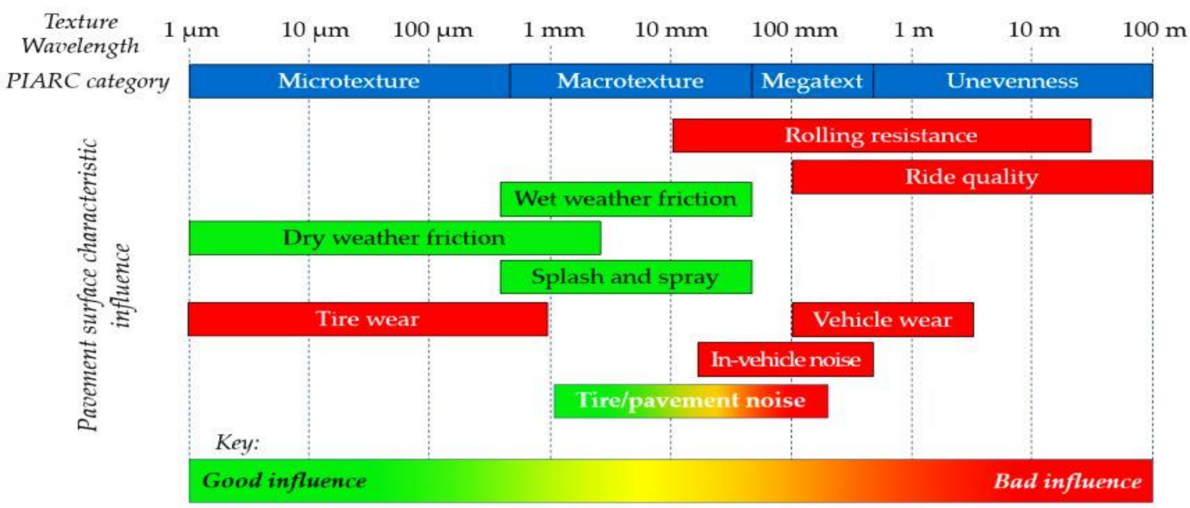

Figure 2- 5 Texture wavelength range for each of the categories and their influence (safety, comfort, noise, wear, etc.) (Vázquez et al., 2019).

Vázquez et al. (2019) investigated the functional performance (tire/pavement noise) of two SMA bituminous mixtures (SMA11 and SMA16). At 80 km/h, the bituminous mixture SMA11 outperforms the SMA16 in terms of noise reduction. The differences between the two mixtures were smaller at 50 km/h. This outcome could be related to their maximum aggregate size (MAS). The SMA 16 is noisier at frequencies beginning at 700 Hz, regardless of reference speed, according to the sound spectra.

2.4.3 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 (Wallman et al., 2001). Adhesion and hysteresis contribute to skid resistance/friction force, which is primarily determined by the pavement's surface texture. Plate (2-3) illustrates the mechanisms of pavement 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).

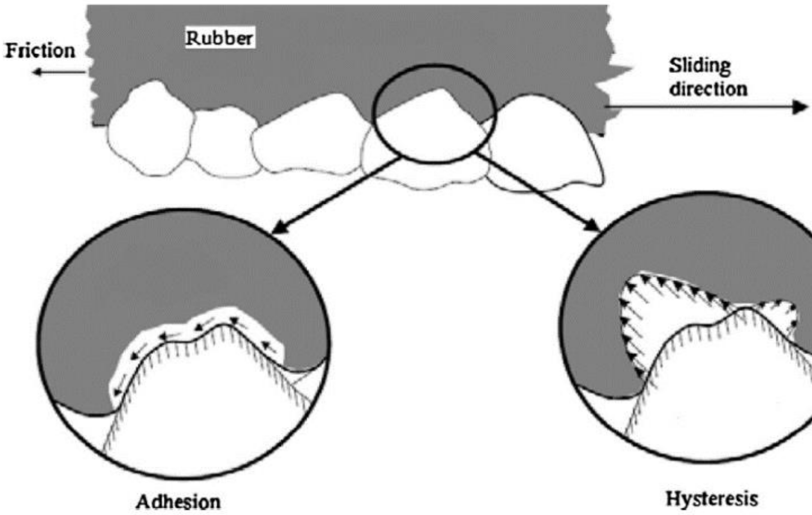

Plate 2- 3 Key mechanisms of tire-pavement friction (Kogbara et al., 2016a).

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 macrotexture (which regulates the escape of water beneath the tire and, as a result, the loss of skid resistance at high speeds (Asi et al., 2007). Plate (2-4) shows the difference between the macro and microtexture.

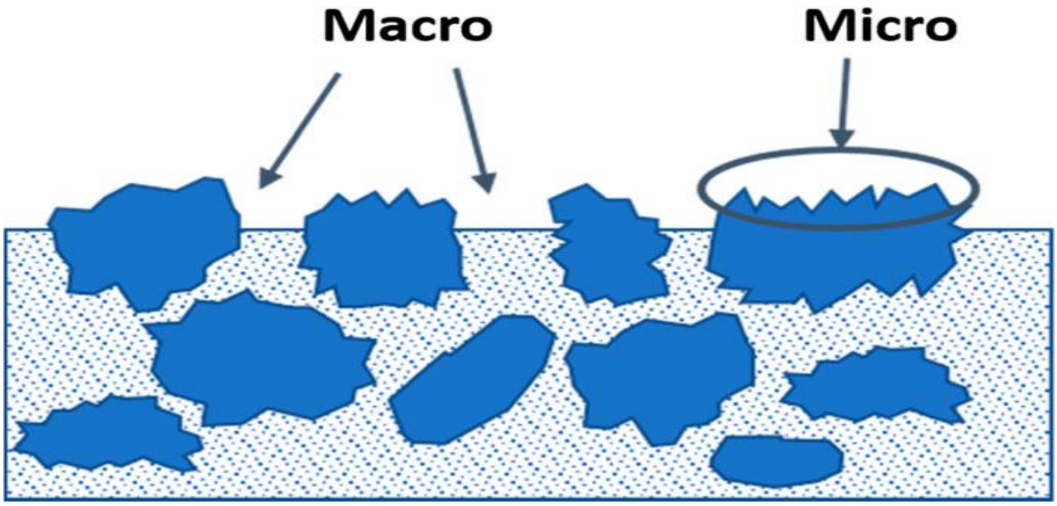

Plate 2- 4 Difference between macro-texture and micro-texture (Jamieson et al., 2020)

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 measurements can be used to assess various materials and building practices.

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 (Woodward et al., 2016).

Plate 2- 5 SMA Pavement Surface https://pavementinteractive.org/wp-content/uploads/2009/06/SMA_Surface11.jpg.

Liu 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 (P_{NMSA}), passing the control sieve Size (P_{CS}) and asphalt content (AC). Among them, P_{NMSA} found to be the greatest impact on skid resistance, followed by AC, while the P_{CS} appears to have the smallest impact on skid resistance. Figure (2-6) shows a comparison of the variation of skid resistance with respect to P_{NMSA}, P_{CS} and AC parameters, through different types of SMA mixtures.

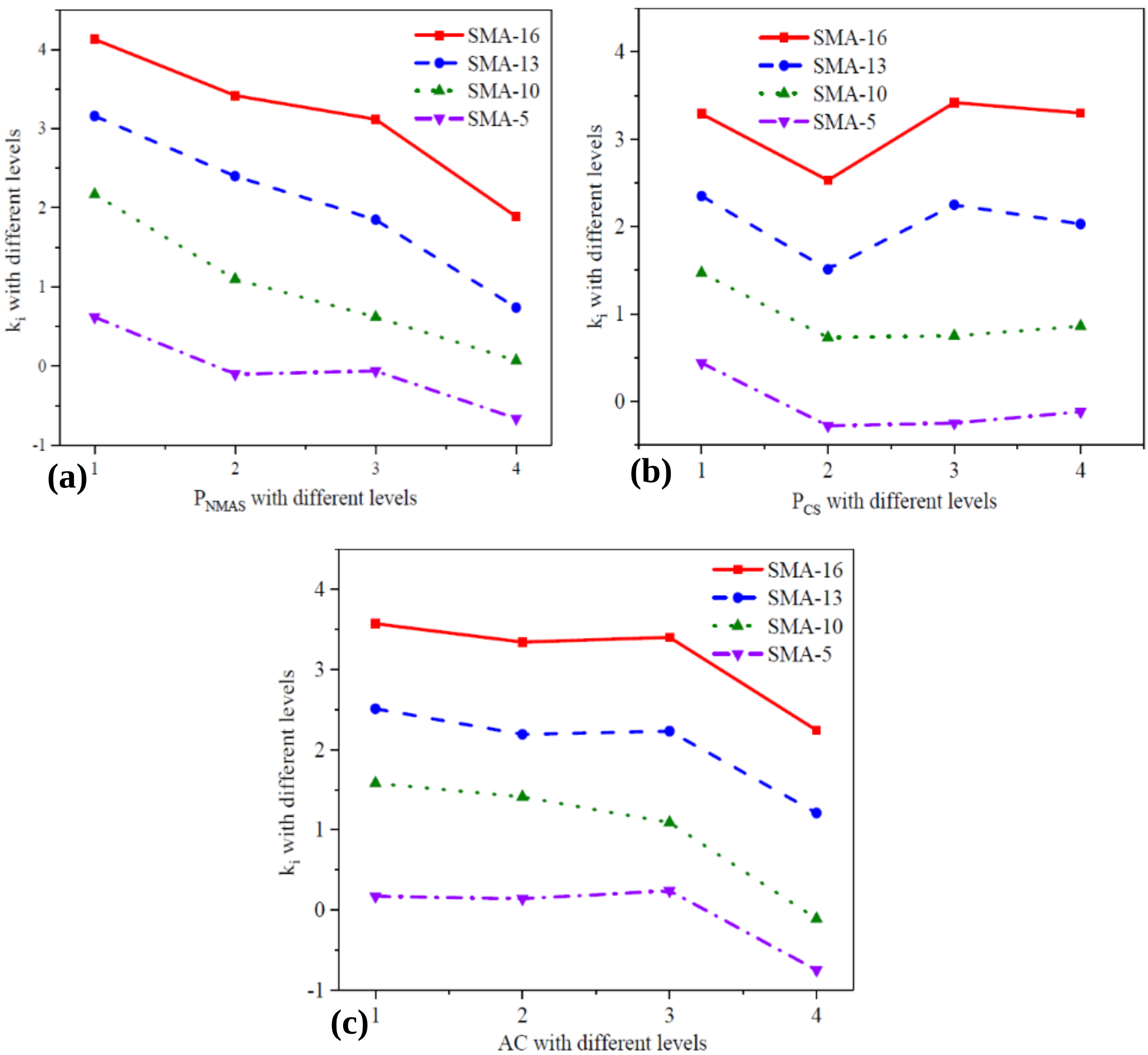

Figure 2- 6 Relationship between skid resistance and (a) PNMAS, (b) PCS, (c) AC of SMA pavement (Liu et al., 2019).

2.5 Distinguished performance indices by SMA mixtures

2.5.1 Durability

Durability is defined as the mixture's resistance to distresses and subsequent failures over the lifetime of the pavement layers under various loading and weather conditions. The majority of researchers' findings have confirmed that SMA has high durability, in addition to high rut resistance and improved resistance to reflective cracking (Nejad et al., 2010), see Plate (2-6).

Plate 2- 6 Reduced reflective cracking in SMA (right lane) versus conventional mix (left lane) (Watson, 2003).

Wu et al. (2017) showed the field performance of the SMA and HMA in the Eastern Region of Washington State Pavement Management System (WSPMS). From 2002 to 2020, the SMA performance curve is above the threshold, whereas the HMA performance curve exceeds the threshold, indicating that SMA outperforms HMA in the field. Table (2-1) and Figure (2-7) summarizes the rutting and cracking performance of these pavements as determined by the WSPMS.

Table 2- 1 SMA and HMA sections by field inspection (Wu et al., 2017).

Section	***Cracking (PSC)***	***Rutting (PRC)***	***Rut depth(mm)***
HMA	74	61	7.1
SMA	80	88	5.8

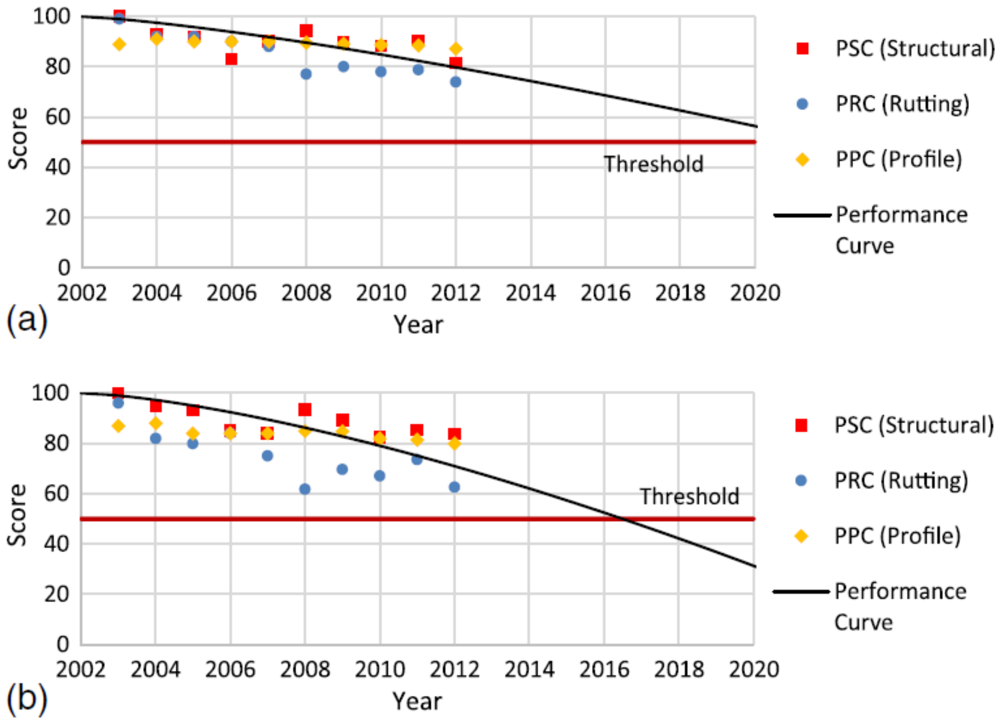

Figure 2-7 Field performance comparison by WSPMS, a) SMA, b) HMA (Wu et al., 2017).

Watson (2003) displayed that several SMA projects are still in good condition, condition after 5 and 9 years of service, Plate (2-7) depicts an SMA project that is still in excellent condition after 9 years of service with a traffic volume of 70,000AADT.

Plate 2- 7 Reduced reflective cracking in SMA (right lane) versus conventional mix (left lane) (Watson, 2003).

2.5.2 Stone-on-stone

The performance of SMA is primarily related to high particle packing, also known as the stone-on-stone effect (see Figure (2-8)), which has been identified as a key factor influencing the SMA's most important properties, namely rutting resistance, durability, permeability, and workability (Miranda et al., 2019).

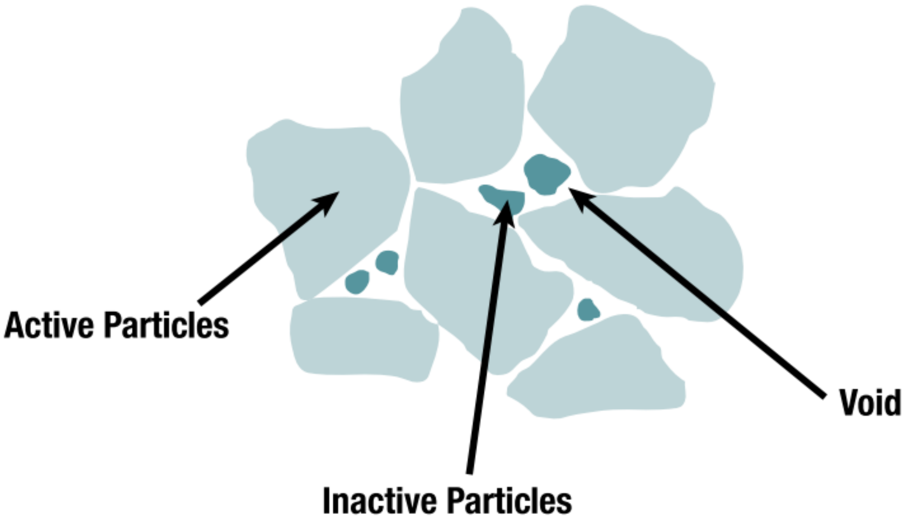

Figure 2- 8 SMA's stone-on-stone concept (NAPA, 2002).

Zhang et al. (2019) demonstrated that aggregates retained on sieve sizes of 2.36 and 4.75mm (typically used as breakpoint sieves in the stone-on-stone design) can contribute more than 50% to the traffic load resistance. Aggregates retained in sieve sizes ranging from 0.3 to 1.18mm, on the other hand, can contribute more than 50% to the stability of the stone-on-stone structure (Miranda et al., 2020). When compared to dense-graded asphalt, SMA can provide an extremely high rut-resistant and durable HMA mixture. This enhancement is realized in SMA by the formation of a stone-to-stone aggregate skeleton (Qiu et al., 2006).

As shown in Figure (2-9), three different structural types of asphalt can be distinguished based on their inner structure and load carrying function as suggested by Partl et al. (2012), Rilem state-of-the-art reports:

a. Mastic concept (no voids, stones "swim" in the binder, binder gluing dominates)

b. Packing idea (some voids, densest stone packing, friction between stones dominant)

c. Skeleton concept (high voids, gap graded stone skeleton, dominant lateral confinement).

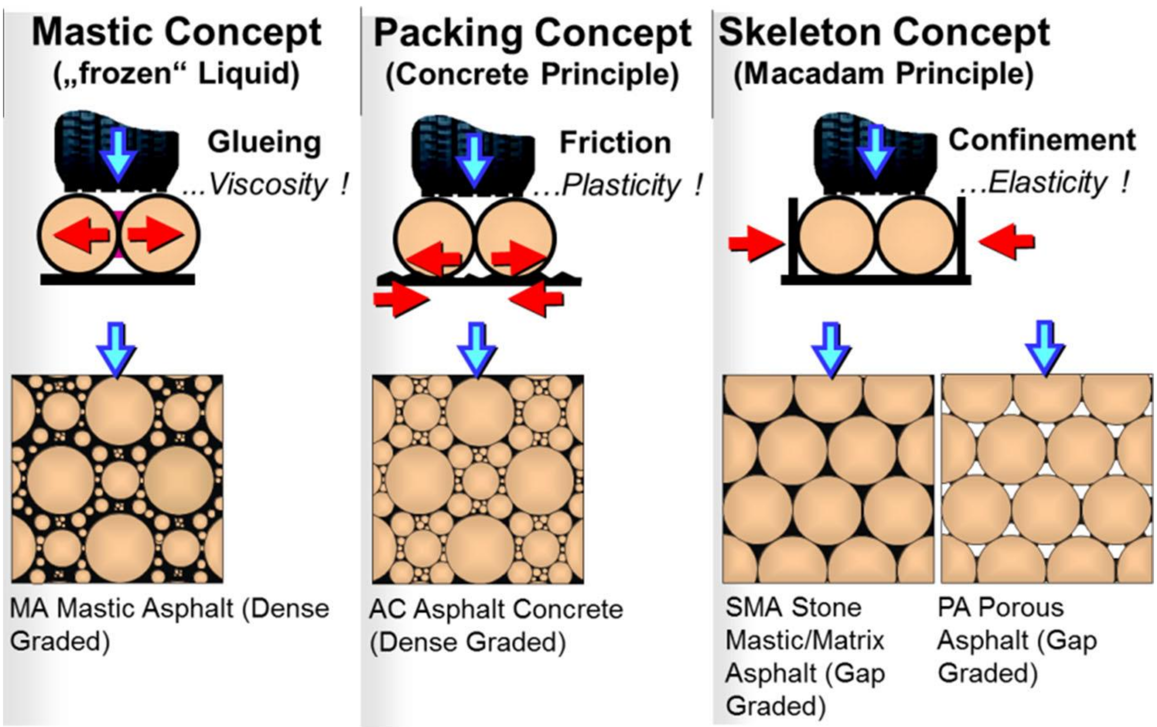

Figure 2- 9 Basic concepts for structural functioning of asphalt pavement mixtures (Partl et al., 2018).

In order to evaluate the stone-on-stone effect, several SMA studies and mix design methods have been developed (Van de Ven et al., 2003, Jacobs et al., 2004, Chen et al., 2017). Miranda et al. (2020) investigated nine SMAs with various optimized aggregate skeleton matrices. Figure (2-10) and Plates (2-8 and 9) show the SMA grading curves and aggregate skeleton matrix obtained for each SMA tested in this study for resistance to permanent deformation. Except for the S12-Gr, all SMA produced in this study exhibited a good stone-on-stone effect. In terms of resistance to permanent deformation, SMA with coarse aggregate optimized with Proctor did not clearly distinguish itself from dry-rodded and steel roller compaction.

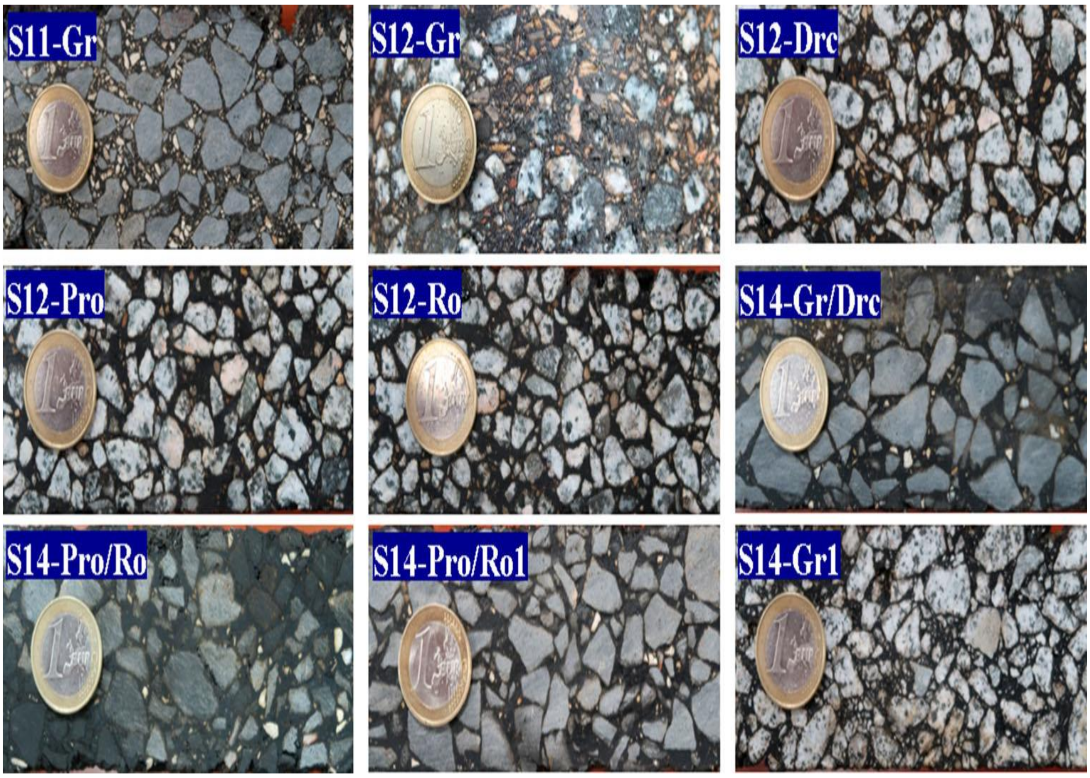

Plate 2- 8 SMA aggregate skeleton matrix (Miranda et al., 2020).

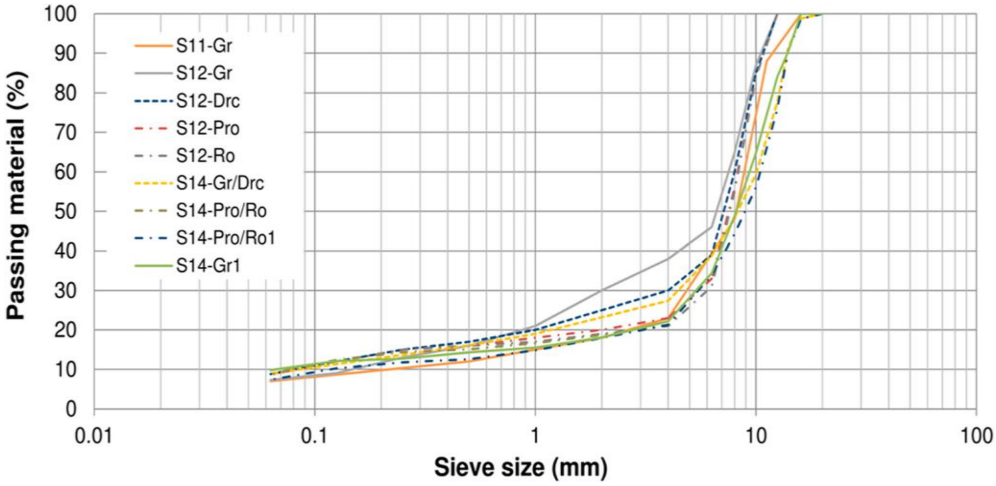

Figure 2- 10 SMA grading curves (Miranda et al., 2020).

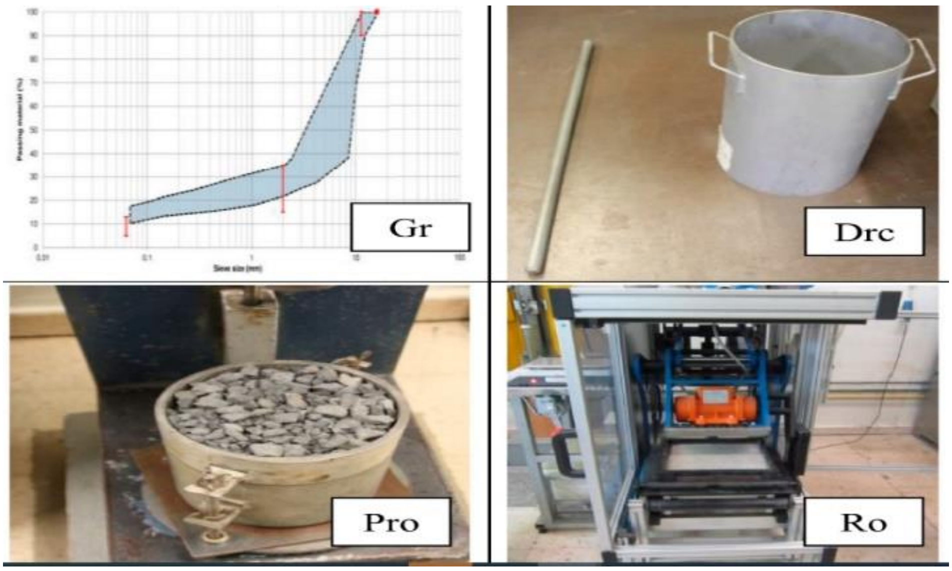

Plate 2- 9 Aggregate compaction methods(Miranda et al., 2020).

2.5.3 Binder drain-off

Draindown is an expression used to describe the downward migration of asphalt binder from around the aggregate particles during the production and construction stages, as well as when the mixture is subjected to elevated temperatures. SMA mixes, due to their high binder content, necessitate the use of a stabilizer to prevent excess binder drainage during the production, storage, transport, and paving phases of asphalt works (Jamieson et al., 2020). Fibers and polymers can be used to reduce the amount of draindown. As stabilizers, various polymers (such as styrene–butadiene–styrene (SBS), ethylene–vinyl–acetate (EVA), polyethylene, or polypropylene) have been successfully used. Polyester fiber, mineral fiber, and cellulose fiber are examples of fibers that are usually used as stabilizing additives in this type of asphalt mixture (Mokhtari et al., 2012). Binder drain-off requirements are typically specified as a percentage of stabilizer by mass, which is typically less than 0.3 % based on laboratory performance (Jamieson et al., 2020).

Several SMA studies have been developed in order to prevent drainage (Xue et al., 2013, Ahmadinia et al., 2012a, Dalhat et al., 2020, Rahman et al., 2020b). Mojabi et al. (2020) investigated the effect of this type of composite fibers on the prevention of SMA drainage using SBS polymer asphalt and non-fibrous and non-polymeric SMA. Figure (2-11) shows that the drain down of bitumen decreases as the amount of fiber increases in a drain down test. When compared to non-fibrous and non-polymeric asphalt, the sample containing 0.5 % C25 fibers has the least drain down of the samples, implying easier carriage and implementation of asphalt mixtures as well as better compressibility. Furthermore, the beneficial effect of cellulose fibers on the absorption and retention of excess bitumen around aggregates contributes to reduced drain down.

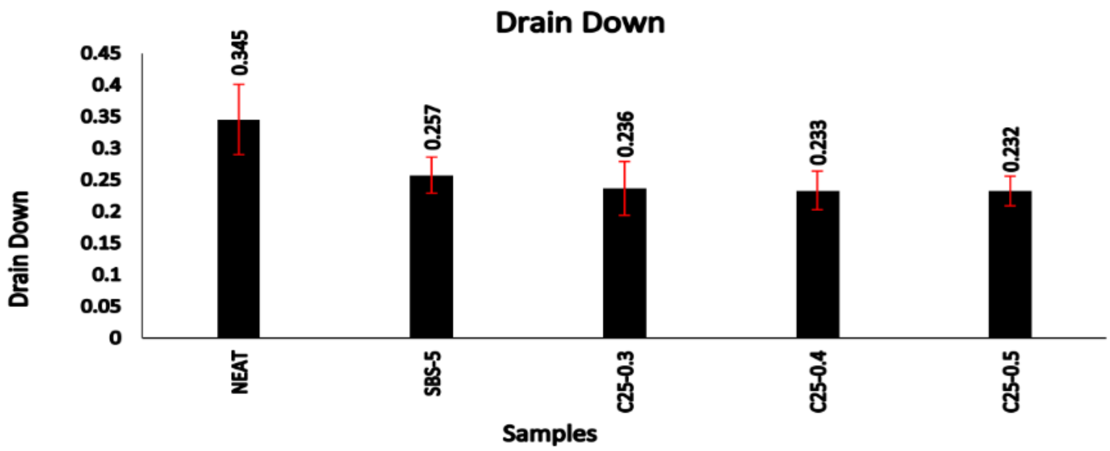

Figure 2- 11Draindown of prepared samples with different fiber and polymer dosages (Mojabi et al., 2020).

2.6 Applications of stone matrix asphalt mixtures

SMA mixture is suitable for the following uses (NAPA, 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 times 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 (2-12).

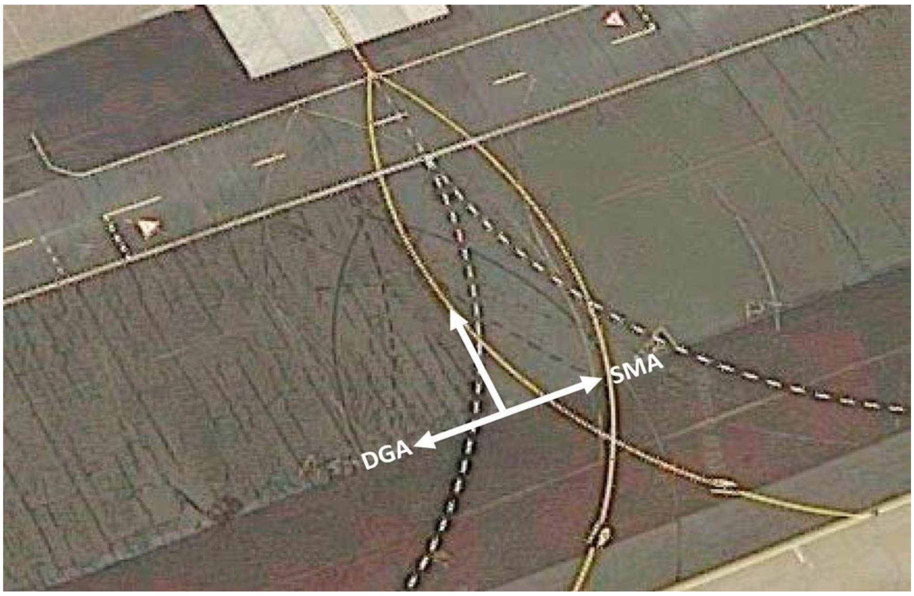

Figure 2- 12 Aerial image of Cairns airport–SMA Bay 19 compared to DGA (Jamieson et al., 2020).

2.7 Strength and weakness of SMA

SMA's rapid and widespread growth can be attributed to several undeniable advantages, including the following (Blazejowski, 2019):

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 macrotexture 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 Composition of SMA mixtures

2.8.1 Aggregate

Aggregates have a significant impact on pavement load transfer because they account for approximately 85 % of the total mixture volume of HMA. As a result, aggregate properties have a significant impact on HMA in general and SMA in particular. Angularity (shape), roughness (texture), and gradation are instances of these properties. Plates (2-10 and 11) show the morphological characteristics of aggregates and the grading used in SMA mixtures.

Plate 2- 10 Illustration of morphological characteristic of aggregates: (a) angular aggregates; (b) sub-round aggregates; (c) shape characterization (Wang et al., 2016).

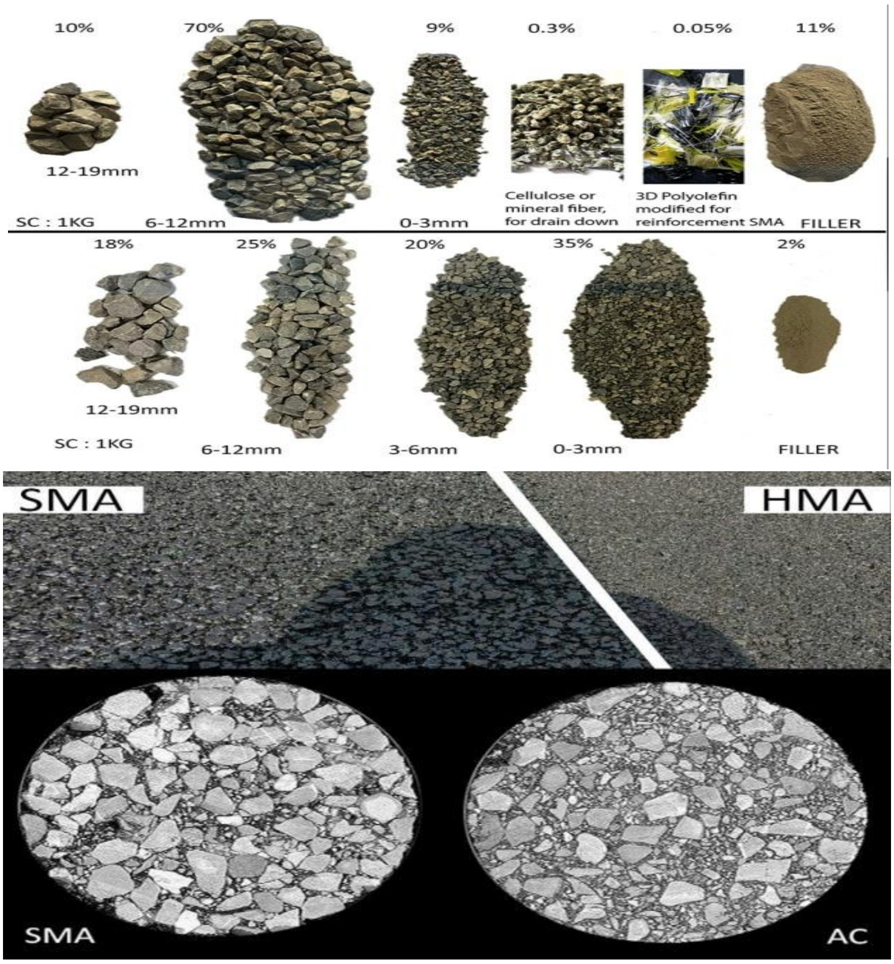

Plate 2- 11 Aggregate in SMA and AC
http://sirjannano.com/english/products/90/Asphalt-SMA-(Mastic).

The rutting resistance of asphalt pavements under environmental and traffic loads is closely related to the stability of the aggregate structure of SMA. The Strategic Highway Research Program SHRP classifies aggregate characteristics such as gradation and shape as two of the most important factors influencing the stability of HMA (Pan et al., 2006).

Aggregates play a significant role in providing the SMA mixtures with the required strength because they make up a larger portion of the matrix. The coarse aggregate content of SMA accounts for 70-80% of the total stone content. In contrast with dense graded asphalt mixtures, as the coarse aggregate skeleton creates a structural framework that offers good contact between aggregate particles (i.e., better stone-on-stone contact). That in turn resulting in improved the shear strength, resistance to cracking, and efficient loading patterns for vehicles to withstand heavy traffic load.(Sarang et al., 2015b, Liu et al., 2017).

Previous research works have discovered that 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 (Adiseshu et al., 2011, Wang et al., 2016). Cubic particles (polyhedral) are contributing to providing good internal friction properties, as well as, enhance the resistance to permanent deformation to the used aggregate. While, the flat and elongated aggregates work on reducing the interlock between aggregate particles, and as well, the breakdown of it, that in turn affects the mechanical properties of the aggregate structure (Chen et al., 2013a). Therefore, the aggregate angularity is the more familiar aggregates used in the design of asphalt mixtures due to their ability to provide aggregate particle interlock. As asphalt mixtures containing angular aggregates have higher shear resistance than those without them. Rougher aggregate surfaces promote particle-to-asphalt binder interface connection, which helps in overcome or reduce the problems related to workability and fatigue defects of asphalt mixtures (Tutumluer et al., 2005, Bessa et al., 2015). Moreover, from the point of comparison between the sharp-angular and flat-elongated aggregates, Kogbara et al. (2016b) stated that the sharp and angular aggregates particles are the better one because they can help in offering better interlock and surface texture versus the elongated and flat aggregates that presenting a lower texture depths.

Based on laboratory performance test results from the eight types of SMA mixtures, Liu et al. (2017) investigated coarse aggregate morphological properties such as sphericity, flatness ratio, elongation ratio, angularity, and texture. It was found that the careful selection of morphological characteristics of coarse aggregates appears a clear enhancement in the resistance of mixture to fatigue and rut. The regression analyses displayed that the angularity, sphericity, and texture possess a significant impact on the rut depth. As well, it indicated that the usage of more angular, equidimensional, and rougher coarse aggregates improved the resistance of SMA mixtures against permanent deformation. As it can be seen in Figure (2-13).

The used aggregates in SMA mixtures should have the following properties (Cao et al., 2013, Mu et al., 2020):

a. A highly cubic shape with a rough texture that resists rutting and movement
b. A hardness that can withstand fracturing under high traffic loads.
c. a high level of polishing resistance
d. High abrasion resistance

Additionally, another most important factor influencing the performance of an asphalt mixture is the gradation of the aggregate, aggregate gradation is not only important for volumetric properties, it is also a determining factor in asphalt mixture performance. Asphalt mixture stiffness, stability, durability, permeability, workability, fatigue resistance, skid resistance, and moisture sensitivity are all known to be affected by aggregate gradation (Kandhal et al., 2001). The best gradation is difficult to define 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 et al., 2015). The NMAS is a critical criterion for determining SMA thickness. It is one sieve size larger than the first sieve that retains more than 10% of the aggregate material (Institute, 2014b). The ratio of NMAS to SMA thickness should be kept between 3:1 and 5:1 to ensure adequate compaction (Brown, 2004, Im et al., 2015).

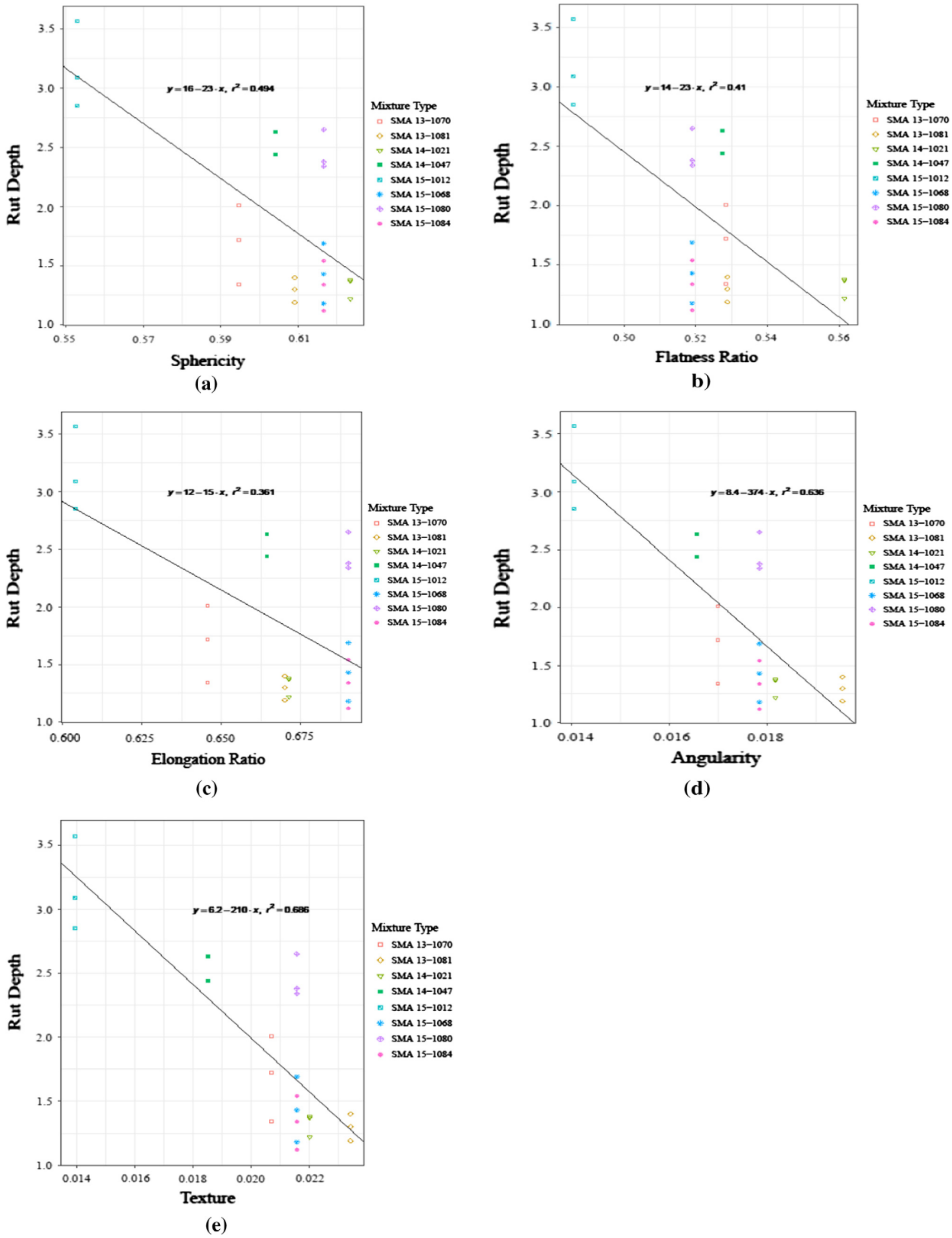

Figure 2- 13Relationships between rut depth and morphological characteristics: (a) Sphericity, (b) Flatness Ratio, (c) Elongation Ratio, (d) Angularity, and (d) Texture.(Liu et al., 2017).

Moreover, HMAs with a larger maximum aggregate size have better resistance to permanent deformation than mixes with smaller maximum aggregate size. The effect of NMAS on SMA designed mixtures is very interesting. A laboratory investigation into the Wear Stone Mastic Asphalt Road surfacing material was summarized by Woodward et al. (2016). Using the Road Test Machine, they discovered that 14 mm and 10 mm SMA behave similarly. The main distinction is that SMA14 has a greater possible macrotexture.

2.8.2 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 (Martin et al., 2006, Kalantar et al., 2012). 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 (2-14) display a description of the asphalt structure and its formations (Read et al., 2003, Nejres et al., 2020).

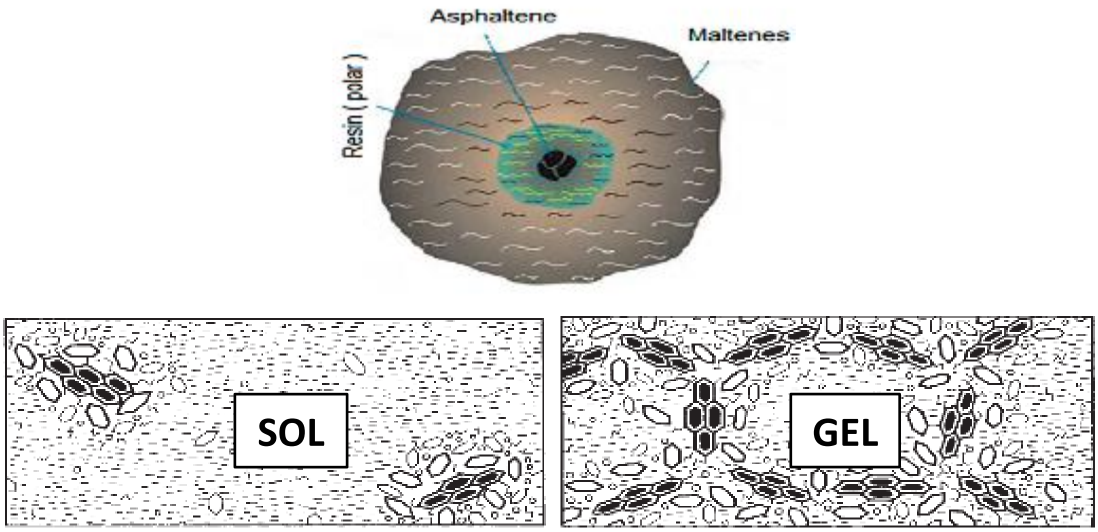

Figure 2-14 Representation of the asphalt structure and its SOL, and GEL forms (Read et al., 2003, Nejres et al., 2020).

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 draindown problems (Sarang et al., 2015b, Devulapalli et al., 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 (Kumar et al., 2011, Cong et al., 2012, Ameri et al., 2016, Zhang 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 (Panda et al., 2002a, Andrés-Valeri et al., 2018). 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 (Arabani et al., 2017c).

2.8.2.1 Modified Asphalt Binder

Many asphalt researchers around the world have suggested various modifiers with asphalt binders to improve their properties and performance over the last four decades. Asphalt binder is a sensitive material distinguished by its viscoelastic properties, susceptibility to aging, and mechanical response dependent on loading time and temperature(Diab et al., 2019). This action may result in the emergence of more potential failures such as rutting, fatigue, and rutting under repeated traffic loads. As a result, the use of various modifiers, such as virgin polymers, fibers, and ashes (including recycled), can help improve its properties and increase pavement service life (Cong et al., 2012, Ameri et al., 2016). The final properties of polymer modified bitumen are determined by the characteristics of the bitumen and polymer, the manufacturing processes, and the amount of used polymer (Zhu et al., 2014). Polymers included plastomers (e.g.

polypropylene (PP), polyethylene (PE), ethylene–butyl acrylate (EBA), ethylene–vinyl acetate (EVA)) and thermoplastic elastomers (e.g. styrene–isoprene–styrene (SIS), styrene–butadiene–styrene (SBS) and styrene–ethylene/butylene–styrene (SEBS)) (Tapkın, 2008) . SBS polymer has a high degree of compatibility and tensile strength under strain. It has the ability to increase the elasticity of asphalt and improve its performance at low temperatures (Yildirim et al., 2007). Rahman et al. (2020a) disclosed that combining ground rubber with asphalt mixture improved rutting resistance, as shown in Figure (2-15).

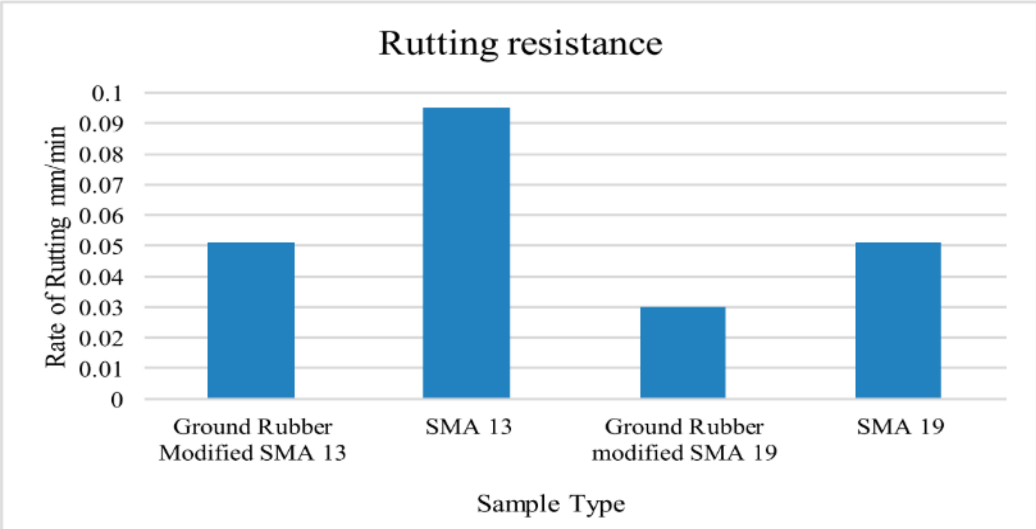

Figure 2- 15 Rutting rate for SMA modified with ground rubber (Rahman et al., 2020a).

Polyethylene (PE) is the most widely used plastic in the world; it is a semi-crystalline material with noticeable chemical, fatigue, and wear resistance, as well as low moisture absorption rates. When used to improve asphalt pavement, this material works to increase the fatigue resistance, improve adhesion between the asphalt binder and the aggregate, and reduce pavement deformation. Polyethylene has a very simple structure, consisting of a long chain of carbon atoms linked by two hydrogen atoms. Polyethylene types are classified based on density: Low-

Density Polyethylene (LDPE), Linear Low Density Polyethylene (LLDPE), and High Density Polyethylene (HDPE) (Yang et al., 2014). Figure (2-16) shows LDPE structure.

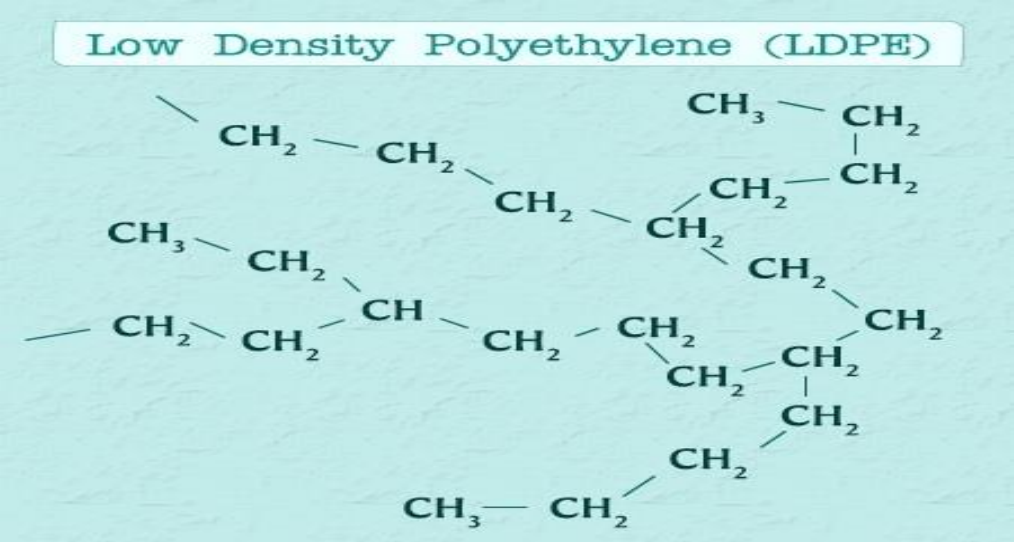

Figure 2- 16 LDPE Structure (https://sciencestruck.com/ldpe-vs-hdpe).

LDPE is commonly used in the manufacture of carrying bags for household goods. After using these bags, they become solid waste, posing a significant environmental risk (Panda et al., 2002b). For example, plastic bags were discovered to account for the majority of plastic waste in Australia, with approximately 30 million bags consumed annually. In Europe, according to statistics, approximately 3 million tons of plastic bags were produced in 2008, but only 6% of them were recycled (Jamshidi et al., 2020). To mitigate the impact of this issue, even partly, on the one hand, and to develop the performance of asphalt pavements on the other, waste LDPE from carrying bags was used to modify asphalt cement. A search of the literature revealed that there are only a few researchers working on studying the properties of asphalt mixtures modified with LDPE polymer. Al-Busaltan et al. (2020) stated that using recycled LDPE in different proportions (1,2,3,4,5, and 6%) reduces significantly the draindown property of modified mixtures, see Figure (2-17).

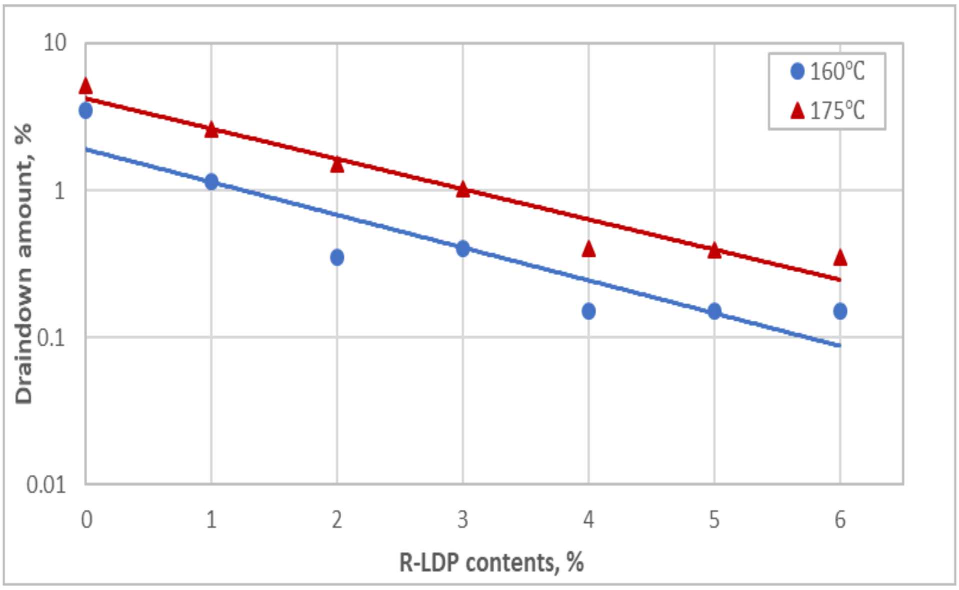

Figure 2- 17 Drainage of RM and R-LDP modified OGFC mixtures (Al-Busaltan et al., 2020).

Al-Hadidy et al. (2009a) studied the impacts of LDPE on SMA mixtures, and lab tests such as Marshall, moisture sensitivity, and low-temperature cracking were then conducted to assess the performance of SMA samples constituted. A mechanistic-empirical method was used to assess the benefit of modification. According to their findings, LDPE could decrease binder drain down and enhance the properties of asphalt binder and SMA mixtures; 6 percent LDPE was discovered to be the better dose for constructing SMA mixtures. Besides that, the addition of LDPE to the SMA mixture increased the life of the pavement by 1.359 times when compared to the unmodified SMA mixture.

Ahmadinia et al. (2012b) examined the impact of used plastic bottles (PET)) on SMA, included various percentages of PET waste as 0 %, 2%, 4%, 6%, 8%, and 10% by weight of bitumen content. The results showed that incorporating waste PET into the mixture has a significant positive effect on the properties of SMA, potentially increasing the mixture's resistance to permanent deformation Figure (2-18) depicts the results of the wheel tracking tests show that the waste PET mixture is significantly more rutting resistant than the conventional mixture. When compared to the conventional mix, the mix containing 4% PET had the lowest rut depth, which was reduced by 29%.

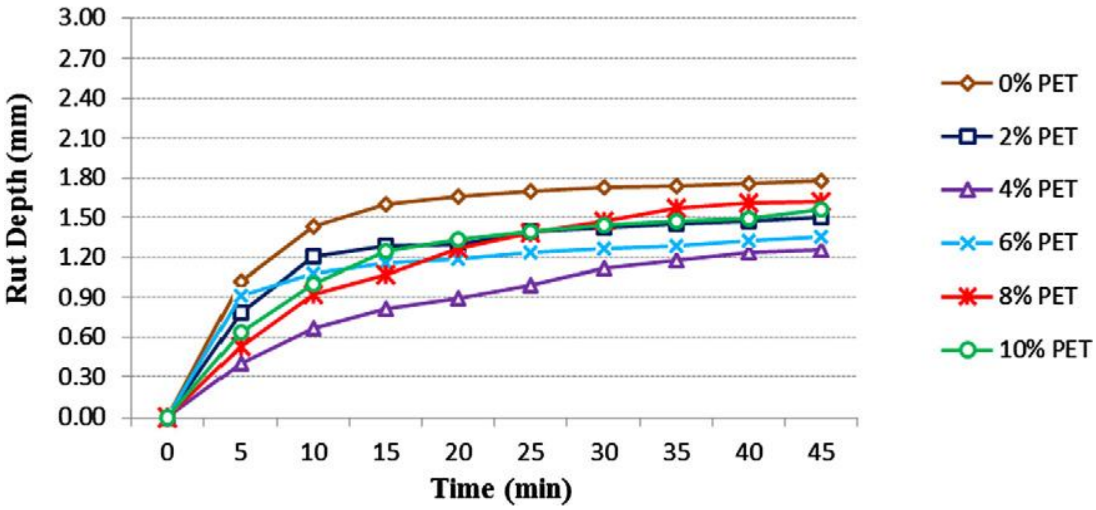

Figure 2- 18 Wheel track test results of SMA comprising PET (Ahmadinia et al., 2012b)

Besides, the addition of fibers to the binder or bituminous mixtures ensures their mechanical strength and stability. A sufficient amount of fibers alters the properties of the asphalt, reducing penetration and increasing softening point. It also alters the ductility and viscoelasticity behavior of the bitumen. Furthermore, adding fibers to asphalt concrete increases its dynamic modulus, reinforces the mastic, and reduces thermal susceptibility, while improving material strength, fatigue behavior, and ductility. Furthermore, fibers have been found to reduce binder drainage, beside increasing moisture resistance and compressive strength in SMA mixtures (Slebi-Acevedo et al., 2019).

A Large number of fibers to produce fiber-modified asphalt binders are available, such as lignite, polyester, polyacrylonitrile, carbon, brucite, cellulose, glass, aramid, steel, waste fibers, and hybrid (Mohammed et al., 2018b). Fibers are objects with a high aspect ratio (length/diameter) (Stokke et al., 2013, Elseify et al., 2019). Natural fibers and man-made fibers are the two types. Natural fibers come from natural sources. Natural fibers are classified into two types: protein fibers derived from animal resources, such as wool, hair, and silk, and cellulosic fibers that derived from plants, such as jute, flax, hemp, and date palm (Elseify et al., 2019). There are different types of cellulosic that differ between them with the different plants adapted to produce them. For example, fibers named by bast fibers that derived from the stem and fibers that derived from the leaves are denoted by leaf fibers. Besides that, Figure (2-19) demonstrates other types of plant fibers like fruit, seed, stalk, or grass(Long et al., 2013).

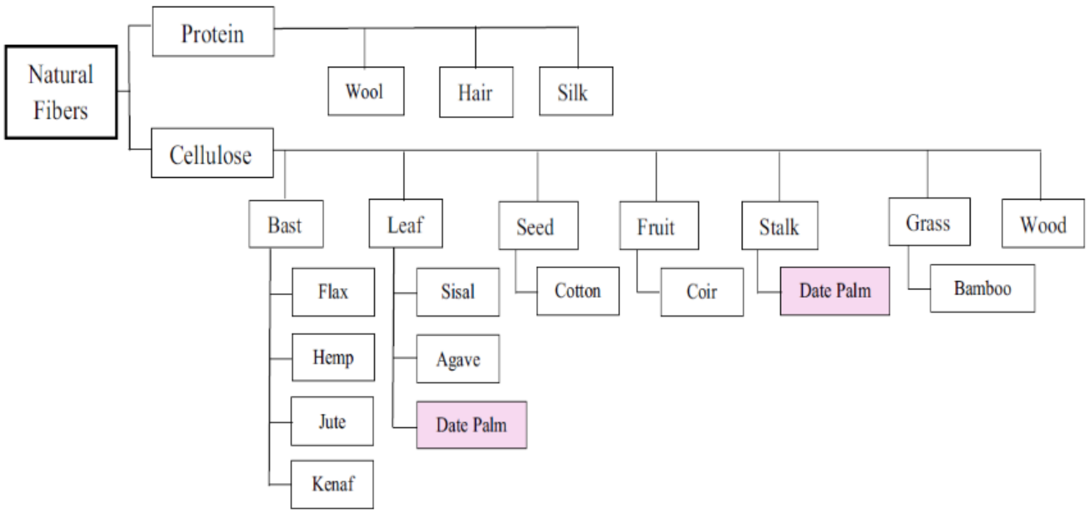

Figure 2- 19Natural fiber classifications illustrating the origins of date palm fibers (Al-Oqla et al., 2014).

Lignocellulosic fibers or Cellulosic natural fibers possess a composite structure consists of three major inorganic components: hemicellulose, cellulose, and lignin, as represented by Figure (2-20). Where the cellulose encircled by hemicellulose and integrated in lignin as a matrix (Stokke et al., 2013). Lignin is an amorphous organic polymer composed of aromatic and aliphatic chains. Lignin is an organic glue that connects the cellulose fibers. Non-woody plants have a weight fraction of 10–25% Lignin, while woody plants have a weight fraction of 20–30 %. Hemicellulose connects the cellulose microfibrils to the lignin. Cellulose is made up of many covalently linked glucose anhydride molecules. It has a unit weight that ranges from 30% to 45 %.

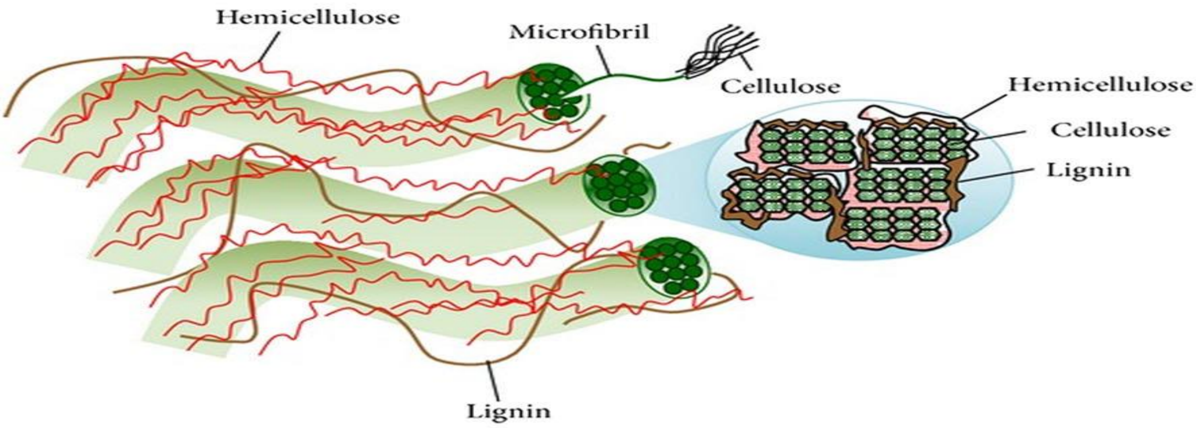

Figure 2- 20 The microstructure of natural cellulosic fibers (Cheng et al., 2014)

Natural fibers can also be divided into two types. First, some fibers are present in the form of fibers. Then there are fibers embedded in a natural matrix. Fibers of the first type are used immediately because they are already in fiber form; they do not require further extraction and may only require washing, drying, and cutting. The second type, on the other hand, necessitates additional processing via a variety of extraction or separation methods. Chemical, biological, or mechanical approaches could be used (Nishino, 2017).

Researchers studied the effect of incorporating fibers into asphalt to improve its properties, such as Afonso et al. (2017) who investigated the effect of cellulose fibers. In general, they discovered that fiber properties (i.e., length, adhesion, absorption, and swelling) play an important role in forming the three-dimensional network into asphalt molecules, and then works on bonding these molecules with each other, as confirmed by others (Chen et al., 2008b). This, in turn, increases the interlock between the asphalt binder and aggregate particles, improving the mixture's resistance to moisture, fatigue, thermal cracking, and rutting (Yu et al., 2010, Alrajhi, 2012), as well as aiding in the elimination of the binder-aggregate separation phenomenon (Putman et al., 2004, Alvarez et al., 2009).

The paper industry generates a large amount of waste, which has the potential to have serious environmental consequences. The European Union generates 11 million tons of waste per year, with the paper recycling industry accounting for 70% of this total. Some of these wastes have a high reutilization potential; as a result, some studies into the use of this type of waste in road construction have been conducted in the last decade (Zhang et al., 2015, Larsson et al., 2015). Pasandín et al. (2016), Chew et al. (2020b) studied the influence of Paper on properties of asphalt mixture, they concluded that using these materials as fillers increases the viscosity of asphalt mastics, Marshall stability, and the stiffness modulus, as well as improving the resistance to rutting of asphalt mixtures by increasing the adhesion between asphalt binder and aggregate.

The morphology of the surface produced by the composites and fibers is examined using SEM to determine the fiber's ability to act as a good reinforcement. When scanning with an electron beam focused across the surface and detecting the secondary or backscattered electronic signal, SEM produces detailed high-resolution images of the fibers (Sanjay et al., 2019), see Plate (2-12).

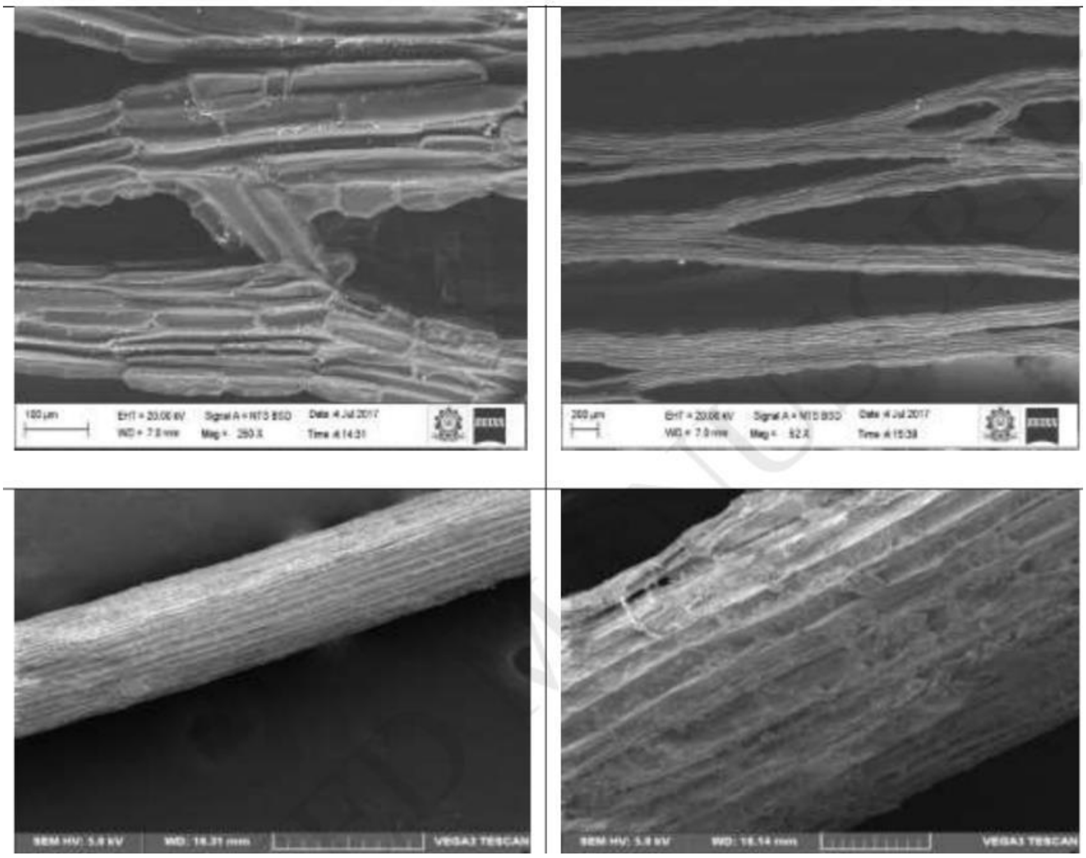

Plate 2- 12 SEM micrographs of a natural fiber (Saravanakumaar et al., 2018, Manimaran et al., 2018, Manimaran et al., 2019).

2.8.3 Mineral Filler

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 draindown in the mix throughout building projects, that also enhances the mix's durability by retaining the original amount of asphalt used in the mix. (Zeng et al., 2008).

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). Plate (2-13) shows different filler types with their scanning electron microscopy.

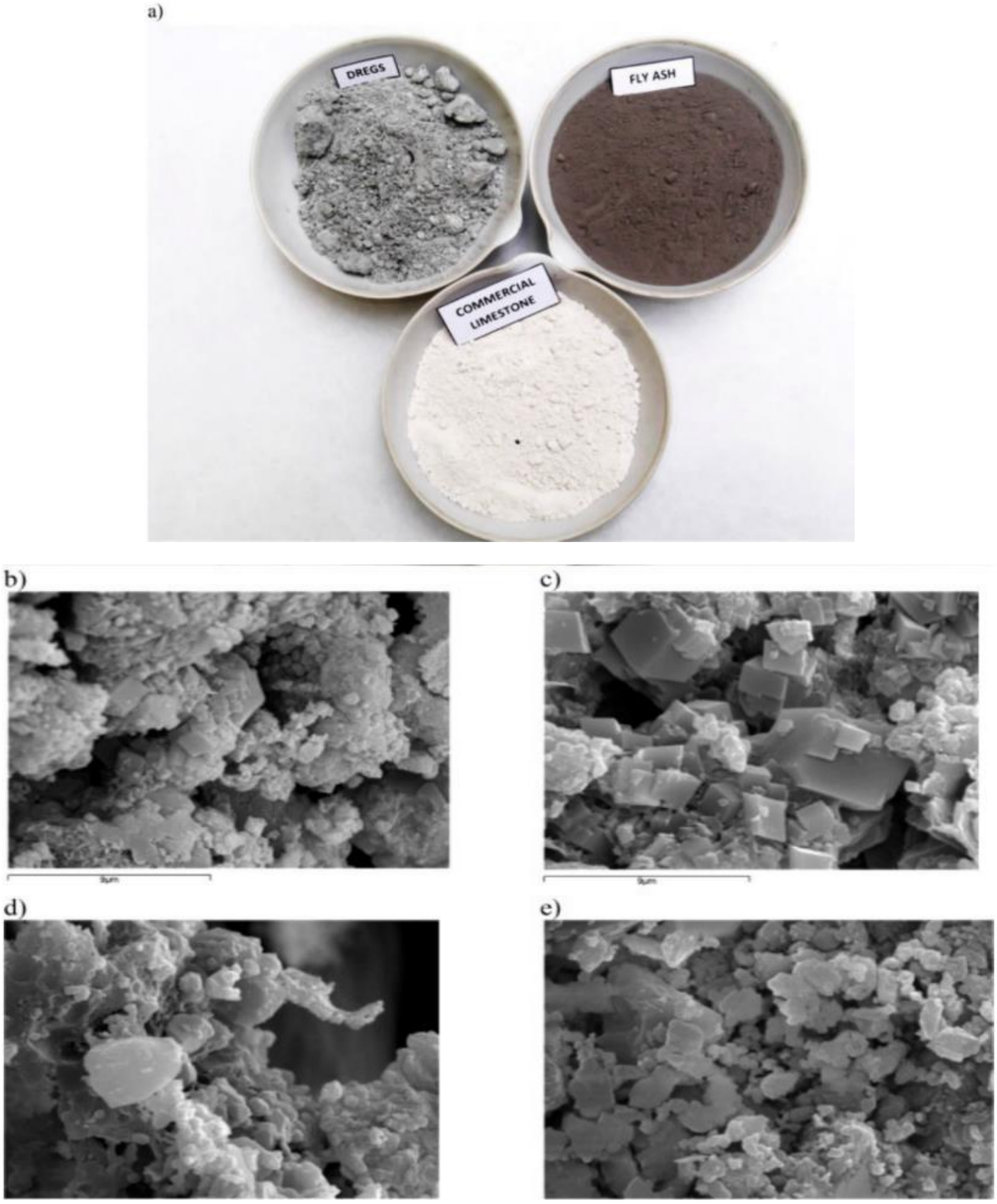

Plate 2- 13 Fillers(a)filler types (b–e) SEM of the three fillers: (a) dregs, fly ash, and commercial limestone; (b) dregs, (c) detail of cube-shaped crystals of dregs; (d) fly ash; and (e) commercial limestone (Silvestre et al., 2013).

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 (2-21).

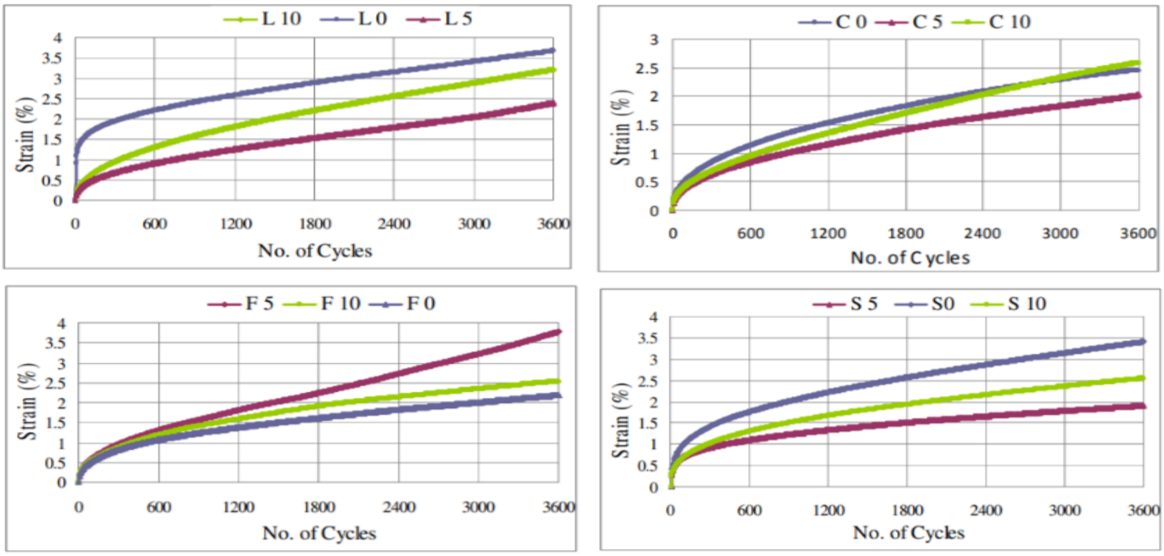

Figure 2- 21 Axial strain versus number of load cycles for SMA Mix with limestone as control, ceramic waste, coal fly ash, and steel slag (Muniandy et al., 2012).

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 (2-22), 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.

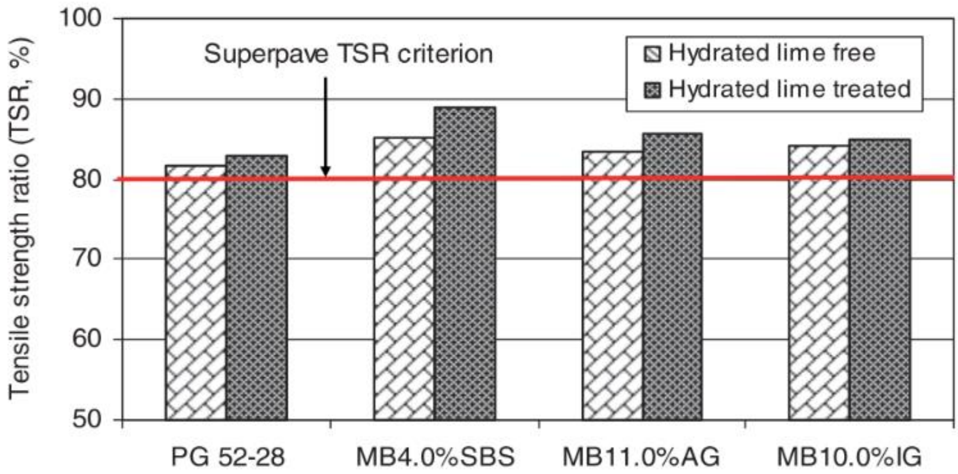

Figure 2- 22 Tensile strength ratio values of mixtures (Yilmaz et al., 2015).

2.9 Resistance of SMA for Different Types of Distresses

Pavement lifespan is a critical issue for a country's economy. The United States spends $25 billion per year on road maintenance and traffic services. A quality pavement should have a smooth riding profile, be able to withstand high traffic volumes, and efficiently transfer stress to the underlying sub-grade support. Although the behavior of bituminous mixtures under traffic and environmental conditions is highly complex, the factors that affect their performance have been thoroughly studied. Bituminous mixtures must be able to distribute distresses in order to perform satisfactorily in a pavement system, resistance to cracking, and resistance to moisture damage. Asphalt pavement distress and other flaws are a major engineering and economic concern. Excessive cracking from fatigue and rutting from permanent deformations are the most common types of damage (Kok et al., 2007). In Europe, SMA has been in use for more than 40 years. SMA was first used in Europe as a mixture to resist wear by studded tires, but it also had the added benefit of being durable and highly rut resistant. SMA crushed aggregate has a gap grading that allows for mechanical interlocking and rut resistance. A large portion of the high VMA is occupied by mastic, which is composed of asphalt, mineral filler, and fiber (voids in mineral aggregates). The mastic prevents the mixture from being permeable aids in crack resistance (Chen et al., 2015, Jamieson et al., 2020), Plate (2-14).

Plate 2- 14 Minor Distresses of Pavement Surface (Chen et al., 2015, NAPA, 2002

2.9.1 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.

2.9.2 Rutting

Rutting refers to the permanent deformation of pavement layers that can occur over time. It is caused by deformation in one or more asphalt pavement layers. Surface rutting refers to the uppermost layer, whereas structural deformation refers to the main component of deformation that originates in the sub-grade. Deformation in the underlying aggregate base or subgrade causes rutting (Institute, 2014b). Figures (2-23, 24) depict rutting caused by a weak subgrade or underlying layer.

Defects in HMA, where mixtures are not properly designed, produced, or placed, can also cause asphalt pavement distresses. Moisture damage, low air voids, poor quality aggregate, and poor construction practices can all cause excessive permanent deformation within one or more asphalt layers (Sousa et al., 1991).

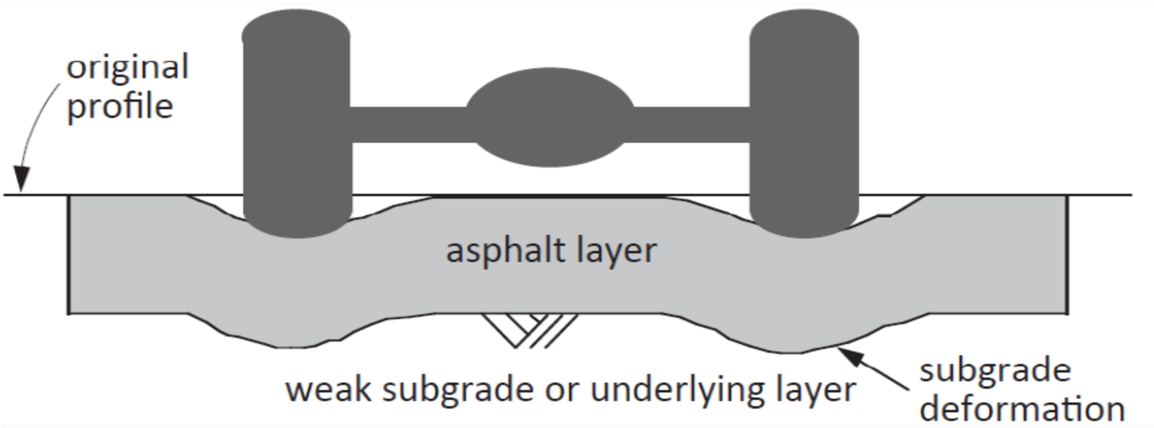

Figure 2- 23 Rutting from Weak Subgrade (Institute, 2014b).

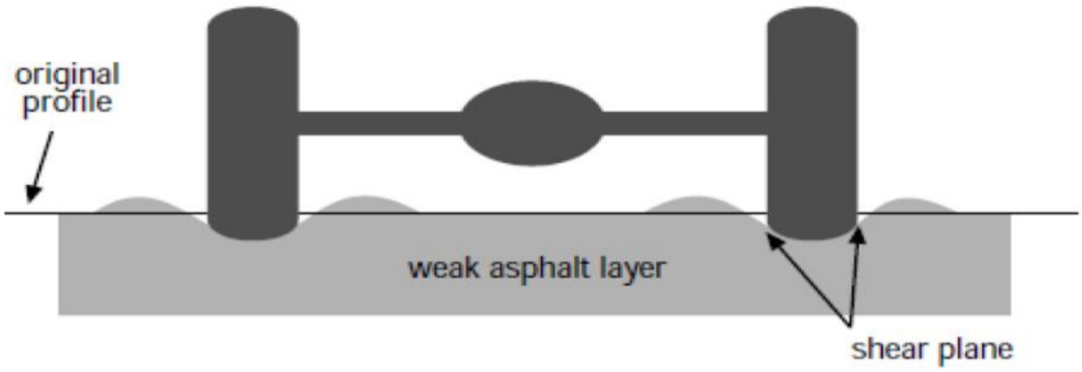

Figure 2- 24 Rutting from Weak Subgrade (Institute, 2014b).

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.

2.10 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. The researchers concentrated on the use of cellulose fibers and other substances in SMA blends to prevent the binder slurry from draining out. Applications Paper fibers, which are primarily composed of cellulose, are examples of unconventional fibers. It is broadly and inexpensively available around the world, but it is not mentioned in the literature, particularly in SMA blends. As a result, it was suggested that this material be used as a stabilization additive in the preparation of SMA mixes. It would alleviate the solid waste management problem to a large extent while also investigating the probability of using non-traditional waste materials in a non-traditional mix like SMA.

Chapter Three

Materials, 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 fulfil 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 Aggregate

The aggregates used to fabricate SMA mixtures in this research are crushed limestone aggregates that were supplied from Karbala quarries. 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 Kerbala laboratories. The test results for both aggregates are shown in Table (3-1).

Table 3- 1 Physical properties of coarse and fine aggregates.

Aggregate's properties testing	***ASTM Specifications***	***Results***		***requirements***	
		coarse	***Fine***	***coarse***	***Fine***
Bulk specific gravity of coarse aggregate(gm/cm³)	C127 (ASTM, 2015b)	2.59		–	
Bulk specific gravity of fine aggregate (gm/cm³)	C128 (ASTM, 2015b)		2.641		–
Water absorption of coarse aggregate (%)	C127 (ASTM, 2015b)	2.251		5 max	
Water absorption of fine aggregate (%)	C128 (ASTM, 2015b)		2.41		–
Los Angeles abrasion value (%)	C131 (ASTM, 2003a)	25.5		30max	
percentage of fractured particles in one side, %	D5821 (ASTM, 2013c)	100		100	
percentage of fractured particles in two sides, %	D5821 (ASTM, 2013c)	95		90	

For filler, this portion of aggregate has a more impact on the asphalt mixture properties. Where the selection of the suitable filler in terms of acceptable physical and chemical composition, as well as, the right gradation and shape, making the mixture gained preferable properties. As it leads to improving the resistance of the mixture to water damage, increased bearing strength, increased bitumen viscosity, and reduced mixture brittleness (Modarres et al., 2015). Generally, the content finer than 0.075 mm is commonly referred to as filler in practical applications (Institute, 2014a). In this study two types of fillers were used in a compound form: one is Conventional Mineral Filler (CMF) and the other is Hydrated Lime (HL). The CMF generally represents the remaining material on the pan after the screening process of the used aggregates, while HL was gotten from the Furat Lime Plant. An amount of 1.5% from total aggregate weight was adopted from HL as a filler in this study as recommend by GSRB R9 specification (GSRB, 2003). The physical and chemical properties of these fillers are summarized in Table (3-2).

Table 3- 2 Physical and chemical properties of fillers used.

Chemical properties		
Oxide/property	**Concentration/amount**	
	CMF*	**HL***
SiO_2	81.892	0.891
Al_2O_3	3.784	-----
Fe_2O_3	1.923	2.254
CaO	7.371	90.586
MgO	3.455	3.602
K_2O	0.736	0.589
Na_2O	0.192	1.002
Physical properties		
Density (g/cm3)	2.650	2.300
Surface area (m2/Kg)	224	1240
* Chemical and physical tests of fillers were conducted at the University of Technology/ Materials Engineering Department		

Moreover, the other part that affects the mixture properties is the selection of proper aggregate gradation. Where, the suitable aggregate gradation provides a large space for the air voids volume in the asphalt-aggregate mixture, meanwhile, achieve the design air voids desired to permit the thermal expansion of the asphalt within the mixture during hot weather (Institute, 2014a). The aggregate with NMAS of 12.5 mm was adopted here according to the limits suggested by AASHTO M325 (AASHTO, 2012), gradation is illustrated in Table (3-3) and Figure (3-1). It is worth mentioning that a gradation finer than mid limits was selected to satisfy the required volumetric properties.

Table 3-3 Gradation of SMA mixture as recommended by AASHTO M325 (AASHTO, 2012).

Sieve (mm)	**Size (in)**	**%Percent passing**	**% of Passing/ selected gradation**
19.0 mm	[3⁄4 in.]	100	100
12.5 mm	[1⁄2 in.]	90 – 100	93
9.5 mm	[3⁄8 in.]	50 – 80	60
4.75 mm	[No. 4]	20 – 35	25
2.36 mm	[No. 8]	16 – 24	18
0.075 mm	[No. 200]	8 – 11	9

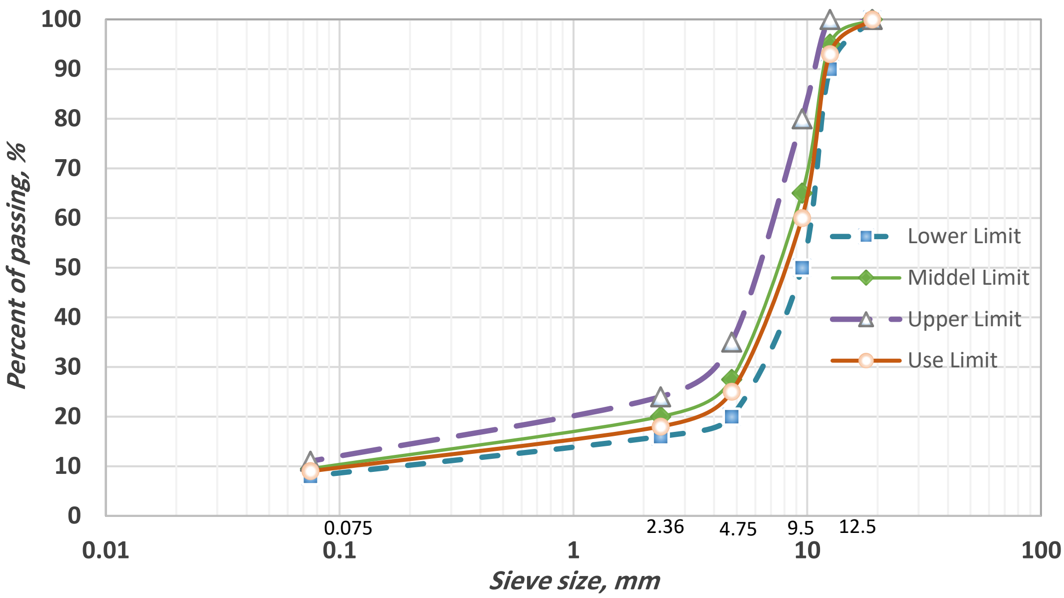

Figure 3- 1 Aggregate gradation limits suggested by AASHTO M325 (AASHTO, 2012).

3.2.2 Neat and modified bitumen

The bitumen usedin this study was supplied from the Al-Nasiriya plant, with penetration grade of 40/50, which is commonly adopted in Iraq for dense graded HMA. It was suggested in the research to fulfill the requirements of SMA mixture design as a control binder. The physical properties of neat bitumen (B0) are represented by Table (3-4).

Table 3- 4 Physical properties of neat bitumen (B0).

Property	***Specification***	***Amount***	***SCRB requirements***
Penetration, 25℃, 0.1mm	ASTM D5-D5M (ASTM, 2013a)	42.8	40-50
Softening point, ℃	ASTM D36-95 (ASTM, 2009a)	44	_
Ductility, 25℃, cm	ASTM D113-07 (ASTM, 2007)	143	>100
Flash point, ℃	ASTM D92-05 (ASTM, 2005)	355	>232
Rotational viscosity	ASTM D4402 (ASTM, 2002a)	860	≤ 3000 centistokes
Specific gravity	ASTM D70-09 (ASTM, 2009)	1.03	_
Loss on heat			
Penetrationagingindex (PAI)	ASTM D1754/D1754M (ASTM, 2014)	0.76	_
Softening point index (SPI)	(Cong et al., 2012), (Zhang et al., 2018)	4.6	_

For modified bitumen (MB), two modifiers were added to stabilize the neat binder for suitable and efficient uses of SMA mixture applications, as shown below:

3.2.2.1 Recycled -Low-Density Polyethylene (R-LDPE)

LDPE is a type of polyethylene material that comes from the polymerization process of ethylene that is forming a long chain from one monomer (Othman, 2010, Akinci et al., 2011). it is the main content of nowadays facilities, such as goods bags. R-LDPE is characterized by its availability and low cost, as can be gotten it from the recycling of bags of domestic goods after becoming a solid waste. The use of R-LDPE has been found to aid in the reduction of problems associated with deformations due to its unstable crystallization property, which leads to an improvement in asphalt rigidity. In general, the use of such materials aids in the reduction of cracking at high and low temperatures, the improvement of mixture hardness, the increase of mixture fatigue resistance, and the reduction of water damage problems (Al-Hadidy et al., 2009b, Yan et al., 2015). The R-LDPE used was made from recycled materials obtained from a small factory in Karbala. Plate (3-1) displays the form of R-LDPE, and Table (3-5) shows the physical properties of the R-LDPE modifier.

Plate 3- 1 R-LDPE polymer material used in this research.

Table 3- 5 Physical properties of R-LDPE (Al-Busaltan et al., 2020).

Properties	***Amount***
Tensile strength (MPa)	8.5
Density (g/cm^3)	0.91
Tensile elongation (%)	>350
Melting temperature (◦C)	110
Hardness shore D	45
Flexural modulus (MPa)	7.2

3.2.2.2 Waste-Paper Fiber (W-PF)

Waste-Paper Fiber (W-PF) represents a type of cellulose fiber, comes from the recycling process of the waste papers that are widespread locally. Therefore, using such material can be considered as a way to sustainability, which helps in reducing the pollution problems of environmental and human health. The presence contains high content of CaO and SiO_2 which increase the stiffening rate resulting in stiffer mastics which allows strengthening of the aggregate-binder bond and improve effective strength properties of asphalt mixture. The used W-PF used is a shredded form with a size 3-12 mm, as can be seen in Plate (3-2). The chemical properties of W-PF were demonstrated in Table (3-6).

Plate 3- 2 Shredded used waste paper fiber.

Table 3- 6 Chemical and physical properties of W-PF (Chew et al., 2020a).

Chemical Analysis	
Chemical compositions	***(%)***
CaO	37.35
SiO_2	5.011
MgO	0.696
Al_2O_3	3.431
$P2O_5$	0.0443
SO_3	0.1869
Cl	0.0420
K_2O	0.0740
TiO_2	0.126
MnO	0.0126
Fe_2O_3	0.3959
CuO	0.0181
ZnO	0.0339
SrO	0.0308
ZrO_2	0.0165
LOI	52.52
Physical Properties	
Property	***Value obtained***
Specific surface area (m^2/kg)	*1000*
Porosity (%)	*55*

3.2.2.3 Preparation of modified bitumen

In this study, three asphalt binders were prepared: the first and second, by combining neat asphalt with R-LDPE or W-PF, separately, while the third, by combining both modifiers collectively. For one hour, a shear mixer with a 3000-rpm rate was used to prepare the modified binder. Three dosages of W-PF, named 0.3%, 0.5%, and 0.7% by total weight of bitumen, were adopted as suggested by previous research study (Iastremskii et al., 2020). While for R-LDPE, one dosage of 3% by total weight of bitumen was used, because it has been remarked as the better dosage by other researchers like Al-Busaltan et al. (2020), Mahdy et al. (2020a), and Abduljabbar et al. (2020). The third modification was done by using the Mix Contents (MC) from the aforementioned modifiers with dosages equal to 3.3 %, 3.5 %, and 3.7 % (i.e., for example,3.3% is 3 R-LDPE+ 0.3 W-PF).

The preparation begins by heating the B0 in an oven at 165 °C for a specified time to making it fluid enough for mixing. To achieve a homogeneous bitumen-modified blend, a particular experimental technique was used. The fluid bitumen was then applied to the shear mixer shown in Plate (3-3), and the modifier materials were slowly added to the heated bitumen as mixing proceeded at a steady speed rate to prevent the modifiers from agglomeration. This process was repeated with each additive substance until all forms of the modified binder were done, as suggested by previous studies (Jun et al., 2008b, Mohammed et al., 2018a). Table (3-7) illustrated all the information related to the modification process.

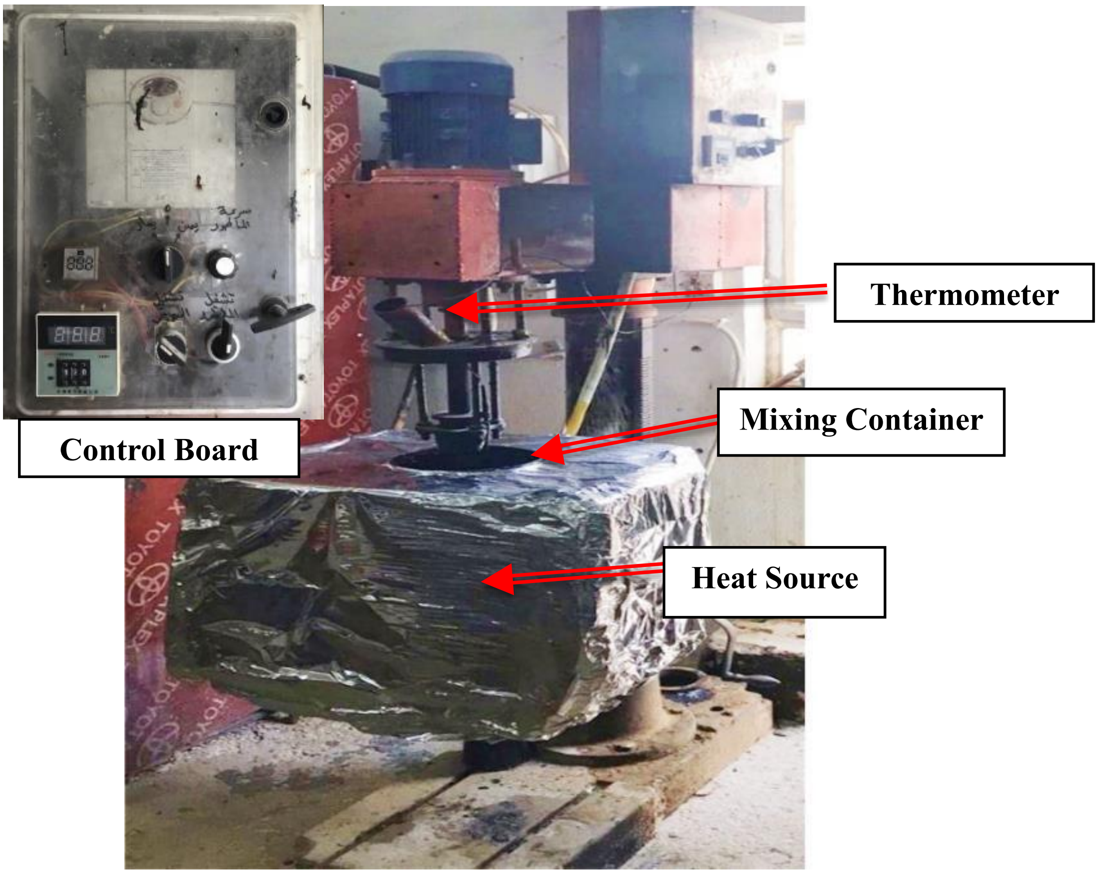

Plate 3- 3 Shear mixer device.

Table 3- 7 Information of modification materials.

Material	**Abbrev.**	**Dosages by weight of bitumen, %**	**Codded values, %**	**Mixing temperature used, °C**	**Mixing velocity (rpm)**	**Mixing time (min)**
Recycle Low Density Polyethylene	*R-LDPE*	3	3	170	3000	60
Waste Paper Fiber	*W-PF*	0.3	0.3			
		0.5	0.5			
		0.7	0.7			
Mix Collective Additives	*MC*	(3+0.3)	3.3			
		(3+0.5)	3.5			
		(3+0.7)	3.7			

3.2.2.4 Physical tests of modified bitumen (MB)

The physical characteristics of MB are described by the set of characteristics listed in Table (3-8). See Chapter 4, section 4.3 for more information.

Table 3- 8 Physical properties of bitumen.

Property	***ASTM, specification***	***Test condition and unit***	***Limits***
Penetration depth	D5-D5M (ASTM, 2013a)	25 °C, 100 g, 5 s, 0.1 mm	-----
Softening point	D36-95 (ASTM, 2009a)	Ring & ball / °C	-----
Ductility	D113-07 (ASTM, 2007)	25 °C, cm	-----
Rotational viscosity	D 4402-02 (ASTM, 2022)	135 °C, 155 °C, 175 °C, 200 °C, centistokes	≤ 3000 centistokes
Loss on heat D1754/D1754M (ASTM, 2014)			
PAI	(Cong et al., 2012), (Zhang et al., 2018)	5 hr, 163 °C	-----
SPI			-----

3.3 Preparation of SMA mixture

Eight SMA asphalt mixtures, including the control mixture (CM) and Modified Mixtures (MMs) were prepared to characterize their variations. 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, with three contents of B0 ranging from 6.28% to 7.28% with 0.5% increment. In order to complete the requirements of determination the SMA-CM with Optimum Asphalt Content (OAC) as documented in AASHTO R46 (AASHTO, 2001b). 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 50 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, draindown, 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 3.2.2.3). 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 3.5.2.5).

Plate 3- 4 Marshall specimens.

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 (3-9).

Table 3-9 Tests Program.

<table>
<tr><th>Property</th><th>Volumetric Properties</th><th>Mechanical Properties</th><th>Durability Properties</th></tr>
<tr><td rowspan="6">Test Method</td><td>Bulk Density</td><td>Marshall Stability and Flow</td><td rowspan="6">Cantabro Abrasion Loss</td></tr>
<tr><td>V.M.A</td><td>Indirect Tensile Strength</td></tr>
<tr><td>V.F.B</td><td>Creep Compliance</td></tr>
<tr><td>VCA</td><td>Skid Resistance test</td></tr>
<tr><td rowspan="2">Draindown</td><td>Wheel Track test</td></tr>
<tr><td>Unaged Cantabro Abrasion Loss</td></tr>
<tr><td rowspan="6">Standard</td><td rowspan="3">AASHTO R46 (AASHTO, 2001b)
AASHTO T166 (AASHTO, 2005)</td><td>ASTM D6927 (ASTM, 2015b)</td><td rowspan="6">ASTM D7064M (ASTM, 2013d)</td></tr>
<tr><td>AASHTO T283 (AASHTO, 2007a)</td></tr>
<tr><td>AASHTO T322 (AASHTO,2003)</td></tr>
<tr><td rowspan="3">AASHTO M325-08 (AASHTO, 2012)</td><td>ASTM E303 (ASTM, 2013c)</td></tr>
<tr><td>EN BS 12697-22 (BSI, 2003)</td></tr>
<tr><td>ASTM D7064M (ASTM, 2013a)</td></tr>
<tr><td rowspan="6">Importance of Tests</td><td rowspan="6">Providing indications that help to evaluate the level of compaction, aging, bleeding, etc.</td><td>Evaluating the resistance to plastic permanent deformation</td><td rowspan="6">Evaluating aging</td></tr>
<tr><td>Evaluating the potential of cracking</td></tr>
<tr><td>Indicating the crack progression and fatigue characteristics</td></tr>
<tr><td>Evaluating resistance to slipping</td></tr>
<tr><td>Evaluating resistance to rutting</td></tr>
<tr><td>Evaluating surface abrasion resistance.</td></tr>
</table>

3.4.1 Volumetric properties tests

The volumetric properties of any compacted paving mixture are a critical criterion for determining the quality of an asphalt mixture. The volumetric properties represent one of the required properties to determine the best asphalt content to the mixture. Also, it acts as a valuable predictor for the mixture's performance over its service life (Institute, 2014b). The volumetric properties include density, voids in total mix, voids in mineral aggregate, voids filled with asphalt and draindown.

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 (AASHTO, 2001b) 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, as observed by Fakhri et al. (2012), Alvarez et al. (2010) and (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 2.6 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 (AASHTO, 2001b) the percentage of voids in coarse aggregate in the compacted mixture (VCA mix) must be less than VCA in the dry rodded condition (VCA_{DRC}). The test procedure suggested by AASHTO T19M/T19-00 (AASHTO, 2004a) was followed here, and Equations (3-1, 2 and 3) were used to calculate the $VCA_{DRC,}$ VCA_{MIX} ,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 (AASHTO, 2005).

$$VCA_{DRC} = \frac{G_{CA}\gamma_W - \gamma_S}{G_{CA}\gamma_W} \times 100$$ *Equation 3- 1*

$$VCA_{MIX} = 100 - \left(\frac{G_{mb}}{G_{CA}} \times P_{CA}\right)$$ *Equation 3- 2*

$$PCA = \frac{\%\,R_{BS}}{100} \times \left(1 - \frac{\%\,P_b}{100}\right)$$ *Equation 3- 3*

Where:

G_{CA}: bulk specific gravity of the coarse aggregate,

γ_s: bulk density of the coarse aggregate fraction in the dry-rodded condition (Kg/m^3),

γ_w: density of water 998 Kg/m^3 (62.3 Ib/ft^3),

P_{CA}: percent coarse aggregate in the total mixture,

G_{mb}: bulk specific gravity of the compacted mixture,

% R_{BS}: percent of aggregate retained on the breaking sieve, and

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

3.4.1.2 Draindown test (DRT)

Draindown test is one of the most important tests that has been considered during the design of SMA asphalt mixtures because it contains a higher amount of bitumen and filler content than dense graded mixtures, thus making it susceptible to draining out especially during mixing, hauling, storage, and compaction (Devulapalli et al., 2020). As a result, the potential draindown of SMA mixtures must be investigated. AASHTO M325-08 (AASHTO, 2012) recommends that the maximum acceptable level of draindown 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 (3-5), 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 draindown sample will then be conditioned for 1 hour ± 5 minutes in a force draft oven, as shown in Plate (3-6), 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 draindown amount is calculated using Equation (3-4), and the test requirements are summarized in Table (3-10).

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

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- 5 Draindown test basket and sample.

Plate 3- 6 Force draft oven used.

Table 3- 10 Standard limits of draindown test and used test conditions according to AASHTO T305 (AASHTO, 2001a).

Parameters	***Standard limits***	***Test condition***
No. of samples required	4	4
Anticipated plant production temperature	(120-175) °C	165 °C
Anticipated plant production temperature +15	+15	180 °C
Time required to complete the test	1 h ± 5 min	1 h ± 5 min
Mass of samples, gram	1200 ± 200	1000
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 (Institute, 2014b). 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 (3-11). 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 3-11 Marshall Test Conditions According to ASTM D6927.

Parameter		**Test standard**	**Used value for testing**
Number of specimens		3	3
Mix temperature, °C		130-180	165
Temperature of aggregate, °C		170	170
Asphalt temperature, °C		150-165	165
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 test, min	*In a water bath*	30-40	30 min in a water bath
	In oven	120-130	
Specimen compaction		50 blows each face	50 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)

The significance of the indirect tensile strength (ITS) test for asphalt mixtures stems from the need to determine the tensile properties of bituminous materials that are related to cracking problems in asphalt mixtures. The test procedure was carried out following AASHTO T283 (AASHTO, 2003a). To prepare the samples required for this test, the aggregate and asphalt mixture was placed in a container and left in an oven at 60 °C for 16 hours, as shown in Plate (3-7). Then placed in an oven at mixing temperature for two hours, and finally, the specimens were compacted using Marshall hammer. The air void ratio that should be achievable for this test is 6±0.5%, according to the specification. This ratio has gotten after conducting several compaction trials until reached the acceptable air voids level. A total of three samples were prepared to conduct the test in the dry condition at 25°C. Each sample was subjected to a diametrical axes load, as displayed in Plate (3-8) to obtain the required ITS. Table (3-12) specifies all the requirements related to the ITS test. Moreover, Equation (3-5) was used to calculate the ITS as reported in AASHTO T283 (AASHTO, 2003a)

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

Where:

ITS: Indirect tensile strength, kPa.

P: maximum load, N.

D: specimen diameter, mm.

t: specimen height immediately before test, mm.

Plate 3- 7 Curing of ITS Specimen in an Oven at 60 ºC for 16 hr.

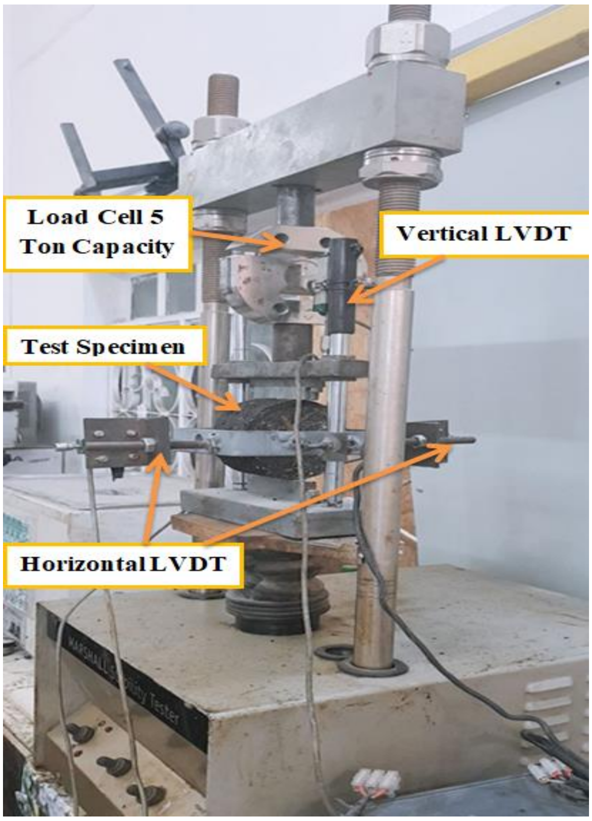

Plate 3-8 Indirect tensile strength device.

Table 3-12 Indirect Tensile Strength Test Conditions According to AASHTO T283 (AASHTO, 2003a).

Parameter	***Test standard***	***Used value for testing***
Temperature of test, ºC	*25 ± 2*	*25*
Accuracy of the device	*Min. 0.01 N*	*0.01 N*
Rate of loading, mm/min	*50 ± 5*	*50*
Number of specimens	*3*	*3*
Thickness of specimen, mm	*63.5±2, 95±5*	*63.5*
Diameters of specimen, mm	*100, 150*	*101.6*
Compaction	*Compacted to 6 ± 0.5% air void*	*Depending on the required air void 7%*
Curing	*Placed in over for 16 hr at 60 °C*	*Placed in over for 16 hr at 60°C*
Specimen conditioning before test	*2 hr at 25°C*	*2 hr. at 25°C*

3.4.2.3 Creep compliance test (CCT)

The creep test is a non-destructive test that is used to simulate the ability of asphalt mixtures to resist thermal cracking that may occur particularly in cold weather. The output results from this test indicate the compliant of the mixture under the applied load to provide the relaxation required to avoid the appearance of these cracks (Islam et al., 2018). This test also represents a key to evaluate the mixture resistance to permanent deformation because it is a time-dependence test (Romeo et al., 2018). The procedure was used as recommended by AASHTO T322 (AASHTO, 2003b), and the device shown in Plate (3-9) was used to perform this test. The analysis of thermal-cracking is generally conducted using a set of three temperatures (0, -10, -20 °C), according to AASHTO T322 (AASHTO, 2003b), while fatigue analysis should be performed at 20 °C or less. Due to time constraints, this study concentrated on the effect of thermal-cracking analysis at 0°C. For a specified period, a static load is applied along the diametrical axes of the temperature-controlled specimen for 1000 seconds. The vertical and horizontal deformations are measured using LVDTs during the loading period, as shown in Plate (3-9). The Creep Compliance test conditions are given in the Table (3-13). As well, the set of Equations from (3-6 to 8) were used to calculate the creep compliance of the tested sample.

$$\boldsymbol{CC_{(t)}} = \frac{\Delta \boldsymbol{X} \times \boldsymbol{D_{avg}} \times \boldsymbol{b_{avg}}}{\boldsymbol{GL} \times \boldsymbol{P_{avg}}} \times \boldsymbol{C_{cmpl}}$$ *Equation 3- 6*

Where:

$CC_{(t)}$: creep compliance at time t ,1/kPa

ΔX: trimmed mean of the horizontal deformations, mm

D_{avg}: average specimen diameter, mm

B_{avg}: average specimen thickness, mm

P_{avg}: average force during the test kN,

GL: gage length, mm, and

C_{cmpl}: creep compliance parameter at any given time, computed as:

$$C_{Cmpl} = 0.6345 \times \left(\frac{X}{Y}\right)^{-1} - 0.332$$ *Equation 3- 7*

Where:

X/Y is the ratio of horizontal to vertical deformation, taken at the mid testing time.

The limitations of the Ccmpl value as shown in the following equations:

$$\left[0.704 - 0.213\left(\frac{b_{avg}}{D_{avg}}\right)\right] \le C_{Cmpl} \le \left[1.566 - 0.195\left(\frac{b_{avg}}{D_{avg}}\right)\right]$$ *Equation 3- 8*

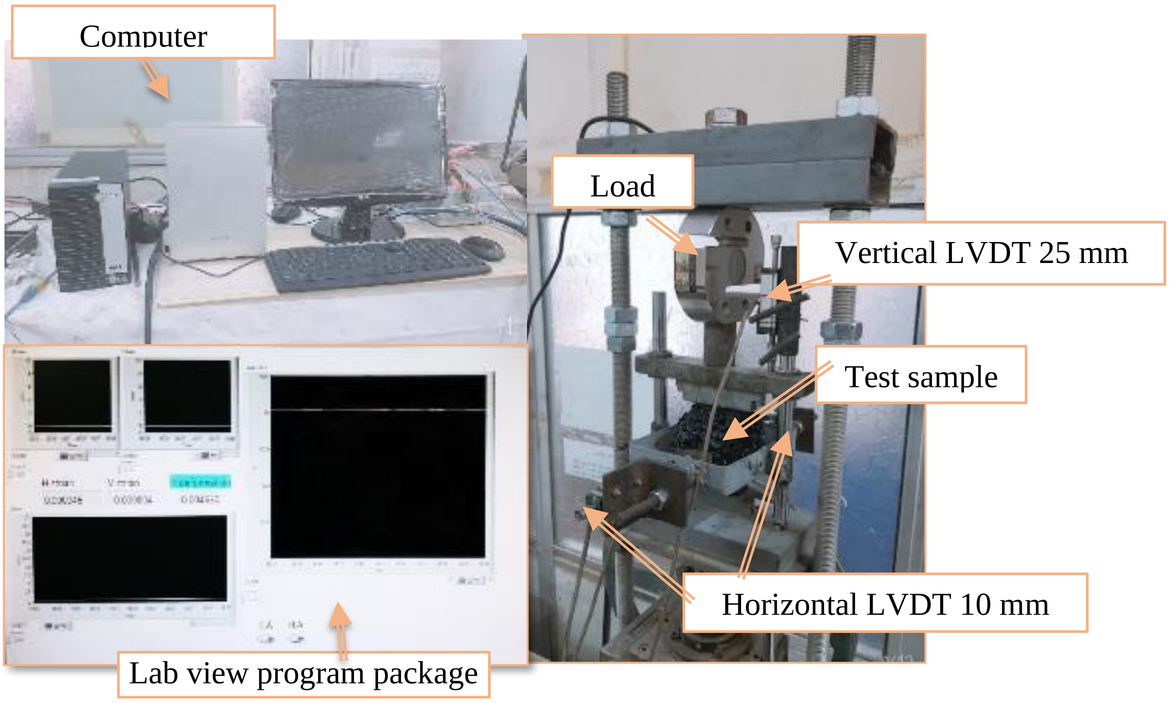

Plate 3- 9 Laboratory Creep compliance device used.

Table 3- 13 Creep compliance test conditions according to AASHTO T322 (AASHTO, 2003b) .

Parameter	*Standard limits*	*Test condition*
Ram movement (vertical), mm/min	12.5	12.5
Device accuracy	0.001N	0.001N
Strain rate, mm	0.00125-0.019	Within rang
Testing time, sec	100 ± 2 or 1000 ± 20.5	1000
Testing temperature, ℃	0, -10, -20, +10	0
No. of specimens	3	3
Specimens' diameter, mm	150 ± 9	101.6
Specimens' height, mm	38 - 50	63.5
Compaction (using Marshall hammer)	Compacted to 7 ± 0.5% air voids	Compacted using 50 blows on each face for air voids content of 7 %

3.4.2.4 Skid Resistance

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 (3-10). 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.

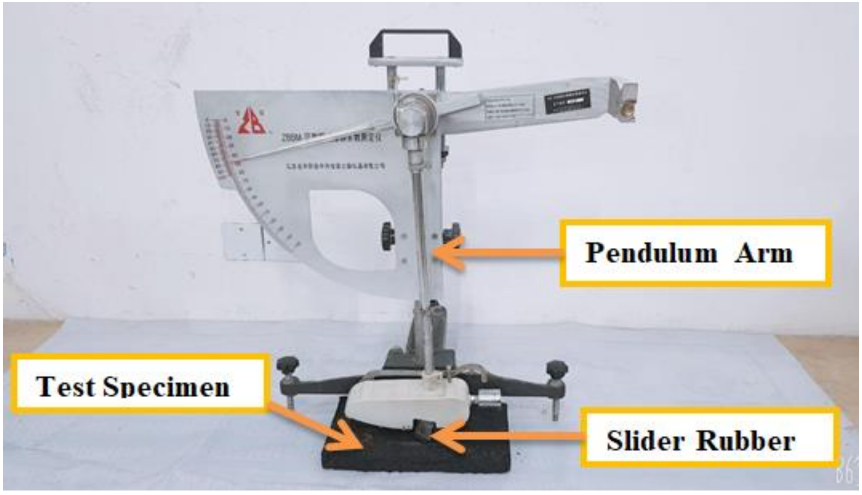

Plate 3- 10 British Pendulum Device in Highway Lab at the University of Kerbala.

3.4.2.5 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 (BSI, 2003a). 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 (3-11) shows an example of the used samples. As well, Plates (3-12,13) illustrates the device system used. 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 discription are represented in Table (3-14). The wheel track test not only determines the rut depth and rate of rutting but also provides data for calculating the dynamic stability of asphalt mixtures. That represents the number of the wheel that pass in a given time that results in a unit rut depth in asphalt mixtures. The DS of SMA mixtures was calculated using Equation (3-9).

$$DS = \frac{N_{15}}{D_{60} - D_{45}}$$ *Equation 3- 9*

Where:
DS: dynamic stability, (passes/mm)
N_{15}: no. of wheel passes after 15 min of testing, passes, and
D_{60} - D_{45}: the change in rut depth at the last 15 min of testing, mm

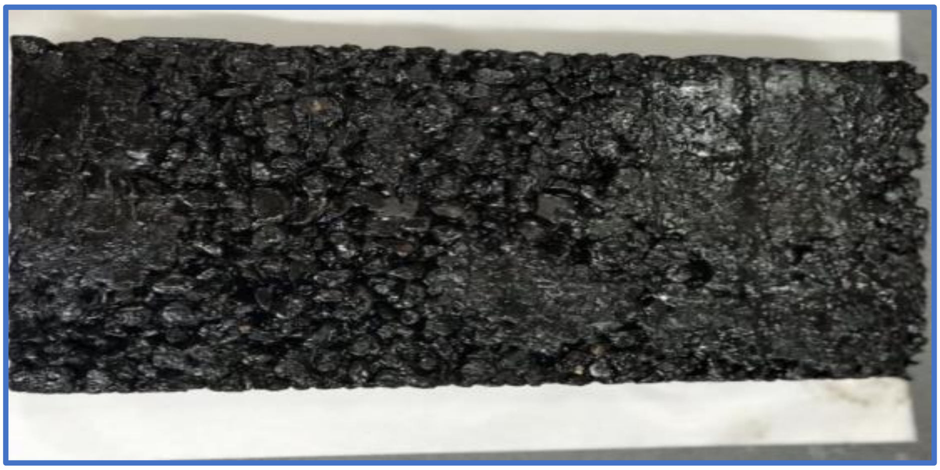

Plate 3- 11 Wheel track slabs.

Plate 3- 12 Apparatus for Wheel Track Device.

Plate 3- 13 Computer system of wheel track device.

Table 3- 14 Limitations of wheel-track test according to BS EN 12697-22:2003 code (BSI, 2003a).

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%

3.4.3 Testing 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 Cantabro abrasion loss test

The Cantabro test procedure was carried out in accordance with ASTM D7064/D7064M (ASTM, 2013b) as used by other researchers, for example (Alvarez et al., 2012, Mansour et al., 2013, Chen et al., 2013b, Al-Jawad et al., 2019). 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 Cantabro loss. The cylindrical specimens were fabricated using Marshall hammer with 50 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 (3-14) 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 (3-10), 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°C as suggested by ASTM 7064/ 7064M (ASTM, 2013b). After that, samples shall be extracted and leave it in the air for a while to cool down, then placed in a 25 °C force draft oven for four hours. Finally, the abrasion process was conducted as mentioned earlier and the abrasion loss was determined from Equation (3-10) as well.

$$P = \left(\frac{P_1 - P_2}{P_1}\right) \times 100$$ *Equation 3- 10*

Where:
P: abrasion loss percentage,
P_1: specimen weight before abrasion test, and
P_2: specimen weight after abrasion test.

ASTM D7064/D7064M (ASTM, 2013b) recommends that the percentage of weight loss of the open 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.

Plate 3- 14 Los Angeles abrasion machine.

Table 3- 15 Cantabro test characteristics according to ASTM D7064/D7064M (ASTM, 2013b).

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	50×2	50×2
Time of preparing specimen prior to conducting the test	4 hours	4 hours
Test temperature	(25 ± 5) °C (77 ± 10) °F	(25 ± 5) °C
No. of revolutions	300	300
Operating speed, revolution/min	30-33	30-33

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 (3-16). While the flowchart in Figure (3-2) summarizes the stages of this research, which included:

1. Creating the SMA-CM in order to determine the volumetric and mechanical properties of this mixture.
2. Adding the sustainable modifiers to asphalt binder, such as R-LDPE and W-PF, at different percentages individually and collectively. 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 3-16 Matrix of experimental plan.

Property		Identifying OAC	SMA mixture types							
			Characterizing the control mix with 6.75%OAC	Modifying asphalt mix with R-LDPE%	Modifying asphalt mix with W-PF%			Modifying asphalt mix with R-LDPE%+W-PF%		
				3	0.3	0.5	0.7	3.3	3.5	3.7
Volumetric properties	BD	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AV	✓	✓	✓	✓	✓	✓	✓	✓	✓
	VCA	✓								
	VMA	✓	✓	✓	✓	✓	✓	✓	✓	✓
	VFA	✓	✓	✓	✓	✓	✓	✓	✓	✓
	DRT	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mechanical properties	MS		✓	✓	✓	✓	✓	✓	✓	✓
	MF		✓	✓	✓	✓	✓	✓	✓	✓
	CC		✓	✓	✓	✓	✓	✓	✓	✓
	ITS		✓	✓	✓	✓	✓	✓	✓	✓
	SR		✓	✓	✓	✓	✓	✓	✓	✓
	WTT		✓	✓	✓	✓	✓	✓	✓	✓
Durability properties	TSR	✓								
	CAL		✓	✓	✓	✓	✓	✓	✓	✓

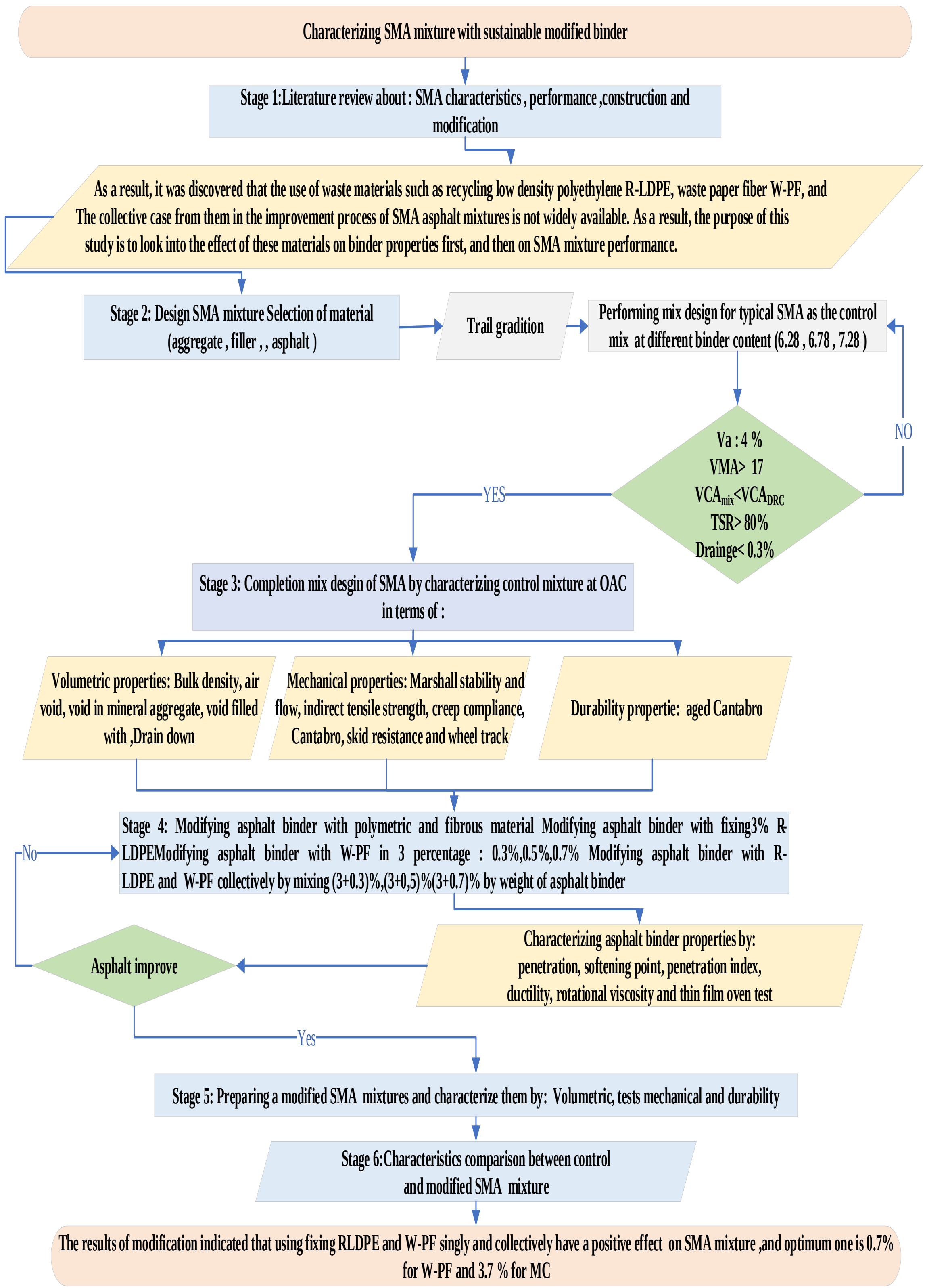

Figure 3- 2 Methodology flowchart.

3.6 Summery

This chapter described the materials' properties, materials used in this research to design the SMA asphalt mixtures (unmodified and modified), including aggregate gradation, fillers, neat bitumen, and additives materials used in this research, mix design method, laboratory tests to examine the materials and mixtures, and research methodology. Volumetric, mechanical, and durability tests were precented. Bulk density, voids in total mix, voids in mineral aggregates, voids filled with asphalt and draindown are all volumetric properties tests. Marshall stability, indirect tensile strength, creep compliance, skid resistance, and wheel track test are examples of mechanical properties. Cantabro test are among the durability tests. The methodology included a view related matrix and the sequence of the research steps, beginning with studying the historical background of the SMA and ending with designing and characterizing the control and modified mixtures used in this research to achieve the main goal of this research.

Chapter Four

Results and Discussion

4.1 Introduction

This chapter offers all information related to the analysis and interpretation of the obtained results from the modification process of bitumen. Besides its effect on the properties of bitumen itself, as well as, the volumetric, functional, and mechanical properties that performed on compacted Marshall specimens, slab specimens, and loose mixtures. The chapter introduces a comparison between the results of the unmodified and modified SMA mixtures as well.

4.2 Characterization of unmodified SMA asphalt mixture

The unmodified SMA mixture was designed using B0 with a penetration grade of (40-50), virgin coarse and fine aggregates, and two types of filler, namely CMF and HL. The aggregate gradation was used with a NMAS of 12.5 mm. To create the unmodified SMA mixtures, three asphalt contents were used: 6.28 %, 6.78 %, and 7.28 % , and selected as recommended AASHTO R46 (AASHTO, 2001b). The evaluation of SMA mixtures to air voids content, void in the coarse aggregate, voids in mineral aggregates, draindown, and tensile strength ratio were as suggested by AASHTO M325 (AASHTO, 2012). In this study, the mixture with OAC was used as a control mixture (CM), 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 volumetric properties of the mixture serve as the foundation for the SMA design. The unmodified SMA mixtures were initially designed using three gradation trials

(i.e., coarse, middle, fine) with three AC (i.e., 6.28%, 6.78% and 7.28%) as mentioned earlier, (see Chapter 3, sections 3.2.1). Then the optimum gradation was selected depending on the criterion of the air voids (Va), voids in mineral aggregate (VMA) and voids in coarse aggregate (VCA). Thereafter, the optimum gradation is selected between the middle and fine gradation (see Chapter 3, section 3.2.1). Finally, the optimum gradation with the aforementioned AC was adopted to design the SMA mixtures required to determine the OAC depending on a set of tests mentioning below with their results.

4.2.1.1 Density of unmodified SMA mixtures

Density should be controlled precisely to ensure the required air void limits, due to the strong relation of them with density level, that in turn have a great impact on the final mixture design (Ahmadinia et al., 2011b). Figure (4-1) depicts the variation of Bulk Density (BD) of compacted SMA mixtures with asphalt content variation (AC). Density gradually increases as AC increases until it reaches its maximum value at 7.28% 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).

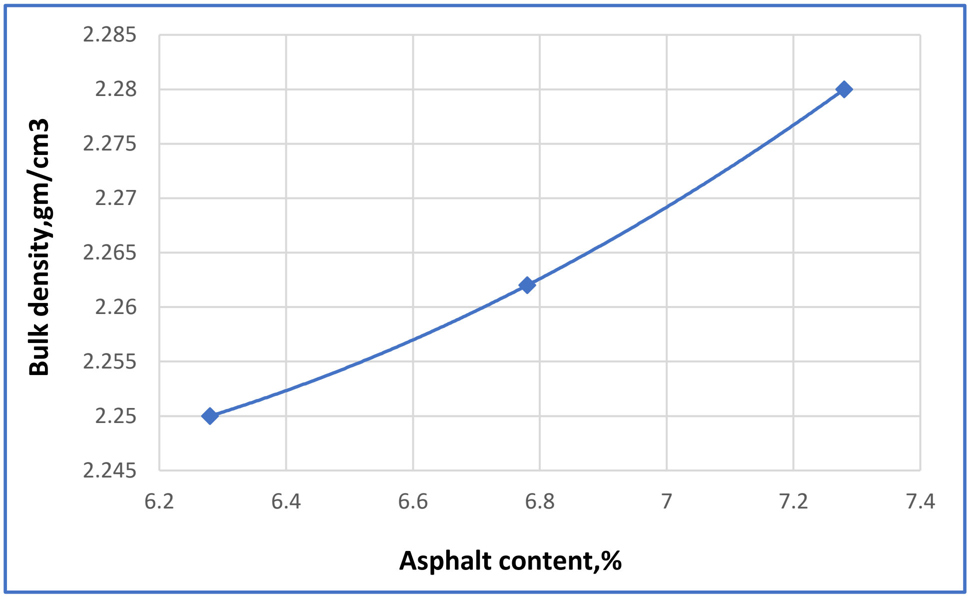

Figure 4- 1 Bulk density of unmodified SMA asphalt mixtures.

4.2.1.2 Determination of VCA of unmodified SMA mixtures

The VCA represents an indicator for the availability of stone-on-stone contact property through the used aggregate gradation, that in turn possesses an influence on the resistance of mixture rut and durability. 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}). The mixture will be recorded as having a stone-on-stone contact when this ratio is equal to or less than one (Sarang et al., 2015b, Devulapalli et al., 2020). The related VCA results are shown in Table (4-1). The VCA_{DRC} is solely determined by the gradation used and is unaffected by the variations in the mixture characteristics. Thus, it remains constant as can be seen in Table (4-1), where it achieves a percentage equal to 40.3%. Furthermore, the results show that there is a slight decrease in VCA_{mix} with increasing AC. The reason for this is that the increment in AC causes an increment in the asphalt film thickness that coats the aggregate, lead to an increase in the BD of the SMA mixture, see section 4.2.1.1, as well as, a slight reduction in the stone-on-stone contact property. The obtained trend of results appears to be similar to what was observed by Suresha et al. (2010) in their study.

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

AC, %	***G_{CA}***	***P_{CA}***	***BD***	***AV***	***VCA_{DRC}***	***VCA_{mix}***	***VCA_{mix}/ VCA_{DRC}***
6.28	2.600	70.52	2.251	6	40.3	38.99	0.967
6.78	2.600	70.12	2.267	4.01	40.3	38.85	0.964
7.28	2.600	69.75	2.281	3.2	40.3	35.95	0.892

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 3.2% at 7.28% 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. The obtained results appeared to reconcile with those observed by Sarang et al. (2015a).

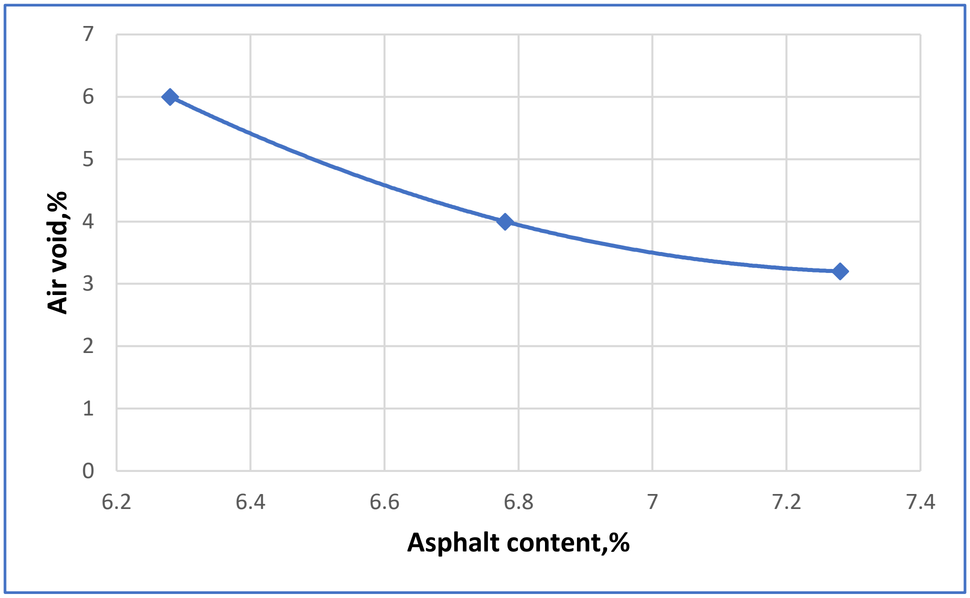

Figure 4- 2 Air voids of unmodified SMA mixture.

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

The space available between each aggregate particle and the other and filled with effective asphalt are called voids in mineral aggregates (VMA). 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., 2011a, Institute, 2014a). Figure (4-3) represents how the percentage of VMA changes as the AC changes. The curve is shaped like a flattened U. The percentage of VMA decreases to its minimum value at 6.78% AC, then the percentage rises until reached 18.92 % at 7.28 % 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. (2015a).

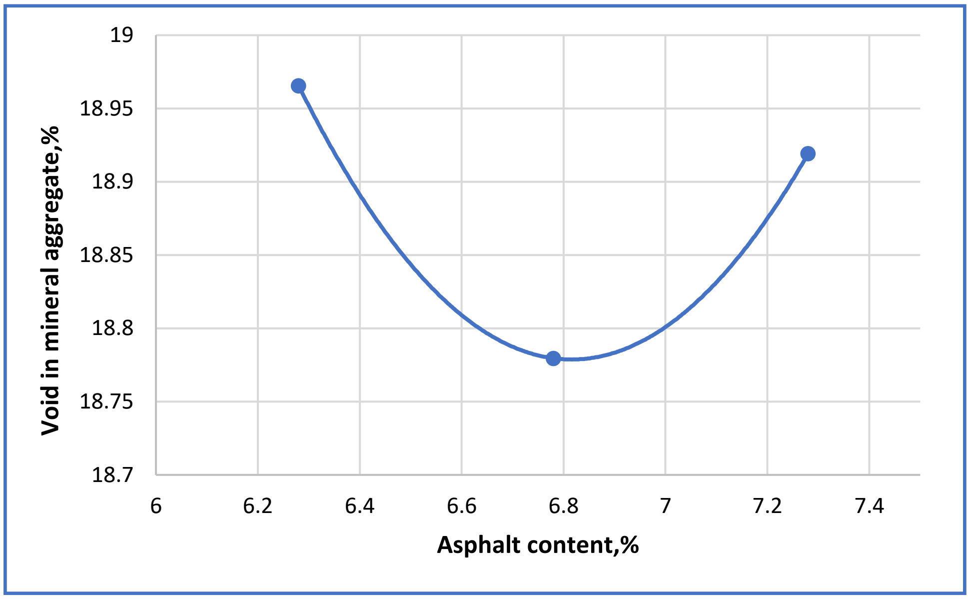

Figure 4- 3 VMA of unmodified SMA mixtures.

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

The air voids that are occupied with the effective binder in the compacted mixture are referred to as void filled with asphalt (VFA). VFA limits referred to the proper asphalt film thickness coating aggregates, also, it gives an indication about the mixture durability. If it is too low, the mix will be unstable and vice versa. 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 83% at 7.28% 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.

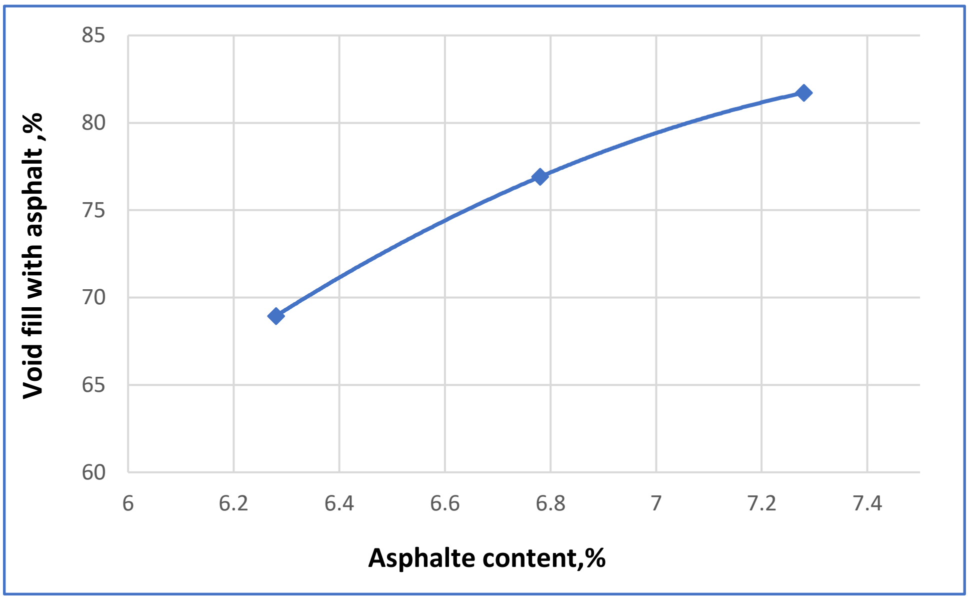

Figure 4- 4 VFA of unmodified SMA mixtures.

4.2.1.6 Draindown 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 segregation impact of these materials from the SMA mixture. Especially, during design, hauling, placing and compaction besides the elevated work temperature. The amount of draindown in SMA mixtures should not exceed 0.3 % (Devulapalli et al., 2020). Figure (4-5) shows the results of draindown at two temperatures with respect to the variation in AC, and Plates (4-1 and 2) demonstrate how draindown varies with variation in AC. It can be seen that draindown levels appear higher than the recommended level at all AC and both temperatures (anticipated and anticipated+15). Where the amounts of increment reach approximately 2.2% and 3.1% at 165°C and 180°C, respectively, when using 7.28% 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 bitumen causes a portion of asphalt with small amounts of fillers to separate from the mixture, then lead to an increase in the amount of draindown. Furthermore, Figure (4-5) also demonstrates that the bond between draindown and AC at both

165°C and 180°C temperatures goes up as an exponential mode for draindown at both temperatures as AC increases. The relationships, on the other hand, show that 180°C temperature has a greater effect on SMA mixture draindown than 165°C temperature.

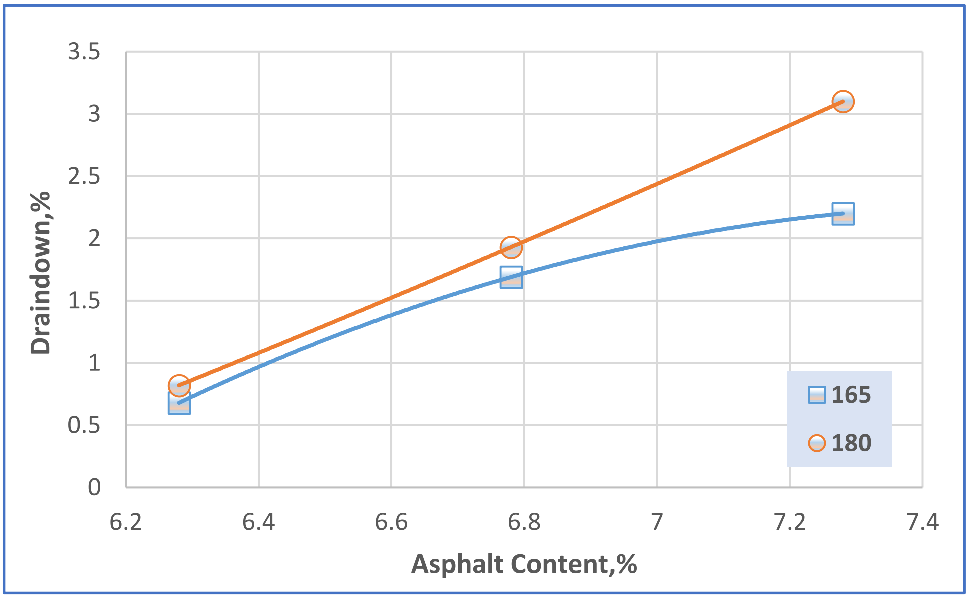

Figure 4- 5 Draindown of unmodified SMA mixture.

6.28% - 165°C **6.78% - 165°C** **7.28% - 165°C**

Plate 4- 1 Draindown of unmodified SMA mixture at 165°C.

6.28% - 180°C **6.78% - 180°C** **7.28% - 180°C**

Plate 4- 3 Draindown of unmodified SMA mixture at 180°C.

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, 2007) 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 7.28 % 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.

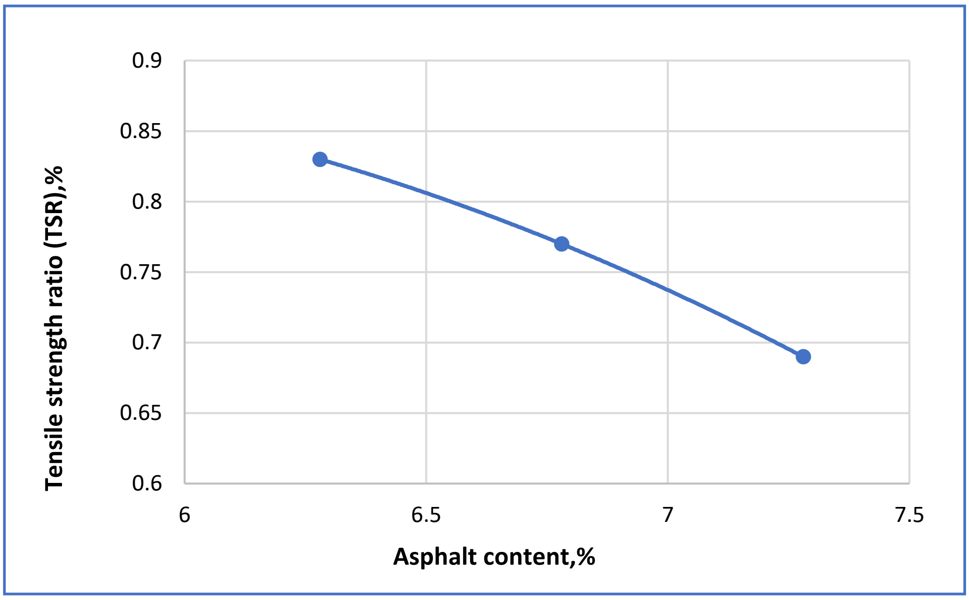

Figure 4- 6 Tensile strength ratio of unmodified mixtures.

4.2.3 Characteristics of Control SMA Mixture with OAC

The observed result confirms that 6.75% of asphalt meets the best limits of air voids, draindown, and tensile strength ratio tests, in addition to VMA and VFA properties. The SMA mixture with the OAC mixture will be used as a control mixture (CM) to carry out the improvement process. However, the obtained results demonstrate that the utilization of the B0 results in a lower SMA mixture strength especially in terms of draindown and moisture sensitivity. Therefore, this confirms the requirement for the development of the NB, as well as, the SMA mixture in order to get a mixture with better strength. For this, the following sections will offer briefly ways for the modification of bitumen, and the mixture.

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 bitumen; achieved through sections 4.3.1 to 4.3.6, 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.

Bitumen 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**	**PAI**	**SPI ,°C**
Neat bitumen	B0	42.8	44	143	-2.603	860	0.76	4.6
Modified bitumen	3% R-LDPE	32.2	52	100	-1.298	1330	0.8	3.3
	0.3% W-PF	28	50	83	-2.169	1120	0.79	3.1
	0.5 W-PF	26.6	54	71	-1.305	1368	0.85	3.2
	0.7% W-PF	23.5	56	62	-1.352	1440	0.86	2.7
	3.3 % MC	20.3	59	50	-0.707	1520	0.84	4.3
	3.5 % MC	18	64	44	-0.110	1777	0.87	3.6
	3.7 % MC	16	73	30	1.044	2330	0.93	2.5

4.3.1 Penetration test properties

The penetration test provides information about the consistency and stiffness of the bitumen. According to Arabani et al (2017a), a decrease in penetration values indicates high bitumen stiffness, and therefore an improvement in the mechanical strength of bitumen against damage. The test was done through two cases: before aging and after aging to notify the variation into bitumen penetration after being subjected to a higher temperature. Before aging, the results of penetration depth at 25°C for all types of modified asphalt (R-LDPE, W-PF, and MC) are shown in Figure (4-7). In general, the results show that adding modification materials to asphalt (i.e., R-LDPE, W-PF, and/or MC) helps to reduce the penetration depth of asphalt mastic. The results show that using R-LDPE and W-PF separately reduces penetration depth as the dosages increase.

The use of R-LDPE to modify asphalt binder results in a significant reduction in penetration values. Whereas the addition of 3% R-LDPE reduced penetration by about 24% compared to neat bitumen (B0). This is due to swelling phenomena caused by the diffusion of maltenes (oil fraction of binder's) in the polymeric phase, in addition to the interactions between the polar molecules of asphaltenes and polymer, which result in improved asphalt polarity and the formation of a polymer network, as stated by Read et al. (2003), Polacco et al. (2005), Dehouche et al. (2012), Yan et al. (2015), and others.

While for the utilization of W-PF, the results indicate that penetration values decrease noticeably as the W-PF content increase, where at 0.7% W-PF, the reduction ratio reached 45% compared to B0. This behavior can be attributed to the chemical composition of paper, which contains CaO and SiO_2. In addition to the network properties of fiber, all the mentioned factors work combined resulting in stiffer asphalt mastic. As a result, the binder's resistance to mechanical damage was improved (Arabani and Tahami, 2017, Chew et al., 2020). The behavior of bitumen here obtained is similar to that obtained by Chen et al. (2019).

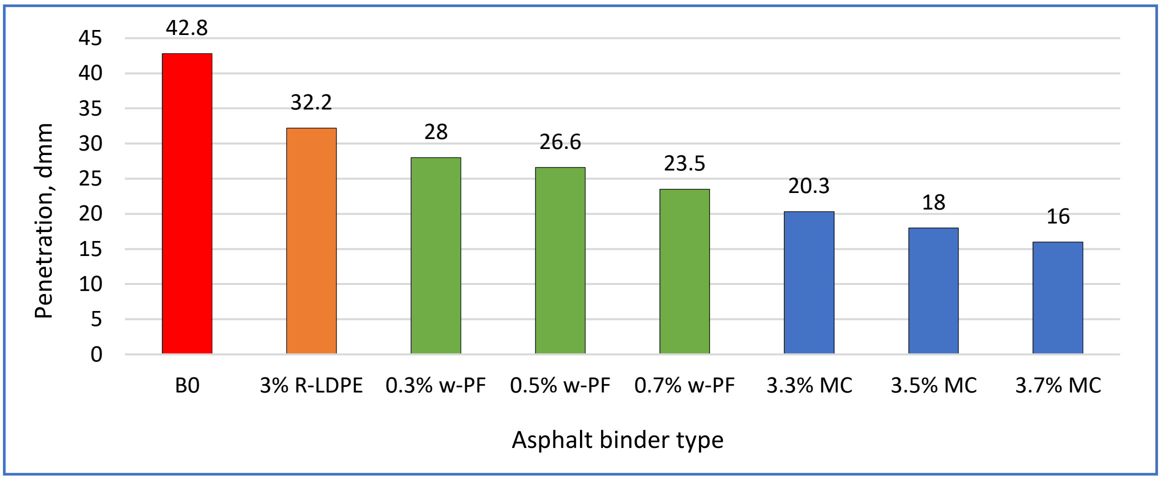

Figure 4- 7 Penetration depth of neat and modified binders.

Figure (4-7) displays that the incorporation of the MC between R-LDPE and W-PF appeared that is lead to a greater reduction in the penetration than the separate case modification. Where it achieves a reduction of 62% at 3.7% MC (i.e., 3 % R-LDPE + 0.7 % W-PF) compared to B0. This reduction is due to the neutralization of the polarity variation in R-LDPE and W-PF, where the addition of W-PF to R-LDPE modified asphalt causes some W-PF particles to attack the surface of the R-LDPE particles and work on changing their polarity. This, in turn, causes the polar nature of R-LDPE polymer to be neutralized (Ouyang et al., 2006), and the polymer rich phase to be swollen by maltene, in addition to the formation of asphaltene rich phase (Polacco et al., 2006, Okhotnikova et al., 2019). As a result, this interaction helps in reducing the penetration depth.

4.3.2 Softening point (SP) 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 binder 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 with R-LDPE to B0, the amount of incrrease in SP reached 20%. This increase could be attributed to the improvements of asphalt binder structure properties, as well as, the network properties of R-LDPE polymer, as mentioned earlier.

The results in Figure (4-8) also show that incorporating W-PF into asphalt helps increase SP to 30% at 0.7% W-PF compared to B0. This is due to the presence of CaO and SiO_2 particles in the chemical composition of W-PF, which gives the asphalt some rigidity. Furthermore, the high surface area and porosity of W-PF tend to absorb more lightweight bitumen. Moreover, the presence of fiber in the binder structure may result in the formation of a network that reinforces the binder itself. All these factors work on increase the asphalt binder stiffness and therefore the levels of SP increase. The results are consistent with those obtained by Mohammed et al. (2018a).

The results also show that the rising in MC (R-LDPE + W-PF) leads to higher levels of SP. When using 3.7% MC, the amount of rising reached greater than 60%. This is due to the neutralization of the polarity nature of R-LDPE when adding W-PF to the R-LDPE modified binder, which leads to the occurrence of several chemical reactions that help in increase the SP levels of asphalt binder. Jun et al (2008a) and Arabani et al. (2018) both observe a similar trend for softening point variation.

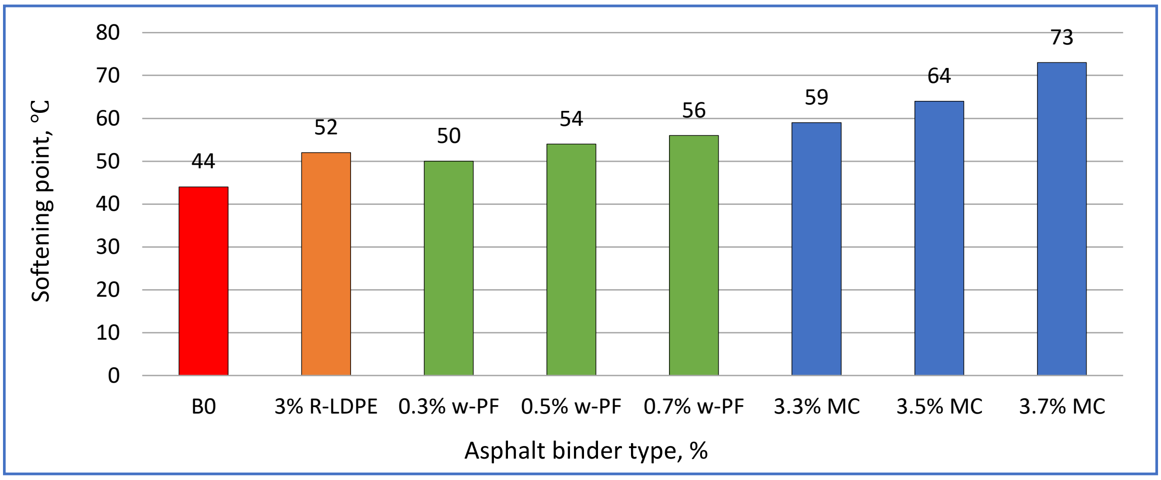

Figure 4- 8 Softening point of neat and modified asphalt binders.

4.3.3 Penetration index (PI)

The term penetration index (PI) refers to the temperature susceptibility of the asphalt binder, and it is represented as a function for penetration and softening point. According to Read et al. (2003), the limits of PI ranged between -3 and +7. Figure (4-9) demonstrates the PI results for neat bitumen and modification bitumen. The results show that the use of modification materials decreases the sensitivity of bitumen to temperature by varying levels. According to Arabani et al. (2017b), this increases the asphalt's resistance to rutting and low temperature cracking. When compared to B0, the use of R-LDPE resulted in a significant reduction in temperature susceptibility. Where the difference in reduction appears equal to 1.305, this returns to the increase in the elastic behavior of the asphalt binder after the addition of R-LDPE due to the formation of the polymer network. Al-Hadidy et al. (2009a) reported a finding similar to that observed here.

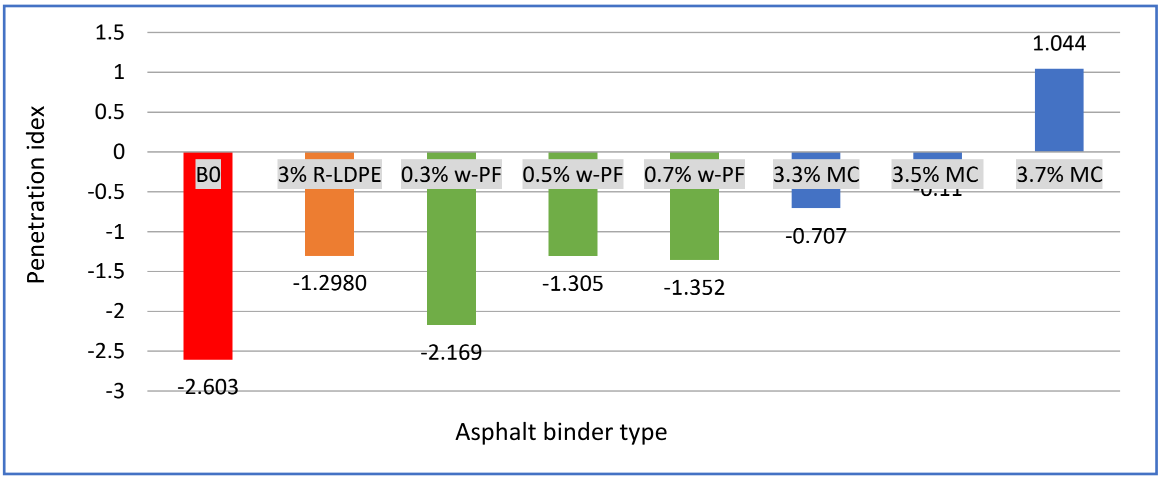

Figure 4-9 Penetration index of neat and modified asphalt binders.

Figure (4-9) shows that as the amount of W-PF increased, the value of PI decreased and the amount of reduction difference reached -1.305 with 0.5 %W-PF. This is due to the chemical composition of W-PF, which contains CaO and SiO_2 particles, as well as, the other effects mentioned in the previous sections, which help in increasing binder flexibility and decreasing binder sensitivity.

Chew et al. (2020b) offered a similar trend for PI. The addition of MC to asphalt binder resulted in a greater improvement in temperature susceptibility, where PI reaches +1.044 at 3.7% MC. This brings us back to the combined effect of R-LDPE and W-PF, which help in further reducing asphalt binder temperature sensitivity.

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 compared to B0, asphalt modified with 3 % R-LDPE had a 43% lower ductility. This returns to the polymer network, which increases binder stiffness, then contributes to the reduction. Figure (4-10) also shows that the incorporating of W-PF results in a reduction in ductility level to greater than 50% at 0.7 % W-PF. This is due to the presence of CaO and SiO_2 particles in its chemical composition, as well as the other reasons mentioned in the preceding sections. The ductility trend, on the other hand, appears to be similar to that observed in Mohammed et al. (2018a) study when using cellulose fiber to improve the properties of asphalt binder. Furthermore, the results show that using MC as a modifier result in a greater reduction in ductility level, reaching 80% at 3.7% MC (i.e., 3 % R-LDPE + 0.7 % w-PF). This returns to the combined effect of these materials that will result in a series of chemical reactions with the chemical components into the asphalt molecule, resulting in a further reduction in ductility.

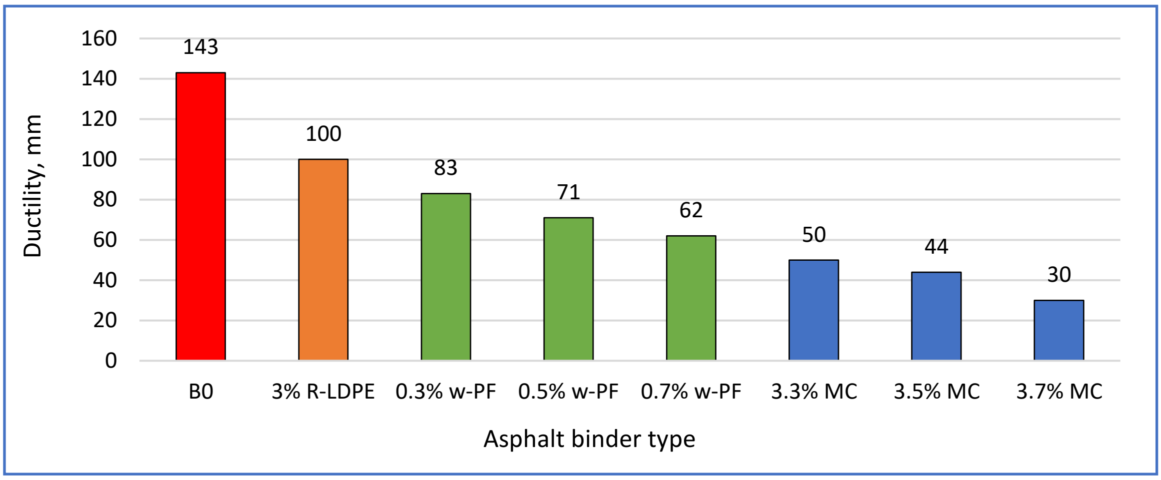

Figure 4- 10 Ductility limits of neat and modified asphalt binders.

.3.5 Viscosity test

The viscosity of bitumen at the application of temperatures was determined using the rotational viscosity test. Figures (4-11 to 13) show the relationship between viscosity and temperature for unmodified and modified asphalt binders. It can be seen that the viscosity values decrease as the test temperature increase for all bitumen types. Moreover, results indicate that asphalt modified with different modifier ratios has a viscosity higher than the viscosity of B0.

The results also show that the viscosity decreases in an exponential manner as the temperature rises, and the parameters for the exponential curves could provide a clear indication of the effect of the modification. It can be seen that the amount of viscosity reduction at high temperatures for modified asphalt binder, is lower than that of the unmodified, indicating an improvement in high-temperature performance. SHRP recommended that the viscosity of asphalt be no more than 3000 centistokes at 135 °C for practical applications to achieve the required workability and pumpability (Yan et al., 2015). Figure (4-11) displays that when 3 % R-LDPE was used, the amount of viscosity increased by 1.5 times when compared to B0. This is due to the same reasons mentioned earlier, where the formation of a polymer network helps to increase the bond between asphalt molecules. As well as, a change in asphalt binder structure from sol to gel-type structure, which results in increase asphalt stiffness and durability, then its viscosity. These findings are consistent with those obtained by Ameri et al. (2016).

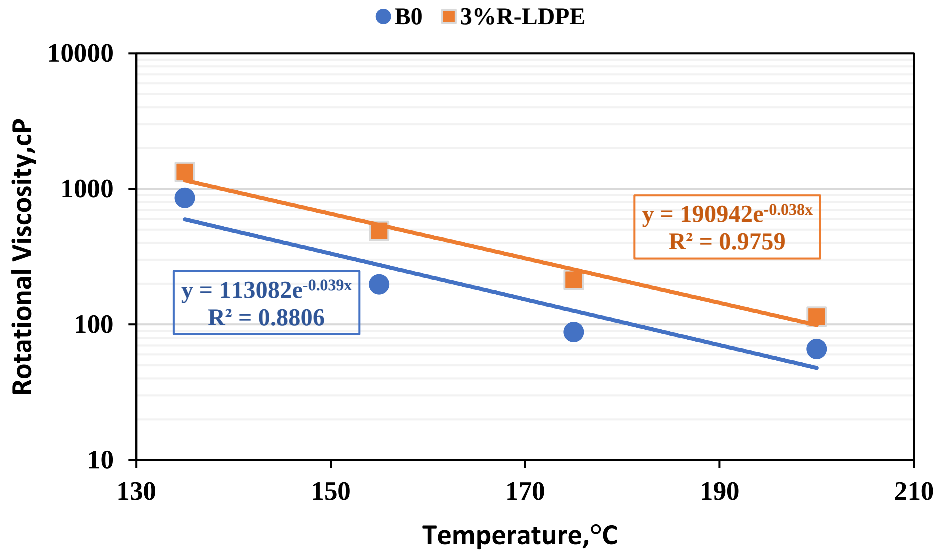

Figure 4- 11 Rotational viscosity of neat and w-LDPE modified asphalt binders.

Moreover, Figure (4-12) shows that the incorporation of W-PF into asphalt binder increases viscosity by about 1.7 times when compared to B0. This was due to the presence of CaO and SiO_2 particles, as previously mentioned, as well as, the porosity, high surface area, and reinforcement ability of W-PF. All of these factors work together to increase the flexibility and stiffness of the asphalt binder, which then aids in increasing the level of asphalt binder viscosity to that level. Mohammed et al. (2018a) found similar results in their study.

The results presented in Figure (4-13) show that the usage of MC from R-LDPE and W-PF combined, the same trend for viscosity is observed. The level of viscosity rises as MC rises until it reaches a level equal to two times the B0. This increase reverses the effect of R-LDPE and W-PF on the chemical composition of the asphalt binder. When W-PF is mixed with R-LDPE, some W-PF particles attach to the surface of the R-LDPE particles and improve their polarity, making the polar adhesive component of the asphalt binder stronger, in addition to the formation of a polymer-rich phase, and as a result, the asphalt viscosity increased even more.

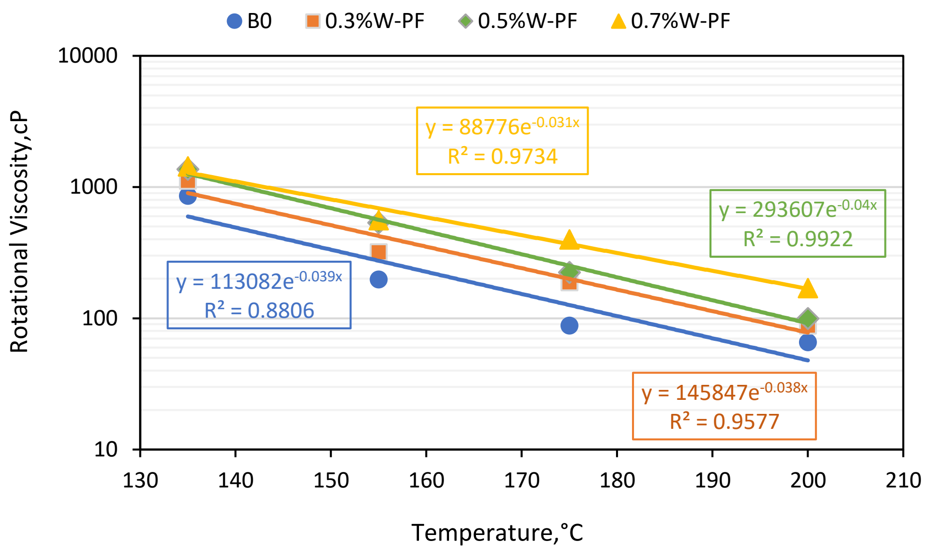

Figure 4- 12 Rotational viscosity of neat and W-PF modified asphalt binders.

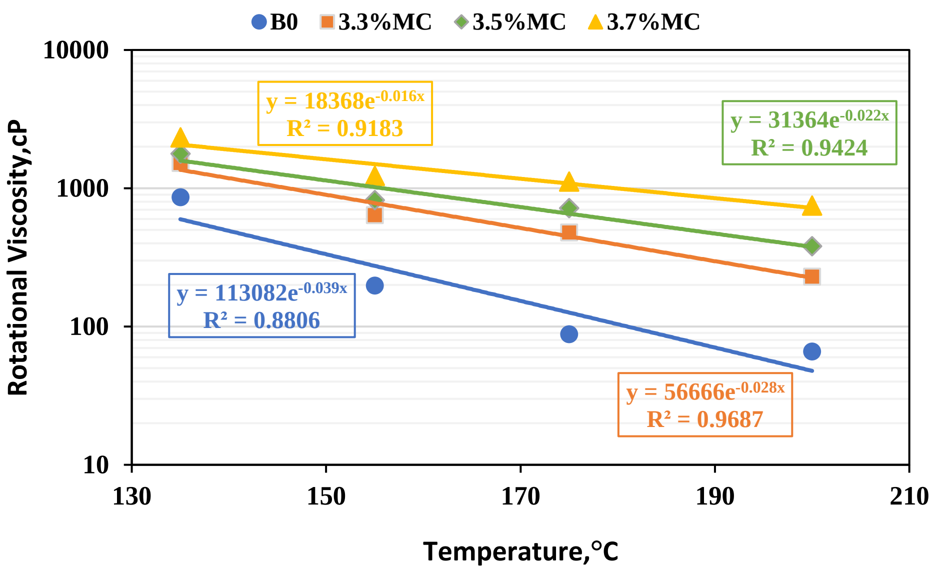

Figure 4- 13 Rotational viscosity of neat and MD modified asphalt binders.

4.3.6 Characterization of the aging behavior of physical properties of asphalt binder

In this study, the thin film oven test (TFOT) was used to simulate the short-term aging of the asphalt binder. Figures (4-14, and 15) show the penetration and softening point of all types of asphalt binder after being subjected to a temperature of 163°C in TFOT. In general, the results show that the physical properties of neat and modified asphalt binders are influenced by the higher temperature in different ways. The results show that the use of modification materials resulted in a reduction in penetration depth that exceeded 25.8% at 3% R-LDPE and 20.1% at 0.7% W-PF, but does not exceed 14.8% MC. Furthermore, the amount of increase for SP appears to be greater than 55% in the case of 3% R-LDPE and 75% MC, whereas it reaches 58 % for 0.7% W-PF. On the other hand for all types of asphalt binder, the results of penetration after aging appear lower than that before aging (see section 4.3.1), and as a result, softening point levels after aging increase higher than that before aging (see section 4.3.2). This is due to the oxidation of the asphalt binder caused by the higher temperature of the test, which is working on increasing the asphaltene and resin fractions while decreasing the maltene fraction (Read et al., 2003).

Figure (4-14) also shows the aging index of penetration (PAI) for all types of asphalt binder before and after aging, as recommended by ASTM D1754 (ASTM, 2014) and used by other researchers, such as Cong et al. (2010), Zhang et al.(2013), to demonstrate the variation in aging resistance among different asphalt types. In order to demonstrate the differences in aging resistance between different asphalt types. Whereas the use of additives appears to be effective in resisting aging, and all types of modified asphalt (i.e. R-LDPE, W-PF, and MC) show closer values PAI. Nonetheless, at 3.7% MC, the higher aging resistance provided by MC modified asphalt reached 0.93. In terms of penetration depth, the lower one reached 0.79 at 0.3% W-PF, as shown in Figure (4-14). The pattern appears to be similar to that obtained by (Diab et al., 2019). According to the findings, the resistance of asphalt binder to aging increases when MC modifier was used, followed by R-LDPE and W-PF modified asphalt. This return to the polymer network formation in the case of R-LDPE alone and the combined effect of reinforcement of the polymer (i.e., R-LDPE) and the fiber (i.e., W-PF) into MC modification compared to the separetelted case of W-PF. This will lead to a noticble increment into PAI.

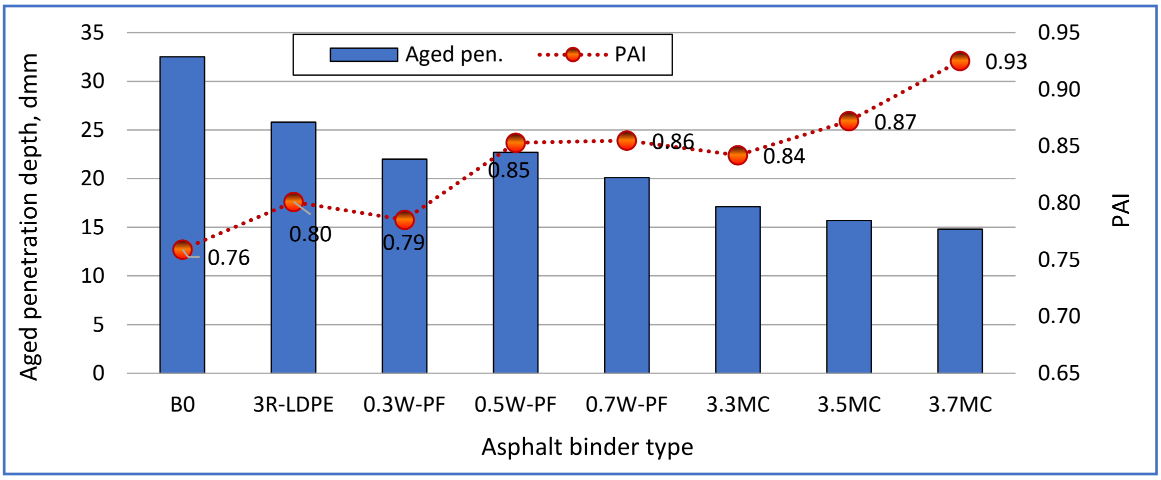

Figure 4- 14 Penetration depth and aging index of neat and modified asphalt binders.

While For softening point, the results indicate that rutting resistance of asphalt binder enhanced, where notice that the higher resistance to rut achieved at softening point difference index (SPI) before and after aging equals to 2.5°C as shown in Figure (4-15) at 3.7% MC, followed by 2.7°C at 0.7% W-PF and 3.3°C at 3% R-LDPE. The reason is that when R-LDPE and W-PF are combined, the asphaltene fraction increases significantly more than that when using the separately case modification. These results are in agreement with the findings of Sun et al. (2014), and Zhang et al. (2018).

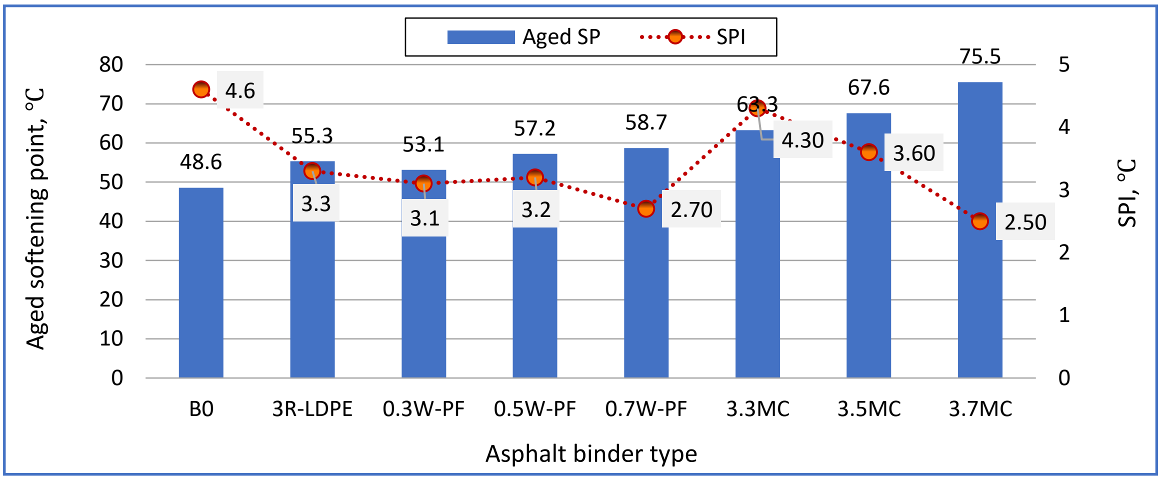

Figure 4- 15 Softening point and aging index of neat and modified asphalt binders.

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 incorporating W-PF and R-LDPE, (see section 4.2). The modified asphalt was then used to prepare seven mixtures of SMA. 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 SMA mixtures with various additives and additive contents is shown in Figure (4-16). When compared to the CM, the density values increase when the asphalt is modified with R-LDPE polymer. This could refer to the higher viscosity of asphalt with R-LDPE polymer that is lead to a rise in the required temperatures at both mixing and compaction to help in achieving 100% aggregate coating. Ahmad et al. (2014) indicated a result similar to that obtained here.

Moreover, results indicate that the comprising of W-PF with asphalt mixtures increases the density of these mixtures up to a specific dosage. The highest bulk specific gravity values were found in the SMA mixture containing 0.3% W-PF, where the mixture containing 0.7% W-PF had the lowest values. The bulk specific gravity values found ranged from 2.287 to 2.257. This behavior is related to the increment of viscosity level with respect to the W-PF content. As the continuous increment will reduce the mixture lubricity and making it stiff, then result in a decrease in the mixture density consequently. Sheng et al. (2017) in their study indicated a result similar to that obtained here.

Figure (4-16) also displays that the use of MC demonstrated the same trend of reduction into density levels with the increment into MC. This is due to an increase in viscosity values caused by the fixation of R-LDPE content and an increase in W-PF content. Punith and Veeraragavan (2011) and Ahmadinia et al. (2011a) showed a similar trend for decreasing mixture density as viscosity increases.

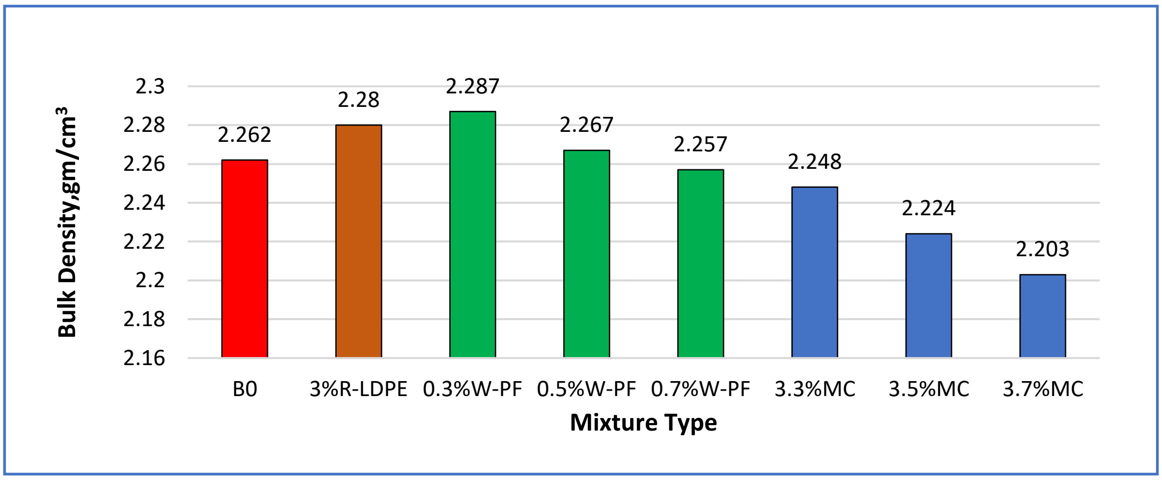

Figure 4- 16 Bulk densities of unmodified and modified SMA mixtures.

4.4.1.2 Air Voids

Figure (4-17) shows the amounts of air voids in SMA mixtures with various additives. Results demonstrate that there is a noticeable variation in the level of air voids with the utilization of the different modifiers. Adding 3% R-LDPE results in a decrease in the amount of air voids to about 18% compared to the control mixture (B0). This is related to the network properties of R-LDPE polymer, as well as, the high viscosity of R-LDPE modified asphalt that is resulted in more blocked air voids compared to the other modifiers. The reduction in air voids prevents entrapped air from absorbing moisture and oxidizing bitumen. As a result, the Marshall Stability value will improve, as stated by Ahmadinia et al. (2011a).

The W-PF result shows a reverse relationship between air voids increase and fiber content. Where the amount of rising reaches 8% after comprising 0.7% W-PF. This potential due to the porous nature of W-PF that is work on absorbs more light molecules weight asphalt fractions. Besides, the high viscosity level of asphalt after the incorporation of W-PF, which help together increase the amount of air voids consequently. Sheng et al. (2017) showed a similar trend for the increase in mixture air void with increasing fiber content.

Furthermore, results display that the usage of the MC between R-LDPE and W-PF shows higher increment into air voids level between (20-70) %. This related to the higher surface area resulted from the comprising of both modifiers (i.e., R-LDPE+W-PF) with asphalt, as well as, high viscosity values. That is work on absobing more light weight asphalt then work on increase the amounts of air voids more.

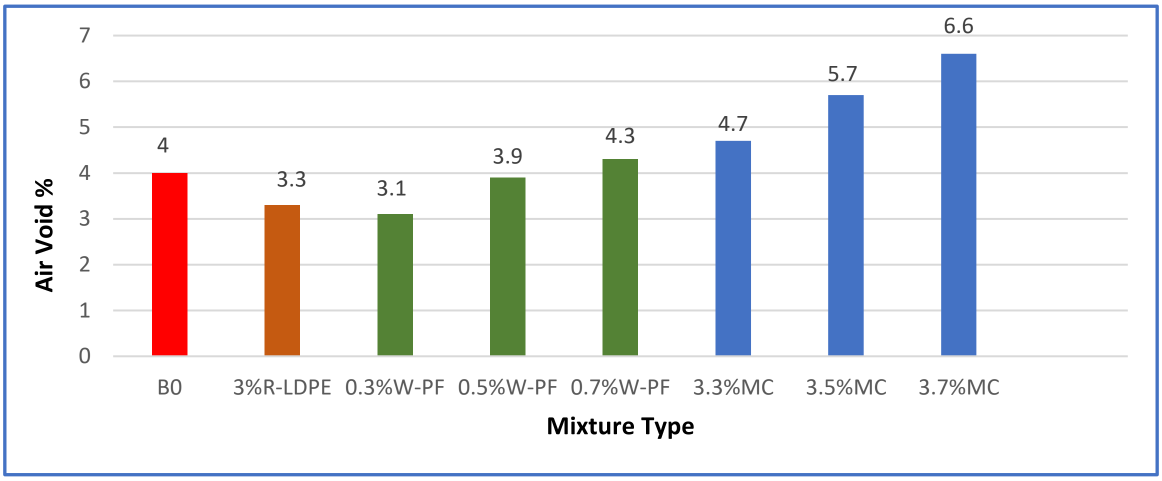

Figure 4- 17 Air voids of unmodified and modified SMA mixtures.

4.4.1.3 Voids in the Mineral Aggregate

Figure (4-18) illustrates the VMA trend of SMA mixtures with various additives. In general, the results show that the influence of modifiers has a positive impact on the amounts of VMA in terms of W-PF and MC modified SMA mixtures. While the incorporation of R-LDPE polymer achieves a slight reduction. Where the comprising of W-PF show slight improvement into VMA values as the increase in its content by no more than 1% at 0.7% W-PF compared to B0 mixture. Whereas, the use of MC mixture soffer better enhancement reached 11% at 3.7% MC in contrast with B0 mixture. In terms of R-LDPE modified SMA mixture, the resulted trend attributed to that when adding R-LDPE polymer resulted in more blocked air voids due to its network properties. Meanwhile, the amounts of VFA increased consequently, then this leads to a decrease in the amount of effective asphalt binder coating aggregate, and as well the VMA was reduced.

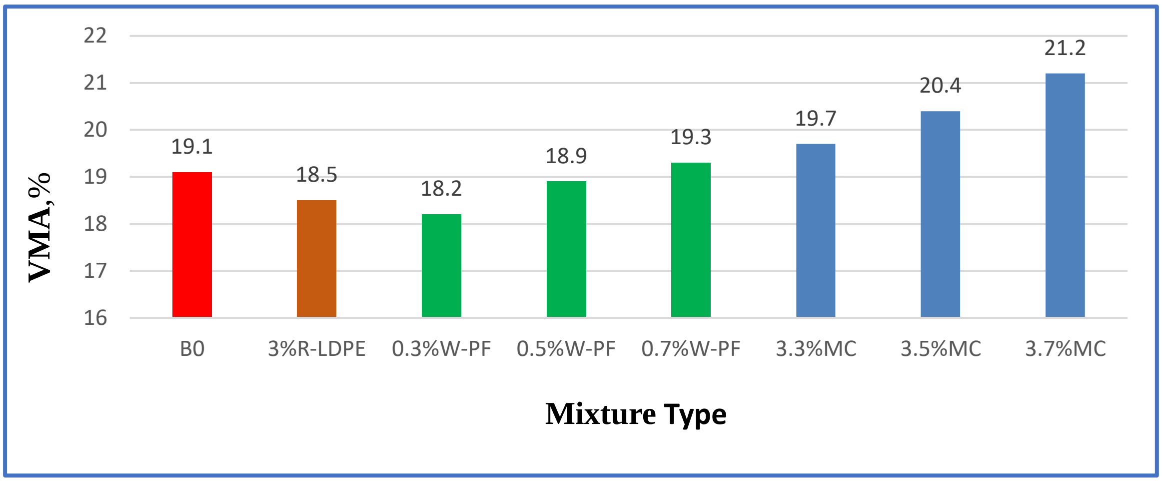

Figure 4- 18 Voids in mineral aggregate of unmodified and modified SMA mixtures.

While, in the case of W-PF, the increment into VMA appeares gradually with respect to W-PF dosage. As the amount of fiber increases, this lead to absorb more asphalt binder, and as a result, work on decrease the VFA. Then help to increase the amount of effective binder film coating aggregate, thereafter, the trend of VMA appeared as indicated by Figure (4-18). The same behavior is offered by the usage of the MC modifier, as the incorporation of the two modifiers causes high asphalt absorption due to their higher surface area. Then making the amounts of VFA decreased more than the individual case, and the VMA increased more as mentioned earlier.

4.4.1.4 Voids Filled with Asphalt

Figure (4-19) offers the percentage of voids filled with asphalt (VFA) in SMA mixtures with varying additives. According to the data in Figure (4-19), additive types and contents have a clear impact on VFA. Results show that adding R-LDPE leads to an increase in VFA when compared to the B0 mixture. The same pattern was noticed by Ahmad et al. (2014). While, the addition of W-PF and MC show a gradual reduction in the percentage of VFA by about 1% and 12% at 0.7% W-PF and 3.7% MC, 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. However, the comprising of R-LDPE polymer shows a slightly rising of no more than 5% compared to the B0 mixture. This is related to the network properties of polymer that work on block more air voids then lead to increase VFA as mentioned earlier.

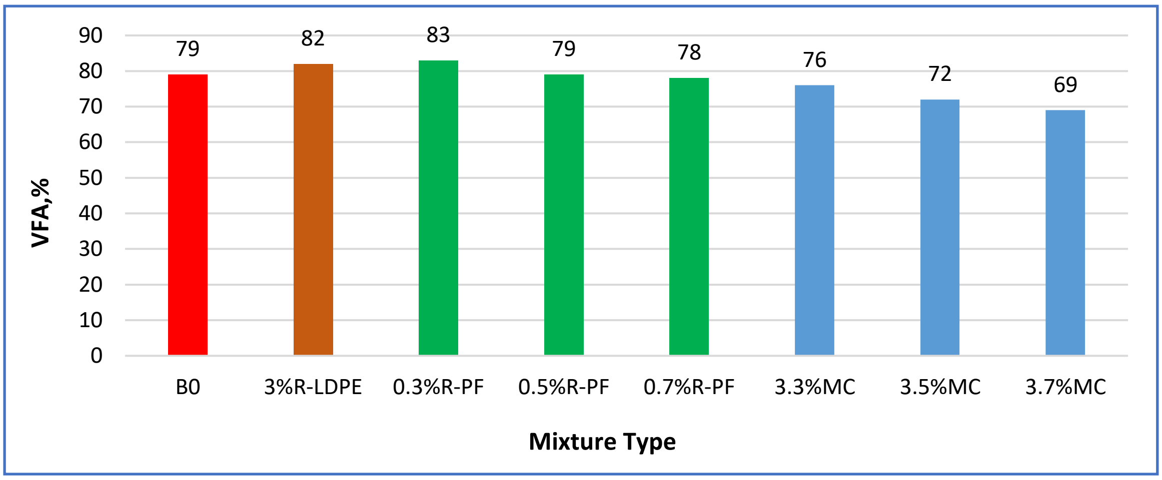

Figure 4- 19 Voids filled with asphalt of unmodified and modified SMA mixtures.

4.4.1.5 Draindown

Figure (4-20) summarizes the results of the draindown test performed on different mixtures after one hour conditioning in a force draft oven, and Plates (4-3 and 4) show illustrative captures of the variation in draindown amounts for the various SMA mixtures. The rate of draindown 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 comprising of R-LDPE polymer, success in eliminating the amount of mixture draindown is achecived to 0.43 and 0.69% at 165°C and 180°C, 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 combinedly in reducing the segregation of binder from the mixture. The behavior of the mixture looks pretty similar to that obtained by Al-Hadidy et al. (2009b) when an LDPE polymer modified SMA mixture was used, and also similar to what was studied by Ahmadinia et al. (2012a) when using polyethylene terephthalate (PET) in SMA.

Results offer by Figure (4-20) also indicate that comprising W-PF shows a similar pattern: as the amount of fiber increase, the amount of bitumen drainage decreases. The sample containing 0.7 %W-PF fibers has the least draindown of about 0.35% and 0.98% at both temperatures 165°C and 180°C, respectively. This could be due to the asphalt binder's high viscosity values with W-PF, as well as the presence of CaO and SiO_2 compounds. Which promote adhesion bonding between asphalt binder and aggregates, significantly improving performance by acting as a reinforcing material, this led to decreasedraindown. Mojabi et al. (2020) showed a similar trend of SMA modified with C25 fiber.

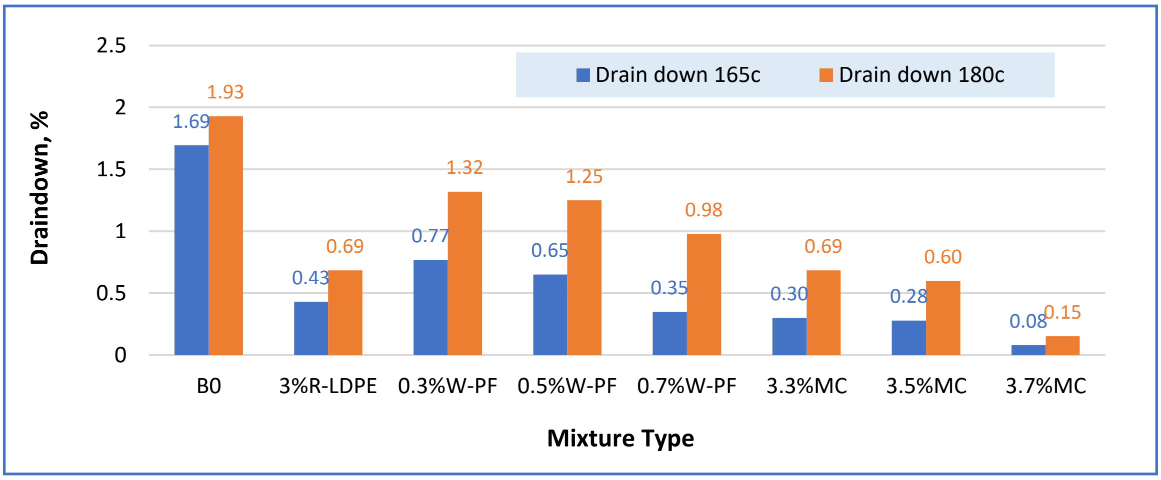

Figure 4- 20 Draindown amounts of unmodified and modified SMA at 165°C&180°C.

Furthermore, the results of the MC modification shown in Figure (4-20) indicate that the use of this case achieves draindown amount within the acceptable level at both temperatures (i.e., 165°C and 180°C), as its reached 0.08% and 0.15% at these temperatures, respectively when using 3.7% MC. This is related to the high surface area resulted from mixing the modifiers (i.e., R-LDPE+W-PF) that work on absorbing more light molecule weight asphalt. As well, increases the viscosity of the asphalt binder higher than the separate case, then helps in reducing the potential problems of draindown. Manosalvas-Paredes et al. (2016a) observed results reconcile with those obtained here when they used two different types of modification materials in a combined state.

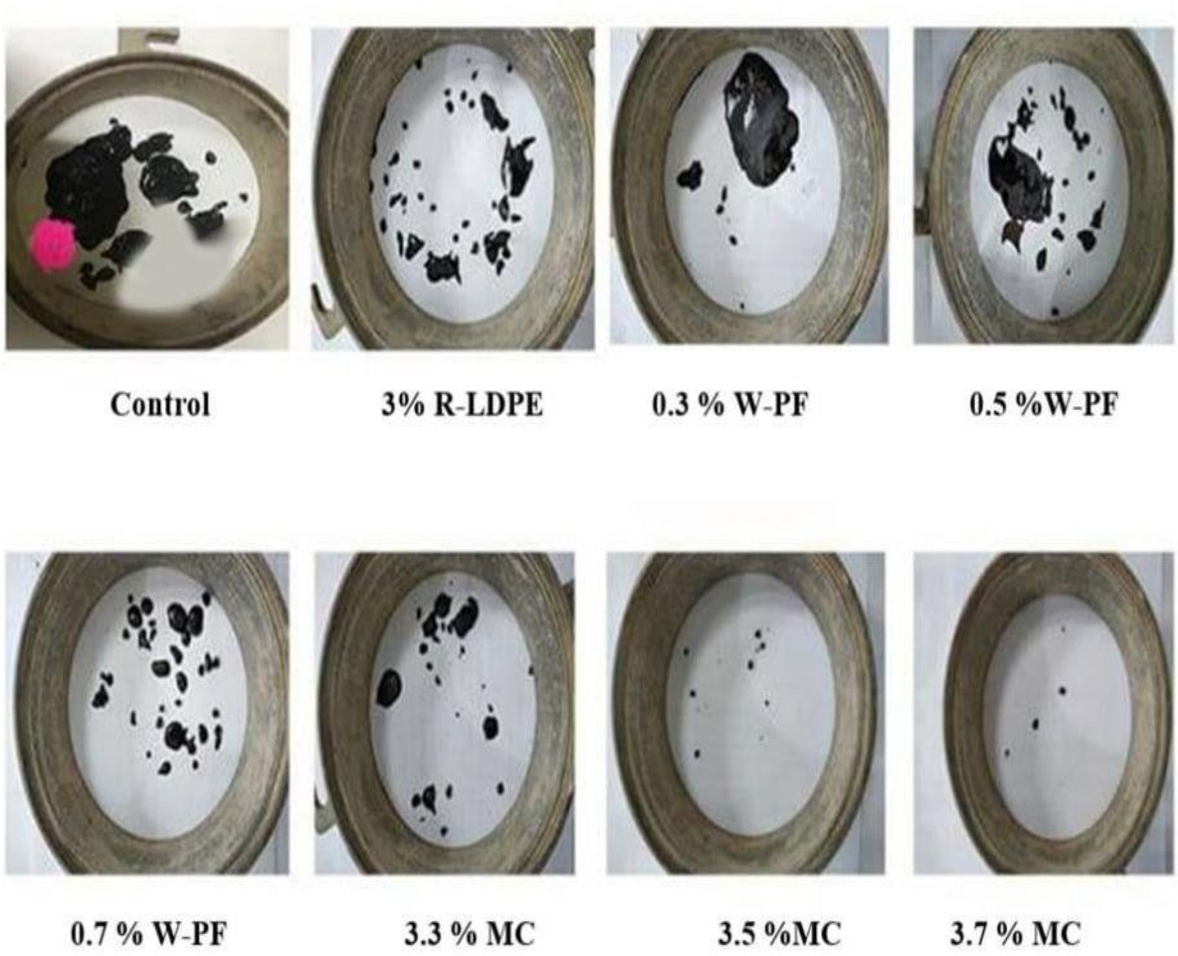

Plate 4- 4 Draindown of unmodified and modified SMA at 165°C.

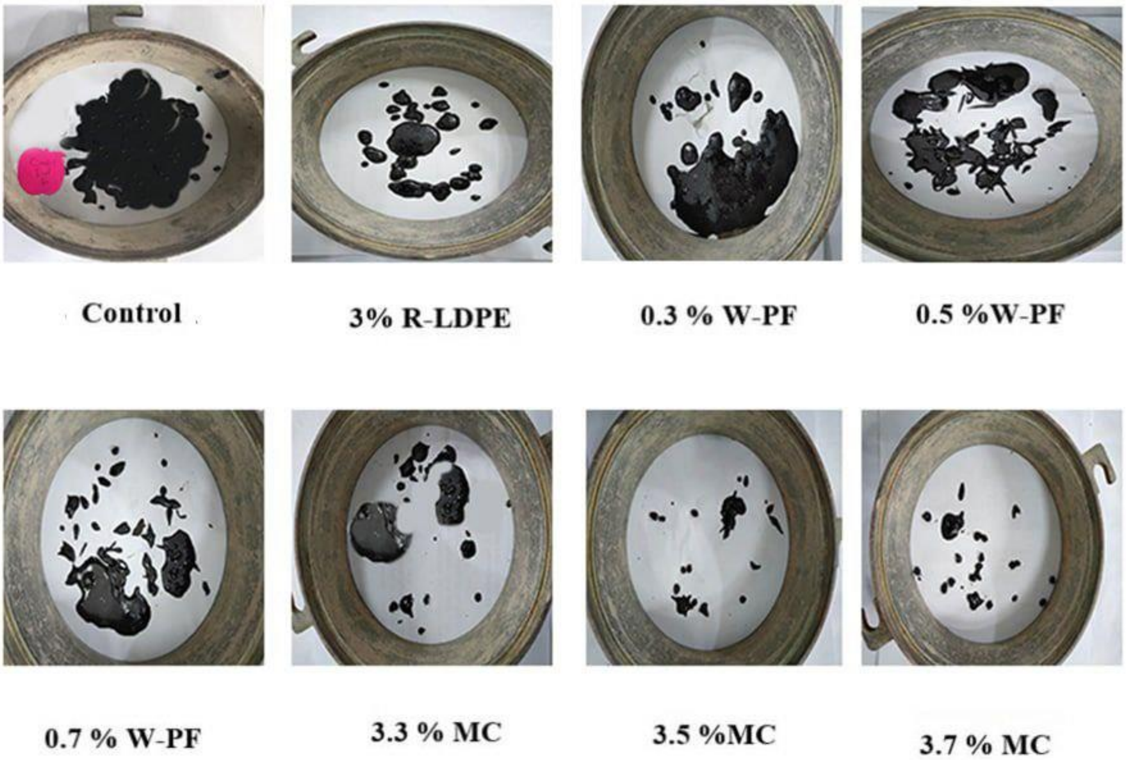

Plate 4- 5 Draindown of unmodified and modified SMA at 180℃.

4.4.2 Mechanical Test Results

4.4.2.1 Marshall Stability and Flow

Figures (4-21 and 22) summarize the results of the Marshall Stability and flow tests, and Plate (4-5) shows an example of the tested samples. Generally, results show that Marshall Stability (MS) values of the modified SMA mixture appeare higher when compared to the control mix. It can be seen that adding 3% R-LDPE results in an increment in MS of about 8% compared to the B0 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. This finding is consistent with that observed by Ahmadinia et al. (2011a).

Moreover, results show that SMA mixtures containing W-PF given more stability. Where the maximum stability is achieved by adding 0.5% W-PF by about 70% in contrast with the B0 mixture. This return to the increase of the adhesion properties between asphalt and aggregate due to the adhesive effect of CaO and SiO_2 particles in the chemical composition of W-PF. Besides the higher viscosities of W-PF 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. As well, it can be seen that the trend of improvement began to decrease after increasing the amount of W-PF to more than 0.5%. This may be due to the porous nature of W-PF, which works on increasing the absorption of the light molecules weight of asphalt binder. Then resulted in a slight reduction in the adhesion properties that in turn reflected on the mixture stability. This finding is nearly identical to Mojabi et al. (2020) explanation. It is worth mentioning that the volumetric properties are also affected substantially in this reduction. The result of combining R-LDPE and W-PF exhibits reverse behavior as represented by Figure (4-21). As the rate of mixture stability reduced gradually until reached 5% at 3.7% MC compared to the B0 mixture. This is attributed to the high surface area of the MC blend that is working on occupying a high amount of asphalt's weight. In other words, increases air void and decreases the desnsity of the mix. Then reduce the required adhesion between aggregate and asphalt, this, in turn, contributes to the decrement of the mixture stability.

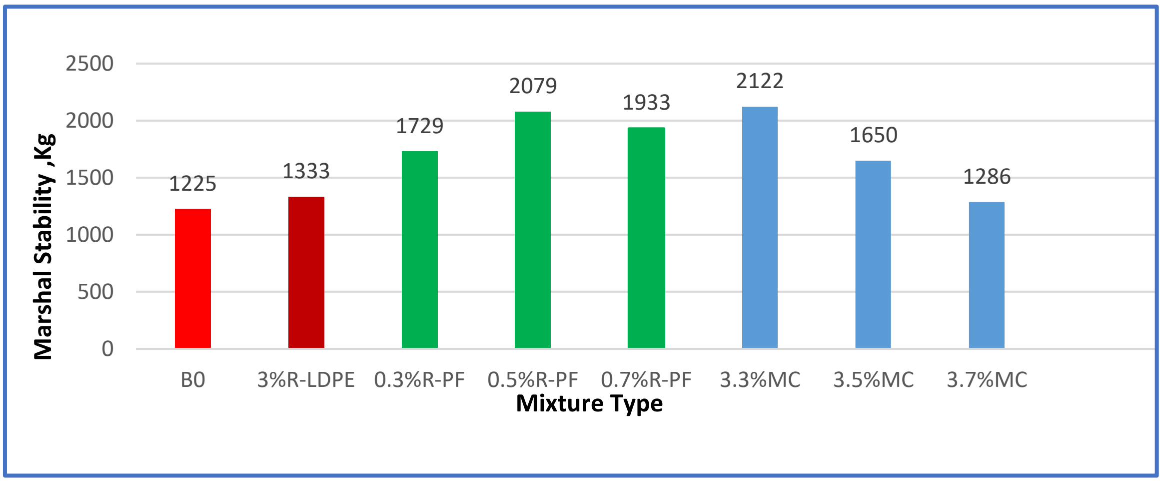

Figure 4- 21 Results of Marshall Stability Test for Control and Modified SMA Mixtures.

The flow with asphalt in SMA mixtures with varying additives was given by Figure (4-22). Due to the hardness of the mixtures, flow values showed a noticeable decrease after the addition of R-LDPE by approximately 31%. This finding is consistent with Al-Hadidy et al. (2009). Figure (4-22) also indicates that increasing the W-PF causes the flow value to decrease slightly to about 31% compared to the B0 mixture. Then begin to increase again by approximately 22% compared to the B0 mixture. These results agree with that observed by Mojabi et al. (2020). The combination of the two materials may reduce the ability of mixtures to flow when loaded lower than the individual case, but show an increment with respect to MC dosage, for the same reason that mentioned above.

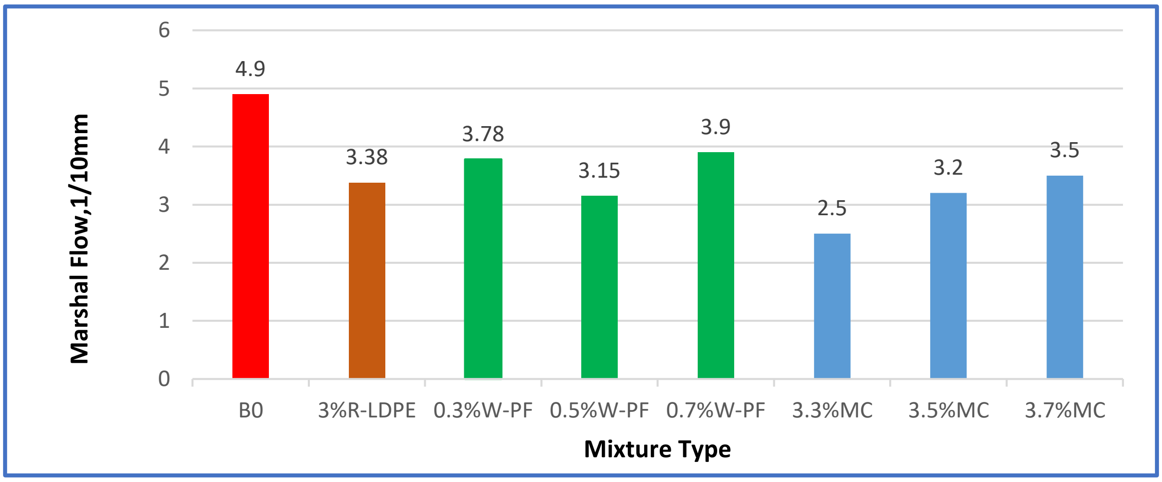

Figure 4- 22 Results of Flow for Control and Modified SMA Mixtures.

Plate 4- 7 Marshall stability and flow samples of control and modified SMA mixture.

4.4.2.2 Indirect Tensile Strength Test

Figure (4-23) compares the results of the control and modified SMA mixtures. The results show that the addition of R-LDPE increased the ITS of the SMA mixture by more than 80%. This means that R-LDPE has a positive effect on improving the resistance of the asphalt mixture to the tensile effort. This could be due to the 3D-network formation by R-LDPE polymer, in addition to the formation of the asphaltene rich phase. Which then works on increase the mixture compatibility and making it more stable against tension through reinforcing the bitumen and increase its molecule's interlock. The observed trend appears similar to that acquired by Ahmadinia et al. (2011a).

Results in Figure (4-23) also confirms that the use of W-PF leads to a decrease in the ITS as the W-PF content increase, but remaining more than the Control mixture. With the addition of W-PF appear that the amount of increment ranged between (5%-34%). This behavior is attributed to the presence of CaO and SiO_2 that gains asphalt its rigidity properties. Besides the porous nature of W-PF modifier, that works on absorbing more amount of the light molecules weight of asphalt as the dosage of W-PF increase. This making the asphalt and SMA mixture hard to compact with more air void and leess density, as well as, the bonding between aggregate and asphalt is reduced consequently. These factors in turn making the mixture suffer from tensile cracks more. The results obtained in the studies by (Manosalvas-Paredes et al., 2016b, Dalhat et al., 2020) showed a similar trend.

In the case of MC modifiers, Figure (4-23) shows that the addition of MC significantly increases the resistance of the mixture to cracking that by approximately 27% at 3.5 % MC. Because of the addition of W-PF, the polarity of the R-LDPE modified asphalt mixture was neutralized, resulting in the formation of polymer rich phase and asphaltene rich phase. Meanwhile, this action increased the resistance of the mixture to tensile cracking. On the other hand, the ITS decreases slightly as the MC dosage increase. The reason is that increasing the surface area of the modification material containing bitumen causes the mixture to absorb more amount of bitumen, then making the mixture brittle and more susceptible to cracking further to volumteric effect that mentioned above.

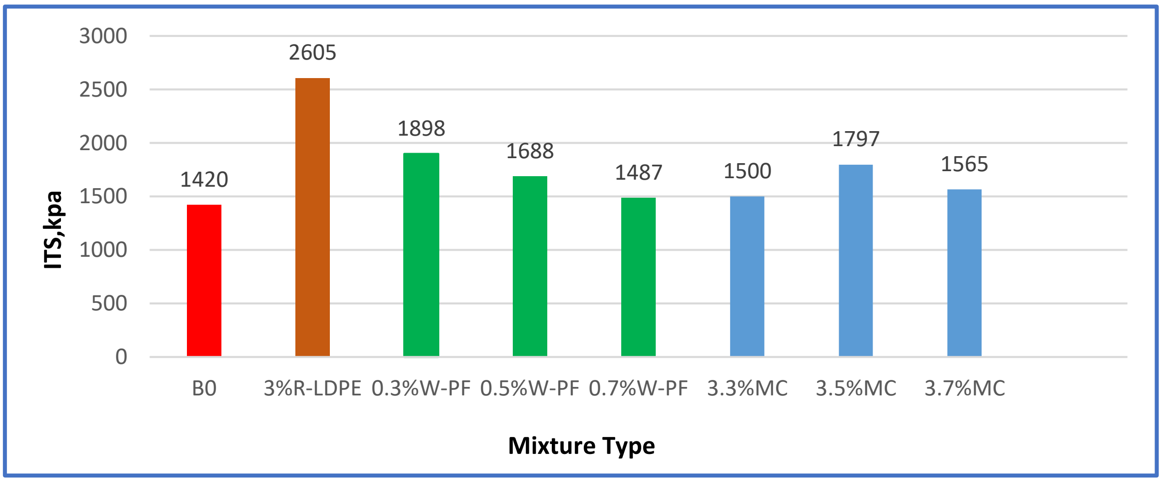

Figure 4- 23 Indirect tensile strength for Control and Modified SMA Mixtures.

Plate 4- 8 SMA samples after ITS test.

4.4.2.3 Skid resistance

The degree of micro-roughness of the pavement surface is indicated by skid resistance. Figure (4-24) shows how the use of additives increases the skid resistance of SMA mixtures surface in both dry and wet conditions. All modified SMA mixtures offered noticeable enhancement into the resistance of mixture surface to skid by about 12%, 22% and 27% when comprising 3% R-LDPE ,0.7% W-PF and 3.7% MC, 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 (Adamu et al., 2018). The findings are consistent with that of Mahdy et al. (2020b).

Results in Figure (4-24) 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 B0 mixture. Where the amount of reduction reached 11%, 17% and 28% when adding 3% R-LDPE, 0.7% W-PF and 3.7% MC, 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.

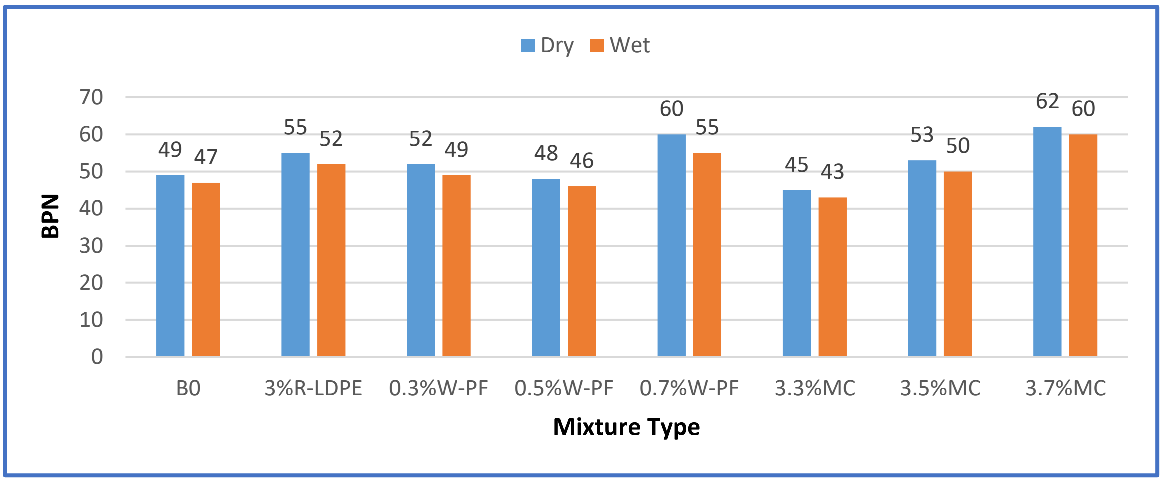

Figure 4- 24 Skid Resistance for Control and Modified SMA Mixtures.

4.4.2.4 Wheel track Test

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. Figures (4-25, 26, and 27) 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, however, it goes up reversely with respect to the modifier dosage. Where the presence of modification materials in the SMA mixture works as a base to absorb an amount of the applied stresses, The SMA mixture is then more resistant to permanent deformation than the B0 mixture. The results in Figure (4-27) shows that the SMA mixture modified with MC has the best rutting resistance.

Figure (4-25) display the effect of R-LDPE on rutting resistance in mixtures. After 10,000 cycle, the rut depth for the mixture with 3 % R-LDPE is enhanced by about 40% compare to the B0 mixture. This is attributed to the enhancement of the mixture stiffness after the addition of R-LDPE polymer. Where the comprising of it, works on forming the polymer rich phase and the asphaltene rich phase, then gained the mixture some reinforcement that enables it from withstanding the effect of ru comparable to what was observed tting. The rut depth trend of the R-LDPE modified SMA mixture appears to be by Ahmadinia et al. (2012b).

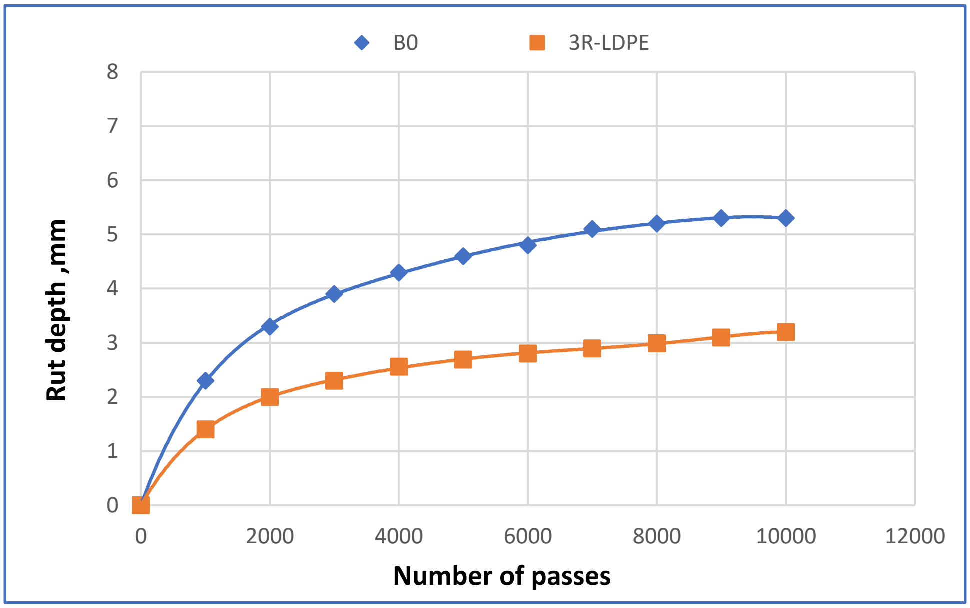

Figure 4- 25 Rut depth for Control and R-LDPE SMA Mixtures.

The SMA mixtures with W-PF show a reduction in rut depth by approximately 44% at 0.7% W-PF in contrast with the B0 mixture, as represented in Figure (4-26). This is related to the presence of CaO and SiO_2 in the chemical composition of W-PF that gaining the mixture its rigidity properties, then causes a decrement in the depth of rut. In addition, to increase the asphaltene adhesive part due to the polar nature of W-PF, this may lead to increase cross-linking between aggregate and bitumen, resulting in a lower rut depth than the B0 mixture. The behavior of this mixture was similar to that obtained by Xue et al. (2013), Dalhat et al. (2020).

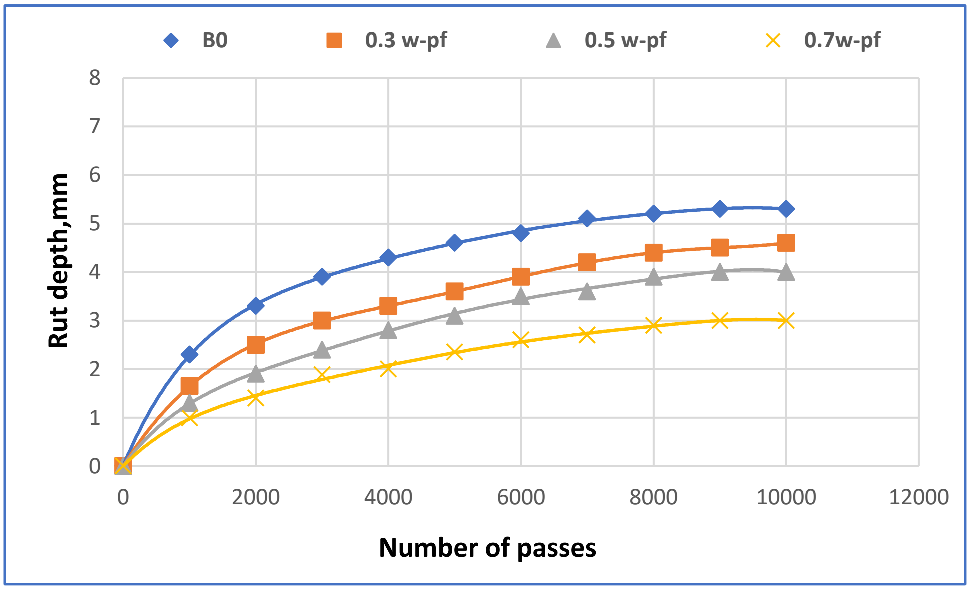

Figure 4- 26 Rut depth for Control and W-PF SMA Mixtures.

The mixtures containing the two modifiers demonstrate a significant improvement against rutting, resulting in a greater reduction in rut-depth and closer results for all contents. Whereas the use of MC results in a reduction of higher than 60% at 3.7% MC (i.e. 3% R-LDPE + 0.7% W-PF) compared to the B0 mixture. The reason for this could be that some W-PF particles are attached to the surface of R-LDPE particles, then neutralizing their polar properties and increasing the polarity of the asphalt mastic and forming the polymer rich phase and asphaltene rich phase. Furthermore, the use of MC causes higher viscosity levels due to the increment into the asphaltene fraction that is responsible for the asphalt’s hardness. Besides, the high surface area of the MC modifier works to reduce the amount of asphalt binder, as well as, the amount of pores filled with asphalt and thus improve the mixture's resistance to rutting. The behavior of MC mixtures follows a similar pattern to that obtained by Ameli et al. (2020).

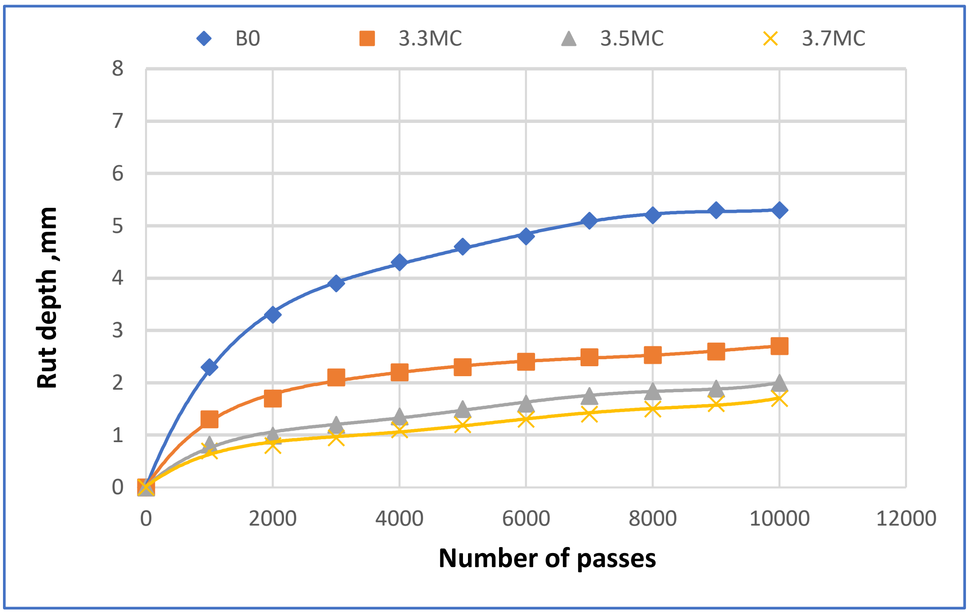

Figure 4- 27 Rut depth for Control and modified SMA Mixtures.

Meanwhile, the outputs of the wheel track test give a key to determine the dynamic stability and Rutting Increase Rate of SMA mixtures, as indicated in Figures (4-28 and 29). In general, results show that when R-LDPE is used, the Rutting Increase Rate (RIR) decreases to 1.7% mm/min and DS increases by 66% compare to the B0 mixture. As previously stated, this behavior returns to the network properties of the comprised polymer. Zhao et al. (2009) show similar behavior to dynamic stability when using SBS and SBR modified asphalt mixtures. In the case of W-PF, the results show that RIR decreases to 1.6% mm/min at 0.7% W-PF and DS increases by approximately 77% compared to the B0 mixture. This is because of the porosity and high surface area of W-PF, besides the reasons mentioned earlier that work on increase the mixture stability and as well the rate of decrement in rut. This mixture's behavior is similar to that observed Dalhat et al. (2020) when using Chicken Feather fiber to modify hot mix asphalt concrete.

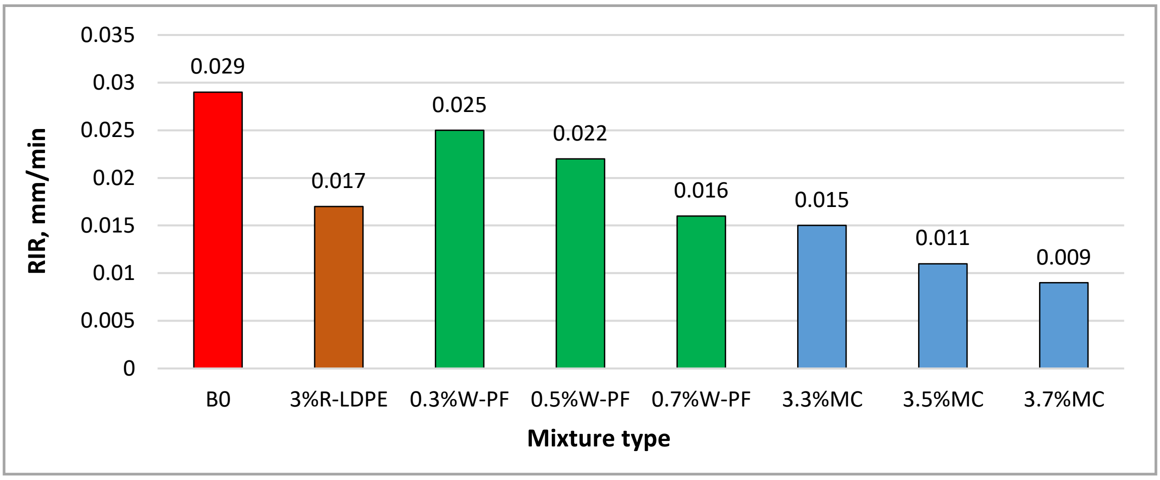

Figure 4- 28 Rate of rut depth for Control and modified SMA Mixtures.

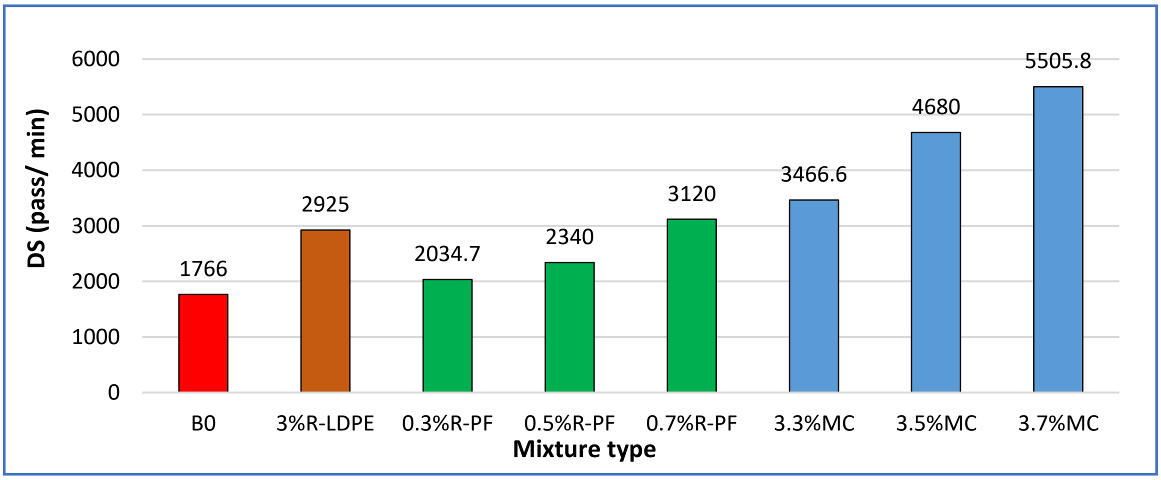

Figure 4- 29 Dynamic stability for control and modified SMA Mixtures.

Furthermore, the results also show that the use of MC has a similar trend. Where it results in a decrease in the RIR of the mixture to 0.9% mm/min and enhancing the DS by 3 times the B0 mixture. This is related to the higher viscosity levels that improve the mixture's resistance to rutting for the same details mentioned above. As a result, the dynamic stability and rate of the rut of the SMA mixture modified with MC are enhanced as offered by Figures (4-28 and 29).

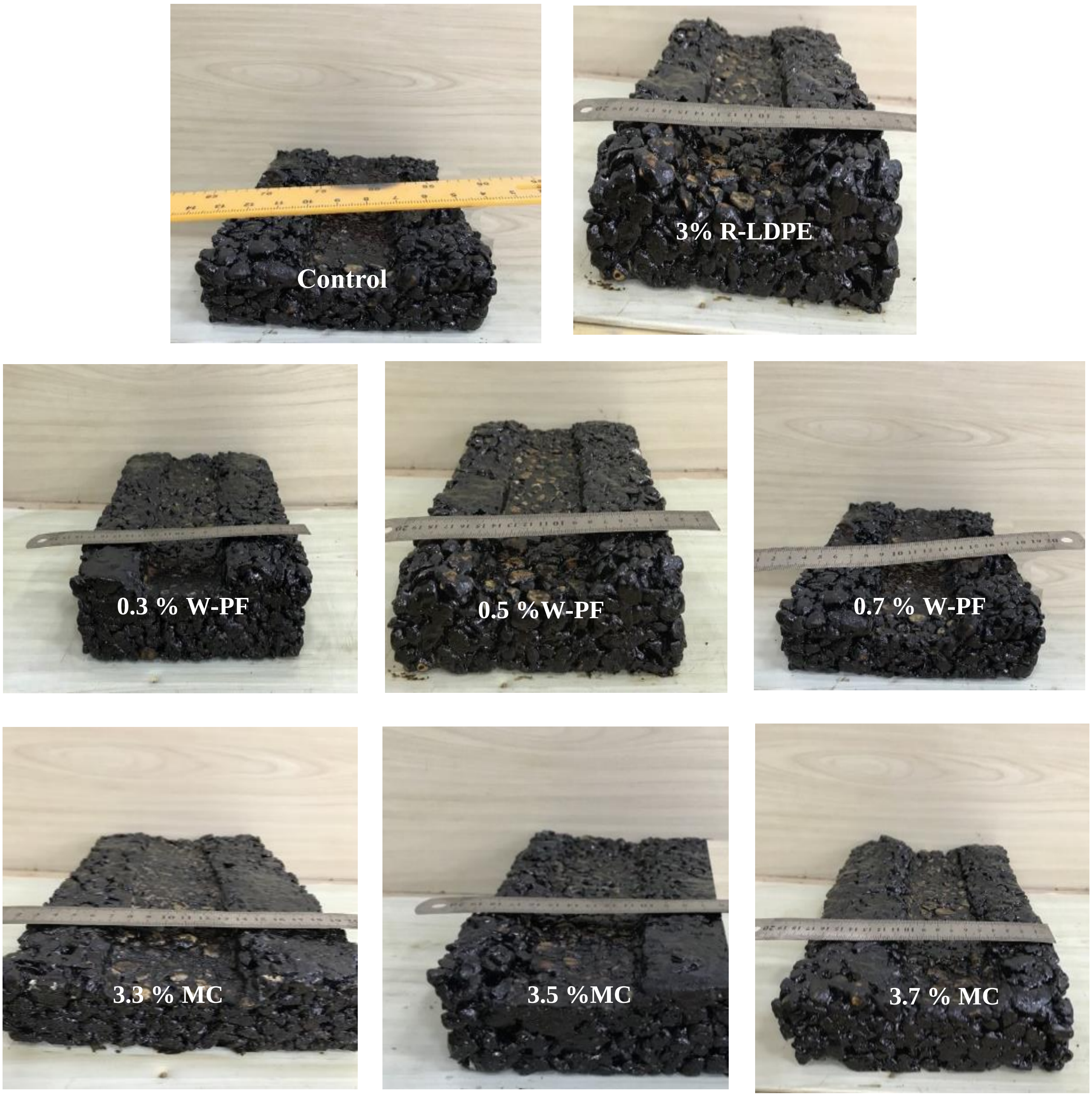

Plate 4- 10 Rut depth of control and unmodified SMA.

4.4.2.5 Creep Compliance Test

The creep compliance is determined from the applied stress and the measured strain over a specified period. Figures (4-30, 31, and 32) show the relationships between creep compliance and time for each SMA mix, after 1000s duration and at 0 ºC. Results indicate that creep compliance values increase over time and decrease as additives dosages increase. The results show that the creep compliance rate of SMA asphalt mixture modified with MC decrease with increasing additive content until reaching 0.00115 1/Mpa at 3.7% MC at the end of the test. While the amount of mixture compliant to creep shows a rising trend when using R-LDPE and W-PF in a separately manner compared to the MC case. Where it rises to 0.002 1/Mpa and 0.0033 1/Mpa at 3% R-LDPE and 0.7% W-PF, respectively.

When compare to the B0 mixture, the use of R-LDPE improves the anti-cracking resistance of the SMA mixture to low temperature cracking. Creep compliance values were enhanced by about 50% when the asphalt binder was modified with 3% R-LDPE. This return to that the comprising of R-LDPE polymer increases mixture flexibility due to the formation of the network

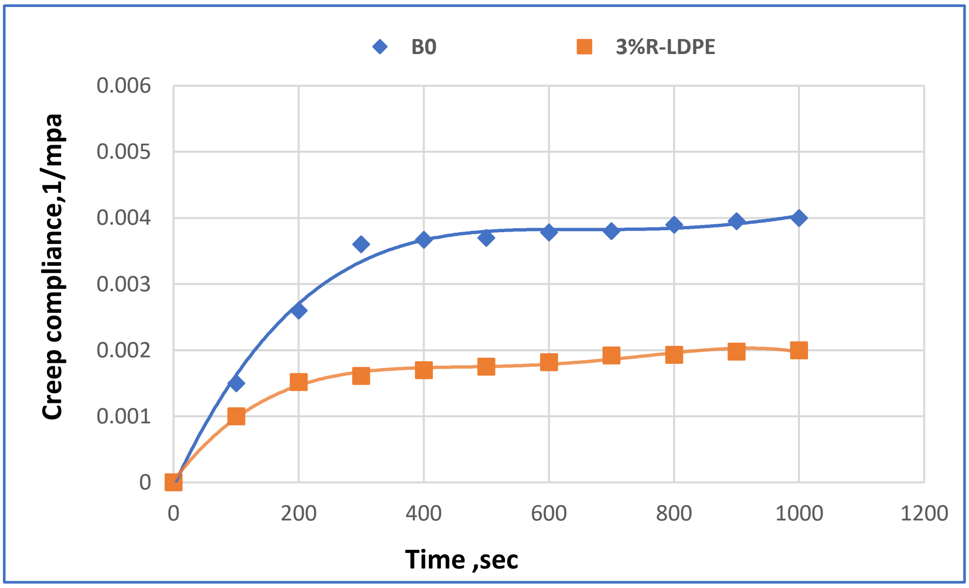

Figure 4- 30 Creep compliance for Control and Modified SMA Mixtures with R-LDPE.

structure of the polymer, as well as, the formation of the asphaltene rich phase, which aids in increasing mixture stiffness. Besides, the increment of the bond between aggregate and asphalt film as R-LDPE increase, resulting in increased mixture toughness. As a result, the resistance to fatigue cracking or crack progression is increased. This outcome is consistent with Angelone et al. (2016), Yao et al.(2018) and Diab et al. (2019).

Results in Figure (4-31) shows that the addition of W-PF helps in increase the ability of the mixture to withstand the thermal cracking by about 48% at 0.7% W-PF compared to the B0 mixture. This is related to the higher surface area of this modifier, porosity nature, and the presence of CaO and SiO_2 particles in their chemical composition. These parameters in turn lead to an increase in the mixture stiffness and as well its resistance to the impact of thermal cracking. The trend appears similar to that obtained by Saltan et al. (2017) and Roberto et al. (2018).

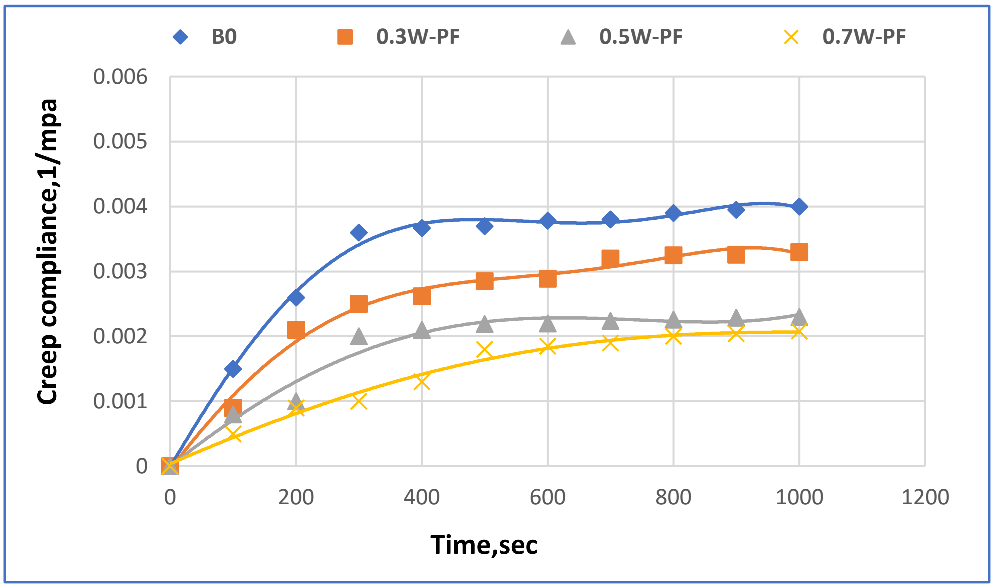

Figure 4- 31 Creep compliance for Control and Modified SMA Mixtures with W-PF.

Moreover, the results indicated in Figure (4-32) display that when comprising the two modifiers together, achieve a more positive effect on the resistance of mixture to thermal cracking. Where obtained that the utilization of 3.7% MC achieves the higher enhancement reached to 71% in contrast with B0 mixture. As the use of collective case from modifiers leads to neutralize the chemical reactions into asphalt molecule , in additament to this modifier's larger surface area. As a result, the mixture's flexibility to resist cracking improves.

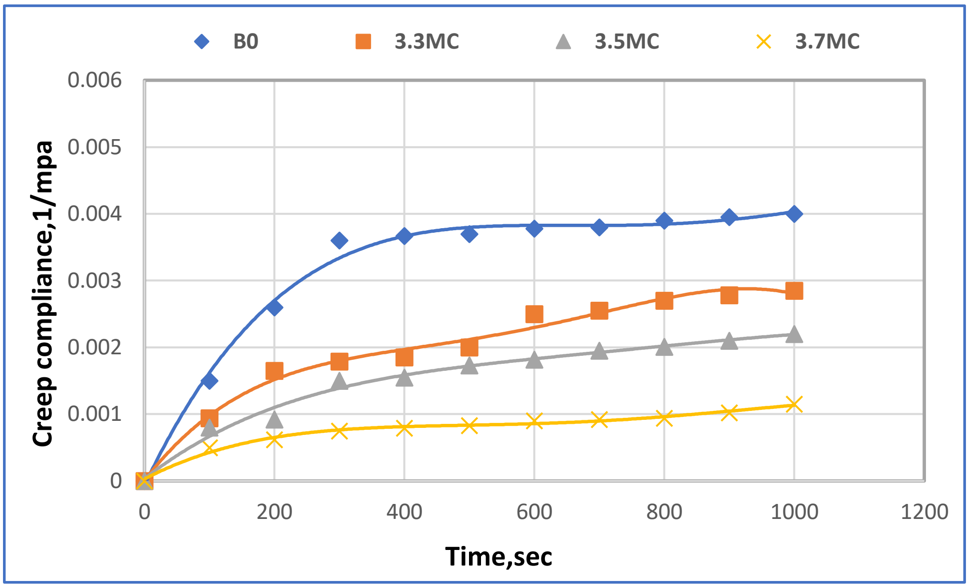

Figure 4- 32 Creep compliance for Control and Modified SMA Mixtures with MC.

4.4.3 Durability properties

4.4.3.1 Cantabro Abrasion Loss Test

The resistance of the SMA mixture to raveling is indicated by the abrasion ratio evaluation. Figure (4-33) demonstrates the Cantabro test results after 10 minutes in the Los Angeles abrasion machine for each type of SMA mixture, while Plate (4-8) 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 R-LDPE appeared lower than B0 mixture by about 39% and 31% for unaged and aged conditions, respectively. With the addition of R-LDPE, 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 are consistent with those obtained by Mohammad et al. (2014).

Results represented by Figure (4-33) also indicate that the use of W-PF showed an upward trend, resulting in an increase in the amount of abrasion with respect to W-PF content. Where the maximum increment into mixture resistance to abrasion, at 0.3% W-PF. As a result, the presence of CaO and SiO_2 particles in the chemical composition of the W-PF, increase the mixture stiffness and flexibility as mentioned earlier. Besides the porous nature and high surface area of this modifier making the absorption of the light molecule weight asphalt more. Then, help in eliminating the exposure of mixture to abrasion. However, after the dosage of 0.3% W-PF, the resistance of the mixture begins to decrease again due to the agglomeration ability of the W-PF, which leads to reduce the mixture bonding. In addition to the high absorption of the asphalt by the high amount and surface area of W-PF making brittle mixture and more subjected to abrasion (Arabani et al., 2011).

While, the usage of the collective case from the aforementioned modifiers shows a more positive trend of abrasion loss, as offered by Figure (4-33). Where the amount of enhancement into mixture ability abrasion reached higher than 50% for both unaged and aged conditions, at 3.7% MC. This return to increment in the mixture stiffness as a result of the neutralization of the chemical and physical reactions after comprising both modifiers together. Besides the increment of mixture bonding then help mitigating the mixture's ability to abrasion loss.

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.

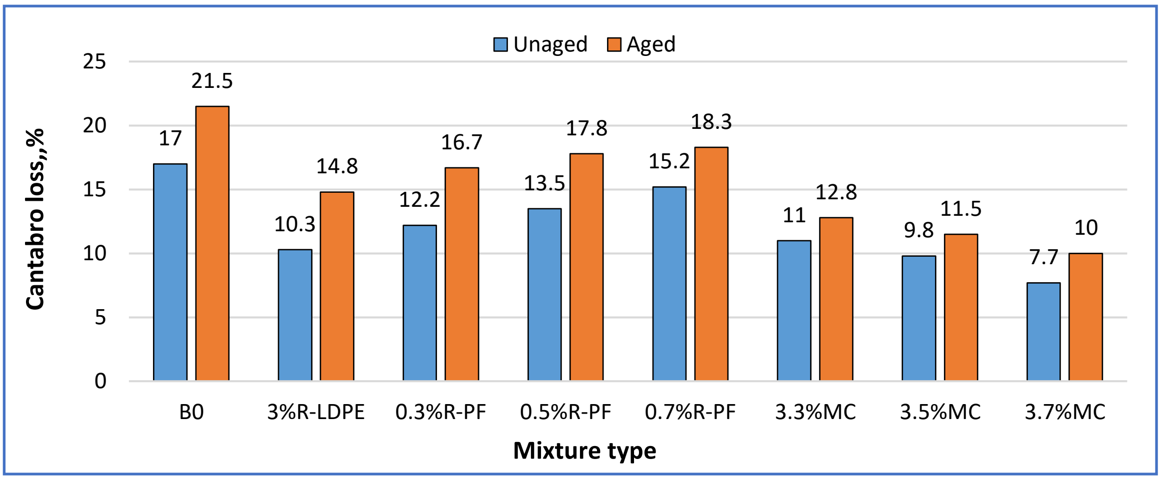

Figure 4- 33 Cantabro abrasion loss for control and modified SMA mixtures before and after Conditioning.

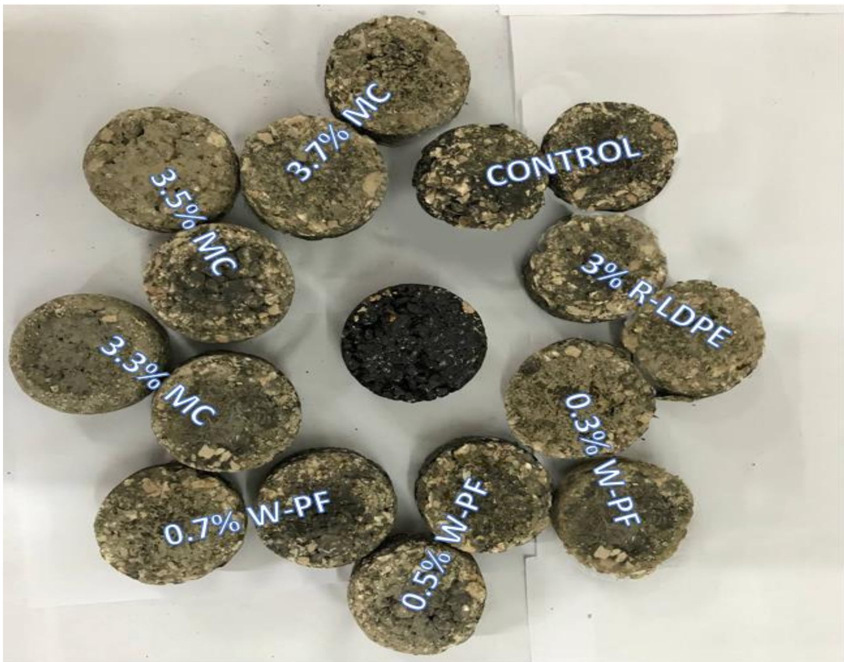

Plate 4- 11 The Specimens After Cantabro Test Before and After Aging.

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. Three 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. 2.The second section is about treating asphalt with two different types of sustainable materials. The results show that the individual additives can be improved further when added to the group of selected materials.
3. The third section summarizes all results related to the modified SMA control mixtures, which include three modified binder types with varying dosages, and compares the modified mixtures to the unmodified control mixture. The comparison was carried out by characterizing SMA mixtures using a set of volumetric, functional, and mechanical properties.
4. Test methods show that waste polymers and fibers, such as R-LDPE and W-PF, can be used individually and collectively to modify binder, resulting in improved mixtures in terms of function and durability.

Chapter Five

Conclusions and Recommendations

5.1 Introduction

The purpose of this study was to improve the performance of SMA by using sustainable materials, namely R-LDPE and W-PF. 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 mechanical properties. For example, it has a draindown 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 R-LDPE and W-PF, either singly or in combination, changes the physical properties of bitumen significantly. Adding R-LDPE and/or W-PF to asphalt binder reduces penetration, temperature sensitivity, and ductility while increasing softening point, viscosity, and aging resistance.

3. Modifying asphalt binder by R-LDPE or W-PF individually results in a significant change in the properties of the SMA mixture:

- Draindown decreases to 0.431, 0.69 when using R-LDPE and 0.35,0.98 when using 0.7 W-PF, in both anticipated and in anticipated+15 temperature, respectively.
- Marshall stability increases by 8% when 3 % R-LDPE, while it increases by 41 %, 70 %, and 57 % when 0.3 %, 0.5 %, and 0.7 %W-PF are included, respectively, while flow decreases by 31 %, 22 percent, 35% and20% when the same percentages are included.
- Increasing the percentage of W-PF in SMA mixtures improves skid resistance significantly. Similarly, R-LDPE has a positive effect. The increase amounted is 12%.
- Rutting resistance increases with the presence of R-LDPE, as rut depth decreases by 40 %. The greatest increase in rutting resistance for SMA include W-FP is achieved with 0.7 % W-PF as rut depth decreases by 44 %. compare to the control mix
- Creep compliance increases as the percentage of W-PF increases, but it remains less than non -fibrous and non- polymeric mixtures, while R-LDPE has a decrease in creep compliance of 0.002.
- The use of R-LDPE results in the greatest increase in tensile strength, followed by 0.3 % W-PF.
- By adding R-LDPE, the abrasion resistance is increased to 39 % and 31 %, respectively. Similarly, increase abrasion with respect to W-PF content, with 0.7 W-PF mixture showing a 10.5 % and 14.8 % decrease for unaged and aged.

4. The addition of R-LDPE and W-PF collectively results in a noticeable change in the properties SMA mixture:

- The stability of the SMA mixture improves, the SMA mixture with 3.3 MC has the highest Marshall stability value, which is 42 % higher than the control mixture. Flow values are also observed to be less than the flow of the control mixture, 3.3 %,3.5 % and 3.7% MC decrease flow by 48%,34%, and 26 %.

- Skid resistance is improved by combining the two modifiers with both dry and wet cases.
- When collective modifiers are added, the resistance to permanent deformation improves significantly, and the rut depth decreases as the amount of mix content increases.
- The use of 3.5 % MC resulted in the greatest increase in tensile strength, follows by 3.7 %, 3.3 % MC percentage in the same mixtures with 3.5%R-LDPE, the largest percentage of indirect tensile strength to moisture resistance was also discovered.
- All mixing ratios have a greater positive effect on abrasion resistance due to a decrease in CAL before and after aging than the CAL value of the control mixture. The use of 3.7% MC results in the greatest increase in abrasion resistance, reaching 54% and 53% MC before and after aging, respectively.

5.3 Recommendations

The following recommendations can be made based on the results of the laboratory work:

1. It is strongly advised to use R-LDPE to modify SMA mixtures due to the significant improvement in performance that can be obtained.
2. To improve SMA performance, use W-PF at a high percentage.
3. Recycling waste products for use in alternative building materials may not only be feasible but also necessary. A solution to the global problem of landfill use, but also provides the opportunity to improve asphalt mix design.

5.4 Further Work

Several possible future studies can be recommended based on the laboratory work done during this research, which is 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. Examination of the high-temperature stability and cracking performance (load-induced, fatigue, top-down, etc.) of SMA mixtures with R-LDPE and W-PF
3. Experimenting with different types of recycling waste additives to improve SMA mixtures, such as LLDPE, HDPE, and other types of polypropylene polyvinyl chloride (PVC), polyethylene terephthalate (PET), chicken fiber, cigarettes fiber, polyester fiber.
4. Use appropriate software to analyze the polymeric and fibrous, in increasing the resistance to obtain a more comprehensive analytical study of the behavior of the SMA mixture.
5. Use the dry process

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الخلاصة

تعتبر شبكة الطرق في أي بلد أمرًا بالغ الأهمية للتنمية الاقتصادية والتكامل الاجتماعي والتجارة.

تتوافق الزيادة في تكاليف الصيانة مع زيادة حجم حركة المرور ، مما يستلزم الحاجة الملحة لبناء طرق أفضل وأكثر دواما وفعالية تمنع أو تقلل من مشاكل الرصيف المرن. دفع الطلب المتزايد على الأرصفة عالية الجودة الباحثين إلى تطوير طرق وتصميمات جديدة لتطوير الأداء وعمر الخدمة الفعال للخلطات الاسفلتية. الأسفلت المصطكي الحجري هو تقنية تستخدم لتحسين أداء خلطات الإسفلت. الإسفلت المصطكي الحجري SMAعبارة عن خليط صلب ومستقر ومقاوم للتشقق يعتمد على ملامسة الحجر الصخري للقوة ورابط الملاط الغني من أجل المتانة. يقابل الزيادة المقدرة في التكلفة بنسبة 20٪ إلى 25٪ زيادة في متوسط العمر المتوقع للمزيج ، ويرجع ذلك أساسًا إلى انخفاض التشققات وزيادة المتانة. يعتبر الأسفلت المصطكي الحجري مزيجًا ممتازًا للاستخدام في المناطق ذات الكثافة المرورية العالية وحيث تكون الصيانة المتكررة مكلفة.

من ناحية أخرى ، يستخدم مفهوم الاستدامة الآن على نطاق واسع في العديد من جوانب الحياة ، بما في ذلك صناعة الرصف. يوفر استخدام النفايات في خليط الأسفلت فرصة رائعة لإدارة هذه النفايات بشكل مستدام. يساهم خفض التكلفة وحماية البيئة وتقليل استهلاك الطاقة في الاستدامة. نتيجة لذلك ، فإن الغرض من هذا البحث هو دراسة تأثير المواد المدورة على أداء خليط الأسفلت المصطكي الحجري. لتعديل رابط الأسفلت ، تم استخدام نوعين من المواد المدورة: البولي إيثيلين منخفض الكثافة المعاد تدويره والألياف الورقية المهدورة. ثم تم تحسين SMA على مرحلتين. تضمنت المرحلة الأولى تطوير رابط الأسفلت باستخدام نسب تثبيت من البولي إيثيلين منخفض الكثافة المعاد تدويره (3٪) والألياف الورقية المهدورة بثلاث نسب مختلفة 0.3٪ ، 0.5٪ ، و 0.7٪من وزن الرابط الاسفلتي.

وشملت المرحلة الثانية استخدام المواد المذكورة مجتمعة بنسب مختلفة (3 + 0.3)٪ ، (3 + 0.5)٪ ، و (3 + 0.7)٪ كجزء من الوزن الكلي للاسفلت الرابط. تم استخدام الاختبارات التقليدية مثل الاختراق ونقطة التليين والليونة ومؤشر الاختراق واللزوجة الدورانية لتوصيف رابط الأسفلت. تم استخدام اختبار فرن الغشاء الرقيق للتحقق من تأثير التقادم. علاوة على ذلك ، من أجل تحديد تأثير استخدام هذه المواد على خصائص خليط الأسفلت المصطكي الحجري ، تتضمن خطة الاختبار خصائص الحجم (على سبيل المثال ، الكثافة الظاهرية ، الفراغ الهوائي ، الفراغ في الركام المعدني ، الفراغ المملوء بالإسفلت ، والصرف) ، الميكانيكية الخصائص (على سبيل المثال ، استقرار وتدفق مارشال ، امتثال الزحف ، قوة الشد غير

المباشرة ، فقدان تآكل كانتابرو ، مقاومة الانزلاق و التخدد) والمتانة (فقدان تآكل كانتابرو بعد التقادم ونسبة قوة الشد)

. يحسن استخدام إضافات المواد المدورة الخواص الفيزيائية للرابط الأسفلتي. حيث تم تقليل عمق الاختراق ، والليونة ، وحساسية درجة الحرارة للرابط الاسفلتي ، بينما تمت زيادة نقطة التليين ، واللزوجة ، ومقاومة التقادم. أظهر استخدام البولي إيثيلين منخفض الكثافة المعاد تدويره الأداء الإيجابي لخليط الإسفلت المصطكي الحجري في جميع الاختبارات (التجفيف ، ثبات وتدفق مارشال ، مقاومة الشد غير المباشرة ، مقاومة الانزلاق ، الامتثال للزحف ، الختم ، وفقدان كانتابرو). أدى استخدام نفايات الألياف الورقية إلى تعديل جميع الخصائص المذكورة تقريبًا ، حيث أظهرت إضافة 0.7٪ تحسنًا ملحوظًا مقارنة بالنسب المنخفضة الأخرى ، باستثناء 0.3٪ ، والتي أظهرت تحسنًا ملحوظًا في مقاومة الشد غير المباشرة و مقاومة فقدان التآكل. نتج عن الخلطات الممزوجة مع الأسفلت أفضل أداء للخليط ، مع إضافة 3.7٪ لتوفير أفضل أداء للأسفلت المصطكي الحجري في التصريف ، ومقاومة الانزلاق ، ومسار العجلة ، وتصلب الزحف ، وإضافة 3.5٪ مما يوفر أفضل النتائج في تحسين قوة الشد غير المباشرة.

خلصت الدراسة إلى أن استخدام المواد المدورة محليا كمحسنات للربط الأسفلتي يمكن أن يساهم في تحسين أداء الخلطات الاسفلنية بشكل فعال .لذا فإن استخدام النفايات يساهم في تعزيز مبدأ الاستدامة.

جمهورية العراق

وزارة التعليم العالي والبحث العلمي

جامعة كربلاء

كلية الهندسة

قسم الهندسة المدنية

تحديد خصائص المزيج الاسفلت الماستكي المحسنه بالالياف الصناعيه

رسالة مقدمة الى قسم الهندسة المدنية, جامعة كربلاء وهي جزء من متطلبات الحصول على درجة الماجستير في الهندسة المدنية

من قبل :

ايات حميد جبار

بكلوريوس في علوم الهندسة المدنية لسنة 2016

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