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Engineering Characterisation of Wearing Course Materials with Nanoparticles and Waste Plastic

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DECLARATION

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Date: 05 /08/2022

ABSTRACT

The global construction of hundreds of kilometres of roads every year results in the consumption of large amounts of raw materials and the depletion of natural resources. Technologically advanced countries such as Australia are currently facing serious issues due to the waste generated by their citizens. The disposal of waste is a severe problem for modern city municipalities. Currently, the majority of local plastic waste needs to be dumped in stockpiles, which increases the level of extremely hazardous pollution in Australia. Moreover, the pavement structures have started to collapse frequently due to ever-increasing axle loading, higher traffic volume, and low maintenance levels even after being in service for several years. To reduce pavement damage, rutting and fatigue, the asphalt must be reinforced with certain polymers. These polymers can be used to produce asphalt that can mitigate permanent deformation and fatigue failure. However, utilizing virgin polymers is expensive as well as has less storage stability. Therefore, utilizing nanomaterials-based waste polymers derived from plastic waste could aid in the creation of sustainable, cost-effective and high-performance pavements.

Currently, researchers and industrial organizations are interested in innovating ways for the application of waste materials in civil and construction engineering. This study investigated the impact of utilizing waste polyethylene terephthalate plastic and nano-silica to modify asphalt mixtures following Australian design guidelines and criteria. Various types of asphalt mixtures, plastics and nano-silica were adopted to determine the rheological performance and mechanical properties of the modified binders as well as asphalt mixtures. In this study, nano-silica with 2%–8% contents were utilized. The main objectives of this study were to investigate the impacts of using nanomaterials in addition to recycled plastic as an additive for wearing-course asphalt materials. Experimental processes and testing methods were conducted in stages. Different binder samples and asphalt mixtures were developed and were subsequently tested to determine the optimum sample condition for higher rutting resistance, higher stability and lower fatigue deformation. Moreover, the physical, rheological, and aging properties of modified bitumen were analysed. The Marshall stability and Marshall flow wheel-tracking test, four-point bending fatigue test, tensile strength test, stiffness modulus test, and drain-off tests were also conducted for the modified asphalt mixtures.

Based on the findings of the first stage investigation**,** the 6–8% Polyethylene terephthalate (PET) plastic content was determined to be ideal in terms of improving stability, rutting resistance, and fatigue life of modified bitumen binders. Reflecting on other sorts of waste plastic, 2% and 4% of High-density polyethylene and Low-density polyethylene are acceptable as ideal contents. This suggestion has been proven by penetration, Dynamic Shear Rheometer (DSR), Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) tests. However, the high content of HDPE and LDPE samples are less effective in increasing the binders' elasticity, aging resistance and resistance against permeant deformation. The waste PET up to 8% modified bitumen has demonstrated substantial improvements in physical properties, rheological properties, stiffness, elasticity and aging resistance.

Based on the findings of the second stage investigation, the Marshall stability, Marshall flow, and Marshall quotient (MQ) results displayed substantial enhancements for the

waste plastic PET modified stone mastic asphalt and dense graded asphalt mixtures. The 8% PET produced a high stability (19.78 kN) mixture while having a Marshall flow of 2.65 mm and MQ of 7.46 kN/mm. Rutting properties of 8% PET modified asphalt mixtures demonstrated the lowest rut depth of about 2.08 mm. Most importantly, the addition of 8% PET increased the rutting resistance by 74.1% and 79.2% for SMA mixtures and AC dense mixtures, respectively. Based on the outcomes, the application of waste polymer can produce an effective bituminous mixture from the unwanted residue, which is commonly referred to as 'sustainable asphalt'. This research demonstrated the impact and potential of waste plastic as an alternative cost-effective recycled polymer for the modification of bitumen binder and asphalt mixtures in accordance with Australian standards.

During the third stage of research, different types of nano-silica (NS) were mixed with PET through the wet-mix process to produce a developed hybrid additive for stone mastic asphalt modification, with the goal of improving the rutting, stiffness, fatigue and other essential properties. The physical-rheological properties of the modified bitumen were evaluated based on penetration tests, softening point tests, DSR tests (temperature sweep tests and frequency sweep tests) and RTFOT tests. The manufacturing properties were evaluated within the Marshall stability, Marshall flow, MQ, rutting depth, indirect tensile strength, resilient modulus, fatigue and drain-off tests. According to the findings, the addition of 4%–8% of nano-silica improved the rutting, fatigue life, stability, skid resistance, strength, and stiffness performance of the modified mixtures in contrast to the unmodified mixtures. The increase in nano-silica alongside 6% PET had distinctly increased Marshall stability and Marshall quotient of about 20 kN and 8.7 kN/mm, respectively. The high Marshall stability values indicated that due to the hybrid NS-PET samples, they had developed stiffer. Moreover, it improved the resistance of modified asphalt mixtures to rutting and cracking deformation.

The rutting depth, stiffness, tensile strength ratio, and drain-off were determined to be 1.2 mm, 6100 MPa, 96.42%, and 0.041%, individually. The outcomes indicated an obvious improvement in the performance of the nano-silica-PET-developed hybrid additive. The asphalt modified samples with the hybrid additive of 6% NS and 6% PET demonstrated outstanding performance in terms of stiffness and rutting resistance. Additionally, the hybrid additive of 4%NS-6%PET showed less susceptibility to moisture damage, which could be attributed to its high tensile strength (1.7 MPa) and TSR ratio (96%). Adding no more than 6% PET caused a reduction of drain down by 0.9%. For 6% PET with 8% NS, the drain off reduced to 0.041%. The results justified that the addition of nano-silica with PET effectively lessened drain-off levels. Based on the outcome, the addition of 6% nano-silica to PET plastic enhanced the fatigue resistance to the greatest level and increased its fatigue life to 220490 times of the 6NS-6PET hybrid additive mixture. By introducing the nano-silica to the 6% PET plastic binder, the flexural strength was enhanced. An enhancement of about 6234 MPa, 6641 MPa and 6818 MPa was observed for 2, 4% and 6% of 15nm nano-silica addition. The results demonstrated that the inclusion of nano-silica and waste PET successfully improved the rutting resistance and fatigue life of the modified asphalt mixtures. Future field trials utilizing the optimum mixture outcome of this research would be beneficial to examine the environmental and loading impact on the Australian modified asphalt mixtures.

LIST OF PUBLICATIONS

The following publications are resulted from the work undertaken in this thesis:

Refereed published journal papers:

Mashaan, Nuha, Amin Chegenizadeh, and Hamid Nikraz. 2022a. "A Comparison on Physical and Rheological Properties of Three Different Waste Plastic-Modified Bitumen" *Recycling*, 7, (2): 18.

Mashaan, Nuha, Amin Chegenizadeh, and Hamid Nikraz. 2022b. "Evaluation of the Performance of Two Australian Waste-Plastic-Modified Hot Mix Asphalts". *Recycling*, 7 (2) :16.

Mashaan, Nuha, Amin Chegenizadeh, and Hamid Nikraz. 2022c. "Performance of PET and Nano-silica Modified Stone Mastic Asphalt Mixtures". *Case Studies in Construction Materials*, 16: e01044.

Mashaan, Nuha, Amin Chegenizadeh, Hamid Nikraz. 2021a. "Laboratory Properties of Waste PET Plastic-Modified Asphalt Mixes". *Recycling* 6(3):49.

Mashaan, Nuha, Amin Chegenizadeh, Hamid Nikraz, Alireza Rezagholilou.2021b. "Investigating the engineering properties of asphalt binder modified with waste plastic polymer". *Ain Shams Engineering Journal* 12(2); 1569- 1574.

Award

Gold Medal at Academics World 528th International Academic Conference on Development in Science and Technology (IACDST), Sydney NSW, Australia, 23-24 January 2019.

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LIST OF ABBREVIATIONS

PET	Polyethylene terephthalate plastic
LDPE	Low-density polyethylene
HDPE	High-density polyethylene
NS	Nano-silica
SBS	Styrene-butadiene -styrene
SBR	Styrene -Butadiene-Rubbe
SMA	Stone mastic asphalt
MQ	Marshall quotient
EVA	Ethylene-vinyl acetate
VIM	Air voids
VMA	Voids of the mineral aggregate
PVC	Polyvinyl chloride
PE	Polyethylene
MRWA	Main Road Western Australia
OBC	Optimum Bitumen Content
SEM	Scanning Electron Microscopy
DSR	Dynamic Shear Rheometer
RTFO	Rolling Thin Oven
PAV	Pressure Aging Vessel
G*	Complex shear modulus
δ	Phase angle
G’	Storage modulus
G’’	Loss modulus
G*/sinδ	Rutting factor
G* sin (δ)	Fatigue factor
tan δ	Loss tangent

Chapter One

1.1 Introduction

Roads and bridges are fundamental components of infrastructure, playing a vital role in our lives. Bituminous mixtures are composite materials comprising several distinct materials, and are employed in various civil engineering projects, such as the construction of roads and highways. These mixtures consist of mineral aggregates, bitumen, and air voids, blended and then laid and compacted to form road surfaces (Ali 2013; Hamed 2010).

Rapid economic and industrial growth in Australia is giving rise to an unprecedented increase in waste materials, especially waste plastic. Further, road pavement has weakened rapidly owing to high traffic loads (Mashaan et al. 2021a). The structural stability of a road is usually provided by the pavement, which consists of crushed and carefully selected stone and rock of suitable sizes, which is finally compacted by applying a limited amount of binder. Asphalt concrete is vital to modern life in Australia, playing a role in much of the nation's infrastructure; therefore, it is critical to consider its durability and safety.

The stability of most asphalt concrete pavement structures depends on how it is constructed, what materials are used, and the environmental conditions. However, owing to some of asphalt's disadvantages, the fatigue failure, mechanical strength, and long-term performance of asphalt concrete are greatly influenced by service time and loading, which can lead to pavement cracking (Hamid 2010). Generally, asphalt damage is associated with the properties of the bitumen binder and asphalt mixtures.

Polymer-modified binder mixtures are widely used in civil engineering and construction projects. The addition of polymers to these mixtures improves the stiffness of the pavement mixture and significantly enhances its robustness against temperature fluctuations. This modification, in turn, improves the mixture resistance to pavement cracking (due to fatigue and rutting damage), which is one of the most common issues affecting pavements in hot or tropical regions. In these cases, adding polymers to the mixture creates a softer base binder, which can provide better high-temperature performance. The addition of polymers to the binder results in a significant increase in its cohesiveness and adhesiveness, effectively and strongly binding the mixture of components together (Ali 2013).

In addition, polymers play another important role in generating an aggregate coating substance by improving the irregularity of the aggregate surfaces, producing superior pavement mixtures (Perez-Lepe et al.,2003). Polymers have often been utilized in mixtures to improve their mechanical properties under all service conditions (Airey et al. 2002). After years of service and because of the increasing axle loading and high traffic capacity associated with low maintenance, pavement structures have begun to fail more quickly. To reduce pavement damage in terms of rutting and fatigue, asphalt must be reinforced with certain polymers. Consequently, polymers offer the opportunity to produce asphalt that is resistant to permanent deformation and fatigue failure; however, utilizing virgin polymer is costly (Al-Hadidy and Tan, 2009a; Ozen et al. 2008). Thus, using waste polymers, such as waste plastic, is an inexpensive alternative.

The use of waste polymer yields a new effective bituminous mixture from the unwanted residue, which is commonly referred to as ‘greening asphalt’. In addition, better engineering of complex materials at the nano-level, such as asphalt pavement, can help realize smart features (Enieb and Diab 2017). Furthermore, the added nanomaterial’s large surface area and small size impart several advantageous properties to the asphalt (Li et al. 2017). From this perspective, nanomaterials can significantly enhance the adhesion and cohesion of the asphalt binder/mixture and help bridge the asphalt and nanoparticles, mitigating the growth of cracks. This, in turn, improves the fatigue life and rutting resistance of pavement.

In summary, previous research has classified asphalt modifiers into several categories according to their composition. These include polymers, which can be divided into elastomeric and plastomeric, fibres, hydrocarbons, anti-stripping agents, and waste-tyre rubber. Elastomers and plastomers are popular for use in asphalt pavement modification. However, these polymers are costly and have less storage stability. Thus, recycled plastic polymer with nanomaterials could facilitate the production of sustainable and cost-effective pavement with high performance. Further, nanomaterials display novel properties as additives in terms of bitumen binder modification, which can help overcome the drawbacks of recycled plastic polymers. However, the application of nanomaterials in asphalt pavement mixture modification is limited and still requires further investigation.

1.2 Problem Statement

Since 1 January 2018, the recycling of waste plastic has become an essential concern in Australia. China imposed a proscription on the import of waste, including plastic. A year later, Malaysia and India also prohibited the import of waste plastic. This ban has placed Australian industries, mainly the recycling industry, under severe pressure. Dumping such huge amounts of waste plastic in stockpiles is not recommended; it increases hazard levels and affects health and the environment (Mashaan et al. 2021a).

Furthermore, a study by Zakaria (2020) reported that there has been a global increase in the usage and development of plastic materials over the past 150 years. This is primarily due to plastic's advantageous characteristics, including a relatively low density, high durability, low cost, flexible design, and good strength. These properties contribute to the widespread use of plastics for numerous purposes. Currently, due to rapid economic and industrial growth, the volume of waste polyethylene terephthalate plastic (PET) has witnessed significant growth. It is estimated that, every year, 1000 million units of PET reach the end of their service life. Further, it has been reported that the annual consumption of PET is approximately 300,000 million units. In addition, the lack of appropriate waste management results in additional dumping expenses; increased unlawful dumping could also increase the risk of fire and environmental degradation (Kalantar et al. 2012).

From 2016–2017, in Australia, the yearly utilization of plastic was 3,513,100 million tonnes, of which only 11% was recycled (about 415,200 thousand tonnes). The rate of recycling waste seems to have increased as a result of the 'China ban'. According to O'Farrell (2018), the 2016–2017 Australian Plastics Recycling Survey-National Report described a rapid increase in waste plastic generation over the past 17 years. This significant increase in waste plastic was related to the higher demand on using plastic products. The highest recycling rates were for light low-density polyethylene (LDPE) (17.5%), polyethylene terephthalate (PET) (16.0%), and high-density polyethylene (HDPE) (15.5%) (O'Farrell 2018). Polymer-modified asphalt mixture is a mixture with a wide variety of uses in civil engineering and construction projects (Casey et al. 2008). Adding PET to mixtures improves the stiffness of bitumen and significantly enhances its robustness against temperature fluctuations. Therefore, improving the rutting of mixtures is imperative – this is one of the most common problems in pavement engineering in hot or tropical regions (Awwad and Shbeeb 2007; Modarres and Hamedi 2014).

Studies have shown that using PET in a given mixture enhances the viscoelasticity of bitumen, which results in greater fatigue and rutting resistance (Al-Haydari 2020; Kumar and Khan 2020). The addition of polymers to the binder results in a significant increase in its cohesiveness and adhesiveness, helping it effectively bind the mixture of components together. However, PET plays another important role in the generation of an aggregate coating substance to improve the coating and bonding of aggregate–asphalt mixtures (Awwad and Shbeeb 2007). This research aims at reducing the recycled waste plastic in Australia by using this waste with nano-silica in polymer-modified asphalt pavement.

1.3 Objectives of the Study

The main objectives of this study are to explore the impact of recycled plastic as a modifier for wearing-course asphalt materials, along with the use of nanomaterials. To accomplish the aims of this study, the following tasks will be performed:

1- Assessing and investigating the possibility of using waste plastic as a modifier in C320 bitumen binder using different types and contents of local waste plastic and determining the ideal type and content of waste plastic for the best physical and rheological properties.
2- Exploring the influences of waste plastic on the aging resistance and durability of modified bitumen by conducting RTFOT tests for short-term oxidation and PAV tests for long-term oxidation.
3- Investigating and determining the best asphalt mixtures modified with waste plastic in terms of stability and high rutting resistance.
4- Assessing how nano-silica can mitigate the drawbacks of PET plastic in terms of the viscoelastic, physical, and mechanical properties of non-modified and recycled polymer-modified asphalt.
5- Investigating the stiffness, performance, and skid resistance of asphalt mixtures including waste plastic polymer-modified asphalt with nano-silica.
6- Characterising the rutting and flexural fatigue behaviour of asphalt pavement with waste plastic and nano-silica for practical purposes.

1.4 Scope of Study

Plastics are widely used in every aspect of modern life in both developed and developing countries. Plastic materials are used in consumer products, industrial machinery, and infrastructure. In this study, the use of a type of polyethylene was assessed as an additive in hot mix asphalt.

To prepare the waste plastic polymer-modified binders, PET, HDPE, and LDPE with 2%, 4%, 6%, and 8% by weight of bitumen were mixed with C320 bitumen. The ideal type and percentage of plastic were selected for nano-silica/recycled polymer-modified asphalt. To prepare the nano-silica/recycled polymer-modified binders, PET waste plastic with 0%–8% nano-silica concentration by weight of asphalt was used. Before the addition of nano-silica particles, the polymer was first dissolved in 500 g of the base binder. At the point when polypropylene completely broke down in the base binder, nano-silica particles were uniformly added to the polypropylene modified bitumen and blended with a high-shear mixer at a high shear rate.

Throughout the blending process, the temperature was maintained at 160 ± 5 °C. After selecting the optimum nano-silica/recycled polymer percentage, the ageing was evaluated using the DSR binder test. Finally, the performance of the nano-silica/plastic-modified asphalt mixture was investigated in terms of the rutting and cracking resistance.

The experimental laboratory tests were divided into nanoparticle-polymer-modified binder testing and nanoparticle-polymer-modified mixture testing. In the former, standard bitumen tests such as the penetration test, ring-and-ball (or softening point tests), viscosity tests, and ductility tests were carried out to investigate the physical and rheological performance of the nanoparticle-plastic-modified bitumen binder and nanoparticle-plastic-modified asphalt mixtures. In the latter, ageing and durability were tested through the RTFOT test, PAV test, and DSR test. Finally, rutting tests, fatigue tests, resilient modulus tests, TSR % tests, and drain-off tests were used to investigate the impact and behaviour of the nanoparticle-plastic-modified asphalt mixture.

1.5 Significance of Research

This research aims to propose a revolutionary eco-friendly method of manufacturing asphalt for wearing courses, with optimal resistance to mechanical failure. This aim will be achieved by using a recycled plastic modified with nano-silica. The recycled polymer is obtained from waste plastic and modified with asphalt binder and asphalt concrete. Laboratory investigations will be conducted to understand the rheological, mechanical, durability, and engineering properties of nano- plastic -modified asphalt.

In Australia, using waste materials, particularly waste plastic, would be extremely advantageous to the construction and recycling industries. These advantageous would include improving the properties of asphalt paving construction, decreasing the amount of waste plastic, saving resources, and reducing the environmental impact. Further, the systematic design of asphalt concrete for highway applications is of utmost significance as it represents a high percentage of interstate highway systems with heavier traffic loads.

1.6 Thesis Organisation

The thesis has several chapters, which are listed below with a brief description:

1- Chapter one introduces the topic at hand. The chapter contains the problem statement, the study's objectives, the scope of the study, and its significance.

2- Chapter two covers a literature review and mainly considers the impact of using waste plastic polymer in asphalt modification. Stone mastic asphalt (SMA) is presented, along with the advantages of using it with waste PET in asphalt.

   In addition, the use of nanomaterials and nano-silica for asphalt modification are presented and analysed. The stiffness, durability, rutting resistance, and fatigue of asphalt pavement reinforced with recycled polymers and nanomaterials are summarised and highlighted.

3- Chapter three describes the materials and methods used in this study. The testing used to evaluate the physical and rheological properties, along with the ageing resistance of the modified bitumen binders, are illustrated. The testing method used to measure the materials engineering and mechanical properties are presented and discussed. The stages of the experimental program are described in detail, and the tests used to measure the rutting and fatigue performance of the ideal hybrid additive of PET-NanoSilica-C320 bitumen are described and discussed.

4- Chapter four presents the results and analysis of the physical and rheological properties of unaged and aged treatments for different types and contents of waste plastic modified bitumen binders.

5- In chapter five, after assessing and evaluating the different types of plastic modified bitumen in chapter four, the ideal type and content of waste plastic modified bitumen was used to produce the asphalt mixtures and assess the engineering properties to verify the potential of using waste plastic. The outcome of this chapter is used to strengthen and support the use of waste plastic for modifying asphalt mixtures following the Australian standards and resources.

6- Chapter six is aimed at examining and selecting the optimum type and content of nano-silica to be used with the waste plastic to produce the hybrid nano-plastic-modified asphalt mixtures. The first step of this chapter involved testing the physical properties, followed by testing the rheological properties, stiffness of the binders, rutting resistance of the modified binders, and creep recovery after dynamic shear rheometer tests.

7- Chapter seven is aimed at designing a hybrid additive for waste plastic PET and nano-silica in asphalt reinforcement. This can help improve the properties in comparison to using a single additive. The engineering and performance properties, including the rutting resistance, moisture susceptibility, tensile strength, and fatigue resistance are all tested and evaluated.

8- Chapter eight draws conclusions and provides future recommendations. This chapter covers the results of the study and whether the objectives of the study were met. The chapter presents and summarises the major points discussed in previous chapters. In addition, the conclusion is supported by the literature reviewed, along with the results of the experiments and tests. Finally, the chapter highlights the potential of using waste plastic as a sustainable additive in asphalt mixtures. Some important recommendations are provided to enable future research and development in the field.

Chapter 2

Literature Review

2.1 Introduction

The structural stability of the road is usually supplied by the pavement consisting of crushed and carefully selected stone and rock of suitable sizes, which is finally compacted by applying a limited amount of binder. As shown in Figure 2.1, the standard layers from top to bottom within a pavement are road surface (wearing course), base course (crushed gravel and stone), sub-base course (selected granular material) and sub-grad (natural soil layer). It is noteworthy that: it is possible to further strengthen the used granular material with lime, bitumen, or cement. In heavily loaded roads, in the structure of pavements, concrete or asphalt usually substitute the granular material, especially in the base and sub-base layers (Ali 2013).

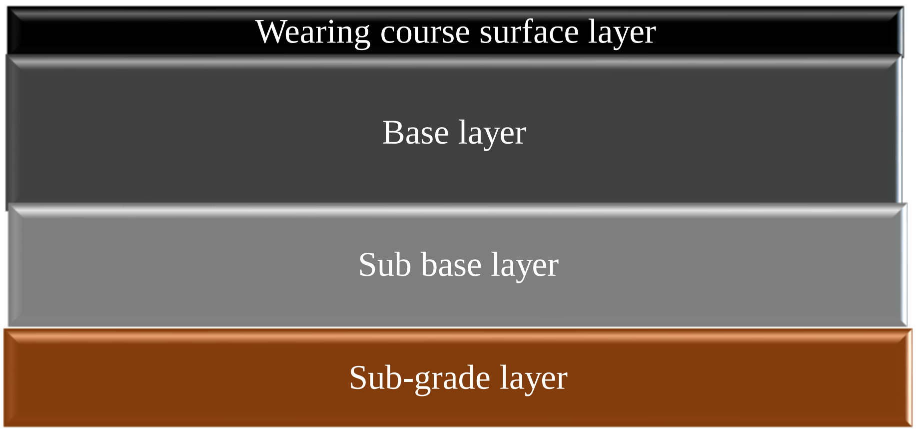


Figure 2.1: Structure of road pavement layers

Frequently, Portland cement concrete or bitumen base surface are used to form the road surfacing. There are several reasons that necessitate surfacing, some of which are to provide a suitable and safe surface for vehicles to turn on easily, to protect the structure and sub-grade of the pavement from the environmental effects, such as moisture and to reduce the stress imposed on the pavement to protect it against any possible deformation or destruction (Hamed 2010).

This chapter reviews the literature related to the data used for analyses and discussions on road surfacing modification in civil engineering. First, the chapter will display the background of road engineering and types of hot mix asphalt used in pavement construction. Consideration to the specification and properties of the stone mastic asphalt are illustrated. After that, comprehensive review on asphalt modification using polymer, waste plastic and nanomaterials. This chapter aims to review the background knowledge and status of road surfacing in the relevant regions to provide a sympathetic description of the significance of waste plastic modified bitumen binder and asphalt mixtures, and its role in providing effective and durable surfacing for heavy-trafficked roads in hot and humid areas. The use of nano materials as additive in asphalt are discussed and evaluated. In this chapter will seek to clarify some of the term and concepts related to debates to enlighten the readers with the necessary background to better engage with the experiments and discussions alongside the investigator.

2.2 Background on Road Engineering

Roads and bridges are one of the most crucial components of infrastructure engineering and they play a vital role in our lifetimes. Bituminous mixture is a composite material made up of other distinct materials, employed in a range of civil engineering tasks, such as the construction of roads. It consists of mineral aggregate, bitumen, and air voids, which are the main components of bituminous mixture, blended and then laid and compacted to form the surface of roads (Ali, Mashaan, and Karim 2013). Mixing of the aggregate and bitumen is done using one of the following methods (Zakaria 2020; Hamed 2010).

A- Hot mix asphalt (HMA) is a mixture of aggregate and bitumen blended through heating. For paving and compaction, the mixture must be hot enough to form the HMA. In cold countries, paving is limited to warm seasons due to the cold weather during winter or autumn, which causes the compacted base to cool down the asphalt mixture too much before it is packed to the desired air void content. Hot mix asphalt is the most common bituminous mix around the world for road pavements with heavy traffic, such as roads and expressways or airport lanes.

B- Warm mix asphalt concrete (WMA) is a mixture created by adding waxes, zeolites, or asphalt emulsions, which are added to the mixture in different stages. This allows a significant reduction in temperature for mixing and laying which, in turn, leads to more savings in fossil fuels and a reduction in the air pollution and environmental contamination resulting from the emission of CO_2, vapours, and aerosols. The lower laying temperature not only helps in improving working conditions, but also makes the surface availability faster for utilisation, especially advantageous in construction projects with critical tasks and time schedules. Furthermore, the application of such additives in HMA can yield more easily compacted mixes, specifically in cold climates for which the length of the hauls is limited by the temperature.

C- Cold mix asphalt concrete is created by emulsifying the bitumen in water with soap, before being mixed with aggregate since the viscosity of bitumen emulsion is lower, which renders the mixture easy to work and compact. After the evaporation of a sufficient amount of water, the emulsion breaks allowing the cold mix to take on the cold HMA properties. Cold mix asphalt concrete is usually used to patch cracked or dug up asphalt parts on roads with lighter traffic services.

D- Cut-back asphalt concrete (CBMA) is created by the dissolution of the binder within kerosene or any other lighter petroleum products before being blended with aggregate. Since the dissolved binder is less viscous, the mixture can be handled and compacted more easily. After the mixture is laid, the lighter petroleum fraction evaporates.

E- Mastic asphalt concrete, sometimes called sheet asphalt, is a mixture of hard grade blown bitumen (oxidised), which is blended in a green cooker while heating to make a liquid of high viscosity, and then the aggregate is added in the mixture. The resulting bitumen aggregate mix is matured through cooking (heating) for approximately 7 hours. The thickness of mastic asphalt concrete usually needs to be about 20-30 mm for road, sidewalks, walker's lanes and about 10 mm for roof and flooring applications (Hamed 2010).

2.3 Hot Mix Asphalt (HMA)

Asphalt pavement or flexible pavement is widely employed throughout the globe. Asphalt pavement has good riding quality, and it is much cheaper than to construct, in comparison to concrete or rigid pavements. HMA mixtures for asphalt pavement are divided into three main categories: dense graded mixture, open graded mixture, and gap graded mixture.

Dense graded mixture is a well-graded mix, which consists of bitumen and aggregate. The distribution of the size of aggregate particles is even and smooth from coarse to fine. Dense graded HMA is conventionally employed in road construction. One of the disadvantages of the dense grade mixture is that it does not have high resistance against rutting (Hamed 2010).

Open graded mixture is intended to let in water through its permeability, which makes it considerably different from other kinds of mixture such as dense graded or SMA, which are both relatively impermeable by comparison. Crushed gravel or stone with a very small percentage of sand, modified bitumen, and possibly fibers can sometimes be incorporated into the surface mixture of open graded mixtures. One of the typical disadvantages of this category is its insignificant structural strength, unlike dense graded mixture or SMA. SMA is a gap-graded mixture, which maximises the durability and rutting resistance by the application of a stone skeleton bound together with a mixture comprising a binder, stabiliser, and mineral filler. SMA is considered to be a premium mixture despite its higher initial cost due to enhanced binder content and application of durable aggregate. Nevertheless, the improved performance makes it suitable for high traffic loadings.

2.4 Stone Mastic Asphalt

Stone mastic asphalt (SMA) is a mixture of a skeleton of coarse aggregate and a bitumen binder rich mortar with 6% - 8% bitumen. SMA consists of crushed coarse mixture, crushed fine aggregate, asphalt binder, mineral filler, and a stabiliser such as cellulose, mineral fibers, or a polymer for the binder (Chiu and Lu 2007). Figure 2.2 displays a typical SMA mixture and traditional dense graded mixture. The image on the left shows a higher percentage of bitumen and fractured aggregate, in comparison with the conventional hot mix asphalt shown in the right-hand image. As Figure 2.2 illustrates, conventional dense graded mixture contains less bitumen content with a more uniform gradation of the aggregate particles.

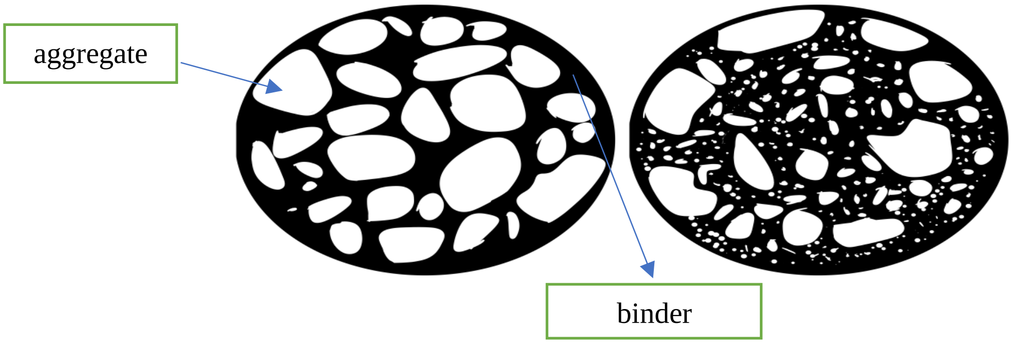


Figure 2.2: Typical SMA mixture (left) and dense graded mixture(right) (figure by author)

According to the case studies on using SMA in pavement construction, the application of SMA in road surfacing shows a significant role in enhancing the mixture's durability, improving rutting resistance and fatigue life. The rutting resistance of SMA is more than that of dense graded mixtures because of "skeleton coarse aggregate"- this feature offers the contact of stone to stone between the coarse aggregate particles (Moghaddam, Soltani, and Karim 2011). The major reason for utilising fully crushed aggregate gap gradation (100%) is the enhancement of the degree of pavement stableness through the interlocking resulting stone-to-stone contact (Ibrahim et al. 2009). This interlock provides the mix with a stronger stone-on-stone skeleton, which is stuck more stably simultaneously, as a result of a strong composition of bitumen binder, filler, and other additives in the mixture to enhance its stability (Moghaddam, Soltani, and Karim 2011).

SMA is characterised by a mixture of gap-graded aggregate, which minimises the fine and medium sized aggregate, resulting in a stable and structurally tough mixture. The strength and stability of the SMA is because of the stone portion of the coarse aggregate skeleton, which consequently increases internal friction rate and the resistance of the mixture to shear, thereby enabling it to resist rutting and wearing out caused by repetitive studded tyre contact. However, some weakness is distinguishable in the SMA structure, such as drain down, which ensues from the absence of mid-sized aggregate in the gap-graded mixture, which has a high asphalt binder content instead. Since the SMA is assembled in the silos and then transported by trucks to the construction site, after it is placed, the asphalt binder tends to drain down, which is called mixture drain down. Mix drains down is usually avoided by adding cellulose fibres, mineral fibres, or other modifiers to hold the binder in place, thereby by providing the mix with durability (Asi 2006).

SMA was developed and used in Germany in the mid-1960s to surface pavements to enhance their resistance against rutting as well as enhance the durability (Ibrahim et al. 2009). It was then introduced to the rest of Europe, because of its better resistance to damage from studded tyres than other types of HMA (Asi 2006). The abbreviation of SMA is obtained from the German term for slip stone mastic asphalt.

Because of the indispensable and significant achievements brought about by the utilisation of SMA in Europe, together with the collaboration of the Federal Highway Administration, it found its way to the US in 1991 and has since been used in the construction of road surfacing in some selected states across the country (Asi 2001; Ibrahim et al. 2009). Nowadays, over 28 states across the US utilise SMA in the construction of asphalt roads. According to reliable sources, the application of SMA has led to a considerable enhancement in pavement durability of up to 20-30 per cent in comparison to the conventional mixes used for such construction before (Al-Hadidy and Tan 2009a). These significant results have contributed to the increase of SMA application to various road constructions in the US. Following the US, Japan was the next country to use SMA for road pavement mixtures, which has also been backed by the strong success and achievements in that country.

Successively, Canada and the UK began to employ SMA in the construction industry of road pavements across several states with significant success. Using SMA to surface the roads which are prone to heavy traffic to render surface treatment economical and cost-effective. Today, SMA is considered as the top choice in pavement surfacing and resurfacing, where high performance and long durability is an essential requirement in pavement construction throughout the globe. SMA application has recently extended its domain to most of the developing countries, especially in Asia and Latin America (Ibrahim et al. 2009).

From the above literature it can be concluded that currently SMA is one of the most common mixtures used for road pavement surfacing. SMA is a kind of HMA, which consists of higher binder content with a coarse aggregate skeleton. Briefly, SMA is used to provide a pavement with high resistance to skidding, to restrict the water splash and spray to maintain good visibility on wet days, to provide an even riding surface; and absorb and reduce noise produced by tyres, especially near domestic and urban areas (Ali 2013).

2.4.1 Advantages and disadvantages of SMA

There are numerous benefits of using SMA mainly provides a pavement with a durable, stable textured, and high rutting resistant. SMA surface texture features are closer to those of OGA, which reduces the noise and improve the skid resistance in comparison with dense grade asphalt and open grade asphalt. It is possible to produce, compact, and process SMA using the same equipment and plant used to produce normal HMA (DGA); SMA is specially applicable to intersections and other parts where traffic stress is high and OGA is not suitable; due to the flexible mastic used in SMA, it can reduce reflective cracking brought by underlying cracked pavements; and the SMA durability should be greater than or, at least equal to the durability of DGA, but it needs to be significantly greater than that of OGA (Ali 2013; Hamed 2010).

Moreover, SMA can also increase skid resistance because of the considerable percentage of fractured aggregates used in it, especially in wet environments. Even though SMA does not let water drain through it, the texture of its surface is like that of open-graded aggregate that absorbs the noise produced by the contact of the tyre with the asp-halt surface. Surfaces with coarser texture can absorb not only tyre noise, but also glare and water spray on the pavement. SMA was initially used in asphalt mixes to enhance their level of resistance against studded tyre wear. Another advantage of SMA is that it can increase the resistance of the mixture against plastic deformation, which is one of the common problems that result from heavy traffic loading, which exerts severe stress on the pavement. Moreover, its rough surface provides adequate friction, especially, when the asphalt loses its surfacing cement film, which wears out through heavy and frequent vehicle traffic. However, other advantages of SMA make it the most preferred mixture for pavement construction projects around the globe in comparison with other conventional HMA types. Some of these properties are showing improved durability, high resistance to reflective cracking and improvement against ageing (Ibrahim et al. 2009; Awwad and Shbeeb 2007).

However, some drawbacks and disadvantages relevant to the application of SMA are as follows: more expensive material due to application of higher filler content and binder; longer time needed for mixing to inject the extra filler, which, may result in lower productivity level. Thus, more time is needed to cool the spread SMA on the roads down to 40 ˚C, which may result in completing road construction or repair to prevent flushing problem. Until removal of the thick binder film off the pavement surface due to traffic, the initial skid resistance is expected to be lower than satisfying level. In urgent cases, tiny grit is needed to be splashed over the surface before launching the road (Xue et al. 2009; Hamed 2010).

SMA surfacing generally requires more care and attention: the initial SMA resistance against skid may be low. This is another disadvantage of SMA, which also needs further care during mixing, producing, transporting and placement on the road. Nevertheless, after achievement of the required capabilities and expertise, SMA is not harder than other mixtures used for pavement surfacing. When polymers are employed, in hot areas or seasons, the distance of the material transportation may be limited (Awwad and Shbeeb 2007; Yildrim 2007).

In summary, as the literature reveals, there are many fundamental advantages, such as high durability, improved resistance against fatigue and reflective, and excessive rut resistance, less noise pollution of traffic and high skid resistance (Xue et al. 2009; Asi 2006). SMA mixtures also suffer from some disadvantages including delays in opening (the roads) to traffic, drainage of the binder, and higher initial costs. Due to the gap graded structure of SMA mixtures, and the high amount of bitumen binder, stabilization is required to control bitumen drain-down (Asi 2006; Ali 2013). In order to achieve this feature, polymer modifiers or fibers should be added to the SMA mixtures to achieve the desired modification, reinforcement and stabilization in the mixture.

2.4.2 Characteristics of materials used in SMA mixtures

In the section, the characteristics of aggregate, bitumen, filler, and additive in SMA mixtures will be reviewed. The quality of aggregates employed in SMA needs to be high with a highly rough texture and cubic shape to be able to resist any displacement or rutting. The hardness of the aggregate content helps the pavement to resist breaking under heavy loadings of frequent tyre traffic. The aggregate should also have high resistance to polishing and abrasion (Hamed 2010).

The grade of bitumen content employed in SMA usually equals the same grade or slightly stiffer grade than used in dense-grade mixtures. When bitumen is stiffer, it minimises any potential drain down and helps to reduce rutting, which is usually expected in higher temperatures. Nevertheless, stiffer bitumen might result in thermal cracking. Using high optimum bitumen content and increased film thickness in the SMA, minimises the possibility of thermal cracking, especially in comparison with dense-graded mixture (Chiu and Lu 2007). The utilisation of binders modified by polymer(s) along with fibre would enhance the resistance of the pavement against problems such as rutting or fatigue cracking. The modified bitumen can be achieved through incorporating a quantity of stabilising (such as polymers) to conventional bitumen.

The function of filler in the SMA is essentially to stiffen the bitumen rich SMA. The application of higher amounts of too fine a filler can led to excessive stiffness of the mixture rendering it difficult to work, which might result in the mixture being susceptible to cracking. A mineral filler is usually added into the mixture as part of the gradation of the aggregate. The content of the filler (passing the 75um sieve) in the SMA mixture can range from 8-10% of the total amount of aggregate. This high content of mineral filler in the mixture plays a significant role in the properties of SMA, especially relating to the air voids (VIM), optimum bitumen content (OBC), and mineral aggregate voids (VMA). Due to the relatively large amount of the filler, the performance of SMA becomes very different from the other types of HMAs (Ibrahim et al. 2009).

During the last decade, a range of additives have been introduced and developed to help improve the physical properties of the bituminous mixtures. Some additives, e.g., rubbers, fibers, artificial silica, polymers, carbon black, or a combination thereof, have been utilised in the mixtures. The role of these materials is to increase the stiffness and durability of the mastic during production and placement in hot conditions, especially in hot or tropical climates (Zakaria 2020).

When polymer is used, it is normally mixed with bitumen before being delivered to the plant, however, in some cases it has been added at the plant. Adding polymer can further stiffen the bitumen and enhance its resistance to drain down. Furthermore, polymer can enhance the adhesion property of the bitumen to the aggregate, especially in wet conditions. The polymers are added to the mixture usually in the range of 3.0-8.0 % by weight of the bitumen (Ibrahim et al. 2009).

2.4.3 SMA mixtures design methods

The methods used for SMA designing, production, and placement are comparable to those applied to the design and production of dense graded mixtures, normally carried out by Superpave or Marshall procedures. SMA primarily uses gap-graded aggregate, while the standard mixture utilises an aggregate gradation that is smoother and evenly distributed throughout the gradation resulting in the production of a denser mixture (Ali 2013).

The design of an SMA plays a key role in the provision of an aggregate grading that will accept a high amount of bitumen, which provides a durable mixture, without binder drainage. However, an unsuitable or incorrect SMA design can develop drainage in the truck bodies and fatted areas of the surfacing, particularly in thick surfacing areas. Conversely, the design of an aggregate that requires a low binder content to prevent binder drainage may result in a mixture with weak and short durability and have a reduced life (Zakaria 2020). Unlike an open-graded asphalt mixture, most of the voids among coarse aggregates within an SMA are usually filled with binder and mineral filler. Normally, 3-5% air void content is provided in the designed SMA. Excessive bitumen will push the coarse aggregate particles apart with a sudden reduction in the resistance of the pavement against shear deformation. The application of too little matrix may, however, lead to higher air voids in the mixture resulting in a reduction of the durability of the pavement, its fast ageing, and susceptibility to damage caused by moisture (Ali 2013).

2.4.4 Marshall Mix Method

The Marshall Method is the most conventional and common method employed for making and evaluating trial mixtures in obtaining the optimum bitumen content. This method was initially introduced by a civil engineer Bruce Marshall, collaborating with the Mississippi State Highway Department (Ali 2013). However, the initial features of this method have been improved through time by the American army corps of engineers, and standardised and elaborated in ASTM D1559. Usually, the Marshall Method is used in the design of SMA to provide verification of the acceptable number of voids in SMA mixes. Specimens were prepared in the lab using 50 or 75 blows per side produced by a Marshall Hammer. It is easier to achieve the compaction of the SMA on the road and the desired density level in comparison to that required by conventional HMA (Ibrahim et al. 2009). The procedures for heating, mixing, and compacting the mixture of aggregates and bitumen are specified by the Marshall Method, which is then subjected to a test of stability-flow test and an analysis of density-voids.

A bitumen specification based on climate and traffic loadings, a volumetric mixture design and analysis system, mixture analysis tests as well as a system of performance prediction including specific software, climatic database, and models of the environment and performance are the three main elements used in the Superpave. Nevertheless, the most important component of Marshall may be its new bitumen grading system, which is designed to link with pavement performance (Modarres and Hamedi 2014). Therefore, Marshall can be considered as a system based on performance. It is a system of specifications applicable to asphalt pavement design that is strong enough to successfully tolerate traffic loadings and climactic stresses.

2.5 Road pavement and modification

Road pavements start experiencing functional deterioration once they are open to heavy traffic or freezing of groundwater during the cold season. Deterioration can include fatigue stripping and rutting. In cold regions, groundwater freezing beneath the surface layer can result in serious cracks in the asphalt mixture even during a single cool season (Aflaki and Memarzadeh 2011). One way to increase the service life of road surfaces is using certain additives such as polymers to modify and improve the properties of the asphalt mixtures.

As mentioned before in the previous sections, several types of additives have been introduced and developed to help improve the physical properties of the bituminous mixtures. Some additives, e.g., rubbers, fibers, artificial silica, polymers, carbon black, or a combination thereof, have been utilised in the mixtures. The role of these materials is to increase the stiffness and durability of the mastic during production and placement in hot conditions, especially in hot or tropical climates (Hamed 2010).

Polymer modified asphalt mixture is a combination with a wide variety of different uses in civil engineering and construction projects (Casey et al. 2008). Adding polymers to the mixtures expands the bitumen’s stiffness and significantly enhances its susceptibility against temperature fluctuations. This, in turn, enhances the mixture resistance to rutting which is one of the commonest problems dealt with in pavement project agents and engineers in hot or tropical regions. In these cases, adding polymers to the mixture allows for the application of softer bitumen, which would offer outstanding low temperature performance. The accumulation of polymers to binders’ results in a significant increase of its cohesiveness and adhesiveness to bind the mixture of components together effectively and strongly. However, polymer plays another important role in the generation of an aggregate coating substance to improve the roughness of the aggregate surfaces and creates an improved asphalt mixture (Awwad and Shbeeb 2007).

2.6 Polymer modified asphalt

Different types of modifiers have been used in asphalt modification. These include polymers which can be categorised as elastomeric and plastomeric, fibres, hydrocarbons, anti-stripping agents, and waste tyre rubber. Asphalt additives contribute to improvement in stiffness and elasticity (Hamed 2010). Modified bituminous mixtures have higher stiffness and resistance against permanent and serious deformations and fatigue cracking (Hamed 2010; Perez- Lepe et al.2003). The modifier type and polymer content have the main role to improve the asphalt rheology and thus in turn improves the elastic recovery and reduces the rutting deformation (Perez- Lepe et al. 2003; Isacsson and Lu 1999). A research study by Bahia and Anderson (1995), indicated better binder-aggregate adhesion in asphalt modified mixtures, thus in increases its toughness level. Moreover, addition of polymer significantly improves the fatigue resistance and recovery properties (Airey, Singleton, and Collop 2002; AI-Hadidy and Tan 2009b; AI-Hadidy and Tan 2009c; Ozen et al. 2008; Khattak and Baladi 2001). This will result in better resistance to permeant deformation and increase the service life of road pavement (Ozen et al. 2008). One of the main advantages of applying polymer technology to bituminous mixtures is to improve the adhesion between the aggregates and binders. A study conducted by Khattak and Baladi (2001) on the influence of polymer as a modifier revealed that the modification can increase the resistance of bitumen to loading, while making it less susceptible to temperature fluctuations.

Furthermore, some polymers increase the bitumen adhesion to the stones and its resistance to cracking. An ideal binder needs to have optimal cohesion and adhesion properties. The engineering properties of polymer modified asphalt can be determined by the type of the applied modifier with respect to its content and depend on the type of bitumen employed. However, the main advantage of elastomers such as Styrene Butadiene Rubber (SBR) and Styrene Butadiene Styrene (SBS) is their capability to increase the strength of the modified bitumen mixtures (Hwang and Ko 2008). Numerous studies confirm that the application of crumb rubber modified binders to pavement mixtures can improve its resistance against fatigue cracking.

According to Bahia and Davies (1994), the impact of crumb-rubber on engineering properties of bituminous mixtures is significant in a way that rubberised mixtures display higher resistance to rutting in comparison to the unmodified bituminous mixtures. Two kinds of blending process for bituminous mixtures are the wet and dry processes. In the wet process, the modifier is mixed with the bitumen prior to adding the aggregate, while in the dry process the modifier is first added to the aggregate and before the addition of the bitumen (Hamed 2010; Perez- Lepe et al. 2003; AI-Hadidy and Yi-Qiu 2009 b).

According to Brule (1996), normal bitumen may not display tremendous engineering properties under “heavy loads and high or low temperature conditions”. It becomes softer in high temperature and more brittle in cold regions. In order to solve this problem, polymer is usually added to bitumen to improve its engineering effect on the pavement performance, which enhances its resistance against fatigue cracking, permanent deformation, and moisture susceptibility. Further investigation claimed that the stiffer the bituminous mixture, the more resistant it is to permanent deformation. Studies have mentioned that adding polymer to asphalt mixture increases elasticity and stiffness properties (Hwang and Ko 2008; Mostafa 2016; Perez- Lepe et al. 2003).

Polymer can be described as a synthetic or natural compound of normally high molecular strength made up of repeated, linked molecules (Tapkin, Cevik, and Usar 2010). The polymers employed for modification purposes in bituminous mixtures are divided into three main categories: plastomers, thermoplastic elastomers, and reactive polymers. The addition of thermoplastic elastomers into binders gives them higher elasticity. However, the application of plastomers and reactive polymers make the binder stronger and more rigid against heavy traffic loadings that usually bring about serious deformation in the surfacing of the pavement (Al-Hadidy and Yi-qiu 2009c). Furthermore, plastomers increase the stiffness and viscosity of the bitumen in moderate temperatures. Nevertheless, the achieved performance through these modifiers concerning the enhancement of bitumen elasticity in sudden and frequent temperature fluctuations is not considered as satisfactory as expected (Awwad and Shbeeb 2007). However, some plastomeric polymers commonly employed for modification purpose are ethylene-butyl acrylate (EBA), and polyethylene (PE) (Al-Hadidy and Yi-Qiu 2009a)

Today, polymer-modified asphalt is quite costly in road pavements. (Chiu and Lu 2007). Therefore, it is important to analyse cost-effective methods to make the construction projects more economical and feasible before discussing its commercial use. For instance, block Styrene-Butadiene elastomer - also known as block SBS/SB rubber, is commonly employed by many countries to modify the engineering properties of the asphalt mixture. Nevertheless, even though its excellent properties, the polymer modified mixture has one main disadvantage, that is, the high price of the block styrene-butadiene elastomer, which restricts its wide application to most construction and pavement projects, especially, in developing countries. One solution for this problem is the application of cheap polymers obtained from waste and disposed materials (Zakaria 2020; Yildrim 2007).

The first patent for bitumen modification processes with synthetic or natural polymers dates to 1843, while the initial test projects in this field were launched in Europe as early as the 1930s, and employment of neoprene latex was first enacted in North America in the 1950s (Yildrim 2007). However, twenty years later (1970s), Europe had already overtaken the US in the application of polymer modified bituminous mixture for road pavement. later in Europe the warranties provided by contractors encouraged unprecedented interest in the reduced costs of the lifecycle despite the higher costs in the initial phases of the projects. These initial costs restricted the use of polymer modified bitumen in the United States. However, the mid-1980s witnessed the introduction and use of new types of polymers in Europe and then the US, where a poor economic outlook increasingly prevailed throughout the whole country. The Australian National Asphalt Specification has provided specifications and guides for polymer modified binders (Yildrim 2007).

An approach to life cycle cost analysis has been developed by the US Federal Highway Administration (FHWA) to assess and measure the life cycle costs applicable to pavement construction that use asphalt modified binders and other additives treatment. The results of relevant studies reveal the cost-effective feature of asphalt rubber.

A survey by the US States Department of Transportation carried out in 1997 discovered that 47 of the 50 states in the country were interested in the application of modified binders in their future projects, while 35 of the respondents said that they would employ the binders even in greater amounts in future construction projects (Yildrim 2007). Many studies have been conducted on the evaluation of the performance of polymer-modified pavement mixtures around the world. Furthermore, experiments on binders have been undertaken in various labs in different regions the results of which are steadily being revealed. Based on a study known as Nevada, in 2003, the viscosity of binders modified by polymer at 60^{o}C is usually greater in comparison to the viscosity of unmodified binders despite the slight modifications of the penetration rate at all temperatures.

2.7 General Studies on Using Additives in Road Construction

In pavement construction, conventional asphalt mixtures are susceptible to extreme temperature variations and climatic conditions, which usually leads to problems such as cracking that may end up in fractures (Yildrim 2007). Moreover, at higher temperatures during the hot seasons in tropical and hot regions, bitumen mixture suffers from creep or flow. A stable pavement surface should not creep or flow under heavy traffic loadings. With this in mind, many researchers have been involved in studies investigating the way they can modify bituminous mixtures by adding various additives to enhance its performance against the aforementioned problems (Hamed 2010).

Modification of the bituminous mix with polymers seems to have great potential for the efficient use in flexible pavements design to enhance their active service or minimise the layer thickness of its wearing course or base layer. Modifying and advancing the properties of bitumen and asphalt mix by using certain additives, such as polymers, is one way of boosting the service life of road surfaces (Al-Hadidy and Yi-Qiu 2009a; Ozen et al. 2008; Casey et al. 2008). Several studies performed to categorize bitumen modifiers according to their composition have been categorised into several groups. These include polymers elastomeric, polymers plastomeric, fibre, and crumb rubber, as illustrated in Table 2.1.

Table 2.1: Several types of polymers used in asphalt modification

Type of additive	Authors and studies	Major Findings
Crumb rubber and waste tyre rubber	Aflaki and Memarzadeh (2011); Hamed (2010); Mashaan and Karim (2013) ; Ali (2013); Shen and Amirkhanian (2005); Bahia and Davies (1994).	- Improve rheological properties. - Improve aging resistance. - Improve stability -Develop a bond between aggregate and binder. - Improve fatigue life. - Better rutting resistance.
Elastomers: -Styrene-butadiene-styrene (SBS), SBR	Ozen et al. (2008); Khattak and Baladi (2001); Ahmed (2007); Widyatmoko and Elliott (2008).	- Increase stiffness - Resist fatigue cracking. - Resist thermal cracking.
Fibre: - Polyester - Fibre glass	Putman and Amirkhanian (2004); Huang (1996).	- Improve tensile strength - Improve cohesion - Improve fatigue life. - Improve durability - Improve stability of mix.
Plastomers: HDPE, LDPE, PE, PET	Awwad and Shbeeb (2007); Tapkın, Cevik, and Usar (2009); Hinislioglu and Agar (2004); Ameri and Nasr (2017); Attaelmanan, Feng, and Al-Hadidy (2011)	- Improve fatigue life. - Increase structural strength - Increase rutting resistance. Increase Marshall stability.

Wu, Ye, and Li (2008) investigated the impact of polyester fibers on fatigue and the rheological properties of bitumen and bituminous mixtures. The shared study reveal that the binder viscosity increases with the addition of more polyester fiber contents into the mixture, particularly, at lower temperatures. The results of their research confirm the possibility of an improvement of the mixture fatigue property through adding fiber, specifically, where the stress level is low. Huang (1996) also carried out research on asphalt overlays modified with polypropylene fiber. The modified and normal asphalt mixture samples of cores were transferred to the laboratory to be investigated and analysed under controlled conditions. It was revealed that the modified asphalt mixtures were stiffer and displayed improvements in durability and fatigue resistance. However, the main problem with polypropylene fiber was that due to its low melting point, the fiber was inherently incompatible with hot bitumen. According to Huang and White, further studies were required to rightly perceive the viscous-elastic properties of the fiber-modified bituminous mixtures.

In this regard, Al-Hadidy and Yi-qiu (2009c) employed starch and styrene-butadiene -styrene (SBS) to add to SMA mixes. Then physiochemical tests were carried out on modified and unmodified bitumen mixtures including performance tests such as Marshall stability, tensile strength, tensile strength ratio and resilient modulus. The tests results reveal that damage caused by moisture and susceptibility of the mixture against temperature fluctuations and variations can be reduced through the addition of ST and SBS into the bituminous mix. According to the same results, ST can also play the role of an anti-stripping agent in the mixture, reduce the plant emissions, save energy by about 30%, and increase its resistance to chemicals and solvents. As per the multi-layer elastic analysis results, pavement mixtures modified by ST and SBS consume less construction materials for the pavement.

Costa et al. (2019) studied the possibility of using waste polymer to modify asphalt. Tests were conducted to evaluate the impact of the waste polymer on the properties of the bitumen. The results showed that 4 % of recycled HDPE is an ideal content that could result in improving the physical-rheological properties of the modified binder. Another research was conducted by Bradley Putman et al. In which they analysed the possibility of applying waste carpet and tyre fibers in the SMA mixture. The added fibers play the role of stabiliser in the SMA to prevent drain down, which is result of high asphalt binder contents. In this study, the researchers compared the performance of SMA mixtures modified by tyre fibers and carpet with mixtures made with normally used cellulose fiber and other polyester fibers produced specifically for use in HMA. Concerning the permanent deformation and susceptibility to moisture, there was no significant difference between the two fibers in their results. However, carpet and tyre fibers significantly contributed to an improvement of the mixture toughness in contrast to the cellulose ones (Putman and Amirkhanian 2004).

2.8 Waste Materials

2.8.1 Waste Materials and Environment

The construction of hundreds of kilometres of roads around the world every year results in the consumption of tonnes of raw materials and the impoverishment of natural resources in different parts of the globe. In addition, as an outcome of a consuming society, developed countries are currently facing a major problem from the huge waste materials produced daily by their citizens. The disposal of these waste materials has turned into one of the critical issues of municipalities in modern cities. However, disposed waste material is not only limited to civil life, as they also come from some other source such as commercial, industrial, and the like. The worst part is a major portion of the produced waste materials leftovers intact for a long time. This issue forcing the authorities to find solutions, such as dumping the waste in landfills around cities (Zakaria 2020).

However, the currently available middens are running out of their capacity while the establishment of new sites for this purpose have encountered regulation stalemate, which restrict the conventional way of waste disposal through its burial around the living areas. This doubles the problem of waste disposal and finding new solutions and middens adds to the disposal costs that are imposed on the municipal authorities, and, ultimately, the taxpayers (Kalantar, Karim, and Mahrez 2012). Solid and synthetic waste material consume natural resources for their production, as well as cause serious environmental pollution of the water, land, and air. It is noteworthy to mention that pollution in any form is a kind of waste itself. Therefore, waste middens and landfill can contribute to serious environmental problems both in the long-term and short-term. Some of the risks and negative effects of waste dumping in middens and landfills around the domestic area can be summarised as follows:

- i- Fire or explosion which is a threat to the living areas adjacent to middens and landfills, especially with organic (biodegradable) waste materials since they can easily generate a highly flammable combination of various gases such as methane, which is known as landfill gas.
- ii- Contamination of the ground and surface water neighbouring the landfills and middens as a result of decomposition of waste materials

in the landfills, which leads to landfill leachates that are highly risky and dangerous for hygienic purposes.

iii- Pollution of the local amenities available in those areas.

iv- Other environmental pollution brought about by odour, dust, noise, aesthetics, and the like, which result from dumping and landfilling operations.

However, the impact of landfill on the environment is not at all negative. If landfill is rationally and logically engineered and controlled, it can yield some benefits as well, such as for the retrieval of derelict land in the necessary area. However, a serious problem for such projects is finding suitable sites and transportation costs, which finally lead to the high expense of landfills and disposal operations. New municipal regulations exacerbate the previous problems making waste disposal even more difficult (Ali 2013; Hamed 2010). Some of these recent regulations:

a) Require high standards of landfill control and management, seeking simultaneously to discourage landfill of certain problematic waste materials

b) Attempt to progressively reduce landfilling operations of biodegradable materials, which form the major portion of the waste materials delivered to the disposal sites.

Since Landfill Tax is imposed on all types of waste materials delivered to middens and landfills, the total amount of waste materials heading to these sites has been significantly reduced resulting in the reduction and recycling of reusable products. There is also evidence that industrial waste is being distributed on agricultural land as fertiliser, which is a good omen for the future of consumer societies.

2.8.2 Recycle of Waste Materials

Recycling waste materials produced by industrial plants and workshops, especially, relating to civil engineering has seen significant developments in recent decades. Some of the successful examples of these developments include coal fly ash, silica fumes and blast furnace slag.

The reuse of hazardous waste has also been the subject of much research throughout years. Such research mainly focused on the impact of the residue on the properties of the construction materials as well as on its effects on the environment. The most recent studies have concentrated on the possibilities of reusing solid waste materials in road construction, which has recently turned into a hot issue. Apparently, this has two main causes, namely, the lack or reduction of natural resources usable for road construction and the existence of solid waste materials that can be reused in many construction projects in civil engineering (Kalantar, Karim, and Mahrez 2012).

2.8.2.1 Recycle of fiber in bitumen and asphalt concrete

Fiber has been used in pavement construction mixtures to enhance the fatigue and rutting resistance. Thus, fiber used as an additive in stone mastic asphalt mixtures and open friction course mixtures (Mashaan et al. 2021c).

Bitumen is susceptible to rutting and cracking under sensitive conditions of high-low temperature fluctuations. As a result, cracking appears during low temperatures, whereas fatigue and rutting develop at medium and high temperatures, respectively. Therefore, the modification of the bitumen arrangement phase by infusion of different fibers is necessary to enhance the performance properties of the asphalt mixture.

Using fiber is primarily collected from numerous types of fibers in several literature sources. Fiber is generally employed to modify and subsequently enhance the mechanical as well as engineering properties of the asphalt mixtures (Kessal et al. 2022).

Fiber is classified into two categories: (i) high elasticity modulus fibers like asbestos and carbon, which are unsuitable for bitumen/asphalt diffusion, and (ii) low elasticity modulus fibers, which are employed in road pavements construction. Throughout the asphalt mixtures process, the fibers suffer severe transportation traffic loads that could affect the compaction and result in further damage (Wu, Ye, and Li 2008).

Several types of fiber including glass, polyester, carbon, cellulose, polypropylene fiber, mineral , asbestos , and waste carpet fiber are some of the different types of fibers with specific applications in the bituminous mixture. These fibers are especially used in SMA and OGFC. Recent research conducted in Australia looked at the engineering properties of asphalt mixtures modified with waste fiber materials such as cigarette butts. These investigations, which used Australian testing methods, indicated a substantial improvement in the performance of asphalt mixtures in terms of better resistance to deformation of stone mastic asphalt and dense graded asphalt (Rahman, Mohajerani, and Giustozzi 2020a; Rahman, Mohajerani, and Giustozzi 2020b; Rahman and Mohajerani 2020c).

Cigarette butts mainly contain a cellulose acetate fiber filter that is packaged in these papers. Rahman et al. (2020a) investigated the penetration properties and viscosity-rheological properties of cigarette butts modified by C320, C170 and A10E bitumen classes as a fiber modifier. Results indicated a significant enhancement in the softening point test, viscosity, and complex shear properties of bitumen-containing cigarette butts. Moreover, investigations were also conducted on the engineering properties of cigarette butts modified stone asphalt mixtures. Different contents of 1% - 3% cigarette butts were used to fabricate the modified asphalt mixtures. Results indicated that the Marshall stability improved by using 1% and 2% cigarette butts modified SMA. In addition, the resistance to rutting deformation had also increased (Rahman, Mohajerani, and Giustozzi 2020b; Rahman and Mohajerani 2020c). The stiffness and mechanical properties of cigarette butts modified dense asphalt mixture demonstrated considerable and significant results in terms of high resistance to distortion (Rahman and Mohajerani 2021).

The above-mentioned studies proved that fiber could improve the optimum binder content in the asphalt mixture design. Fiber can modify the viscosity, elasticity, vulnerability against moisture, increase rutting resistance, improve the creep and enhance the reflective cracking. Moreover, fibres enhance the aging resistance and fatigue life of asphalt mixtures. Several properties such as tensile strength, dynamic modulus, and elasticity can also be improved according to the fiber type and geometrical as well as physical properties (Rahman, Mohajerani, and Giustozzi 2020b; Rahman and Mohajerani 2020c). Nevertheless, the fiber could become overly humid and vulnerable to coagulation. Fiber clumping and distribution during the mixing process as well as fiber water absorption during the storage period are typically responsible for such issues. Furthermore, it is difficult to distribute the long fiber evenly when it is blended with bitumen binders and aggregates in pavement construction (Mashaan et al. 2021c).

Furthermore, it must be noted that some fibers might blast in the mixer plant when mixed with bitumen and mineral fillers (Wu, Ye, and Li 2008). Based on certain other investigations, employing fiber with polymer as a hybrid additive could produce asphalt mixture with better stability and strength. Ishaq and Gisustozzi (2022b) reported that polymer (elastomers and plastomers) mixed with fibres could produce modified bitumen with higher thermal stability and better rheological properties than un-modified bitumen (control bitumen). As a result, fibre turned strong while having enough elasticity to resist rutting deformation. However, it was more subjected to resist fatigue and cracking at low temperatures.

In addition, most of the above-mentioned studies utilized fiber in the dry mix as an alternative to aggregate. The utilization of polymer in the bitumen binder modification is the most common procedure that utilizes the wet and dry mixing methods. It also demonstrated promising results in terms of rutting and fatigue properties.

2.8.2.2 Recycle of polymers in bitumen and asphalt concrete

Modification of the bitumen binder with polymers has excellent potential in asphalt pavements design. The polymer-modified-bitumen design could enhance road pavement active service and minimise the wearing course layer thickness (Nguyen, Cheng, and Nguyen 2021; Ishaq and Gisustozzi 2022a).

There are several applications for polymer-modified bituminous mixtures in both developed and developing countries. Combining the polymer and bitumen improves stiffness and fatigue resistance of the polymer-bitumen modified binders (Joohari and Gisustozzi 2022; Viscione et al. 2022). Therefore, enhances the temperature susceptibility. This characteristic improves rutting resistance of the asphalt mixtures. Consequently, the used polymers permit the application of softer base bitumen which provides advanced fatigue performance of modified asphalt mixtures (Mashaan, Chegenizadeh, and Nikraz 2022a).

Furthermore, polymer-modified binders have a high degree of adhesion and cohesion. The polymer was also used to create aggregate coating material, believed to raise the roughness level of the aggregate surface and generate a superior asphalt mix (Piromanski et al. 2020). In recent times, asphalt mixtures modified by polymer are relatively more costly for road pavements. Therefore, it is important to first analyse cost-effective methods for construction projects that will be economical and feasible at commercial scales. For instance, many nations use block styrene-butadiene elastomer, commonly known as block SBS/SB rubber, to modify the engineering properties of the asphalt mixture (Xu, Zhao, and Li 2022).

Nevertheless, despite its excellent properties, the high price of the block styrene-butadiene elastomer restricts its wide application to most construction and pavement projects, especially in developing countries. The solution to this problem is to utilize cheap polymers obtained from waste plastic and disposed materials (Mashaan, Chegenizadeh, and Nikraz 2022b).

2.8.3 Typical Kinds of Waste Materials

During recent decades, there have been a limited number of researchers focusing specifically on the incorporation of selected waste polymers have been among those employed and utilised for such purposes. Certainly, there are some other materials disposed of, which can be utilised in similar ways to be incorporated into HMA as modifiers in future construction projects. The availability of a sufficient quantity of the target material and continuity of its supply can be among the selection criteria (Ali 2013; Ameri and Danial 2017). The cost of incorporation of the selected waste material can also be another factor, which enlists it as a candidate for such purpose. In general, there are different types of waste (Ali 2013), and these include:

a. Solid waste materials: any kind of disposed of household or office furniture, kitchen utensils, harmless industrial waste materials, construction and renovation debris, municipality and agricultural trash and discarded materials; many other non-toxic/non-hazardous solid waste materials are grouped into this category.
b. Special waste materials: hazardous household or office waste such as chemicals, paints, and paint thinners, rechargeable batteries used in different

devices at home or office, lead-acid batteries used in vehicles, oil, worn out tyres, etc.

c. Hazardous waste materials: any liquid, solid, gaseous or hybrid material disposed of by hospitals, clinics, and health centres. These materials if left uncontrolled can threaten the health of the residents of that area in which they are discarded.

Collection, transportation, and disposal of solid waste materials have turned into a serious concern around the world in recent years. In most countries, conventional technologies and systems can only remove 30-50 per cent of the produced solid waste materials and these wastes are disposed of in ways detrimental to the environment. Therefore, to solve or minimise this problem, the disposed materials can be exposed to recycling, reuse, and accelerated decomposition through economical and environmentally friendly practices (Ma et al. 2021).

2.9 Waste Plastic

The growing quantity of plastic products, such as containers and bottles consumed yearly all over the globe from the most developed to the least developed countries has turned the disposal of this material into a serious problem, especially in developing and developed societies. Plastic containers enjoy certain features that make them attractive and the preferred products of consumers. Plastic offers a strong material with low density that is ergonomic, durable, light, and cheap that is usable in packaging and other industrial, medical, food services and appliances, artificial implants, land/soil conservation, water desalination, flood prevention, housing, communication, and security applications, and so on. The annual consumption of plastic has globally jumped from about 5 million to 100 million tons within the second half of the last century. Hence, plastic has become one of the most important solid waste materials in recent decades (Siddique, Khatib, and Kaur 2008). However, some plastic items, which are used to preserve food are disposable and must be discarded after one-time-use and only a short time after purchase. Reusable plastic items are preferred since they can help save the resources and money of the consumers (Zakaria 2020; Mashaan et al. 2019). Therefore, multi-trip plastic containers have gained more appeal among manufacturers and consumers. This, in turn, contributes to a reduction of plastic waste materials in the environment.

Along with these solutions, recycling the disposable plastic items, or those that need to be discarded after a lifetime, can yield several advantages (Siddique, Khatib, and Kaur 2008) as follows:

a. Preservation of limited fossil resources such as oil of which at least 8% is consumed to produce plastic items in the world, 4 % for petrochemical feedstock and 4 % during manufacture, respectively,
b. Reduction of energy consumption
c. Reduction of disposed and discarded solid materials
d. Reduction of Carbon-dioxide (CO2), Sulphur-dioxide (SO2), Nitrogen-oxide (NO) emissions.

Considering the points discussed above, recycling plastic waste materials contributes to a significant reduction in disposed plastic materials in the environment, as well as helping to preserve the natural fossil resources that form the main source of plastic production and manufacturing around the world.

2.10 Polyethylene Terephthalate (PET)

Plastics have become an inseparable aspect of modern life in developed and developing societies. Plastic materials have touched nearly all aspects of our life from very personal paraphernalia to the industrial pieces and machinery, which are used in clothing, computers, cars, telephones, packaging, etc. Packaging is one of the modern industries that consume plastic for packaging purpose and is the biggest consumer of plastics. Polyethylene terephthalate (PET) is thermoplastic polyester and frequently utilised in the packaging industry (Ameri and Nasr 2017). Plastic bottles used for soft drinks, mineral water, tea boxes, biscuits boxes, and the like are also made of PET.

PET was first registered as a patented product by the Calico Printers ‘association of Manchester in 1941 and by Nathaniel Wyeth in 1973 who patented plastic bottles specifically. The versatility of plastic packaging has made it one of the most applied modern materials in nearly all fields and aspects of modern industry and life. However, there are numerous new applications of this material that are being developed yearly in various industrial and consumer societies. The major portion of PET in the world (60%) is produced from synthetic fibers to be used to make plastic bottles; approximately 30% of the total demand for plastic products around the world. In the discussion of textile usage, PET is commonly known as “polyester” despite its widespread application in packaging services (Zakaria 2020).

2.10.1 PET Structure

Polyethylene terephthalate (PET, also known as PETE, PETP or PET-P) belongs to the polyester family and is made of a thermoplastic resin (Mashaan et al. 2021a). PET is one of the most essential raw materials used in making synthesised fibers. The structure of PET is formed of linear saturated thermoplastic polyesters, which have been in use since 1966 (Modarres and Hamedi 2014). The procedure for making these kinds of polymers consists of two phases:

a) Esterification of dimethyl Terephthalate with ethylene glycol.

b) Polycondensation.

2.10.2 Properties of PET

Common features of polyethylene Terephthalate (PET) can be summarised as follows (Moghaddam, Soltani, and Karim 2014; Modarres and Hamedi 2014):

- Strong, hard, and stiff
- Properly and sufficiently tough, even at lower temperatures
- Adequate creep resistance
- High abrasion resistance and low friction
- High degree of dimensional stability
- Wide range of service temperature, i.e., 40^{o}C to 100^{o}C
- White colour in semi crystalline state
- Transparent in amorphous state (glass clear)
- High insulator to electrical currencies or shocks

- High resistance against tracking
- Lower water absorption capability
- Physiologically acceptable
- High resistance against stress cracking
- High resistance against weathering and high temperatures
- Slightly lower stiffness, hardness, heat resistance in contrast to crystalline PET
- Higher toughness in contrast with crystalline PET.

The large and uncontrolled amount of PET bottles produced in recent decades has contributed to the creation of serious environmental problems, mostly because of the hygienic consideration, in that they are not reusable for refilling. Hence, nearly all the produced bottles are disposed of as waste plastic materials whose decomposition and return to nature is outside of the lifetime of the current generations (Moghaddam, Soltani, and Karim 2014; Mashaan et al. 2019). Recycling these PET bottles can be an effective and immediate solution to this problem in the industrial and consumer societies.

2.10.3 Application of Polyethylene plastic in Asphalt

During the last decade, there were only a few studies on using a plastic polymer as additive and asphalt modifier as illustrated in Tables 2.2 and 2.3. The large and uncontrolled amount of PET plastic bottles produced in recent decades has contributed to the creation of serious environmental problems, mostly because of hygienic consideration, in that these plastics are not reusable for refilling. Hence, nearly all the produced bottles are disposed of as waste plastic materials whose decomposition and return to nature is outside of the lifetime of current generations (Modarres and Hamedi 2014; Mashaan et al. 2019). Recycling these PET bottles can be an effective and immediate solution to this problem in industrial and consumer societies.

Table 2.2: Types of plastic used in previous research studies

References	**Type of plastic waste**	**Shape**	**Size (mm)**	**Melting point ˚C**	**Specific gravity /density (g/cm3)**
Zoorbo and Suparma (2000)	LDPE	Pellet	5.00-2.36	140 ˚C	0.92
Hinislioglu and Agar (2004)	HDPE	powder	2 mm		0.935 g/cm3
Awwad and shbeeb (2007)	HDPE & LDPE	Grinded & Not grinded	2-3 mm	HDPE=125˚C LDPE=110˚C	HDPE=0.035 LDPE=0.033
Al-Hadidy and Yi-qui (2009a)	PP (virgin)	Powder	Not given	Not given	0.82gm/cm3
Ho et al. (2006)	PE LDPE wastes	PE : wax LDPE: pellet and shredded	Not given	Not given	Not given
Al-Hadidy andYi-qui (2009b)	LDPE (virgin)	Grinding to powder	Not given	113.2C	0.9205gm/cm3
Casy et al., 2008	Wastes PP HDPE LDPE	Mulch & powder\ powder	Not given	LDPE: 110C HDPE: 131C	Not given
Vansudevan et al. (2012)	PE PP	Foam, powder	Not given	Not given	Not given

	PS				
Attaelmanan, Feng, and Al-Hadidy (2011)	HDPE (virgin)	Pellet	Not given	149C	0.9430gm/cc (density)
Modarres and Hamedi (2014)	PET	PET chips were crushed and sieved	0.425–1.18	Not given	Not given
Moghaddam, Soltani, and Karim (2014)	PET	PET chips were crushed and sieved	2.36 mm	Not given	Not given
Khan et al. (2016)	LDPE / HDPE + CR	powder	0.15-0.75 mm	Not given	Density LDPE: 922kg/m3 HDPE: 961kg/m3

Table 2.3: Properties of asphalt using plastic

Authors	**Type of waste plastic**	**Plastic %**	**Type of bitumen & asphalt mix**	**Mix conditions**	**Properties**	**Major finding**
Hinislioglu and Agar (2004)	HDPE	4%, 6% & 8% by weigh of bitumen	AC- 20 (4.2% OBC)	Temperature : 145, 155, & 165˚C Time: 5,15, 30 minute. Speed mix: 200 rpm	Marshall stability , Marshall quotient (MQ).	4% HDPE is recommended mix at 165˚C,30min. -Increase in MQ ↑ 50% Compared to control mix.
Awwad and Shbeeb (2007)	HDPE & LDPE	6,8,10,12,14,16% by weigh of bitumen	PG 60/70 (5.4 % OBC)	Temperature : 180-190˚C	Marshall test stability & flow	12% HDPE grinded provide better engineering properties

Al-Hadidy and Yi-qui (2009a)	PP (virgin) Powder	1,3,5 &7 wt.%	SMA mix (5.82% OBC) PG 50/60	Time = 160˚C Time= 5 min	Rheological test (penetration, ductility, softening point). Marshall test stability & flow. tensile and compressive strength.	5% PP is recommended.
Ho et al. (2006)	PE LDPE wastes	PE: 4% LDPE: 1-4%	PG 52-34	PE mix (1h,160˚C, low shear mixer). LDPE mix(1h,185˚C, high shear mixer)	Superpave tests Aging Stiffness	LDPE with low molecular weight is recommended in asphalt modification.
Casy et al. (2008)	Wastes HDPE LDPE	2,3,4, 5%	Not given	Not given	Binder tests (viscosity, penetration, softening point) Asphalt tests (rutting & fatigue)	4% HDPE was optimised.
Al-Hadidy and Yi-qui (2009b)	LDPE & (virgin)	0,2,4,6,8%	PG 50/60 14mm SMA	Not given	Binder tests (penetration, ductility, softening point) Asphalt tests (Marshal test stability & flow.	6% HDPE was optimised.
Vansudevan et al. (2012)	Waste PE PP PS	5,10,15-25%	Dry mix PG 80/100	Not given	Binder and asphalt tests	Use high % of plastic.

Attaelmana, Feng, and Al-Hadidy (2011)	HDPE	1,3,5,7%	PG 80/100	170˚C, 2h, 3000 rpm.	Binder tests (penetration, ductility, softening point) Asphalt tests(Marshal test stability & flow; MQ	5% HDPE results in higher stability and MQ by about 50-55%.
Moghaddam, Soltani, and Karim (2014)	PET	0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, 0.7%, 0.8%, 0.9%, & 1%	PG 80/100 Dry mix	Not given	Marshall test stability & flow; ITSM Creep	PET modified mixtures showed acceptable creep performance in both static & dynamic method
Khan et al. (2016)	LDPE / HDPE + CR	2,4,8,10%	PG 64-10	Not given	DSR tests	8% - 10% LDPE improved the rheological properties
Ameri and Nas (2017)	devulcanized waste PET	0,2.5,5,7.5, 10,12.5 & 15%	PG 60/70	Shear mix of 4000 rpm. Time of 60 minutes and Temperature of160 ˚C.	Indirect tensile strength, rutting wheel track tests and Marshall stability	Ideal content of PET 7.5–10%. PET increases stability, decreases moisture susceptibility, improve rutting resistance.
Fernandes, Silva, and Oliveira (2017)	Waste HDPE & Crumb rubber	3, 4,5,6, 7%	polymer-modified bitumen (PMB 45/80-60 SMA 14	4600-7200 rpm. 20 min. 170-180 ˚C	Binder tests (penetration, softening point, DSR) Asphalt tests (rutting & fatigue)	Using HDPE 5%- 6% improved water sensitivity resistance & Rutting resistance.

Costa et al. (2019)	Waste HDPE & Waste EVA	5%	PG 30/50	600m rpm; 60 min; 180 ˚C	Binder tests (penetration, softening point, DSR) Asphalt tests (rutting & fatigue).	HDPE shows better rutting resistance, EVA shows better fatigue life.

In this study, a kind of polyethylene was used as an additive in SMA. The studies specifically concentrating on the modification of asphalt mixtures through the application of polyethylene are inadequate (Al-Hadidy and Yi-qiu 2009a). The studies covering polyethylene reinforced asphalt mixture and binders form only a small portion of the current publications and there is still a necessity for further studies focusing specifically on this topic.

Joint research by Awwad and Shbeeb (2007) investigated the results of the employment of polyethylene polymers to improve the engineering properties of asphalt mixtures. Their study was conducted to determine the best and the most proper polyethylene type and proportion to be used in the asphalt mixture to obtain the optimal result. Hence, they applied two types of polyethylene to the aggregate coating, namely, Low Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE), respectively. The addition of the polymers to the mixture was carried out in two forms, ground and unground. The produced mixture samples displayed that the ground HDPE imparts better engineering properties to the resulting mixture. The most appropriate percentage of the modifier suggested by researchers to be added to the mixture is 12% by the bitumen weight. The results of this experiment further confirm that the introduced HDPE can contribute to the enhancement of mixture stability, slight increase of air voids (VIM) and voids of the mineral aggregate (VMA) in it, as well as the reduction of the asphalt mixture density (Awwad and Shbeeb 2007). Another study concentrating on the potential of LDPE prospects was jointly done by Al-Hadidy and Tan Yi-qiu to study the engineering properties of this polymer as a modifier that can be applied to asphalt mix modifications and improvements. The obtained outcomes confirm that the softening point of the binders modified by LDPE is comparatively higher, while its ductility values were fixed at the minimum specifications range (100+ cm), which, in turn, resulted in a decrease in loss weight percentage due to heat and air, which means a significant improvement in the overall durability of the original SMA. Furthermore, the results reveal that LDPE modified SMA mixture can provide the optimal mixture for pavement construction and coating in regions with extreme temperature fluctuations and excessive moisture (Al-Hadidy and Yi-qiu 2009b)

Another study used other kinds of waste plastic materials with HDPE to modify binders with various blending temperatures, times lengths, and HDPE percentage. For this experiment, they used Marshall stability, Marshall quotient, and Marshall flow. They concluded that 4 % of HDPE at 165°C mixing temperature blended continuously for 30 minutes is the best condition for Marshall stability, Marshall flow, and Marshall quotient (MQ). As a result, a new condition applied to this experiment, the percentage of the Marshall quotient (MQ) was raised by 50% in comparison to the control mixture. Furthermore, the researchers noted that resistance of the HDPE modified bituminous mix against serious deteriorations and deformation was significantly increased (Hinishoglu and Agar 2004).

A study by Zoorob and Suparma (2000) revealed that using LDPE waste plastic in bituminous mixtures could result in a significant enhancement of its stability, i.e., approximately 2.5 times greater than the stability of the control mixtures, and durability, while decreasingly its density. In addition, the outcomes of the study showed that the plastiphalt fatigue life of the modified mixtures was longer than the control ones (Zoorob and Suparma 2000). Furthermore, the adding of polyethylene into the porous asphalt mixture can also result in significant improvements in its oil-resistance properties.

There have also been other studies on the topic tried to investigate the effects of polyethylene on engineering and rheological properties of bituminous mixtures (Fernandes, Silva, and Oliveira 2017; Ameri and Nasr 2017; Khan et al. 2016; Ho et al. 2006). Based on the results of these experiments, adding the polymer significantly increased the rutting resistance of the asphalt modified mixture. Moreover, using polyethylene as a polymer to asphalt mixture results confirmed that by addition of the polymer results in improving the fatigue resistance, workability, and efficiency of the modified mixture (Costa et al. 2019).

According to investigations' reports (Asare, Kuranchie, and Ofosu 2019; Santos et al. 2020; Jamshidi and White 2020), using waste plastic in asphalt modification would essentially help the reduce environment contamination, balance economic system, by sparing additional cost. Therefore, using waste plastic into asphalt, enhance the temperature susceptibility and stiffness. Thus, waste plastic modified bitumen results in an enhancement in rutting and fatigue resistance (Haider et al. 2020; Al-Haydari and

Al-Haidari 2020; Kumar and Khan 2020). Modifying and advancing the properties of bitumen and asphalt mix by using certain additives, such as plastic polymers, is one way of boosting the service life of road surfaces.

A study by Mashaan, Chegenizadeh, and Nikraz (2021b) has investigated the impact of waste PET plastic on the engineering and performance properties of 14 mm dense-graded asphalt, which is widely used in course surfacing in Western Australia. The study emphasises that the 6% and 8% waste PET are the idealistic contents projected to modify and improve the strength, stiffness, durability, elasticity properties, and rutting resistance of asphalt mixtures. In addition, the rutting and fatigue properties of SMA mixture using waste High-Density Polyethylene (HDPE) have been enhanced (Chegenizadeh, Peters, and Nikraz 2021). The study outcome shows that SMA mixtures modified with 4% HDPE has the best fatigue resistance at fatigue life of 157,090 cycles, however, the 8% HDPE has the better rutting resistance at a rut depth of 1.05mm.

2.11 Nanomaterials in Asphalt Reinforcement

Nanomaterial displays special characteristics as compared to normal material and have showed novel properties. Nanomaterial demonstrates excellent performance due to its small size nature, which makes nanomaterial has vital feature can be applied in asphalt pavement modification (Li et al. 2017). The properties and characteristics of nanomaterials, like its bulky surface area and lesser size, that distinguish it from more commonly used in construction, make it an idealistic material to be applied as an additive in asphalt pavement. Also, nanomaterials possess tremendous abilities that include self-cleaning and self-healing abilities.

The fundamental properties of nanomaterials successfully meet the requirements and standards of present-day highway pavement. Therefore, engineers and scientists consolidated the nanotechnology in pavement materials, utilizing nanoparticles to enhance the efficiency of asphalt (Li et al. 2017). Xiao and his associates added nanoparticles into asphalt to consider their rheological properties. In the last decade, numerous types of nanoparticles have been utilized to enhance the asphalt properties (Xiao, Armen N. Amirkhanian, and Serji N. Amirkhanian 2011a; Xiao, Armen N. Amirkhanian, and Serji N. Amirkhanian 2011b; Amirkhanian, Xiao, and Amirkhanian 2011). From previous research, reports by (Li et al. 2017; Zhang et al. 2016; Mostafa 2016; Yusoff et al. 2014; Yao et al. 2013; Enieb and Diab 2017; Bala, Napiah, and Kamaruddin 2018) showed that nanomaterial can significantly enhance the adhesion and cohesion of asphalt binder/mixture and established bridging impact between the asphalt and nanoparticle, avoiding the growth of cracks. Thus, in turn, the life of fatigue may possibly be extended, and the rutting failure significantly declined (Zhang et al. 2016; Mostafa 2016; Yusoff et al. 2014; Yao et al. 2013). Different studies have been conducted on using different contents and size of nano-silica through using different mixing conditions as illustrated in Tables 2.4,2.5, 2.6 and 2.7.

Table 2.4: Using nano-silica in asphalt

Authors	Asphalt	NS (%)
Yao et al. (2013)	PG 58-34	4% and 6%
Yusoff et al (2014)	PG-76	2%, 4%
Zhang et al. (2016)	60/80	1.86-1.98%
Sun, Xin, and Ren (2017)	AH-70	3%, 5% and 7%
Enieb and Diab (2017)	60/70	2%, 4% and 6%

Table 2.5: Specification of Nano silica based on previous studies

Reference	Nano silica purity (%)	Size/dia. (nm)	Surface area (m^2/g)	Density g/cm^3
Hasaninia and Haddadi (2017)	NS > 99%	10nm	600	Bulk density <0.10 True density 2.4
Saltan, Terzi, and Karahancer (2018)	SiO2+carbon nanotube >95%	10-12	Not given	2.64
Saltan, Terzi, and Karahancer (2017)	SiO2 powder	Not given	Not given	2.645
Taherkhani and Afroozi (2016)	SiO_2 > 99	11-13	200	2.4
Moeini, Badiei, and Rashidi (2020)	SiO_2 > 99	Not given	195	Not given

Table 2.6: mixing aspects and mixing conditions of producing Nana silica

Authors	**Nano %**	**Time**	**Temperature**	**Speed**
Hasaninia and Haddadi (2017)	2%,4%,6%, 8%	2 hours	135C	4000 rpm
Saltan, Terzi, and Karahancer (2018)	1%, 3%, 5%	2 hours	160	4000 rpm
Saltan, Terzi, and Karahancer (2017)	0.1%,0.3%,0.5%	2 hours	160	4000 rpm
Taherkhani and Afroozi (2016)	1, 3, and 5 wt%	1 hour	160	3000 rpm

Table 2.7: Mixing methods of nanoparticles and asphalt

Mixing method	Advantages	Disadvantages	References	Recommendation
Dry blending	1- Easy methods and thus has been used widely. 2- Highly recommended by researchers because of its simplicity and efficiency. 3- For industry perspective, it considers economic method. 4- environmentally - friendly method.	Less homogeneous	Faramarzi et al. (2015) Yu et al. (2007) Shirakawa, Tada, and Okazaki (2012)	Using high shear mixer led to improve the homogenously blend.
Solvent blending	1-Better dispersion. 2- Higher elasticity in term of better performance of	1- Costly and complex method. 2- Not economic, as it required high amount of solvent.	Yao et al. (2013) Khattak et al. (2012)	To have the uniform Nano-solvent mix and homogenous distribution of nanomaterials into asphalt binder, it is found that better to

	ductility and penetration tests. 3- Solvent act as a middle bridging between the asphalt binder and nanomaterials.		Faranarzi et al. (2015) Khattak et al. (2012)	combine the high shear mixing and technology of sonication.

Aging, rutting and fatigue properties of Nano silica were scientifically investigated (Yusoff et al. 2014; Yao et al. 2013; Enieb and Diab 2017; Bala, Napiah, and Kamaruddin 2018) and the published results indicated specifically that nana silica has ability to improve remarkably the bitumen rheological-mechanical characteristics. Academic researchers (Yusoff et al. 2014; Yao et al. 2013; Enieb and Diab 2017) argued persuasively that unique features of Nano silica have considerably contributed to improve tremendously the modified bitumen properties. These features are including extraordinary chemical purity, excellent dispersal skill, adsorption, and outstanding stability. In addition, most of research focuses on nanomaterials modified asphalt binder (Mostafa 2016; Fang et al. 2016) focusing on physical-rheological properties and less attention for nanomaterials modified asphalt mixture. Yao et al. (2013) suggested that chemical reactions and physical dispersion are possible to occur during the blending of Nano silica and bitumen which might produce a new network structure; therefore, future studies need to emphasis this argument.

Performance properties in terms of better stiffness and less sustainability to moisture damage are investigated as shown in Figures 2.3 and 2.4 (Yusoff et al. 2014; Enieb and Diab 2017; Sun, Xin, and Ren 2017). In addition, studies have investigated the use of Nano silica with virgin polymer in bitumen modification in term of improving the physical and rheological properties as shown in Figures 2.5 and 2.6 (Mostafa 2016; Enieb and Diab 2017; Ghasemi et al. 2012). Also, it seems that the reaction between Nano silica and bitumen with polymer in not clear since it is new subject. Thus, in turn lead to lack of knowledge and further research are needed.

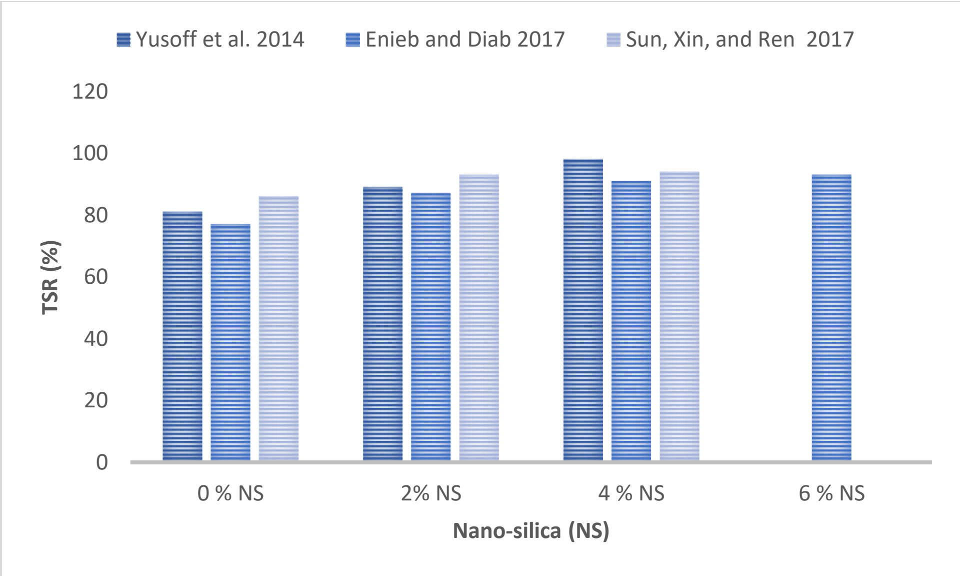


Figure 2.3: Nano-silica and TSR ratio

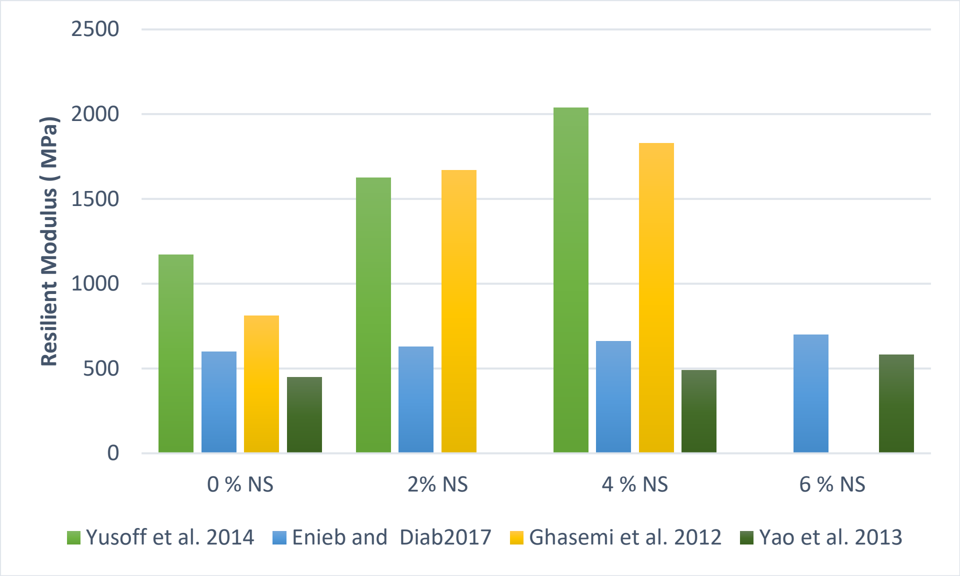


Figure 2.4: Nano-silica and Resilient modulus

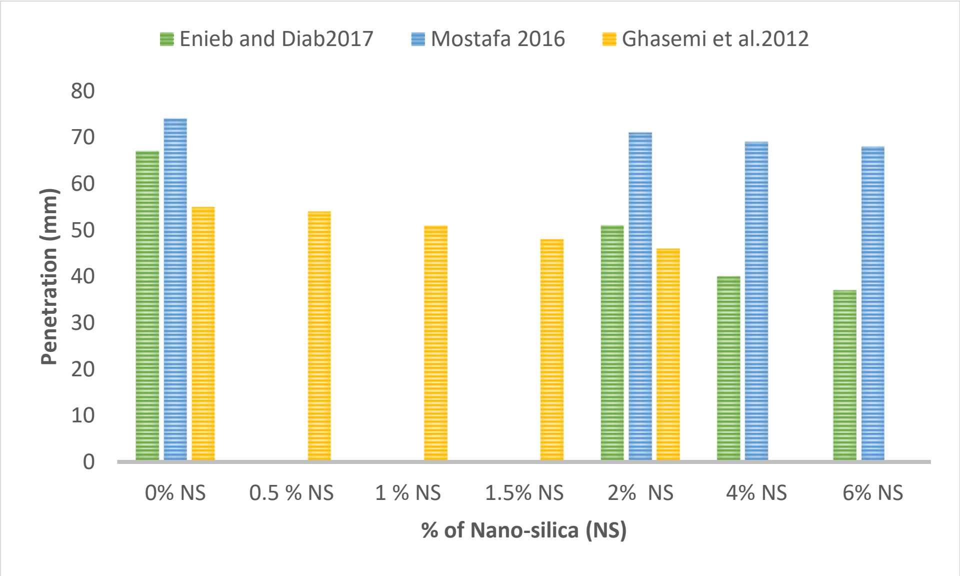


Figure 2.5: Nano-silica and penetration

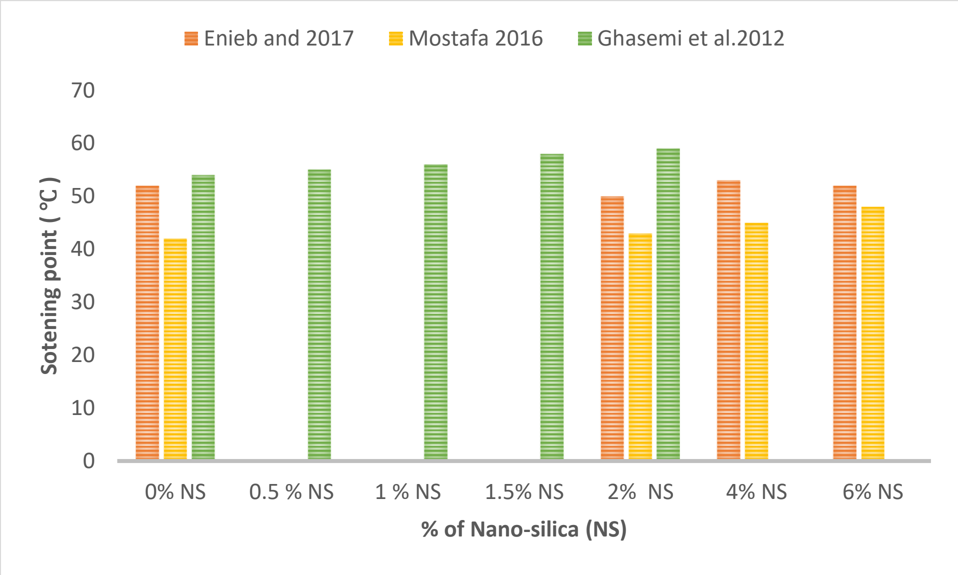


Figure 2.6: Nano-silica and softening point

2.12 Application of nanomaterials and polymer in pavement reinforcement

Besides the use of polymers as modifiers or additives in asphalt mixtures, currently, an impressive additive such as nanomaterials has been used in most hot mix asphalt projects. Nanomaterial displays special characteristics as compared to normal material and have shown novel properties and excellent performance due to its small size nature, which make nanomaterial has a vital feature that can be applied in asphalt pavement as an additive (Li et al. 2017; Abdelrahman et al. 2014). According to the literature studies (Xiao, Armen N. Amirkhanian, and Serji N. Amirkhanian 2011a; Xiao, Armen N. Amirkhanian, and Serji N. Amirkhanian 2011b; Amirkhanian, Xiao, and Amirkhanian 2011; Abdelrahman et al 2014; Ameri, Kouchaki, and Roshani 2013), adding nanoparticles into asphalt improves their physical, engineering, and rheological properties.

Studies by (Li et al. 2017; Mostafa 2016; Enieb and Diab, 2017; Bala, Napiah, and Kamaruddin 2018; Zhang et al 2016; Yusoff et al 2014; Yao et al. 2013) showed that nanomaterial could fundamentally improve the adhesion and cohesion of asphalt binder/mixture and established bridging impact between the asphalt and nanoparticle, avoiding the growth of cracks. Thus, in turn, the life of fatigue may be (extended, and the rutting failure significantly declined (Enieb and Diab 2017; Yusoff et al. 2014; Yao et al. 2013). The aging, rutting and fatigue properties of Nano-silica were scientifically investigated (Enieb and Diab 2017; Yusoff et al 2014; Yao et al. 2013) and the published results indicated specifically that nana-silica can improve remarkably the bitumen rheological-mechanical characteristics.

According to the literature, nano-silica is an excellent additive in pavement modification. There was a new approach of using polymers with nanomaterials as a hybrid polymer to overcome some disadvantages properties of using a single polymer. Tables 2.8 and 2.9 illustrate the different types of polymers and nanomaterials used in asphalt modification and the major findings (Bala, Napiah, and Kamaruddin 2018; Ganjei and Aflaki 2019; Sun, Xin, and Ren 2017; Obaid 2020). The application of combining 2% - 4% nano-silica and 5% SBS polymer results in improving the asphalt mixture's performance, in terms of better rutting and fatigue resistance (Bala, Napiah, and Kamaruddin 2018; Ganjei and Aflaki 2019; Sun, Xin, and Ren 2017; Ghanoon, Tanzadeh, and Mirsepahi). The combination uses of 1% nano-silica with waste 5% polyvinyl chloride (PVC) emphasize that modified SMA mixture would have the best performance in terms of high stability, good moisture failure resistance and high rutting resistance (Nguyen et al. 2021). Obaid 2020 characterised and evaluated the asphalt mixture modified with nano-silica/waste polypropylene polymer (PP). The addition of 5% Nano-silica with 3% PP shows a positive impact on moisture sensitivity, fatigue life and rutting resistance (Obaid 2020).

In summary, most of the literature focuses on the application of nano-clay/polymer in asphalt modification. In addition, previous studies mostly had highlighted the rheological and physical properties of the bitumen binder modified by Nano-silica. The application of nano-silica with SBS polymer is well investigated as discussed in the literature review, nevertheless, no investigation on the combination of nano-silica and waste PET plastic modified C320 bitumen. As such, there is research necessity to investigate and evaluate the engineering, mechanical and deformation performance properties of the combining nano-silica and waste PET plastic polymer as a “sustainable hybrid additive”. The current thesis aims to investigate, evaluate, and find the ideal mixing contents to produce the sustainable hybrid additive, which can be effective in both sectors of asphalt modification engineering and polymer recycling industry.

Table 2.8: Types of Polymer and nanomaterials in asphalt modification

References	**Polymer type & content**	**Nano type**	**Bitumen binder /asphalt mixes**	**Mixing conditions**
Nguyen et al. (2021)	5% polyvinyl chloride (PVC) virgin	1,2 3% nano silica (NS)	Bitumen AH-70 stone matrix asphalt (SMA-16)	Binders heated to 170˚C and stirring for 45-60 minutes at 3500-4000 rpm using a high shear mixer
Obaid (2020)	3% PP waste	2-5% Nano-silica	Penetration grade (40/50). warm mixture asphalt (WMA)	Samples mixed at temperature of 150˚C and 3500 rpm speed using a special mixing machine

Ameli et al. (2020)	5% SBS	2,3,4, 5% Nano-clay	Bitumen penetration grade of 60–70 SMA mixture	Binders heated to 160˚C and stirring for 1 hour and at 5000 rpm using a high shear mixer
Gunay and Ahmedzade (2020)	3% SBS	2% , 4% nano-TiO2	Bitumen penetration grade of 50–70	Binders heated to 180˚C and stirring for 1 hour and at 3200 rpm using a high shear mixer.
Mirsepahi, Tanzadeh, and Ghanoon (2020)	3% SBS	4%, 6% nano- clay 4%, 6% of nano- lime	Bitumen penetration grade of 58–16	Binders heated to 160˚C and stirring for 1 hour and at 3500 rpm using a high shear mixer.
Ghanoon, Tanzadeh, and Mirsepahi (2020)	3% SBS	2%, 4%, 6% of nano-clay 4%, 6% of nano- lime	Bitumen PG 64-22	Binders heated to 160˚C and stirring for 60-80 minutes and at 3500 rpm using a high shear mixer.
Ganjei and Aflaki (2019)	1%, 3%, 5% SBS	0.5, 1, 2% of nano-silica	Bitumen penetration grade of 60–70 19 mm Dese graded HMA	Binders heated to 170˚C and stirring for 1 hour using high shear mixer.
Bala, Napiah, and Kamaruddin (2018)	5% polypropylene polymer	1%-4% of Nano-silica	Bitumen penetration grade 80/100 19 mm Dese graded HMA	Binders heated to 150˚C and stirring at 4000 rpm using high shear mixer.

Sun, Xin, and Ren (2017)	Butadiene Rubbe (SBR) 3,4,5% SBR Butadiene Styrene (SBS) 1,4,5% SBS polyethylene (PE) :2% & 3% PE	5%SiO_2 5%Bentonite 5%$CaCO_3$ 5%TiO_2 5%Fe_2O_3 5%ZnO	Bitumen AH-70	Binders heated to 170˚C and stirring for 30 minutes and at 5000 rpm using a high shear mixer.

Table 2.9: Major findings of applying polymer and nanomaterials

References	Hybrid polymers Nano-polymer binders	Binder testing	Mixture testing	Major findings
Nguyen et al. (2021)	1%, 2%, 3% NS with 5% waste PVC	Penetration, softening point, rotational viscosity, dynamic shear rheometer (DSR), multiple stress creep recovery (MSCR), and standard rolling thin film oven (RTFO)	Marshall stability Water stability Rutting tests.	SMA mixtures modified with 5% PVC and 1% nano silica showed the best performance in term of high stability, good moisture failure resistance and high rutting resistance.
Obaid (2020)	2-5% nano-silica 3% PP waste	No tests.	Moisture resistance test, rutting resistance test, and fatigue resistance tests.	The addition of 4 % and 5% Nano-silica with 3% PP show positive impact on moisture sensitivity, fatigue life and rutting resistance.

Ameli et al. (2020)	2,3,4, 5% Nanoclay with 5% SBS.	Beam Rheometer (BBR), Dynamic Shear Rheometer (DSR), Rotational Viscosity (RV), Multiple stress creep and recovery test MSCR test.	Resilient modulus test, Dynamic creep test, Hamburg wheel track test.	Using 3% of SBS- naoclay to bitumen binders improve the low and high temperature performance. SMA mixture modified with 3% nanoclay/SBS polymer has the highest resistance to rutting and deformation.
Gunay and Ahmedzade (2020)	2%, 4% nano-TiO2 with 3% SBS	Penetration, softening point tests, Rolling thin film oven test (RTFOT), DSR and MSCR tests.	No tests.	Rheological properties were improved after using the 4% nano-TiO_2 and SBS polymer, in term of better rutting resistance.
Mirsepahi, Tanzadeh, and Ghanoon (2020)	4%, 6% nano- clay and 4%, 6% of nano- lime with 3% SBS	Shear Rheometer (DSR), Rotational Viscosity (RV), Multiple stress creep and recovery test MSCR test.	No tests.	The addition of nano/polymer to bitumen results in an increase in rutting resistance, in term of improving the stiffness and viscosity.
Ghanoon, Tanzadeh, and Mirsepahi (2020)	2%, 4%, 6% nano-clay and 4%, 6% of nano- lime with 3% SBS	Shear Rheometer (DSR), Multiple stress creep and recovery (MSCR) test.	No tests.	The ideal combination was using 3% SBS, 4% nano-clay and 6% nano-lime, which showed improved in

				rutting resistance results.
Ganjei and Aflaki (2019)	0.5, 1, 2% of nano-silica with 1%, 3%, 5% SBS	No tests.	Fatigue and indirect tensile tests.	The ideal combination was using 4% SBS, 2% nano-silica which showed improved in fatigue and cracking resistance results.
Bala, Napiah, and Kamaruddin (2018)	1%, 2%, 3% & 4% Nano-silica with 5% virgin polypropylene polymer.	No tests.	Four-point beam fatigue test, Indirect tensile stiffness modulus (ITSM), Indirect tensile strength test (ITS), Drain down test	The combination use of nano-silica and PP polymer shows better fatigue life with 3% nano-silica. Highest stiffness modulus and high tensile strength of the mixes using 2% nano-silica.
Sun, Xin, and Ren (2017)	0.5 & 1 % Nano-silica 3,4,5% Bentonite With 1-5% of SBR & PE	Softening point, ductility, viscosity, BBR, DSR, RTFOT tests	Rutting test, low temperature bending test, Marshall stability tests.	The combination of 0.5% Nano-silica+5% SBR+ 1% PE shows better binders' performance in term of improving the low and high temperature performance and aging resistance.

2.13 Summary

This chapter shows the several section of bitumen, asphalt mixtures, polymers and waste plastic in pavement engineering. The chapter reviews and evaluates the influence of using waste polymer in improving the rheological and engineering properties of the modified binder and mixtures.

This chapter reviews the literature related to the data used for analyses and discussions on road surfacing modification in civil engineering. First, the chapter will display the background of road engineering and types of hot mix asphalt used in pavement construction. Consideration to the specification and properties of the stone mastic asphalt are illustrated. After that, comprehensive review on asphalt modification using polymer, waste plastic and nanomaterials. This chapter aims to review the background knowledge and status of road surfacing in the relevant regions to provide a sympathetic description of the significance of waste plastic modified bitumen binder and asphalt mixtures, and its role in providing effective and durable surfacing for heavy-trafficked roads in hot and humid areas. The use of nano materials as additive in asphalt are discussed and evaluated. This chapter will seek to clarify some of the term and concepts related to debates to enlighten the readers with the necessary background to better engage with the experiments and discussions alongside the investigator.

Reports and studies had investigated the advantages and importance of using polymer in bitumen modification, yet showing gap of research, in terms of the role of waste polymer in improving the durability, aging and fatigue life in the long term of service. In addition, the chapter attempt to point to the role of using nano material as single and as combined with other polymers in asphalt mixtures modification.

Chapter 3

Methodology

3.1 Introduction

The chapter demonstrates the materials employed in this research and methodology conducted. This research involves a detailed methodology program designed to investigate the efficiency and sustainability of using waste materials as an eco-environmentally friendly modifier in asphalt reinforcement for enhancement of mechanical and engineering properties. The chapter displays the selection of materials used including bitumen binder, aggregate, waste plastic and Nano silica. In addition, the chapter illustrates the modified bitumen binder samples preparation and asphalt mixtures fabrication. The comprehensive methodology of mixing and testing were divided mainly to three stages. First stage is to prepare the several modified binder samples using bitumen and waste plastic and examine the physical, rheological and aging properties. Second stage is to examine the engineering properties and Marshall properties of modified asphalt mixtures. Next stage is to evaluate the performance properties of hybrid additive of plastic-nano-modified mixture, numerous tests were conducted comprising Marshall stability Marshall Flow, wheel tracking test, four point bending fatigue test, Tensile strength test, stiffness modulus test, and drain-off tests.

3.2 Materials

3.2.1 Bitumen

In this study, C320 bitumen was used. C320 bitumen was provided by SAMI Bitumen Technologies, which is in Perth city, Western Australia. This type of bitumen binder has been selected following the specification and the recommendation of Main Road Australia and Australian Asphalt Pavement association, which recommended the use of C320 binder in wearing course materials design. Table 3.1 illustrates the physical and rheological properties of bitumen binder (Mashaan et al. 2021a).

Table 3.1. Bitumen's properties (Mashaan et al. 2021a)

Properties	**Data**	**Unit**	**Methods**
Penetration @ 25˚C	41	0.1 mm	AS 2341.12
Brookfield Viscosity @ 135˚C	0.50	Pa.s	AS 2341.2
Flash point	249	˚C	AS 2341.14
Viscosity @ 60˚C	320	Pa.s	AS 2341.2
G*/sinδ at 64˚C, unaged, should be > 1000 kPa	1.77	kPa	AASHTO T350
G*/sinδ at 64˚C, after aged REFOT should be > 2200 kPa	3.82	kPa	AASHTO T350
G* sin at 25˚C, should be < 5000 kPa	2200	kPa	AASHTO T350

The grade of bitumen content employed in stone mastic asphalt usually equals the same grade or slightly stiffer grade than used in dense-grade mixtures. When bitumen is stiffer, it minimises any potential drain down and helps to reduce rutting, which is usually expected in higher temperatures. Nevertheless, stiffer bitumen might result in thermal cracking. Using high optimum bitumen content and increased film thickness in the SMA, minimises the possibility of thermal cracking, especially in comparison with dense-graded mixture (Mahrez, 2008; Troutbeck and Kennedy 2005). According to Ali, Mashaan, and Karim (2013), the utilisation of binders modified by polymer(s) along with fibre would enhance the resistance of the pavement against problems such as rutting or fatigue cracking. The modified bitumen can be achieved through incorporating a quantity of stabilising (such as polymers) to conventional bitumen.

3.2.2 Aggregate

In Western Australia, the dense graded asphalt (14 mm) and Stone mastic asphalt (10mm) are used for wearing course materials layer. In this study, the aggregate used were produced from naturally excavated gravel and rock quarries within Perth region. In addition, the aggregate used were in accordance with the specification of MRWA (Main Road Western Australia). In first trial mixtures, conventional 14 mm AC asphalt and 10 mm SMA asphalt using the granite aggregate, that is the most common natural aggregate would be used in Western Australia, have been used in laboratory investigation at Curtin University, Australia. Table 3.2 and 3.3 illustrate the physical properties of the aggregate. Figure 3.1 and 3.2 show the particle size distribution of the AC14 mixture and 10 SMA mixture aggregate.

Table 3.2. AC Aggregate physical properties (Mashaan et al., 2021a).

Properties	**Methods**	**Value**
coarse aggregate		
Water absorption (%)	AS 1141.6.1	0.41
crushed value (%)	AS 1141.21	22.81
particle density (g/cm^3)	AS 1141.6.1	2.682
dry density (g/cm^3)	AS 1141.6.1	2.6
density after SSD (g/cm^3)	AS1141.6.1	2.6
Fine aggregate		
Water absorption (%)	AS 1141.5	0.599

particle density (g/cm³)	AS 1141.5	2.68
dry density (g/cm³)	AS 1141.5	2.64
density after SSD (g/cm³)	AS1141.5	2.66

Table 3.3: SMA aggregate physical properties

Property of used aggregate	**Standard**	**Value**
coarse aggregate		
Water absorption (%)	AS 1141.6.1	0.4
Aggregates crushed value (%)	AS 1141.21	23.81
particle density (g/cm³)	AS 1141.6.1	2.7
dry density (g/cm³)	AS 1141.6.1	2.6
density after SSD (g/cm³)	AS1141.6.1	2.67
Fine aggregate		
Water absorption (%)	AS 1141.5	0.59
particle density (g/cm³)	AS 1141.5	2.58
dry density (g/cm³)	AS 1141.5	2.6
density after SSD (g/cm³)	AS1141.5	2.657

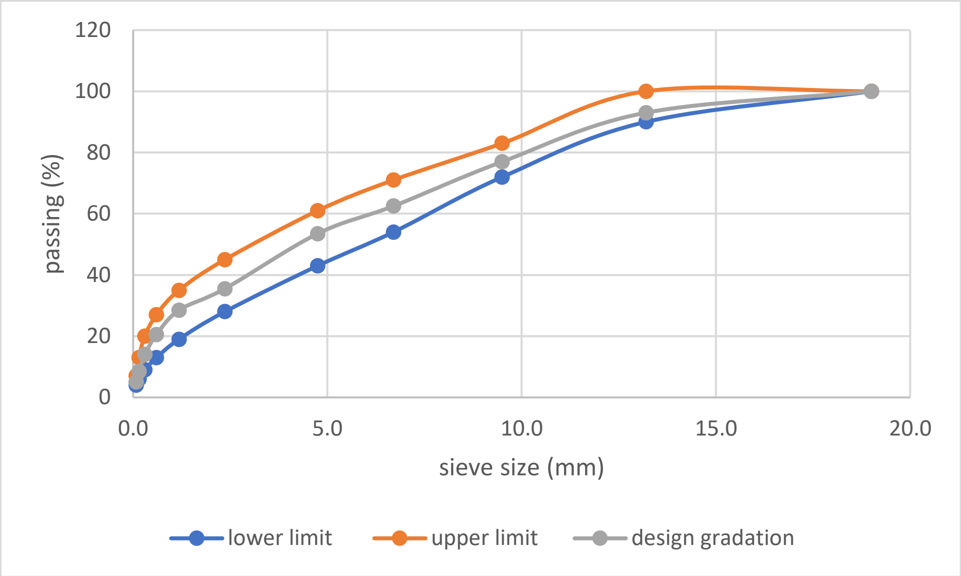


Figure 3.1: Aggregate particle size distribution of AC mixture

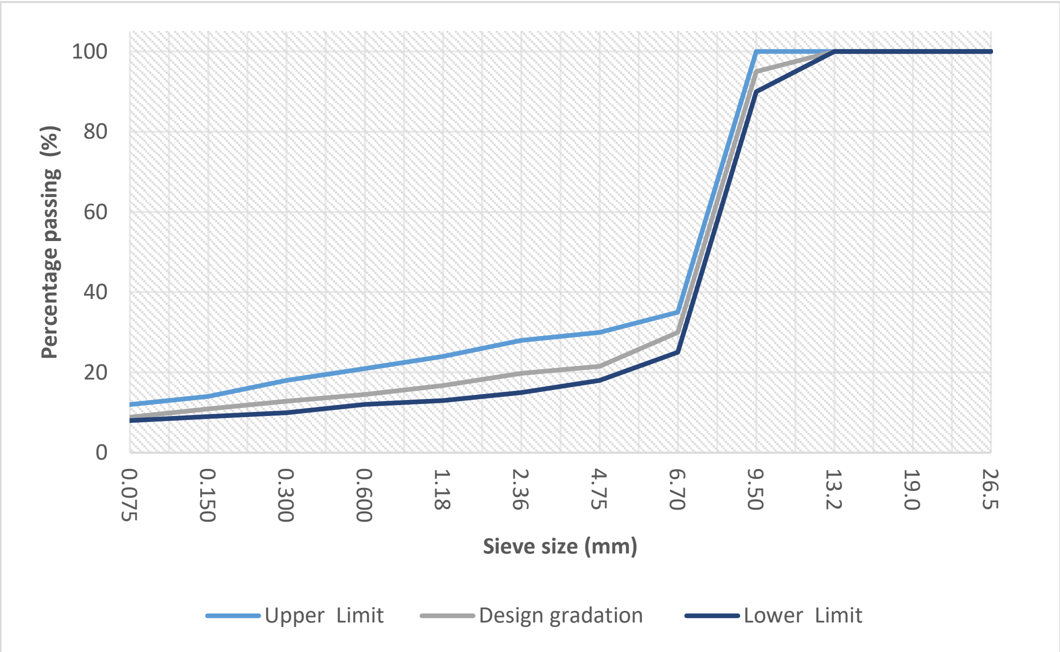


Figure 3.2: Aggregate particle size distribution of SMA mixture

The quality of aggregates employed in asphalt mixture needs to be high with a highly rough texture and cubic shape to be able to resist any displacement or rutting. The hardness of the aggregate content helps the pavement to resist against breaking under heavy loadings of frequent tyre traffic. Specifically, the aggregate should also have high resistance to polishing and abrasion and in accordance with stone mastic asphalt specification.

However, the first measure taken in designing the intended mixture is the careful selection of aggregates to meet the requirements of the mixture specification. The requirements of quality of aggregate are presented in Table 3. Since the contact of stone-on-stone is the essential backbone of SMA, the characteristics, specifically the shape and hardness of the aggregate, are more important in SMA rather than conventional AC dense graded mixes.

Natural dust obtained through crashing procedure of aggregate was used as mineral filler. Following the recommendation of Main Road Western Australia specifications and requirements, percentage of filler by mass of dry aggregate were used was 1.4 - 1.5% hydrated lime. Using hydrated lime was to improve the moisture resistance of the asphalt mixtures.

Generally, the function of filler in the asphalt mixtures is essentially to stiffen the bitumen rich in asphalt. The application of higher amounts of too fine a filler can led to excessive stiffness of the mixture rendering it difficult to work, which might result in the mixture being susceptible to cracking. A mineral filler is usually added into the mixture as part of the aggregate gradation. The content of the filler (passing the 75um sieve) in the mastic asphalt mixture can range from 8-10% of the total amount of aggregate. This high content of mineral filler in the mixture performs a major role in the properties of SMA, especially relating to the air voids (VIM), optimum bitumen content (OBC), and mineral aggregate voids (VMA). In addition, using fiber is an essential to enhance the engineering properties of asphalt mixtures, therefore, cellulose fiber (as shown in Figure 3.3) has been used in mixing and production of stone mastic asphalt. Due to the relatively large amount of the filler, the performance of SMA becomes very different from the other types of HMAs, AC for instance.

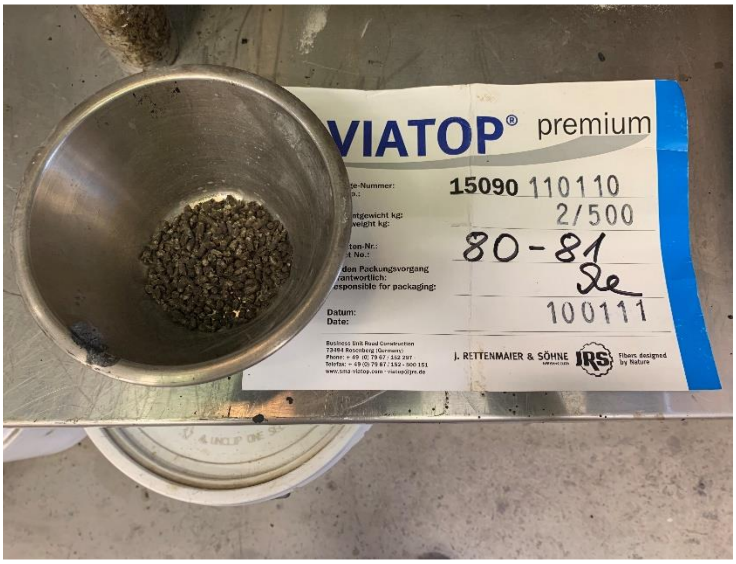


Figure 3.3: Cellulose fiber

3.2.3 Waste polymer

In this research, waste plastic was used as a substitute cost-effective and environmentally friendly alternative polymer than commercial polymers. Domestic waste plastic bottles (PET) were assembled, cleaned, ground to a size of 0.45mm, and used as a bitumen modifier. Figure 3.4 shows the waste PET plastic (obtained from water drinking bottles) and grinding machine used in grinding of waste plastic. Other types of waste plastic such as waste HDPE and waste LDPE have been used in stage of the methodology design as shown in the Figure 3.5 and 3.6 showing the Scanning Electron Microscopy image (SEM) of the different plastic waste.

Figure 3.4: Waste plastic and grinding machine (photo by Nuha Mashaan)

Figure 3.5: Different waste plastic

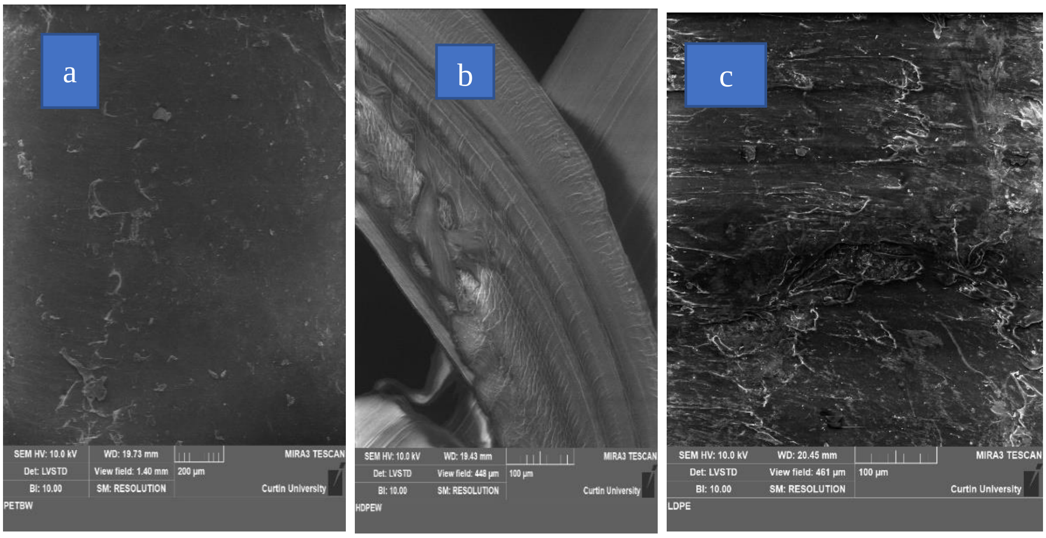


Figure 3.6: SEM image of (a) waste PET, (b) waste HDPE, (c) waste LDPE

3.2.4 Nano-Silica

Nano-silica used in this study has a particle diameter of 15nm, a service area of 600m²/g, bulk density <0.056g/cm³, true density 2.4 g/cm³, and coated with 2wt% Silan- KH220. As shown in Figure 3.7, SEM of high and low magnification of the surface of Nano material. Table 3.4, Table 3.5, and Figure 3.8 shows the EDS component and the properties of nano-silica. As supported in Figure 3.9, the EDS spectrum obtained displays the high-level equivalent to silicon, which emphasized that nanoparticles set are those of silica. The nano material was supplied by US Research Nanomaterials Inc, Houston, United State of America.

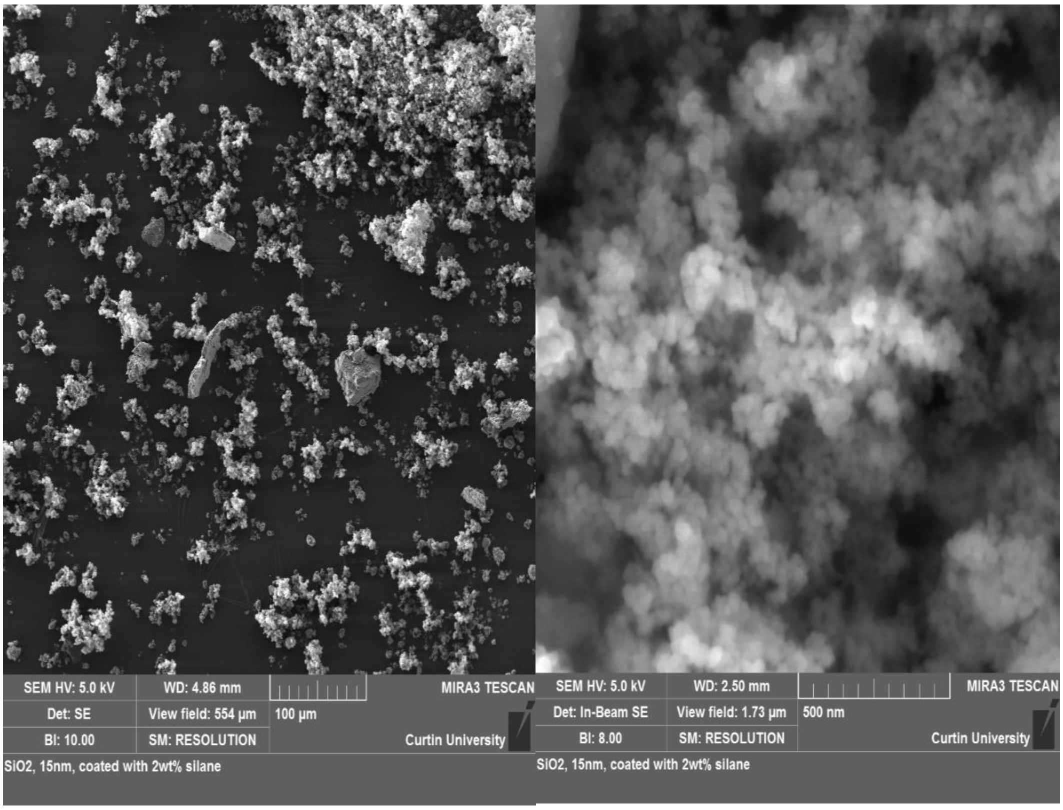


Figure 3.7: SEM of Nano silica at 100 μm and 500 nm magnification.

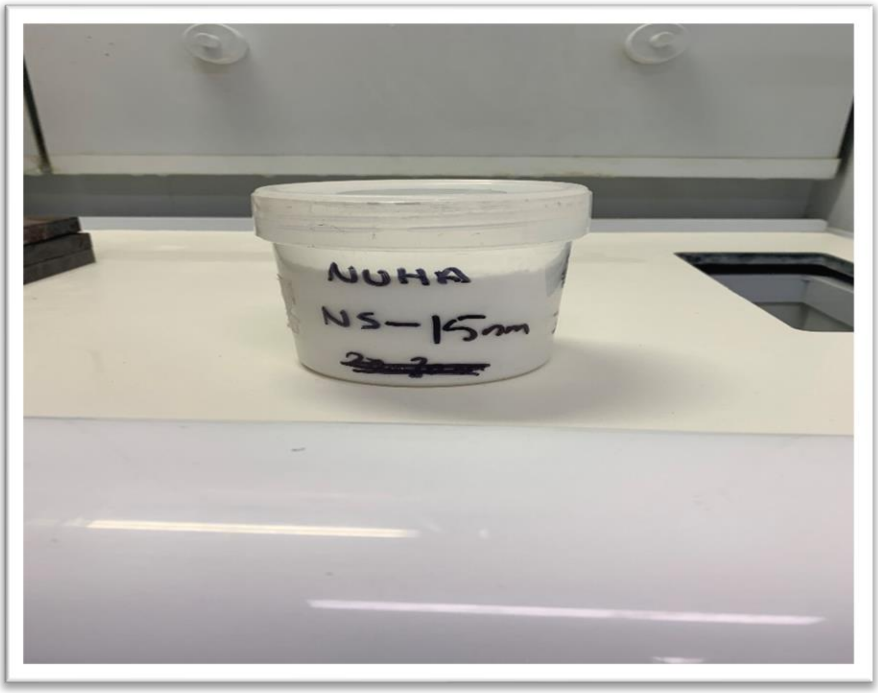


Figure 3.8: Nano silica stored powder

Table 3.4: Elements of NS 15nm.

SiO2- Silan	**Mg**	**Ca**	**S**	**Fe**
97.3wt- 2.0wt%	75 ppm	<220 ppm	<126 ppm	<56ppm

Table 3.5: Properties of NS 15nm.

service area	**size**	**colour**	**bulk Density**	**true density**
600 m2/g	15nm	white	<0.056 g/cm3	2.4 g/cm3

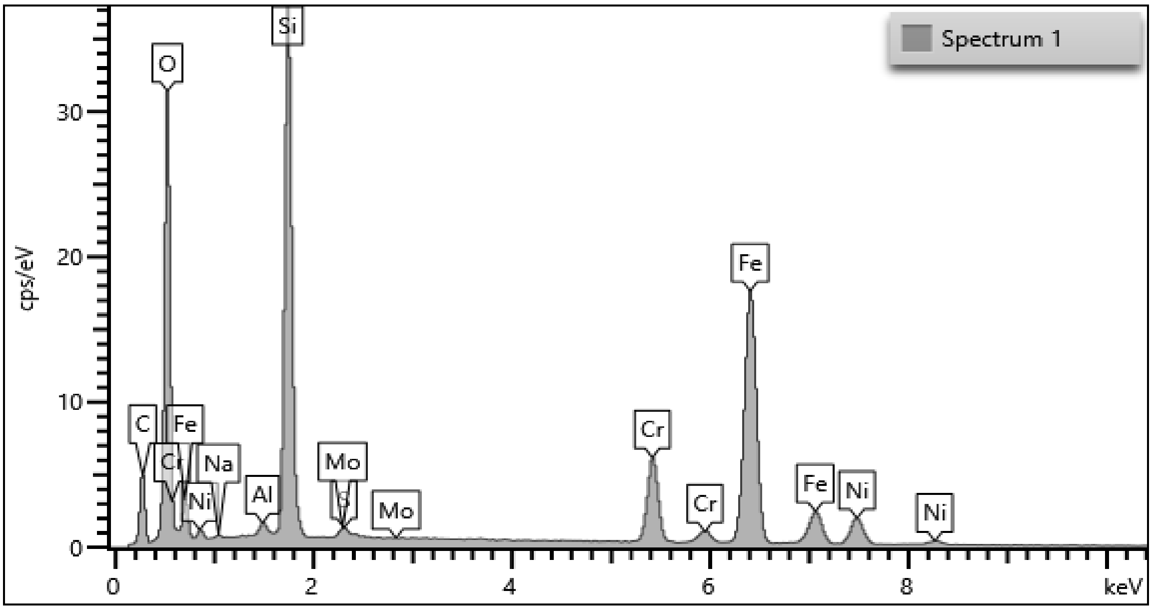


Figure 3.9: EDS spectrum of nano-silica

3.3 Samples preparation

The sample preparation divided into two stages, in terms of modified bitumen preparation and modified asphalt mixtures preparation. In each stage there were several trail mixtures conducted to select the best and ideal conditions mix of preparing the modified mixture. First stage was to set up the samples of plastic modified C320 bitumen. The high shear mixer machine type Silverson L5M-A, as shown in Figure 3.10, was used to make the plastic-modified bitumen using various content of 0%, 4%, 6% and 8% plastic by weight of bitumen. The prepared samples of modified bitumen were stored in 1 litter container to be used for the purpose of testing the physical, viscoelastic, oxidation and durability properties. More amount of the modified binders was kept being use for the second step of preparing the modified asphalt mixtures following the wet method.

Figure 3.10: High shear mixer Silverson L5M-A used in binder preparation (photo by Mashaan)

Different types of waste plastic have been used in the first stage including PET, HDPE, and LDPE. The selected terms of blending requirements were of 45 minutes time, 180 ˚C temperature, and 2000 rpm shear velocity, respectively, and this selection was based on numerous trial blends. The strategy of bending mixing was started at low shea rate of 700-800 rpm for the first 15 minutes to ensure less air void, after that the speed raise up to 2000 rpm for continuous 30 minutes. DSR test was conducted to assess and verify the viscos-elastic performance and examine the rutting and fatigue resistance of modified bitumen binders. Take into consideration the results of DSR performance of the modified binder, the ideal type and content of waste plastic will be selected for the second stage of preparing the waste plastic-modified asphalt mixture.

To prepare the asphalt mixtures using the C320 bitumen and different content of waste plastic. The wet process was used in preparing the modified mixture, as in this method the ready waste plastic modified bitumen heated to 120C and then added to the selected aggregate and mixing for 10-15 using the 5 kg mixer and then compacted at 160℃-165℃ using the Marshall compaction machine as shown in Figures 3.11 and 3.12. The second phase was to blend the aggregate with the selected types of waste plastic modified bitumen to formulate the waste plastic-modified-asphalt. An optimum binder content was used in sampling plastic modified asphalt with a plastic content of 4%, 6% and 8% by weight of bitumen. Additionally, following the recommendation of the Main Roads Western Australia standard, 1.5 % hydrated lime by weight of aggregate was utilized.

Figure 3.11: Asphalt mixer

Figure 3.12: Compaction machine, Marshall type

To prepare the hybrid modifier of Nano-silica and waste plastic modified C320 bitumen binders, using the ideal content of 6% PET plastic with the nano silica concentration of 0%–8% by weight of binder. Proceeding the addition of nano-silica particles, PET polymer is to be first dissolved to 500g weight of the base binder. At the point when PET has broken down totally in the base binder, adding nano-silica particles are to be uniformly to the PET modified bitumen and blended at a high shearing rate of 4000 rpm. All through the blending time, the temperature was kept for 2 hours at 180 °C± 0.5°C. The asphalt mixtures samples were prepared following AS/NZS 2891.2.1:2014**.** Following the Marshall method and the wet-mix process, the PET/NS-modified asphalt mixtures were sampled at optimum binder content. The sample of (control binder) used SMA mixture with 0% PET and 0% NS. In addition, as advisable by the MRWA standard, 1.5 % hydrated lime by weight of dry aggregate is used. In the testing stage, Marshall test, wheel-tracking tests, IDT resilient modulus test, Indirect Tensile strength test, tensile strength ratio and drain-off were employed to sympathize the effect of PET/NS on the engineering and mechanical properties of modified SMA mixtures.

3.4 Experimental methods

Experimental investigation of this research has been conducted using the facilities and equipment testing at pavement laboratory in civil engineering faculty at Curtin University. The testing methods of physical and rheological properties were carried on the modified bitumen binders and modified asphalt mixture samples. Therefore, first level of the work was to test the physical, rheological, and aging properties of the unmodified and modified bitumen binder. To achieve this target, penetration test, Dynamic Shear Rheometer (DSR). Nevertheless, to simulate the aging during construction and aging under road service Rolling Thin Film Oven (RTFO), and Pressure Aging Vessel (PAV) tests were conducted, respectively.

On the other hand, to examine the mechanical and performance properties of the unmodified and modified asphalt mixtures, several tests were conducted. To this level, Marshall test, wheel-tracking tests, IDT resilient modulus test, Indirect Tensile strength test, tensile strength ratio and drain-off were employed to sympathize the effect of plastic on the engineering and mechanical properties of modified asphalt mixtures.

3.5 Bitumen Binders Testing

3.5.1 Penetration test

The test of penetration was conducting following the specification of AS 2341.12. As shown in Figure 3.13, the penetration test measures the distance in millimetre of a standard needle is perpendicularly diffused in the bitumen sample at specific conditions of 5 seconds time, 25℃ temperature and 100 g load. The main purpose of this test is to establish the stability of bitumen and, thus, the ability to resist rutting failure and cracking deformation. The penetration test is kind of popular, which can be used to clarify the different grades of bitumen. Based on previous studies, the reduction in penetration suggests the high rate of rutting resistance of bitumen binder (Ali, Mashaan, and Karim 2013).

The scope of the test is to determine the penetration of semi to solid bitumen materials, as such penetration emphasises and describes the level of stiffness and stability of bitumen materials. The test apparatus contains mainly, needle and its holder, water bath, thermometer, timing tool, and container of the sample. The procedure of the test is quite simple and show efficiency data. To start the test, bitumen samples were heated in oven to reach level of sufficient fluid, and carefully poured in the standard penetration containers, after that allow for cooling down for around 45-60 minutes. The next step was to sock the containers in water bath for 70-80minutes. Before the conducting the test, it is important to examine the needle and its holder to ensure the non-existence of water and others unnecessary material. The bitumen container was placed in the transfer dish and covered entirely with water inside the water bath at controlled temperature of 25℃. Removing the container from the water bath and placed the sample on the stand of the penetrometer and allow the needle to slowly lowering its position to just contacted the sample's surface. Then the pointer was conveyed to zero point and instantly released under the standard time of five seconds. The dial will show the recorded reading. Each sample requires the average of three reading. At the end of the test, after recording the results, cleaning the needle is required and ensure the devise in good conditions for further testing.

Figure 3.13: Penetration test apparatus

3.5.2 Dynamic Shear Rheometer (DSR)

To examine the viscous-elastic behaviour at high temperatures and investigate the bitumen's resistance to rutting and fatigue both of treated and non-treated binder samples, the dynamic shear rheometer (DSR) was conducted following AASHTO 315-

2017 standards. This test focuses on determining the shear stress and liner viscous to elastic properties of bitumen tested in oscillatory shear by using parallel plate. The main aim of the test procedure is to measure the complex shear modulus which is known as stiffness indicator G* and measure the phase angle which is known as elasticity indicator. From engineering point of view, complex shear modulus presents the total resistance to deformation under repeated shear force, as the bitumen with sufficient stiffness would possibly have high resistance to deformation. Whereas the phase angle reflects the lag between used shear stress to the developing shear strain, and the lesser phase angle is more elastic is the bitumen.

Bitumen binder is subjected to stress and strain during the load and temperature variation. As results of this variation, the stiffness and strength properties could be significantly affected. Measuring the bitumen performance from viscous to elastic and in between of viscoelastic is essentially important, as this measurement could predict the bitumen ability to endure high load and high temperature, and hence better rutting resistance. Additionally, getting high fatigue resistance of bitumen ability to withstand the repeated load at low temperature. This mechanism of resistance deformation of rutting and fatigue requires the understanding of the rheological and viscoelastic characterises of the bitumen. The DSR test was conducted to assess and verify the viscos-elastic performance and examine the rutting and fatigue resistance of modified bitumen binders.

Figure 3.14 shows the Dynamic Shear Rheometer (model Kinexus) at Pavement laboratory, Curtin University. During this research, DSR used to determine and record several important data, mainly complex shear modulus G*, which is represent the applied stress and stiffness performance. Another data is phase angle which can be indicate to the elasticity performance and strain developed. Using the DSR software outcome of G* and phase angle to calculate other liner viscoelastic properties, like storage modulus, G’, and loss modulus, G’’, which is indicates the viscous behaviours and measure the dissipated energy after every loading phase. In addition, rutting resistance in terms of G*/sinδ is calculated and used to evaluate the rutting resistance of bitumen binder for aged and unaged conditions.

Figure 3.14: DSR Kinexus tester

The test used different conditions of original condition and aging conditions, as each case has different specimen thickness and diameter, therefore, specimen of 1mm thickness and 25 mm diameter is used to measure the conditions of unaged and short-term aging. On the other hand, specimen of 2 mm thickness and 8 mm diameter is used to measure the conditions of long-term PAV aging. Figure 3.15 shows on left photo the upper and lower plates for the 25 mm sample with large mould size, and the 8mm diameter with small mould size. During this test, different loading testing frequencies and different testing temperatures are used based on the type of conditions testing. In general, the loading frequencies range from 1 to 100 rad/sec, however, specification test mainly achieved at frequency of 10rad/sec (1.59 Hz) which is used to simulate the shearing force linked to traffic speed of 90 km/hr. As for testing temperatures, 4℃ to 80℃ based on the sample's thickness and diameter. As such, using samples of 1mm thickness and 25 mm diameter if testing high temperature over 50℃, and using samples of 2mm thickness and 8 mm diameter if testing temperature between 4℃ - 40℃.

Figure 3.15**:** Plate and mould for unaged and RTFOT aged sample (left), plate and mould for PAV aged sample (right)

3. 5.3 Rolling Thin Film Oven Test (RTFOT)

To simulate the aging conditions during pavement construction and under traffic load, The Rolling Thin Film Oven (RTFOT) test is conducted. Figure 3.16 shows the apparatus of (RTFOT) test at Curtin University. The test has carried out in Curtin laboratory following the procedure and specification standards as AS/NZS 2341.10:2015 (Standards Australia 2015).

The test was used to investigate the aging resistance for unmodified and modified bitumen samples. The first step of testing procedure was to heat the bitumen until becomes fluid, and then filled the RTFOT heat resistance bottles (as shown in Figure 3.17) with 35g of bitumen and placed the bottles horizontally inside the circular carriage inside the oven for period of rest of 30 minutes at temperature around 163℃. The capacity of the circular carriage is up to eight RTFOT heat resistance bottles. After rest period of 30 minutes, activated the carriage which is holding the bottles and rotating at speed of 15 rpm, air flow of 4000 ml/min, 163℃ for a period of 60 minutes.

As the glass bottles start rotating, the bitumen will create a thin film layer, thus allowing bitumen to simply evaporate and oxygen would be able to react with the bitumen layer. Hence, the bitumen was aged for a period of 90 minutes. Once test is complete, the aged bitumen transfer from the RTFOT heat resistance bottles to tin containers and labelled accordingly. The bitumen stored in containers will be examined following the bitumen binder tests.

Figure 3.16: Apparatus of (RTFOT) tester, MATEST model at Curtin University

Figure 3.17: RTFOT heat resistance bottles

3.5.4 Pressure Aging Vessel (PAV)

To simulate the long-term aging of bitumen binder after five to ten years of traffic service, the Pressure Aging Vessel (PAV) is conducted. To achieve this, the bitumen binders are subjected to high pressure of 2.1 MPa for a period of 20 hours and under a high temperature of 110℃. During the PAV test, a sample of 50 g, which has been subjected earlier to RTFOT aging, is melted, and filled the PAV pans. The test has conducted at ARRB laboratory following the standard of AASHTO R28 for accelerate aging of bitumen binder using pressurised aging vessel method. First, the vessel place in the preheated oven chamber at 100°C temperatures and the vessel pans are placed in the rack. Once the designed temperature is achieved, the vessel is removed from the oven. After 20 hours, the pressure was gradually released using the valve. Generally, eight to ten minutes was required to achieve an adequate pressure drop. After this the pans should be removed from the holder and put in another ordinary oven for 30 minutes at 163°C, this step is to remove any entrapped air could be formed in the samples. Finally, the PAV aged samples are moved to tin containers and labelled accordingly. The bitumen stored in containers will be examined following the bitumen binder tests.

3.6 Asphalt Mixtures Testing

3.6.1 Marshall test

The Marshall Method is the most conventional and common method employed for making and evaluating trial mixtures in obtaining the optimum bitumen content. The main goal of this test is to manufacture asphalt mixtures with great resistance to deformation and failure cracking. This method was initially introduced by Bruce Marshall, a civil engineer collaborating with the Mississippi State Highway Department (Ghassan 1992). However, the initial features of this method have been improved through time by the US Army Corps of Engineers, and standardised and elaborated in ASTM D1559 (Garber, 2002).

Usually, the Marshall Method is used in the design of asphalt mixtures to provide verification of the acceptable number of voids in asphalt mixtures. Specimens were prepared in the laboratory using 50 or 75 blows per side produced by a Marshall Hammer. The hammer blows are affected the cylinder sample of 101 mm diameter and height of 64.5 mm, as shown in Figure 3.18. Marshall mixes method shows an important role in considering the air voids, strength performance and durability properties.

It is worth to notice that Marshall mix method shows a considerable and an acceptable result in designing both of dense graded asphalt and stone mastic asphalt. It is easier to achieve the compaction of the SMA and dense graded mixture on the road and the desired density level in comparison to that required by conventional HMA. In the current study, the procedures including heat, mix, and compact of the mixture of aggregates and bitumen are specified by the Marshall Method (AS/NZS 2891.5-2015) (see the Marshall test machine as shown in Figure 3.19). Marshall tests main parameter stability flow, and Marshall quotient MQ.

Figure 3.18: Marshall samples at Curtin laboratory

Figure 3.19: Marshall tests, OVILAB model

3.6.2 Wheel Tracking test

This test has been conducted to evaluate and determine the resistance over the modified mixture to rutting. Australian standard AGPT/T231 has been used as reference of wheel tracking test. The test parameters were temperature of 60° C and vertical load of 700 N. Applied on the top of a specimen using a wheel 200 mm of diameter. For every mix batch, three slabs were contacted using copper roller compactor following the Australian standard AGPT/T220. Before conducting the test, each sample must compact using the wheel tracking compactor. They dimension of each slab are 300 x 300 x 50 mm. Each slab was attached to a moving table. The moving table rate is 42 passes/minute. The test should finish or terminated automatically after reaching the 10,000 passes. The mixture sample on the box machine should stayed overnight before. The test started and put on to ensure accurate and correct conditions and temperature of a test as show in Figure 3.20.

Figure 3.20: Wheel tracking sample and testing at Curtin University

The wheel tracking test is used mainly to determine the susceptibility of asphalt mixtures to plastic deformation at high temperature and pressure which is like filed conditions of traffic road. Rut depth is produced through this test and the lower the rut depth, the better rutting resistance of the modified asphalt mixture is. Hence, the rut depth formed by repeated passing load wheel over the samples is significantly assessed the asphalt mixture's susceptibility to deformation and cracking.

3.6.3 Indirect Tensile test

The indirect tensile test is used to determine the resilient modulus (Mr) of asphalt mixtures and this test was performed in agreement with Australian standard AS 2891.13.1. Standard shows specific conditions of load, Poisson's ratio, temperatures, pulses, and frequency to achieve the performance property and tests. All samples are made at optimum binder content and had been compacted using Marshall compactor under desired air voids. This test is recognized as *a non-destructive test* (undamaged samples after testing) which is contain a compression load applied directly through the sample's diameter in vertical direction, as such resulting in a total of horizontal strain of 50 micron. Testing temperature was set at 25℃ and o.35 of Poisson ratio. These conditions are set to ensure that the asphalt sample satisfactorily distorted when subjected to subjected to loading and remain in elastic behaviour.

Initially, the test start with five loading pluses applied at a selected rise time to the peak under selected period pulse. Later a more five loading pulses are used to verify and obtain the indirect resilient modulus of the samples. The below equation 1 used to measure and determine the value of resilient modulus: As the E, P, V, H, and hc refer to resilient modulus, the ultimate load, Poisson ratio (0.4 was assumed), horizontal deformation of specimen, and specimen's height, respectively.

$$E = P * \frac{(v + 0.27)}{(H * hc)}$$

………. Equation (1)

3.6.4 Indirect Tensile strength and TSR ratio test

Most important distress and failure of asphalt mixtures is primary caused by high moisture susceptibility. This susceptibility is used to assess the bonding and internal structure of aggregate and binder and how this bond become weaker when water penetrate through the structure of aggregate and bitumen. As the water will make the aggregate not adhering into the bitumen. As such, bitumen will not gluing and holding the aggregate and this results in quick failure of pavement structure will happened in the form of “stripping “deformation.

The test of indirect tensile strength ratio is conducted to measure the stripping damage and mositure suscepitibilty of aspahlt. The test was carred out following the specificatrion of AG: PT/T232 (Austroads 2007). Samples of 101.5 ± 0.5mm diameter and 64.5± 0.5 mm height were compacted at optimum binder content. The test has two sets of sampling which are samples in dry conditions and samples in wet conditions. Equation 2 used to calculate the indirect tensile strength test of each condition. As P, t, and D refer to maximum load, thickness and diameter of sample, respectively.

$$TS = 2P \div \pi tD \quad \ldots\ldots\ldots\ldots \text{ Equation (2)}$$

Unconditional group refers to samples that is tested dry at room temperature, while conditional group refers to samples are tested with partial saturation and moisture conditioning, and subjected to vacuum saturation for a bout 5 min before being placed within a 60°C water bath for 24 hours. The ratio of wet to dry tensile strength is called tensile strength ratio (TSR), and it has been used to indicate level of moisture damage of asphalt mixture. The tensile strength ratio is measured according to Equation 3. As S1 and S2 refer to the dry and wet tensile strength.

$$TSR = (S2 \div S1) * 100 \text{ .... Equation (3)}$$

3.6.5 Binder Drain-off

Stone mastic asphalt is identified as a mixture of gap-graded aggregate, which minimises the fine and medium-sized aggregate. some weakness is distinguishable in the SMA structure, such as drain down, which ensues from the absence of mid-sized aggregate in the gap-graded mixture, which has a high asphalt binder content instead. As such, it is very important to test the drain down of the mixtures. Austroads AG: PT/T235 drain-off test was followed used for this purpose. Two samples should be used to obtain the average results and determine the binder's susceptibility to drain. During the test, samples are kept in the oven for 60 minutes at temperature of 170-175℃. It is admirable to mentioned that binder drain off test is considerable fundamental for SMA than that of dense graded asphalt due to the aggregate type and binder content used in SMA. This test initially established and created by AASHTO, it is designed to simulate the site conditions that asphalt mixture will faced during production, construction, placement, storage, and transportation stages.

3.6.6 Four-points bending test

The four-point bending test is conducted to simulate and measure of fatigue deformation asphalt mixtures under repeated load at low to intermediate temperature. The test measures the fatigue life which is defined as the number of applied cycles load resulting to permanent deformation in form of fatigue cracking. The test is conducted in accordance with Austoads AGPT/233 method. This method considers the Australia conditions of using controlled strain mode as this model is more suitable to the thickness layer of Australian road. As pavement layers are designed with thickness lower than 76 mm. During the test, each sample kept under controlled temperature of 20℃ and loading frequency of 10 Hz, and this achieved by allowing the sample to condition for minimum two hours at testing temperature of the test start.

During the test, the slab samples were compacted using the wheel compactor and each slab was cut into three beams using specific machine. The dimension of each beam is width of 63.5, depth of 50 mm and length of 390-340 mm, as shown in Figure 3.21. The fatigue test results are obtained from software linked to the machine test and this test shows a high efficiency in terms of measuring the fatigue life and stain deformation. Figure 3.22 show the four-point bending test used at pavement laboratory at Curtin university.


Figure 3.21: Fatigue beams

Figure 3.22: Four-point bending test machine

3.7 Summary

This chapter designs to illustrate the materials, experimental methodology and testing strategies used in this study. The chapter presents the comprehensive procedure of preparing and testing the bitumen and asphalt samples. Several tests and approaches are used to measure and evaluate the possibility of using the waste plastic as a suitable modifier that could improve the rheology characteristics, ageing and engineering properties of bitumen binder. Table 3.6 summarise the numbers of testing, samples and types of tests. On the other hand, Marshall test, rutting test, fatigue test, moisture susceptibility test and binder drain off are performed to evaluate the mechanical and strength properties and determine the best performance at ideal conditions.

Table 3.6 Summarise the numbers of testing and types of tests

Test name	Numbers of testing	Type of test	Properties
Penetration test	3 samples per each condition	Binder test	Physical
Softening point	3 samples per each condition	Binder test	physical
DSR, MSCR	3 samples per each condition	Binder test	Rheological
RTFOT and PAV	3 samples per each condition	Binder test	Aging resistance
Marshall Test	3 samples per each condition	Asphalt mixtures	Stability
Wheel Tracking test	3 slabs per each condition	Asphalt mixtures	Rutting resistance
Indirect Tensile test	3 samples per each condition	Asphalt mixtures	Stiffness, resilient modulus
Indirect Tensile strength and TSR ratio test	3 samples per each condition	Asphalt mixtures	moisture susceptibility
Binder Drain-off	3 samples per each condition	Asphalt mixtures	susceptibility to drain
Four-points bending test	3 beams per each condition	Asphalt mixtures	fatigue

Chapter 4

Physical, rheological, and aging properties of plastic modified bitumen

4.1 Introduction

With the developing world’s growing population, the quantity of waste generation proliferates. This amount of waste causes a considerable rise in the costs of waste dumping and blocks future sites for land fields. The application of waste materials as an alternative of new materials in the roads construction industry offers important advantages. One is the substantial savings and reduced costs, and the second is the cutting down of wastes that will be disposed of in the landfills. Thus, the potential progress of utilising waste plastic in asphalt modification will take into account the enhancing properties of the pavement construction (Dalhat and Al-Abdul Wahhab 2017; Piromanski et al. 2020**;** Zakaria 2020; White 2020).

This chapter shows the effect and the possibility of using waste plastic as an alternative cost-effective recycled polymer in modification of bitumen binder. The modification targets the physical, rheological properties and the binders' resistance to aging. Short-term aging is developed during construction and mixing, whereas long term aging would develop throughout the life service of the constructed road. Both the long and short aging are investigated to determine the durability and aging resistance of the modified binder using RTFOT and PAV aging. Penetration tests and DSR tests were conducted to investigate and evaluate the complex shear modulus, stiffness, elasticity, and viscous properties. Different contents of different plastic types mainly; PET, HDPE and LDPE as shown in Figure 4.1, were used in this research. As this was the first stage of the project to determine and select the best and ideal type of waste plastic to be used in the next stage of mixture preparation as stated in methodology chapter.

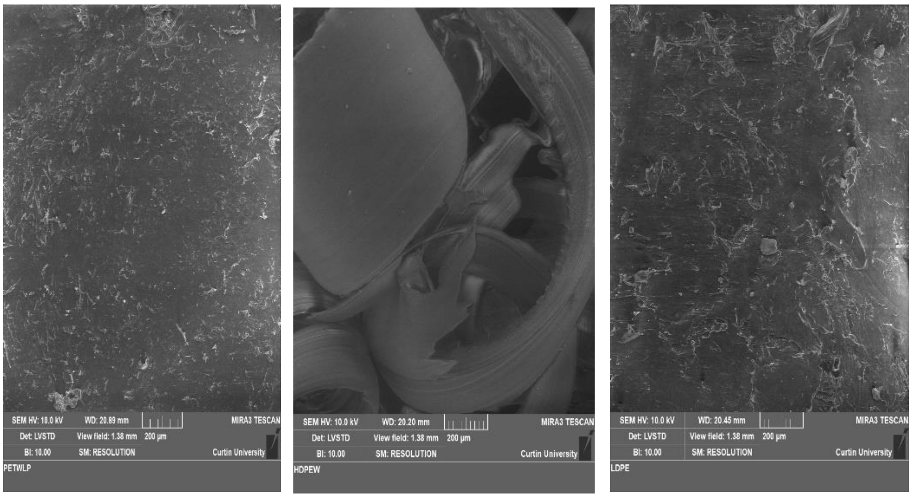


Figure 4.1: SEM of waste plastic from left to right (PET, HDPE, LDPE)

4.2 Conditions and variables of plastic modifier

Different contents and different types of plastic using different binders' tests were conducted in this section. As shown in Figure 4.1, three different types of waste plastic of PET, HDPE and LDPE were used in different percentages of 0%, 2%, 4%, 6% and 8% to prepare the modified binder using the wet method. The control un-modified binder was C320, and the properties of this binder were stated in chapter 3.

4.3 Physical properties of waste plastic modified bitumen (unaged)

To investigate the physical properties of the modified bitumen, a penetration test has been conducted in the first stage. The penetration test is the most ordinary and highly recommended, simple, and quick test to establish the stiffness behaviours of the binder, and to indicate the capability of the bitumen to withstand the permanent deformation.

The penetration of different content types of PET, HDPE and LDPE plastic waste for unaged, were conducted and analysed as shown in Figures 4.2, 4.3 and 4.4, respectively.

Figure 4.2 shows the impact of different content of PET on penetration. As can be seen, the more PET content the lesser penetration values. The penetration of C320 (0% plastic) was 44mm and declined to 30mm by using 8% PET, which in turn indicates the modified binder become stiffer. At 6% and 8%, the behaviour of the modified bitumen looks at the same level of resistance to permanent deformation. However, all PET modified C320 show a significant effect on penetration results compared to unmodified bitumen C320.

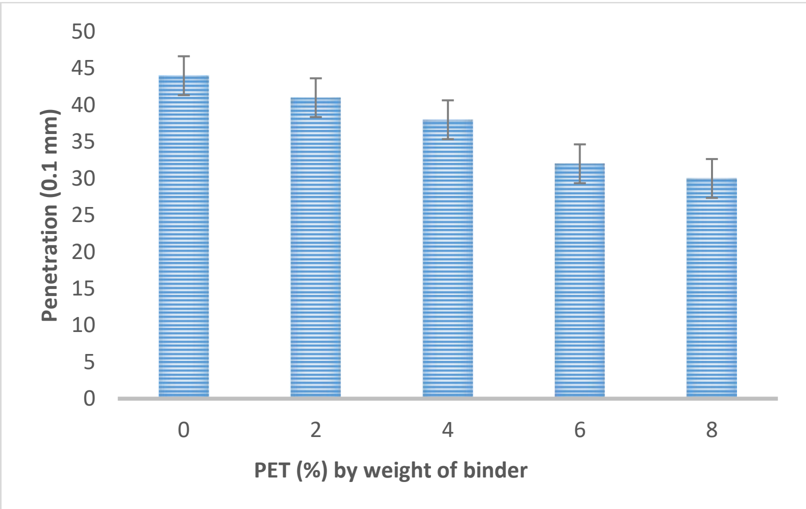


Figure 4.2: Results of penetration of unaged PET-modified bitumen

Figure 4.3 displays the penetration results of various contents of waste HDPE (0 %, 2%, 4%, 6% and 8%. The depth of penetration started to decrease at 2% and 4% of about 42mm and 40 mm penetration, and then the values increase to 44 mm and 45 mm for samples of 6% and 8%, respectively. As can be seen that the more percentage of HDPE has a negative impact as it results in increasing the penetration values. The considerable influence of HDPE on penetration only could be reconsidered at 2 % and 4%, however, the decrease was close to the unmodified C320.

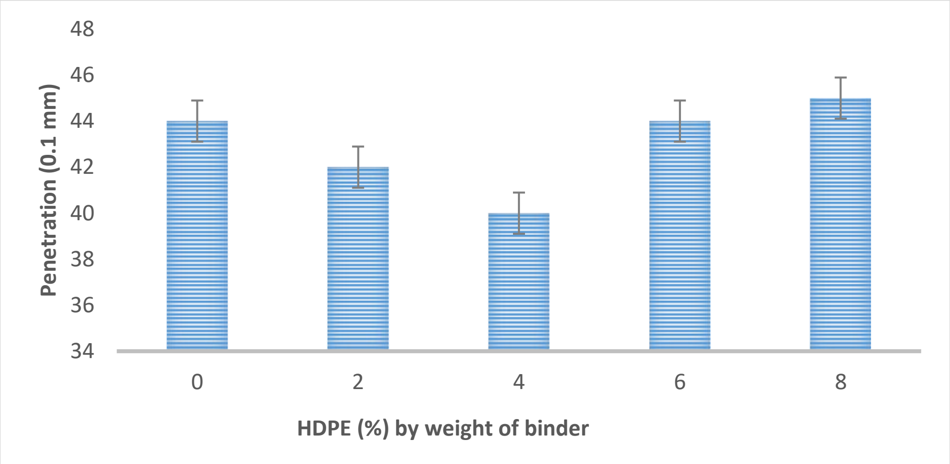


Figure 4.3: Results of penetration of unaged HDPE -modified bitumen

Figure 4.4 shows the results of penetration using different content of LDPE. The results of penetration were 44 mm, 42 mm, 40mm, 40 mm, 42 mm for the LDPE contents of 0%, 2%, 4%, 6% and 8%, respectively. The results show a decrease in penetration as the amount of LPDE increase up to 4%, and the results were kept steady at 6% with the same level as of 4% of about 40 mm penetration. However, by increasing the LDPE to 8% the penetration was increased by about 42 mm. The results show that a high percentage of 6% and 8% of LDPE modified bitumen binder does not significantly affect the penetration.

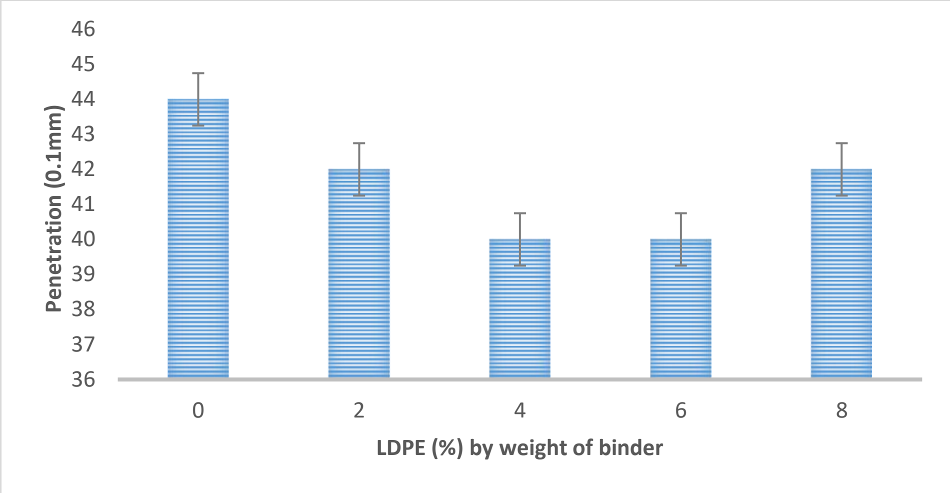


Figure 4.4: Results of penetration of unaged LDPE -modified bitumen

Figure 4.5 shows the impact of different types of waste plastic on penetration results. The penetration decreases significantly by adding more PET content up to 8%. However, the sample of HPED and LDPE modified bitumen show an insignificant decrease of penetration by adding high percentages of these wastes. It can be argued that the PET-modified bitumen has the optimum ability to increase the stiffness modulus and, as such, indicates an increase in viscosity. The significant reduction in penetration values as a result of adding waste PET emphasizes the physical-chemical reaction of the modified bitumen. As such, the PET modified bitumen results highlighted the changes in the properties of the C320 bitumen, and such changes are mainly attributed to increases in asphaltenes content and decrease in resin content with increasing PET during the blending process. The amalgamation between PET particle and bitumen particle results in swelling of the bitumen particles and, as such, increase the dispersion of polymer phase in bitumen and enhanced the elasticity (Mashaan et al. 2021a; White and Jamshidi 2020; Kumar and Khan 2020).

On the other hand, the penetration results of using waste HDPE and LDPE show a non-linear decrease in penetration. The more waste HDPE and LDPE increased the penetration and make the binder lower resistant to permanent deformation and highly susceptible to hardening and rutting failure.

Based on Figure 4.5. results, the PET plastic modified bitumen samples show a linear decrease in penetration with a high value of $R^2 = 0.9779$, which indicate the significant effect of high PET content on the penetration improvement of the modified bitumen. However, the quit low value of R^2 of HDPE and LDPE are o.3214 and 0.1, respectively, showing an insignificant effect of high content of HDPE and LDPE on the penetration of modified bitumen.

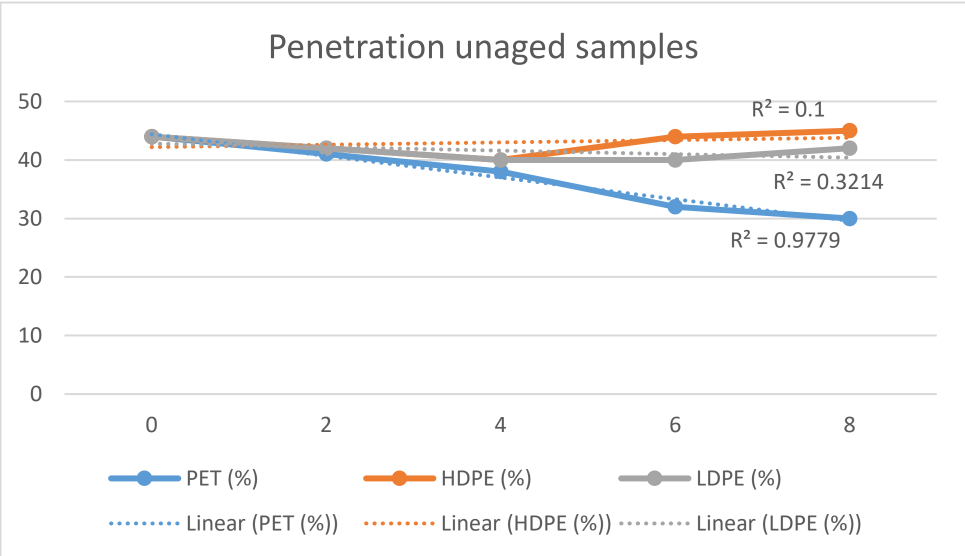


Figure 4.5: effect of waste plastic types on penetration tests

4.4 Penetration properties after RFTOT and PAV tests

To examine the durability and aging resistance of the binders, aging RTFOT and PAV tests were assessed. Figures 4.6, 4.7 and 4.8 show the penetration results after RTFOT tests and PAV test versions of different content of PET, HDPE, and LDPE samples.

Figure 4.6 shows the significant role of PET in improving the aging resistance during construction and after long term services as indicated by the decrease in penetration from 40 mm of 0% PET to 31 mm (after RTFOT) and 29 mm (after PAV) using 8% PET. Figure 4.7 shows the insignificant impact of using a high content of HDPE plastic as this results in less aging resistance. By adding 8% HDPE, the penetration increases to 43 mm after RTFOT and 45 mm after PAV aging. As such, the binder has more sensitivity to shears stress and is highly subjected to rutting and fatigue defamation.

A similar trend was found in using high contents of LDPE as shown in Figure 4.8. As can be seen from the results, penetration results show no significant difference in using more LDPE as this could be related to the incomplete reaction of polymer-bitumen phase in bleeding conditions. Despite there being some improvement in penetration results by using 2- 4% LDPE after RTFOT tests; however, the results after PAV aging were insignificant and show no improvement.

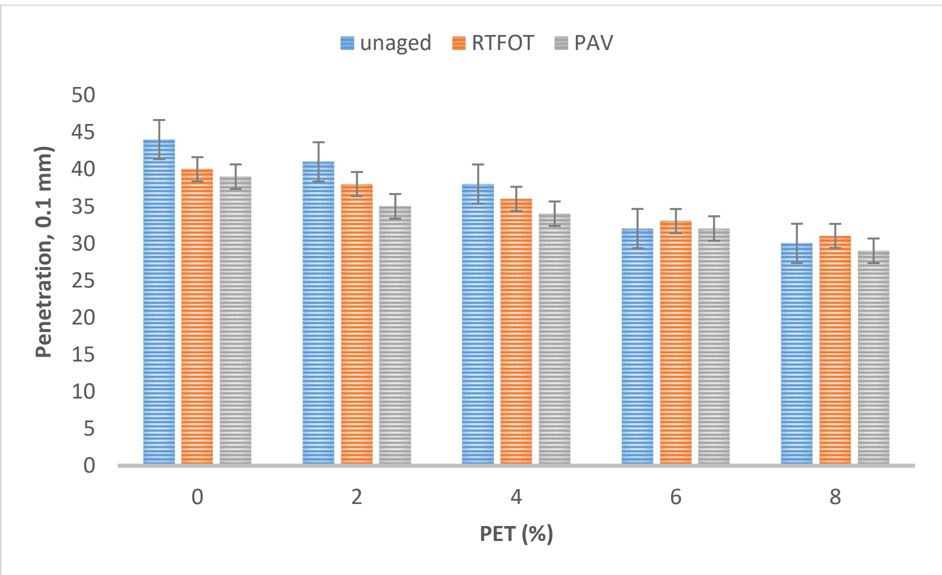


Figure 4.6: Penetration results of PET- modified bitumen after RTFOT and PAV tests

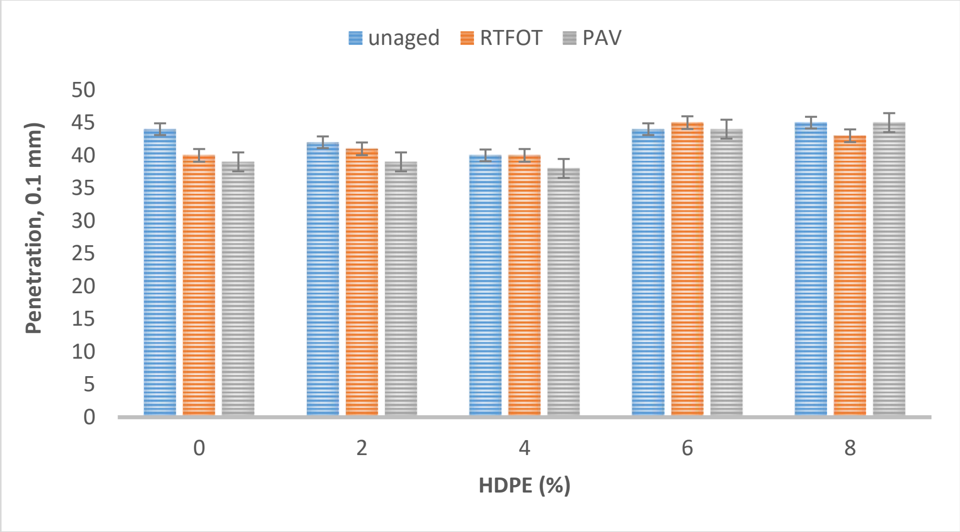


Figure 4.7: Penetration results of HDPE- modified bitumen after RTFOT and PAV tests

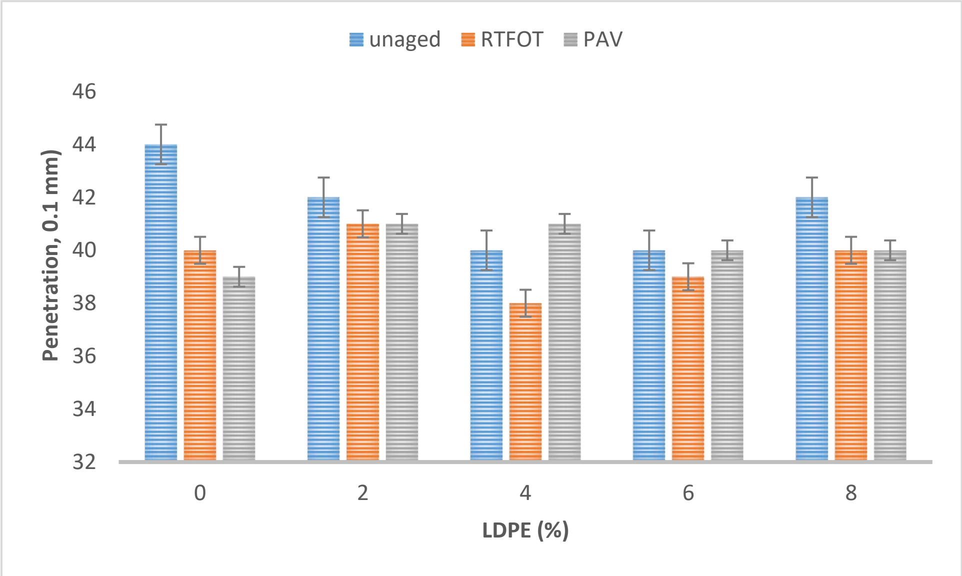


Figure 4.8: Penetration results of LDPE- modified bitumen after RTFOT and PAV tests

4.5 Dynamic Shear Rheometer tests and rheological properties

Dynamic shear rheometer tests offer the data of complex shear modulus and phase angle, and they can be used as indicators of the stiffness, elasticity, viscosity, and resistance to deformation of the bitumen binders. At the different ranges of the temperature of 50℃, 58℃, 60℃, 64℃, 70℃ and 76℃, Figures 4.9 and 4.10 show the effect of LDPE content on complex shear modulus and phase angle of modified bitumen.

It can be seen from Figure 4.9 by increasing the temperature of testing from 50℃-76℃, the complex shear modulus decreases. At 64℃ the 8% LDPE sample was lower than the unmodified bitumen. As result, the high content of LDPE increases the binder's susceptibility to permanent deformation. On the other hand, elasticity and elastic behaviours could be achieved at 4% LDPE, however, the elasticity as indicated by phase angles value was less and does not show significant differences of 6% and 8%. In general, adding polymer to the bitumen should improve the phase angle by reducing its values, however, Figure 4.10 shows the increase in phase angle value, which suggests that LDPE- modified bitumen samples at high content of 6 and 8% are inflexible and not able to return to its shape after deformation. Hence, the resistance to permanent deformation will not be granted and high temperature would lead to mixture failure and deformation (Fernandes, Silva, and Oliveira 2017; Enieb and Diab 2017).

As can be seen from Figures 4.9 and 4.10 that 4% LDPE is ideal in terms of improving the complex shear modulus and phase angle and resistance performance, however, in the current study, we targeted the high content of plastic mainly 6% and higher percentages, so that we can use more of waste plastic and secure the advantages of producing a cheaper polymer, higher performance in pavement design and friendly to the environment.

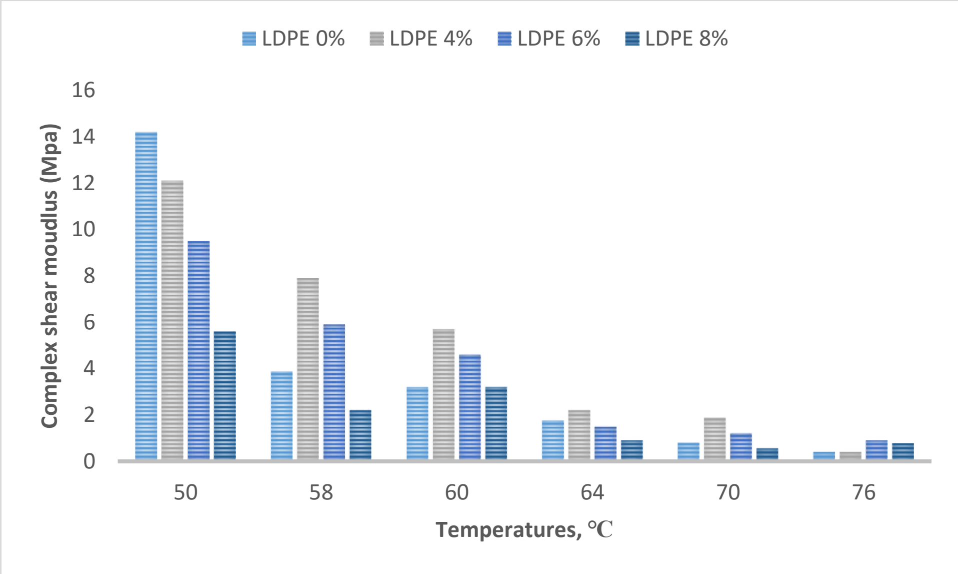


Figure 4.9: LDPE Waste plastic effect on complex shear modulus

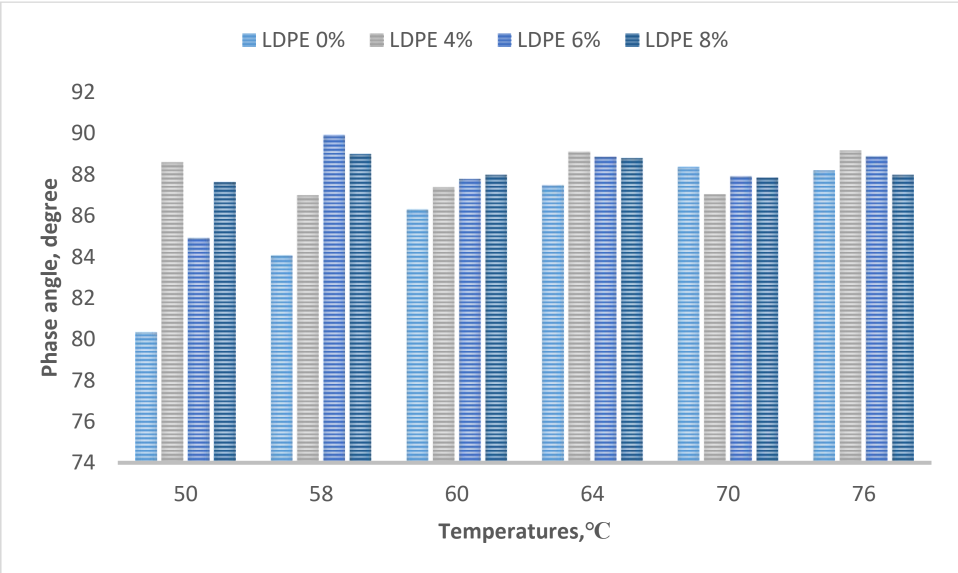


Figure 4.10: phase angle results of LDPE plastic modified bitumen

The rheological properties in terms of complex shear modulus, which is referred to as the stiffness properties, and phase angle, which is referred to as the elasticity properties, are presented in Figures 4.11 and 4.12, correspondingly.

As shown in Figure 4.11, there is an obvious reduction in complex shear modulus when temperatures increased from 50℃-76℃, however, 4% HDPE shows an increase in complex shear modulus at all high temperatures. The phase angle results are presented in Figure 4.12 and show non-linear behaviour through the different temperatures. In general, the HDPE modified bitumen samples show better performance than the un-modified bitumen samplers. At temperatures of 50℃-76℃, the 4% HDPE modified bitumen shows better performance, as the phase angles improved slightly as compared to the un-modified C320 bitumen. From previous studies, it is suggested to use low contents of HDPE as the high contents could result in less compatibility of the blended mixtures. And in addition, the high content of 4% are not able to significantly improve the bonding and cohesion of bitumen-aggregate structure (Costa et al. 2019; Santos et al. 2020; Mashaan, Chegenizadeh, and Nikraz 2021b).

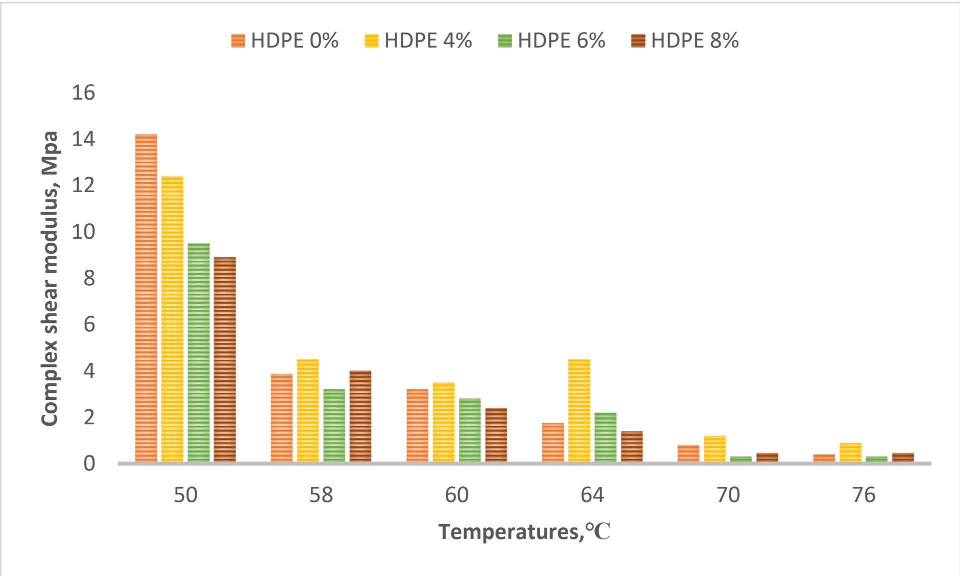


Figure 4.11: HDPE Waste plastic effect on complex shear modulus

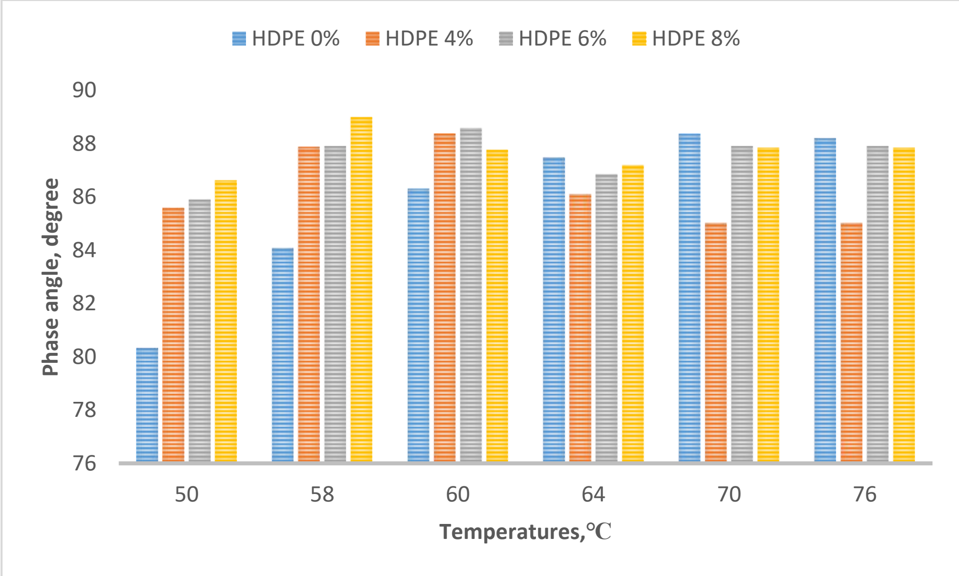


Figure 4.12: phase angle results of HDPE plastic modified bitumen

The use of waste PET in C320 bitumen modification shows an essential role in improving the stiffness and elasticity properties, because of the increase in complex shear modulus and phase angle at different rang of temperature as shown in Figures 4.13 and 4.14.

Figures 4.13 and 4.14 display the influence of various contents of waste PET on rheological characterises of modified bitumen. Different testing temperatures ranging from 50℃ to 70℃ are used to show rheological characteristics of complex shear modulus (G*) and phase angle (δ). As demonstrated from the results in Figure 4.13, that adding waste PET causes an increase in complex shear modulus and decrease in phase angle. In one hand, the waste PET modified bitumen samples have the tendency to work as an elastic material, which in turn reflect the ability of the PET modified bitumen to absorb high load and resist permanent deformation, rutting, for instance. (Santos et al. 2020; Mashaan et al. 2021a). On the other hand, this ability to resist permanent deformation has been confirmed by improved the results of phase angle as shown in Figure 4.14. Phase angle emphasises the bitumen's transformation from behaviour viscous to elastic. Thus, high phase angle means bitumen perform viscous behaviour, however, and other hand, lower phase angle means high elasticity bitumen. As the improved phase angle increase the elasticity performance. Therefore, the PET modified bitumen samples would have better compatibility and good swelling of the plastic-bitumen-interaction phase. From engineering point of view, the better swelling and diffusion during blending the bitumen and modified would enhance the bitumen-polymer-interaction, and as such, physical and mechanical improvement of the resulted modified bitumen binders (Ma et al. 2020; Zakaria 2020).

Moreover, the results of complex shear modulus and phase angle could be contributed to the fact that both of 320 bitumen and PET plastic have non similar properties in terms of chemical and physical properties, and thus they have variety in polar and molecular structure. And again, these properties to high extent would be impacted during the high shear blending and long-time mixing, and lead to changing the dimensions of plastic-bitumen's particles. This change would lead to improve the engineering properties and increase the elasticity. Moreover, increasing the elasticity is fundamental property and would result in better bonding between the molecular and increase the cohesion in the modified binder's structure (Mashaan, Chegenizadeh, and Nikraz 2021b; Zakaria 2020).

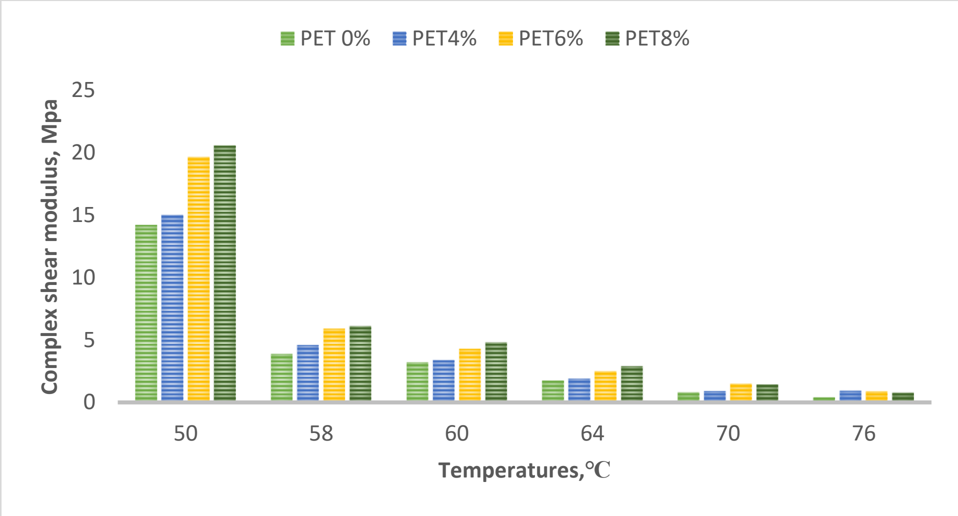


Figure 4.13: PET Waste plastic effect on complex shear modulus

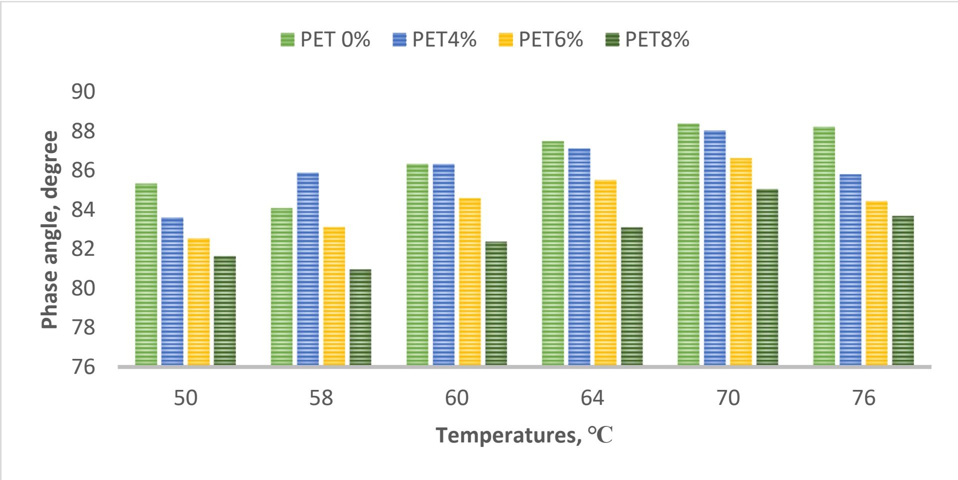


Figure 4.14: phase angle results of PET plastic modified bitumen

From the above results and analysis, it is obvious that the waste PET modified bitumen samples have the potential to significantly enhance the rheological properties of the binders, increase complex shear modulus, increase elasticity, improve stiffness and improve the mechanical properties. Consequently, PET increase binders' rutting resistance and improve viscosity, and show better arrangement of plastic-bitumen particles interaction.

4.6 Bitumen aging and waste plastic modified bitumen

The mixture performance properties related to rutting and fatigue resistance are highly impacted by the physical and rheological properties of the modified binder before and after aging. As such the aging is a very significant factor in determining the suitability of the selected modified polymer in modifying the asphalt mixtures. Aging has an essential role in influencing chemistry properties and physic-rheology characterises; moreover, the use of the two aging treatments of RTFOT and PAV show a strong relationship and comparable results.

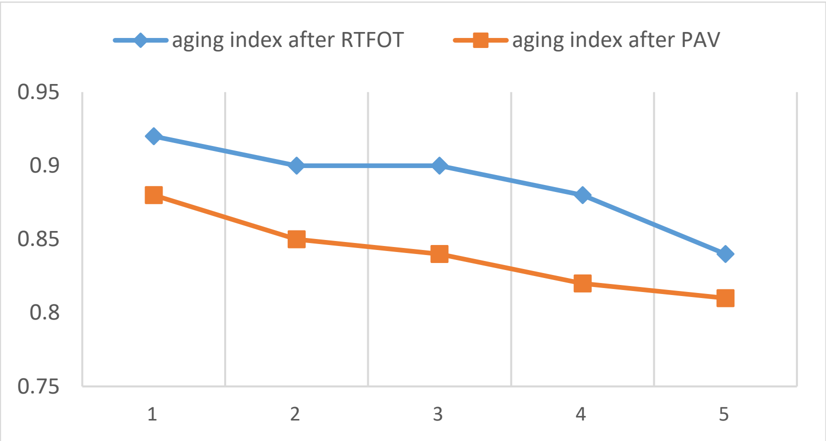
The ideal selection and use of bitumen as a binder in pavement construction would mainly be reliant on bitumen's resistance to the physical changes across various temperatures. As result, aging substantially improved the chemical and physical properties of bitumen. Several physical properties are affected after aging like penetration, softening point, viscosity, elasticity, and stiffness (Ali, Mashaan, and Karim 2013).

Moreover, bitumen aging is an unavoidable progression that indicates bitumen's hardening, which affects fatigue performance and causes cracking, and consequently reduces the durability of asphalt mixtures. Therefore, bitumen's aging should be highly considered and should bear in account the resulted change in bitumen's chemical and physical properties after aging. Four processes control the aging process which involves "oxidation, loss of volatiles, "steric hardening and exudative hardening" (Ali 2013).

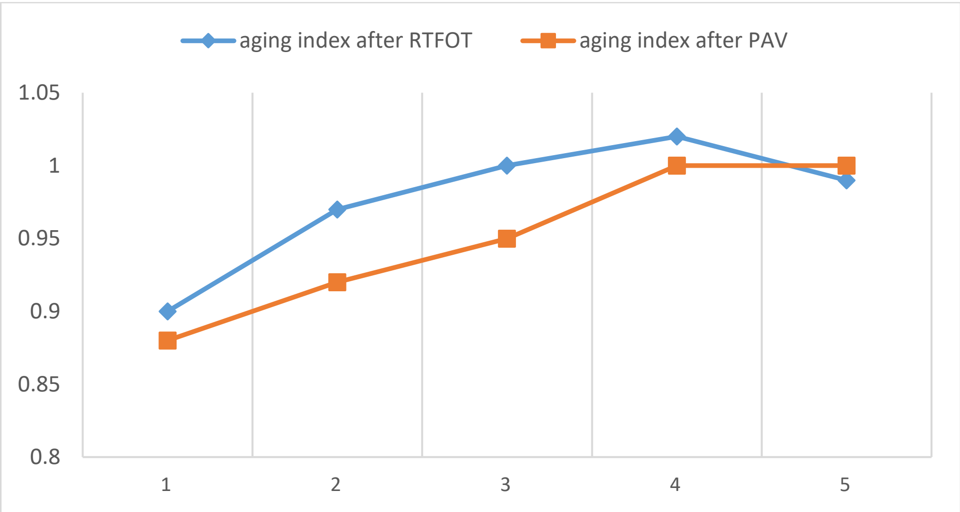
Aging index factor is the main method the determine the aging sensitivity and offers a level of various bitumen types. The definition of the aging index can be "as the ratio of the binder property after aging to that given property before aging", for instance, penetration aging index will be penetration after aging to penetration before aging as shown in below equation (4.1):

Aging index of penetration= (Pen. aged/Pen. unaged)…… (4.1)

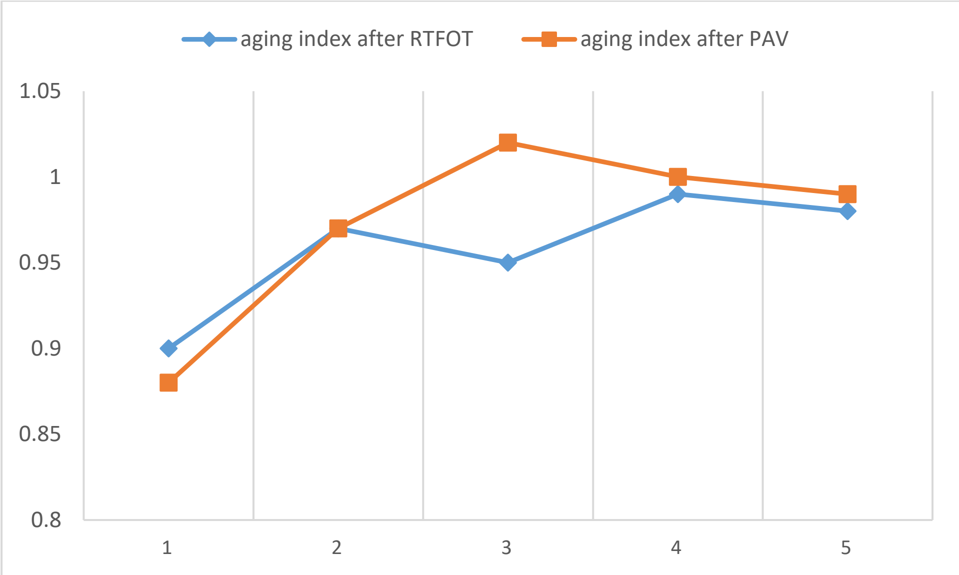
Figures 4.15, 4.16 and 4.17 show the aging index of PET, HDPE, and LDPE after penetration test at 25℃ after RTFOT and PAV aging.



Figures 4.15: Aging index of PET plastic modified bitumen



Figures 4.16: Aging index of HDPE



Figures 4.17: Aging index of LDPE plastic

As noticed from Figure 4.15, that using waste PET as a bitumen modifier resulted in improving the aging resistance in comparison with non-modified bitumen. Results implies that the aging index of PET- modified -bitumen is less significant than non-modified bitumen, hence, suggesting the PET- modified- bitumen could improve the thermo-oxidation aging properties of bitumen (Mashaan, Chegenizadeh, and Nikraz 2021b; Zakaria 2020).

Moreover, the liner increases in PET content show consistent results in a better aging index after aging environments of RTFOT and PAV. The results can be explained by the change happening in the chemical elements of the bitumen binder during the aging stages, which can lead to an increase in the asphaltene content (Mashaan et al. 2021a). The increase in asphaltenes content has a significant effect in improving the viscosity of the modified binder, and thus rutting and fatigue resistance are improved (Ali 2013).

The aging index of Figure 4.15 indicated that the PET-modified-bitumen samples showed lower value after both aging conditions. This result of aging index could be related to the structural change of molecules and polarity of fraction content during aging (Cong et al., 2010). The results of using PET are more significant as compared to other plastic-type like waste HDPE and LDPE.

Figure 4.16 shows the aging index of HDPE modified bitumen after long term and short terms aging. As can be seen from Figure 4.16, the increase in polymer content from 2% and up to 6% and then decreased to 8%, increase the aging index in comparison to the non-modified bitumen. The samples indicated the increase in aging effect was almost uniform across the different contents of HDPE polymer, which could be an indicator of the higher susceptibility to aging. The results of HDPE were in line with results by (Piromanski et al. 2020) which used the aging index to investigate the resistance to aging, which showed that 2% and 8% HDPE have high aging sensitivity, and this can be explained by the less compatibility between bitumen particles and HDPE particles and could be as results of poor mixing outcome for 2% and 8%.

A similar trend was found of using LDPE as shown in Figure 4.17. The increase in LDPE from 2%-8% shows an increase in the aging index as compared to 0% (non-modified) samples. At 4% and up to 8%, the aging index was higher among the other samples, which indicates the increase of aging effect and the binder of being significantly susceptible to aging and as result susceptible to rutting deformation.

As can be seen from the section of original conditions and aging conditions, the PET modified bitumen can improve the physical, rheological, and aging properties as compared to the HDPE and LDPE. The good performance of high content of 6% and 8% PET give the significant evidence of selecting this waste than other two waste. As the main target was to select the ideal waste with high content to be used in the rest of the project.

And as the HDPE and LDPE are only showing good performance at low content of 2% and some improvement at 4%, this was not ideal for selection for the resting stage. However, at this stage, it is good to understand that HDPE and LDPE should be used at low content of 2% in modifying the C320 bitumen. The results of using PET are more significant when compared to other plastic-type like waste HDPE and LDPE. As results show 8%PET has significant impact on the physical, rheological, and aging properties of modified bitumen. Therefore, at this stage the selected ideal waste plastic is PET, and more testing and evaluation will be considered in the next sections.

4.7 Rutting and fatigue of bitumen binders

The objective of performing the dynamic shear rheometer test is mainly to determine the rutting resistance and fatigue cracking of the bitumen samples. According to the Superpave specification of AASHTO T316- 2006, the ultimate value of ($G^*/ \sin \delta$), which is known as rutting factor, should be ≥ 1.00 kPa for unaged bitumen and RTFOT samples, and 2.2 kPa for RTFOT aging samples. In this research, results demonstrated that most samples had agreed parameters and had satisfactory performance. Figures 4.18 and 4.19 show the DSR plates of 25 mm and 8 mm, which are used for unaged RTFOT aged, and PAV aging, respectively.

Figures 4.18: Show the plates of 25 mm and samples of PET-modified C320

Figures 4.19: Show the plates of 8 mm and samples of PET-modified C320

4.7.1 Rutting properties of waste PET

In this research, results demonstrated that most samples had agreed parameters and had satisfactory performance. As shown in Figure 4.20, PET modified bitumen demonstrated better values of rutting factor in comparison with unmodified bitumen binder. Through the testing temperatures of 50℃- 76˚C the waste PET indicated remarkable development, in terms of having low vulnerability to deformation. Consequently, suggesting that 6-8% of PET samples had the better rutting resistance.

Hence, the PET modified bitumen samples would have better compatibility and good swelling of the plastic-bitumen-interaction phase. And from engineering perspective, the better swelling and distribution during blending the bitumen and modified would enhance the bitumen-polymer-interaction, and as such, physical and mechanical improvement (Mashaan et al. 2021a).

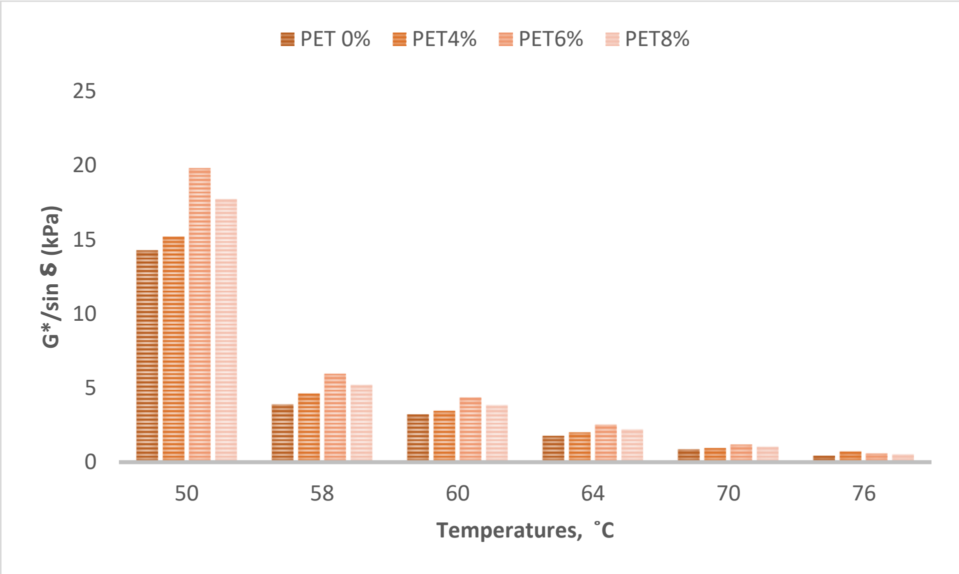


Figure 4.20: Rutting factor of PET modified bitumen

Figure 4.21 indicates that the addition of waste PET would essentially boost the complex shear modulus at temperatures of 50˚C, 58˚C, 60˚C, 64˚C and 70˚C. Hence, confirms that waste PET as bitumen's modifier has better stiffness, and, as such improved durability and ageing resistance in comparison with the unmodified binder samples. This tendency has validated by means of phase angle's result, which displayed in Figure 4.22.

Results of phase angle using 6% -8% PET modified bitumen displays an evident decline in comparison with C320 bitumen. Subsequently, results in increasing the elasticity. On the other hand, increasing elasticity led to enhancing rutting resistance after binders exposed to aging (Mashaan et al 2021a; White 2019; Costa et al. 2019). Thus, Figures 4.23 and 4.24 show high rutting factor with better aging index at different temperatures of 50˚C -70˚C.

Figure 4.24 implies the advanced of applying waste PET to modify C320 bitumen, as it justifies how the modified binders become less sensitive to “thermo oxidative aging”. Thus, growth in rutting factor by about 57% after RTFOT aging in comparison with unaged bitumen. Therefore, PET modified binders will be hardening to a lesser extent and enhance “bitumen-aggregate-phase” contact and bonding; and consequently, creating asphalt pavement with high resistance to rutting, fatigue and cracking (Mashaan et al. 2021a).

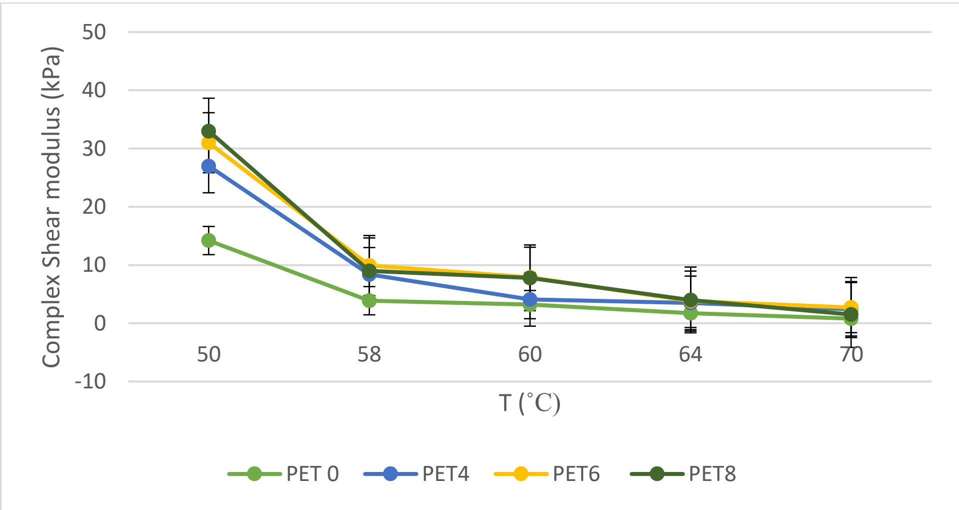


Figure 4.21: Complex shear modulus, after RTFOT ageing

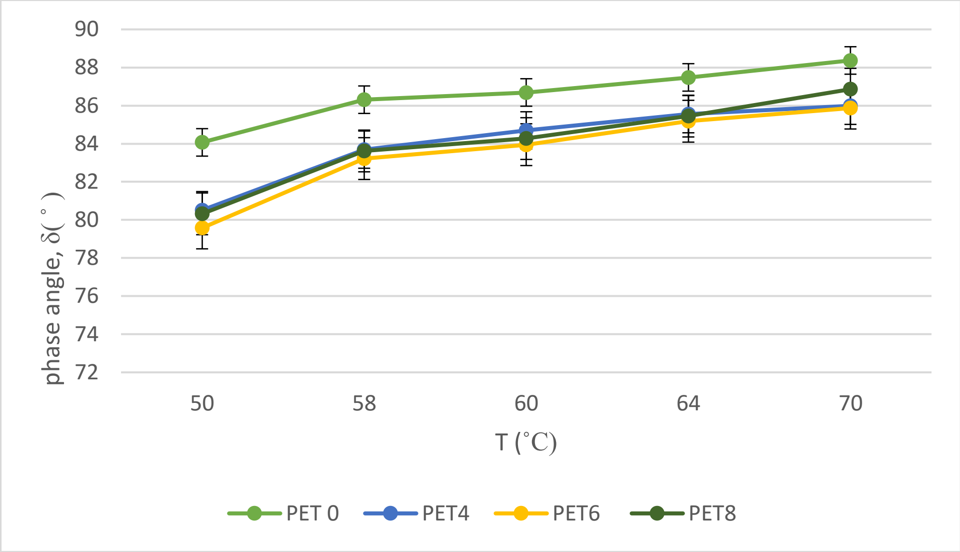


Figure 4.22: Phase angle, after RTFOT aging

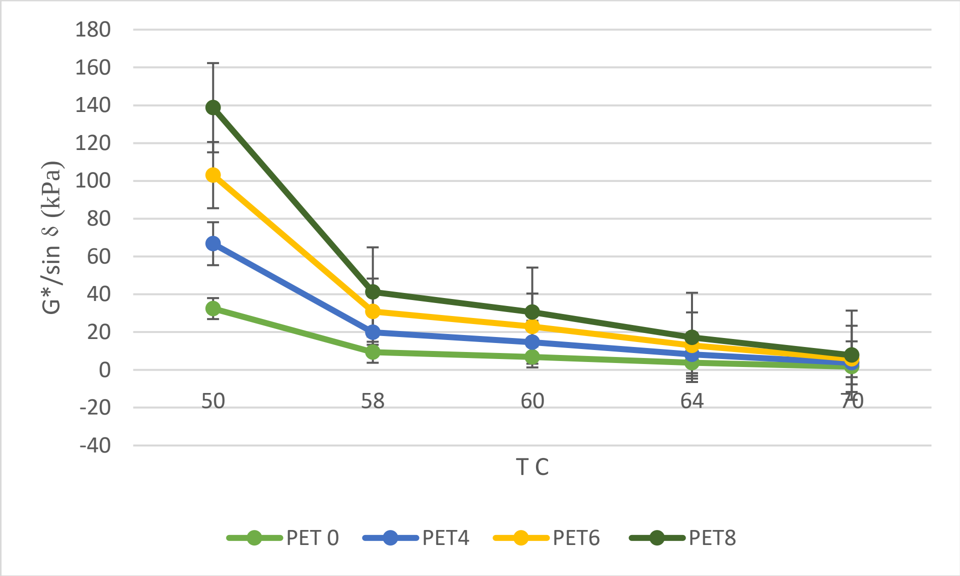


Figure 4.23: Rutting factor after RTFOT aging

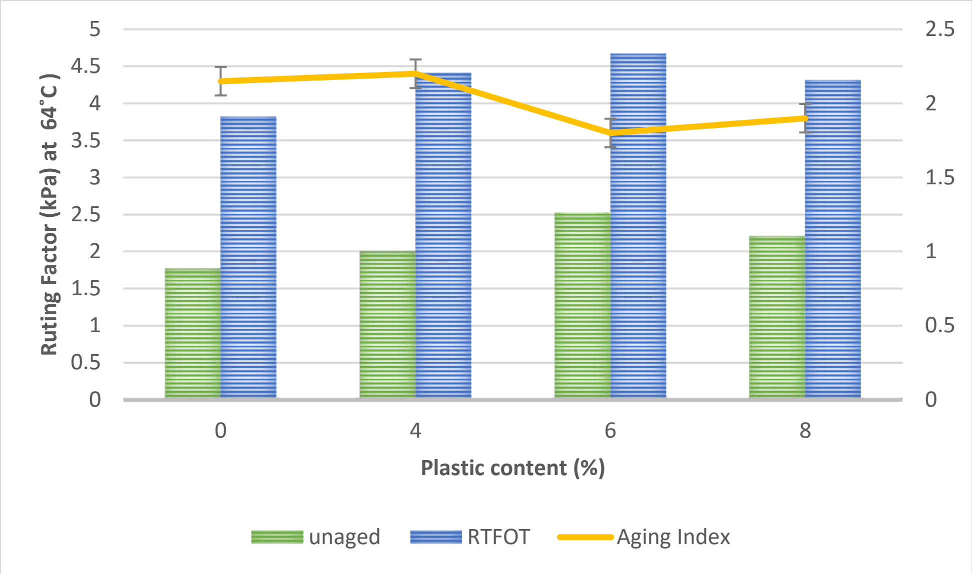


Figure 4.24: RTFOT Aging results and aging index

4.7.2 Fatigue Properties of waste PET

Based on the specification of the Strategic Highway Research Program (SHRP), the ideal and recommended value for fatigue factor, G* sin (δ), is about 5000 kPa. Figures 4.25, 4.26 and 4.27 show the $G*$ sin(δ) values of the C320 bitumen and waste PET modified bitumen after PAV tests. The test was calculated through different testing temperature of 20˚C - 40˚C. Generally, waste PET of 8% exhibits substantial enhancement of fatigue life, and thus, effects in less values of fatigue factor G∗ sin (δ) of modified bitumen. At temperature of 25 ˚C, the fatigue factor was 3201 KPa and 2108 kPa for 8% PET and 0% PET (C302 unmodified). Therefore, the addition of PET has a noticeable result on fatigue parameter of aged, modified bitumen, in terms of stiffness and elasticity. The PET act as a healing agent that would absorb the energy and strain developed through the repeated traffic load, and as such, less opportunity to develop cracking and better fatigue life (Mashaan et al. 2021a).

As seen in Figure 4.26, fatigue factor of PET modified bitumen is lesser than that of C320 unmodified bitumen at 20˚C,25˚C, 30˚C,35˚C and 40˚C. Thus, demonstrating that PET improves the fatigue resistance as a result of developing significant structure of PET-bitumen-phase interface. According to Mashaan et al. (2021a) and Zakaria (2020) adding waste PET polymer to bitumen has a considerable effect in increasing the fatigue life in circumstances comparable with commercial polymer. This established on the statement that the chemical properties of PET particles would probably modify by changing its quantity and its position in the molecule structure. Accordingly, significant increase in asphalt's strength, and thus, have an advantage to the establishment of molecular structures of PET-bitumen that has improved tensile strength and elasticity, which in turn improved fatigue resistance (Mashaan et al. 2021a).

Figure 4.27 illustrates the fatigue life at temperature of 25 ˚C before and after PAV aging. It appears that adding more PET percentage through variation, the modified bitumen turns out to be stiff and shows ability to withstand the released energy of traffic load, which lead to extended fatigue life and better aging index. This indicates that aging index of waste PET modified bitumen is noticeably fewer in comparison with C320 bitumen. Signifying that the PET could augment the binder's aging resistance. This conclusion could be explained by the variation in bitumen's chemical elements during the aging which can increase the asphaltene that is responsible in improving the binder's viscosity (Mashaan et al. 2021a; El-Naga and Ragab 2019).

The Figures 4.25, 4.26 and 4.27 highlighted that PET modified bitumen has favorable capability in improving the rheological and mechanical properties of asphalt. From engineering awareness, the improved asphalt's bond is hugely resistant to permanent deformation at low temperature, causing reduction in cracking and rigidity (Santos et al., 2021; Mashaan et al. 2021a).

The results, as shown in the Figures are clarified by the presence of a big aromatic ring in PET components. This offers a noteworthy creation of a strong, strength, and stiffness structure of polymer, specifically as the PET particles bonds identically from each other in the group of the swelling particles in the plastic-bitumen-interaction phase. Therefore, the extension of plastic-bitumen groups rises at 8% PET and acts as a strengthened agent to resist shear force and decrease fatigue cracking (Mashaan et al. 2021a).

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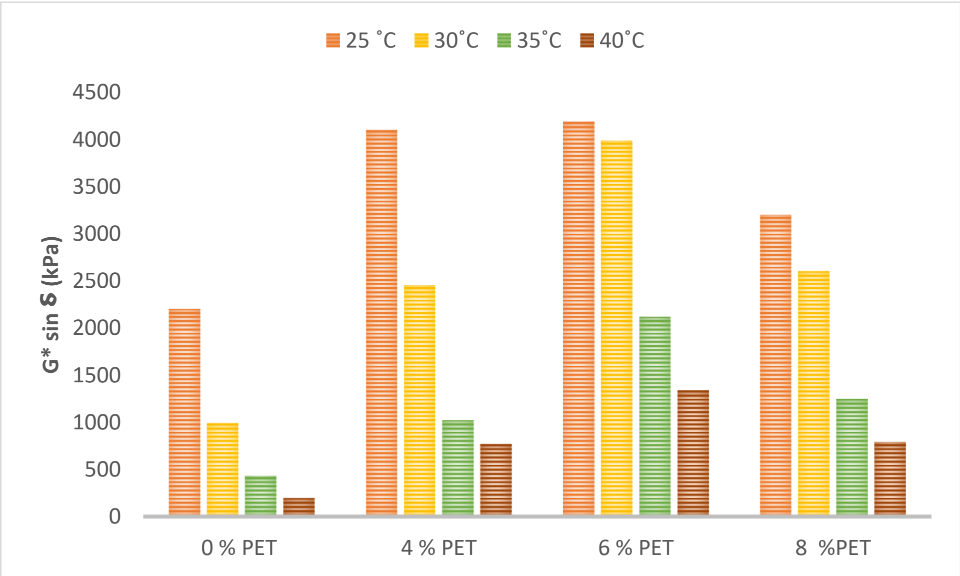

Figure 4.25: Fatigue life of different PET plastic content

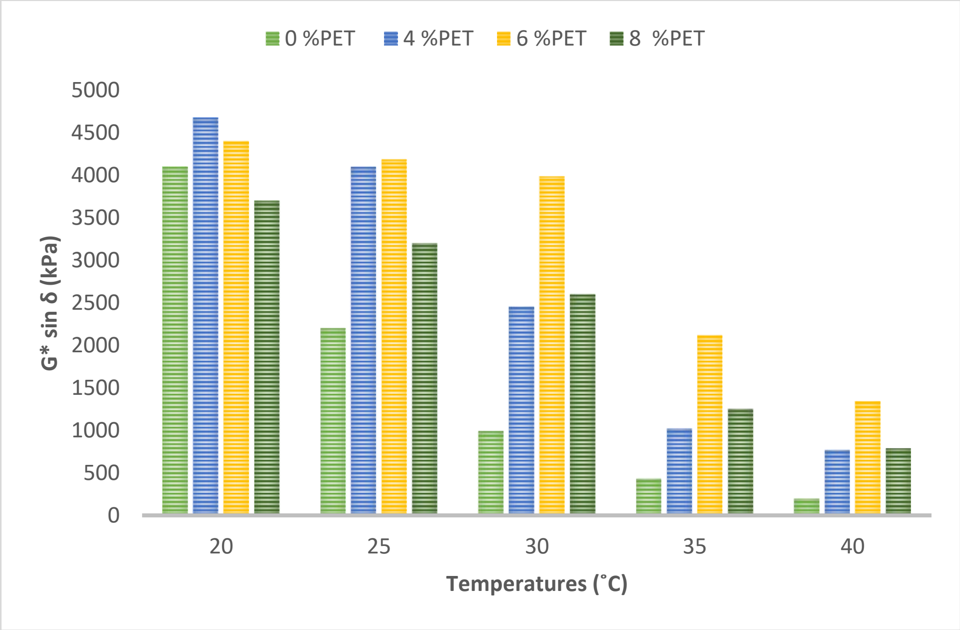

Figure 4.26: Fatigue life vs. temperatures

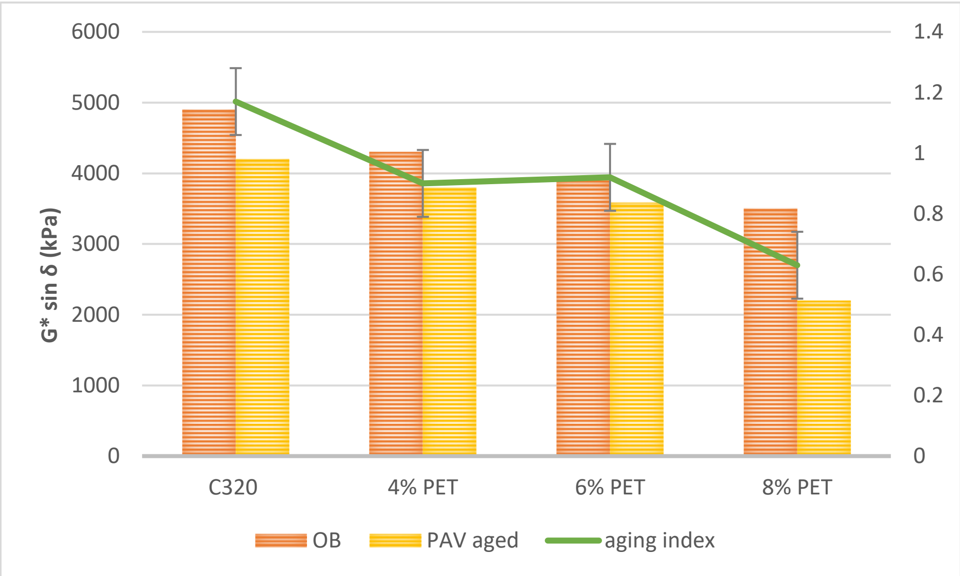

Figure 4.27: Plastic impact and aging index

4.8 Summary and outcomes

The main objective of this chapter was to determine the ideal type and content of waste plastic that can be used to modify C320 bitumen, which can resist permanent deformation. The outcome of the chapter has satisfied the objective as shown below:

- The advance of utilising waste plastic as an ecological-environmentally friendly modifier in Australian's bitumen was performed and examined. The results show the possibility to use waste plastic in modifying C320 bitumen.
- The 2% and 4% of HDPE and LDPE are recommended as ideal content that can show good performance as displayed by penetration tests before and after aging. As for DSR tests, a similar trend found that high content of 6-8% is not significant in improving the stiffness and elasticity. As for aging properties are affected, and the modified binder becomes more susceptible to aging and, as such, samples are more vulnerable to permanent deformation.
- Results of long-term aging display that nearly all waste PET samples had longer fatigue life, lower aging index and as such higher resistance to fatigue and cracking in comparison with C320 bitumen. 6-8% PET selected as ideal contents and type to be used in the next stages of the project.
- Considering more research on using different size of waste plastic, different shape of waste plastic, different bitumen types, different blending conditions of time, temperature and shear velocity are recommended for future research. In addition, using high advance technology to examine the chemical development and change of plastic-bitumen-interaction phase is required for better understanding the engineering properties.

Chapter 5

Investigating asphalt mixture properties modified with waste plastic

5.1 Introduction

Road pavements start experiencing functional deterioration once they are open to heavy traffic or freezing of groundwater during the cold season. Deterioration can include rutting, fatigue cracking, shoving, and stripping. For instance, Figure 5.1 shows the current cracking deformation at road section in Perth city, WA Australia. In cold regions, groundwater freezing beneath the surface layer can result in serious cracks in the asphalt mixture even during a single cool season (Ali 2013; Mahrez 2008). One way to increase the service life of road surfaces is using certain additives such as polymers to modify and improve the properties of the mix. It has been confirmed and reported in several studies that using virgin polymer is costly, and as such it is advisable to use waste polymer (Xu, Zhao, and Li 2022; Ma et al. 2021; Mashaan, Rezagholilou, and Nikraz 2019).

Figure 5.1: Pavement deformation and cracking (photos by Nuha)

Recycling materials produced by industrial plants and workshops, especially, relating to civil engineering has seen significant developments in recent decades. Some of the successful examples of these developments include silica fumes, furnace slag and fly ash. The reuse of risky waste has also been the subject of much research throughout years. Such research mainly centred on the impact of the residue on the properties of the building and construction materials and its effects on the environment. The most recent studies have concentrated on the possibilities of reusing waste materials in pavement construction, which has recently turned into a hot issue. Apparently, this has two main causes, namely, the lack or reduction of natural resources usable for road construction and the existence of waste materials that can be reused in many construction projects in civil engineering (White 2020).

Finding a reliable and long-term-cost-effective method to treat the issue of waste materials is showing a high concern among recycling industry, construction engineering, pavement engineers and local authorities, and researchers. They all trying to find an active solution in terms of saving resources and protecting the environment from resulted hazard of damping the waste materials. Thus, efficient recycling is the main solution to manage the issue of these waste which show a high interest in the industry engineering and scientific research.

According to earlier studies (Zakaria 2020; White 2020; Mashaan et al. 2014; El-Naga and Ragab 2019), that recycling is a crucial method and has several advantages including natural resources impact, environmental impact and cost-effective impact.

Consequently, it is highly recommended to consider the recycling industry as one of the vital today industries.

This chapter aims to investigate the engineering properties of selected waste plastic polymer. As stated, and based on the results of chapter four, waste PET plastic with percentages of 4%, 6% and 8% were used in this chapter. Hence, this chapter is designed to investigate the impact of using community waste plastic (Polyethylene terephthalate) in modifying asphalt mixtures. Different mixture of dense graded asphalt AC and stone mastic asphalt SMA are used to investigate and determine the engineering properties of modified asphalt mixtures. To achieve this goal, several data have been examined based on the results of the Marshall stability, Marshall flow, Marshall quotient, IDT, TSR, fatigue and wheel tracking tests. Figure 5.2 shows the flow chart of the research related to this chapter.

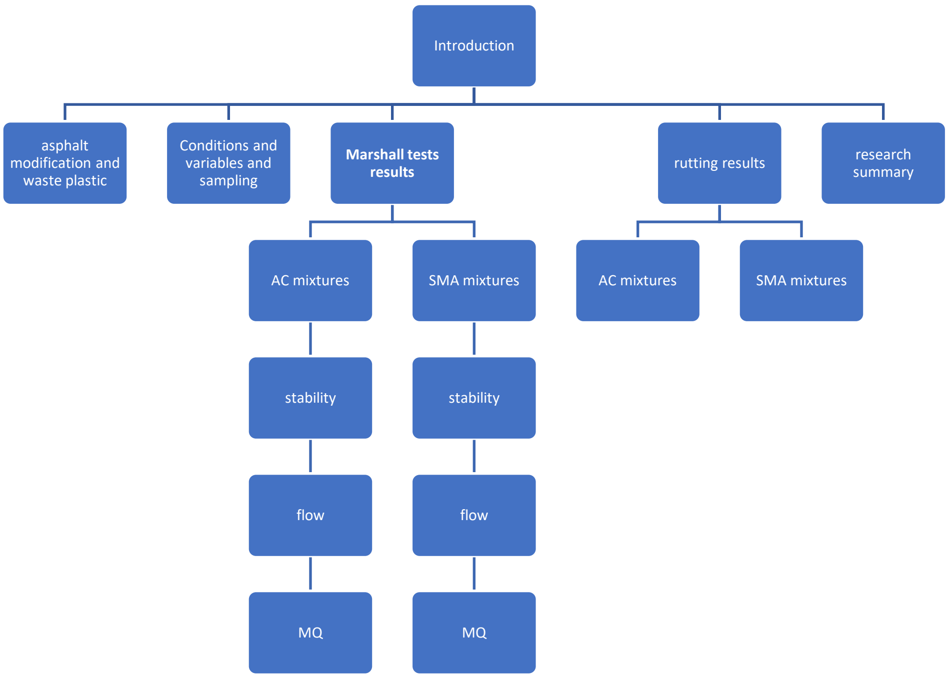

Figure 5.2: Flow chart

5.2 Asphalt modification with waste plastic

The application of waste materials as a replacement for the new materials in roads construction has double substantial advantages. First one is the substantial savings and reduced costs, and the second is reducing the quantity of wastes which will be stockpiles in landfill. Thus, the potential progress of using waste plastic in modification of asphalt will take into consideration the enhancing properties of the mixture (Dalhat and Al-Abdul Wahhab 2015; Zakaria 2020; White 2020).

Modification of the bituminous mix with *waste plastic*s seems to have great potential for the efficient use in flexible pavements design to enhance their active service or minimise the layer thickness of its wearing course or base layer (Ameri and Nasr 2017; White 2020; Mashaan, Chegenizadeh, and Nikraz 2021b). The application of waste plastic in asphalt modification increases stability, life service of pavement, increases ability to tolerate high loads of traffic, reduce the deformation sustainability, and show better aging resistance. In addition, waste plastic asphalt shows capability to meet the requirement for design, coating and construction, and as it seems to be as a substantial, practical and economical alternative if compared to other commercial polymers (Zakaria 2020; White 2020).

Polymer modified bituminous mixtures have a broad variety of applications in most countries (Ameri and Nasr 2017; Costa et al. 2019). Studies that have been conducted to classify bitumen modifiers according to their composition have been categorised into several groups. These include polymers elastomeric, polymers plastomeric, fibre, and crumb rubber. These additives vary considerably in their physical and chemical properties, which have a wide variety of influences on the performance of asphalt concrete

Table 5.1: Additive Classifications used in asphalt

Type of additive	Authors and studies	Findings
Crumb rubber and waste tyre rubber	Aflaki and Memarzadeh (2011); Hamed (2010); Mashaan and Karim (2013) ; Ali (2013); Shen and Amirkhanian (2005); Bahia and Davies (1994).	- Improve rheological properties. - Improve aging resistance. - Improve stability -Develop a bond between aggregate and binder. - Improve fatigue life. - Better rutting resistance.
Elastomers: -Styrene-butadiene-styrene (SBS), SBR	Ozen et al. (2008); Khattak and Baladi (2001); Ahmed (2007); Widyatmoko and Elliott (2008).	- Increase stiffness - Resist fatigue cracking. - Resist thermal cracking.
Fibre: - Polyester - Fibre glass	Putman and Amirkhanian (2004); Huang (1996).	- Improve tensile strength - Improve cohesion - Improve fatigue life. - Improve durability - Improve stability of mix.
Plastomers: HDPE, LDPE, PE, PET	Awwad and Shbeeb (2007); Tapkın, Cevik, and Usar (2009); Hinislioglu and Agar (2004); Ameri and Nasr (2017); Attaelmanan, Feng, and Al-Hadidy (2011)	- Improve fatigue life. - Increase structural strength - Increase rutting resistance. Increase Marshall stability.

The different types of additives, as shown in Table 5.1 illustrates a significant impact on the rheological properties of the modified bitumen and the performance properties of modified mixtures. The shape of being pellet, powder, fine grounded, un grinded, shredded along with size variation of the selected additives are factors that impacted the physical rheological properties of the modified asphalt. Consequently, the fatigue, stiffness, rutting and engineering properties will be affected.

5.3 Conditions and variables and sampling

In this chapter the most comment asphalt mixtures in use in pavement construction of Western Australia, WA were used. The Conventional 10 mm SMA and 14 mm sized dense graded asphalt for course surfacing were employed. This type of aggregate identified as the highly widespread natural aggregate in Western Australia. The size gradation and aggregate's properties were illustrated in detail in chapter three.

Based on the results of chapter four, waste PET was selected as the ideal for this second stage of the project. The source of waste PET was local recycled water bottle where collected, washed and ground to size o.40-0.45 mm. As highlighted in chapter three, the PET modified binder uses the high shear mixture with 4000 rpm and 180°C for 40 minutes. Then as following the wet mix, the PET modified bitumen mixed with the aggregate to fabricate the PET modified mixtures following the Marshall method. The optimum binder content was used in all samples of asphalt mixtures modified with waste plastic using various content of 4%, 6% and 8% by weight of bitumen. Marshall stability, flow, Marshall quotient and wheel-tracking tests were performed to investigate the influence of using waste plastic on the stability and strength properties of asphalt mixtures.

5.4 Marshall tests results

Marshall tests were mainly used to determine and evaluate the ability of asphalt mixtures to resist collapse and permanent deformation, specifically rutting deformation. The results of Marshall test showing the Marshall stability and Marshall flow were displayed in Figures 5.3-5.8 for different asphalt mixtures.

As shown in Figure 5.3, the stability increases as the PET content increase from 4% of 14.19 kN up to 16.72 kN at 8% PET as compared to only 13.2 kN of non-modified mixture (0% PET). On the other hand, Figure 5.4 shows the decrease in Marshall flow from 3.2 mm of 0%PET to 2.2 mm of samples with 8% PET. As can be seen from the above results that the more PET content in the mixture, the improved the stability and the lower the flow; consequently, waste plastic modified asphalt showing improved stability in comparison to the non-modified mixtures.

The high stability indicates the excellent resistance to cracking, deformation, shear stress and rutting deformation. The Marshall Quotient (MQ) can be defined as the ratio of Marshall stability to Marshall flow, which is used as an indicator of rutting resistance and mixtures' ability to withstand high shear stress. The more waste PET content in the AC mixtures, the high MQ values are achieved, as display in Figure 5.5. Therefore, the samples with waste plastic have better ability to resist rutting defecation and the failure of pavement.

Figure 5.6 shows the stability properties of PET modified SMA mixtures. As can be seen that the 8% PET produced a mixture with the highest stability of 19.78 kN. The use of 4% PET and 6%PET increase the stability by 15.5 kN and 16.11 kN, respectively. Moreover, all the PET samples modified asphalt show significant effect of Marshall stability as compared to the non-modified mixtures. The result of Marshall flow was in support of Marshall stability as shown in Figure 5.5. The results in Figure 5.7 show that 6%PET has the highest Marshall flow of 2.8 mm. The increase in PET content results in linear increase in flow values from 0% up to 6%PET than the flow value slightly decreases at 8% PET of about 2.65 mm. The results of MQ were in line with the Marshall stability and showed increase value with increasing the plastic content, as can be seen in Figure 5.8.

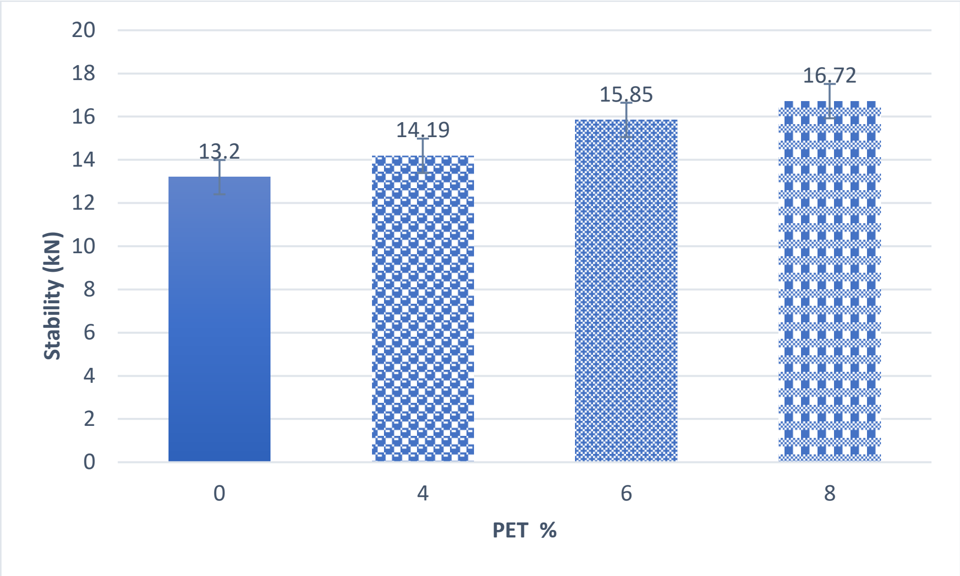

Figure 5.3: Marshall Stability of PET modified AC asphalt mixtures

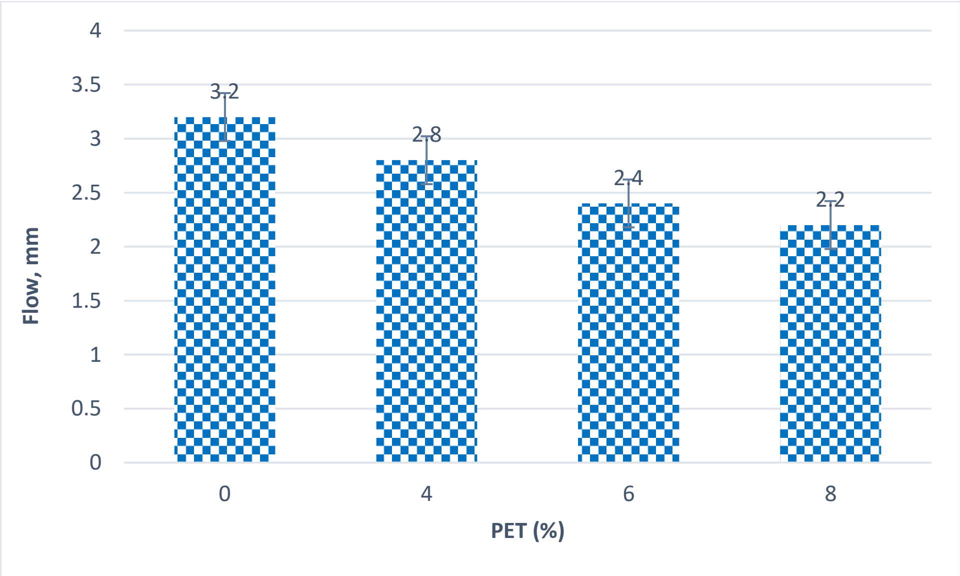

Figure 5.4: Flow results of PET modified AC asphalt mixtures

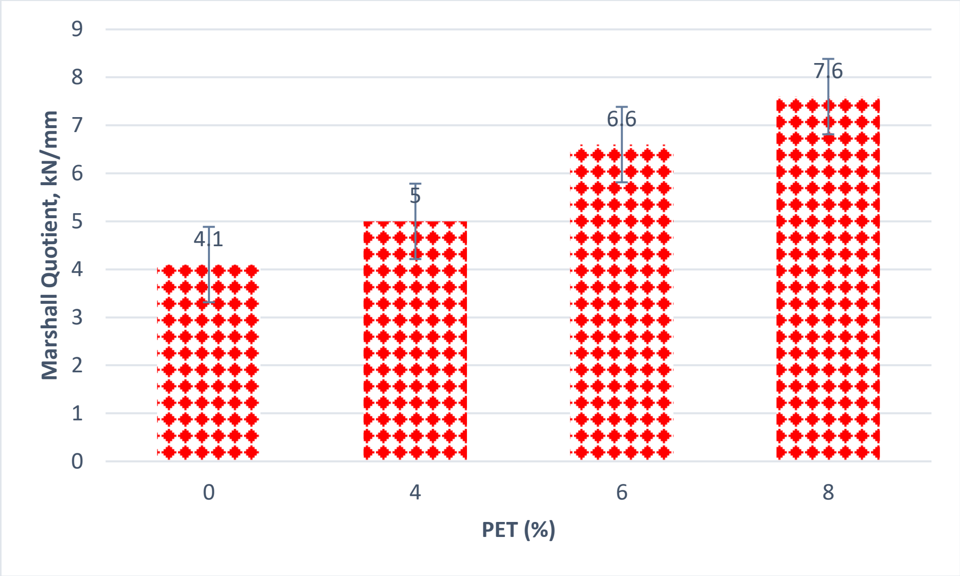

Figure 5.5: MQ results of PET modified AC asphalt mixtures

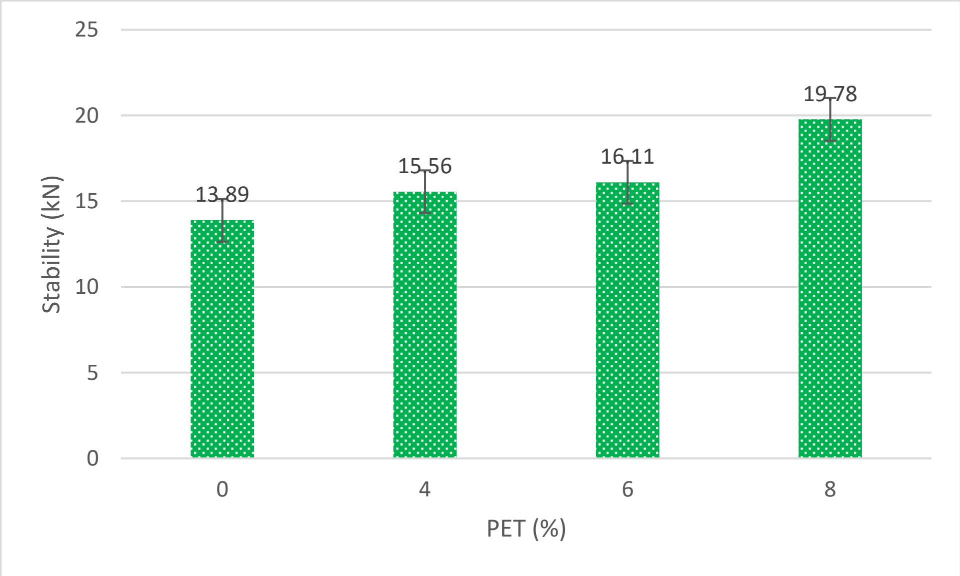

Figure 5.6: Stability of PET modified SMA asphalt mixtures

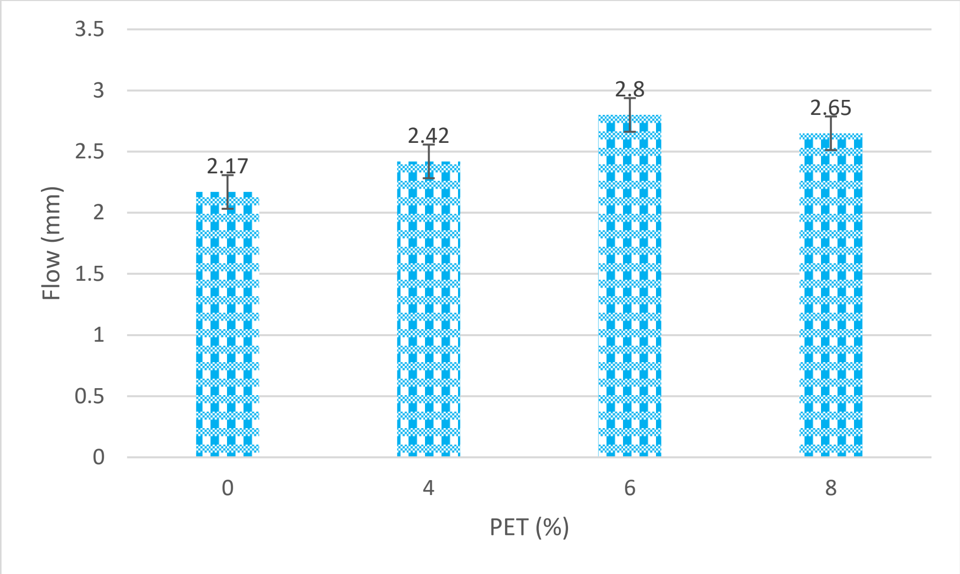

Figure 5.7: Flow of PET modified SMA asphalt mixtures

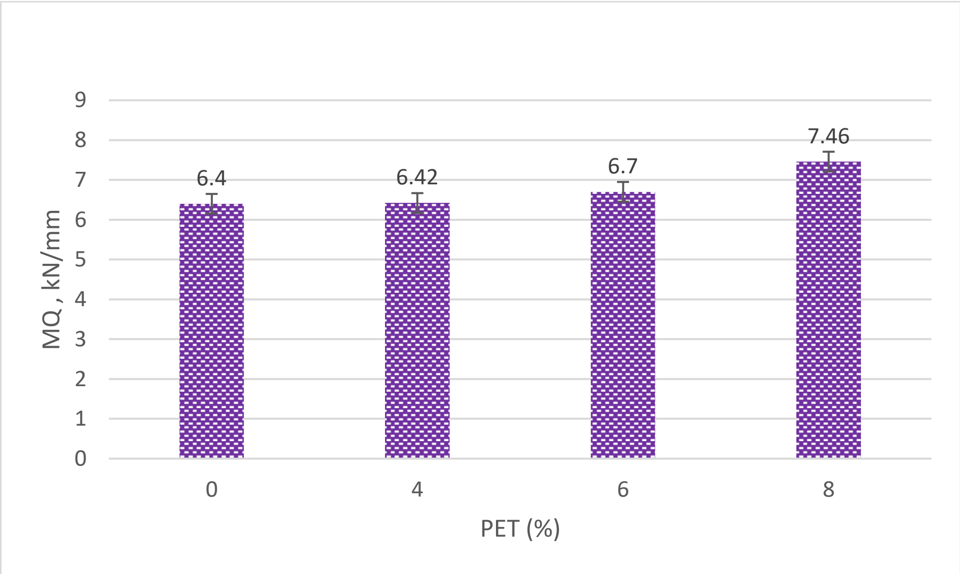

Figure 5.8: MQ results of PET modified AC asphalt mixtures

5.5 Influence of waste PET content on Marshall results

Figures 5.9 and 5.10 show the effect of different PET contents on the Marshall stability and Marshall flow of AC and SMA mixtures. As for the stability, the PET modified SMA mixtures show higher values than that of PET modified AC-14 dense mixtures. At 8%PET the stability values were 19.78 kN and 16.72 kN for SMA and AC mixtures, respectively. All samples of PET modified SMA mixtures were higher than PET modified AC mixtures, even the 0%PET, which reflect the strong structure of stone -stone of SMA. Figure 5.8, however, shows different results of Marshall flow.

As can be noticed that at 0% and 4%PET the flow of AC dense mixtures was about 3.2mm and 2.8 mm. These results were changes when more PET content added to the asphalt mixture results in 2.4 mm and 2.2 mm of 6% and 8% PET modified SMA mixtures. Therefore, the PET content has an obvious impact on the stability, stiffness and flow properties of SMA mixtures in comparison to the AC dense graded mixtures. The reason could correlate to the fact that SMA has more strength and durability than dense graded mixtures (Mashaan, Chegenizadeh, and Nikraz 2022a).

SMA is characterised by a mixture of gap-graded aggregate, which minimises the fine and medium sized aggregate resulting in a stable and structurally tough mixture. The strength and stability of the SMA is because of the stone portion of the coarse aggregate skeleton, which results in an increase in the internal friction rate and the resistance of the mixture to shear thereby enabling it to resist rutting and wearing out as a result of repetitive studded tyre contact (Modarres and Hamedi, 2014; Ali, 2013; Mashaan, Chegenizadeh, and Nikraz 2021b).

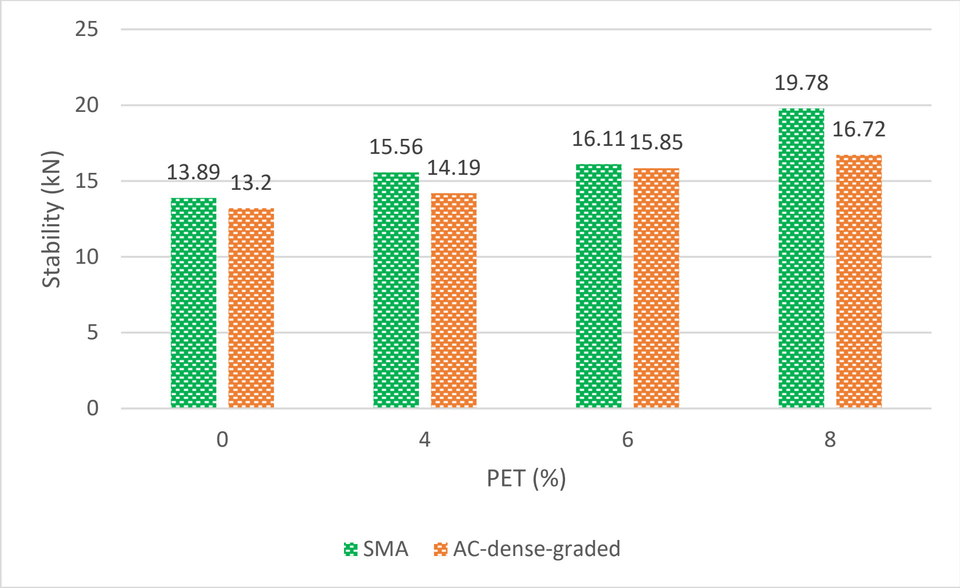

Figure 5.9: Effect of PET on Stability of modified asphalt mixtures

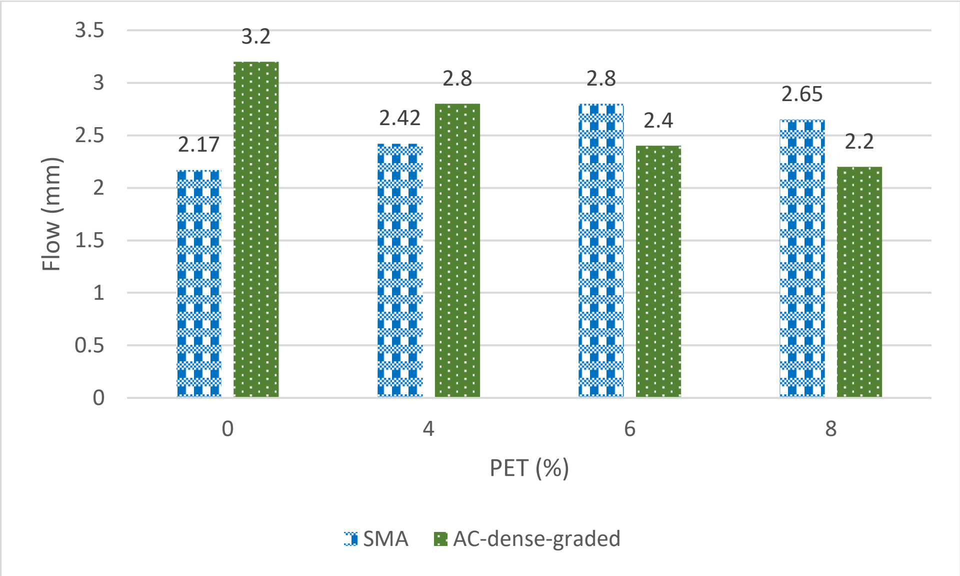

Figure 5.10: Effect of PET on flow properties of asphalt mixtures

5.6 Rutting and plastic modified asphalt

Rutting is one of the permanent deformations of pavement that mostly occur under the wheel path as results of heavy traffic load on the road. As mentioned in the literature review that the bitumen properties, modified binder properties and asphalt aggregate mixtures properties are factors that impacted the asphalt mixtures resistance to deformation. As such it is highly important to investigate and determine the rutting resistance of the PET modified mixtures. It has been reported that rutting resistance is linked to the bitumen binder’s susceptibility to temperatures and stresses (Ameri and Nasri, 2017), therefore, it is necessary to examine the effect of the modified asphalt to expand rutting resistance.

Figures 5.11, 5.12 and 5.13 show the rutting results of using PET as a modifier in different asphalt mixtures. Figure 5.11 shows that adding 4%, 6% and 8% PET has decreased the rut depth of about 8.82 mm, 5.59 mm, and 3.25 mm, respectively, as compared to 12.93 mm of non-modified AC mixtures. The improved percentage in rutting resistance of 8%PET modified mixtures was about 25 % in comparison of the 0% PET un-modified mixtures. As results, the PET modified bitumen binders are significantly enhanced the stiffness of the modified asphalt mixtures, and this in turn improve the rutting resistance.

Figure 5.12 shows the rutting depth of PET modified SMA asphalt mixtures. As can be seen that the more plastic polymer in the mixtures, the better the rutting resistance will be achieved. The rut depth has decrease from 10.35 mm of non-modified mixtures to 7.8 mm by using 4% PET. By adding further amount of 6% PET the rut depth declined to 4.45 mm with 43% improvement in rutting resistance in compassion to the non-modified mixtures. The lowest rut depth was about 2.08 mm for samples modified with 8% PET. The significant difference of using various PET content was an obvious with correlation coefficient of R^2= 0.9958.

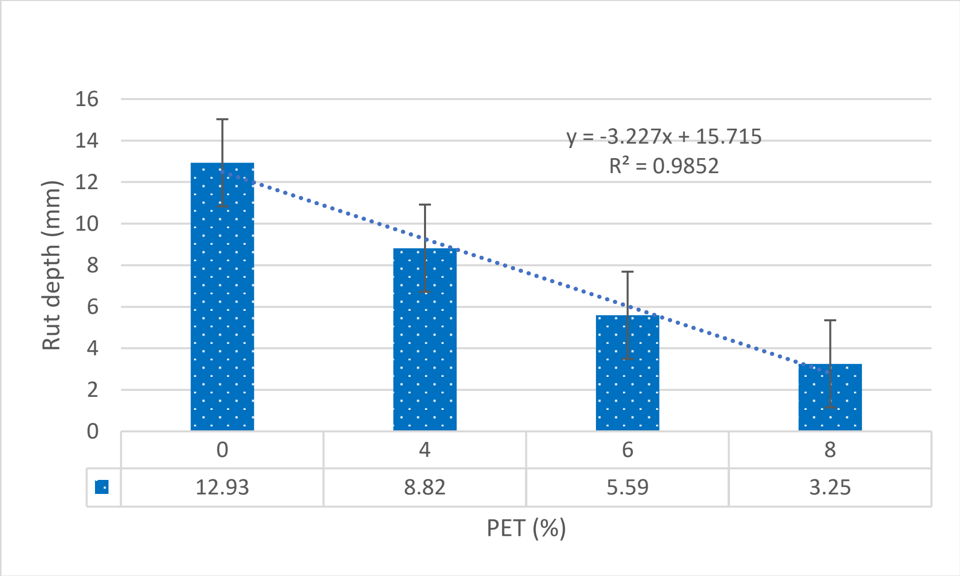

Figure 5.11: Rutting of PET modified AC mixtures

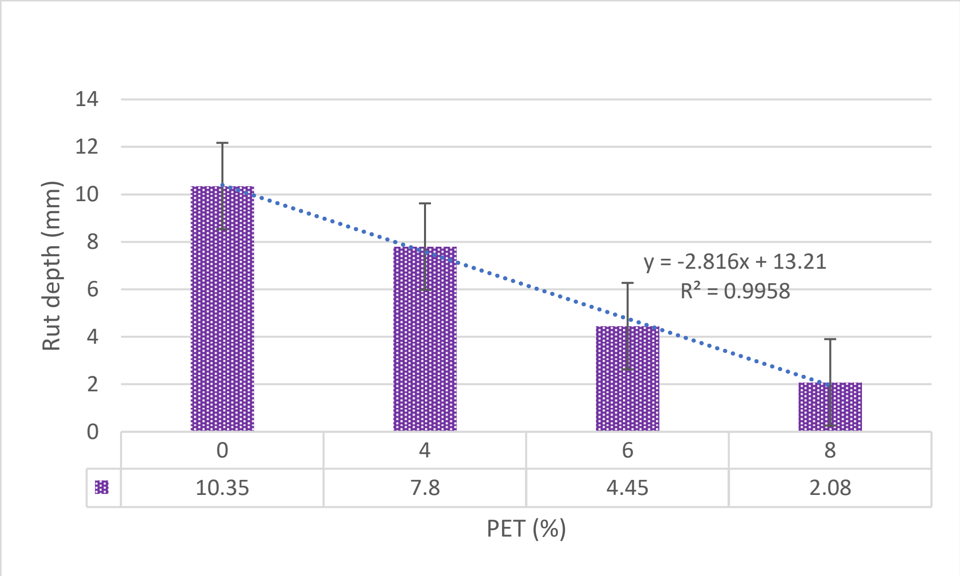

Figure 5.12: Rutting of PET modified SMA mixtures

Figure 5.13 shows the effect of waste PET plastic content on the rutting resistance of SMA mixture and AC dense mixtures at 60˚C. The waste plastic modified mixtures samples show better rutting performance of both types of mixtures. However, the rut depth of PET modified SMA mixtures were significantly higher than that of AC 14 mixtures. At high content of 8% PET, the rut depth of SMA mixtures and AC dense mixtures were 2.08 mm and 3.25 mm, respectively. Therefore, the PET modified bitumen's can coat the aggregate and strength the bond structure of the SMA asphalt mixtures. Another reason is that SMA aggregate quality and bitumen content. The results show liner decreased in rutting depth with $R^2 = 0.9852$ and $R^2 = 0.9958$ for the AC dense mixtures and of SMA mixtures, respectively.

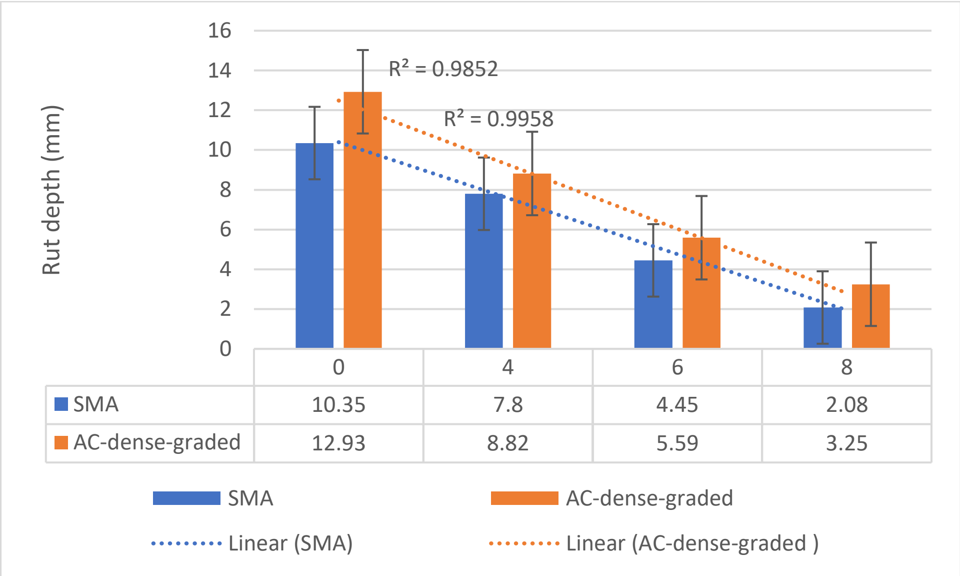

Figure 5.13: Rut depth of different asphalt mixtures modified with PET

The particle shape of the aggregate is essential for the performance and workability of asphalt mixtures. When particles are angular rather than thin and flat, they show better performance against stresses and distresses; hence, the engineers recommend the application of angular particles to HMA. Particles with angular shapes which is a typical property of crushed stones, have stronger interlocking and better performance than round ones, and, consequently, better resistance against rutting brought about by heavy and repetitive traffic loads (Mashaan, Chegenizadeh, and Nikraz 2022b).

As can be seen from Figures 5.14 and 5.15, the rutting deformations are more obvious at 8% PET modified dense AC14 mixtures in comparison to better rutting resistance of 8% PET modified dense SMA mixtures. The use of 8% PET has increased the rutting resistance by 74% and 79% for SMA mixtures and AC dense mixtures, individually. Another advantage of SMA is that it can increase the resistance the resistance of the mixture against plastic deformation, which is one of the common problems that result from heavy traffic loading, which exerts severe stress on the pavement. Moreover, its rough surface provides adequate friction, especially, when the asphalt loses its surfacing cement film, which wears out through heavy and frequent vehicle traffic. However, other advantages of SMA make it the most preferred mixture for pavement construction projects around the globe in comparison with other conventional HMA types. A few of these properties are its superior durability, high-level of resistance to reflective cracking and enhancement against ageing (Mashaan, Chegenizadeh, and Nikraz 2022b; Awwad and Shbeeb 2007).

Figure 5.14: Rutting deformation for 0% PET (left) and 8% PET modified SMA (right)

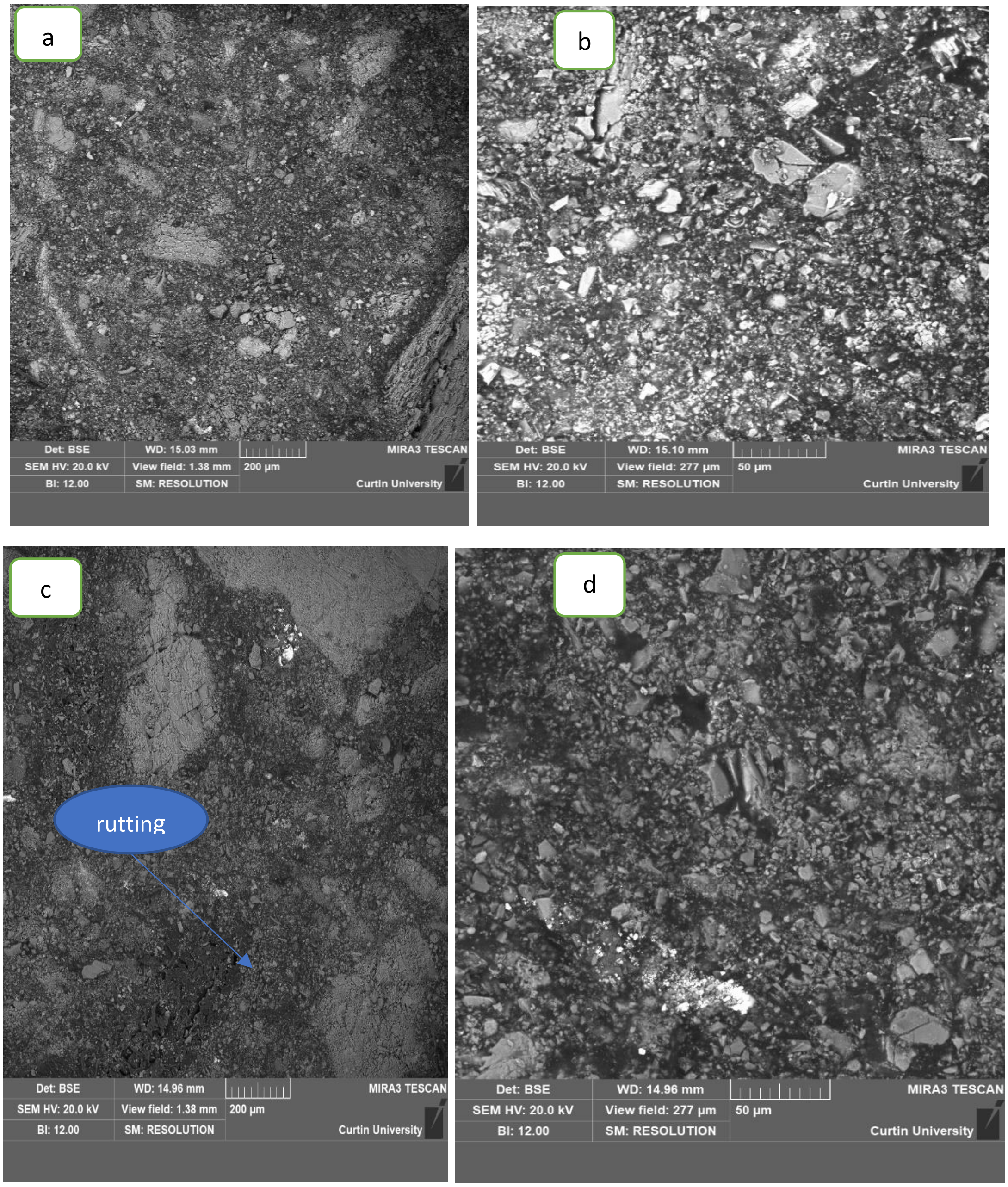

Figure 5.15: SEM structure of asphalt mixtures (a) SMA modified with 8% PET at 200µ magnification, (b) SMA modified with 8% PET at 50µ magnification; (c) dense graded modified with 8% PET at 200µ magnification, and (d) dense graded modified with 8% PET at 50µ magnification.

The major reason for utilising fully crushed aggregate gap gradation (100%) is the enhancement of the degree of pavement stableness through the interlocking resulting stone-to-stone contact. This interlock provides the mix with a stronger stone-on-stone skeleton that is stuck more stably together as a result of a strong composition of asphalt cement, filler, and other additives in the mixture to improve its stability (Mashaan, Chegenizadeh, and Nikraz 2022a; Mashaan, Chegenizadeh, and Nikraz 2021b). SMA was initially used in asphalt mixes to enhance their level of resistance against studded tyre wear.

5.7 Summary

The stability and engineering properties of asphalt mixtures modified with waste plastic are investigated and evaluated in this chapter. Asphalt pavement is susceptible to deformation, cracking and rutting within temperature variations; low- medium temperatures could led to cracking and fatigue; and high temperatures could lead to rutting deformation. Therefore, and in connection with such fact, adjusting and modifying bitumen's composition possibly could improve the engineering properties of the asphalt mixtures. This improvement in engineering properties could be achieved through the infusion of different modifiers into the bitumen and as such improve the bitumen-modifier phase during blending and interaction.

In this chapter, waste plastic has been used as a modifier to improve the engineering properties of different asphalt mixtures. Based on the outcome of the current results, it worth noted to highlight the essential role of waste plastic in improving the stiffness and rutting resistance. The Marshall stability, Marshall flow and MQ of Marshall tests results are exhibited good improvement by using PET in modified SMA and AC mixtures.

And similar trend is found as the PET modified SMA and AC mixtures could resist the plastic deformation and shear stresses which in turn reduce the rut depth of the modified mixtures. However, the highest results of Marshall stability and rutting resistance were achieved for PET modified SMA mixtures.

Based on the above results, it can be concluded that PET as recycled polymer, could substantially improve the engineering properties of the asphalt mixture. In addition, the high content of 6% and 8% can make the SMA mixtures more stable and durable. As such, form engineering point of view, the study shown the use of waste plastic as a bitumen modifier in an economically and environmentally ecological way. Moreover, using waste plastic in asphalt modification could significantly reduce the cracking and rutting deformation.

Chapter 6

Performance Evaluation of Nano-Silica Modified Bitumen C320

6.1 Introduction

Polymer-modified binder mixtures have been widely used in civil engineering and construction projects. The addition of polymers to these mixtures improves their stiffness and significantly enhances their robustness against temperature fluctuations. This modification, in turn, enhances the mixture resistance to pavement cracking (due to fatigue and rutting damage), which is one of the most common problems in hot or tropical regions. In these cases, adding polymers to the mixture creates a softer base binder, which can provide better high-temperature performance.

The addition of polymers to the binder results in a significant increase in its cohesiveness and adhesiveness, allowing it to effectively bind the mixture of components together (Ali 2013). However, using polymers for bitumen modification has certain disadvantages in terms of its storage stability, bitumen–polymer phase separation, and elevated costs. Therefore, researchers have attempted to find an alternative additive that could improve the bitumen binder's properties. From this perspective, nanomaterials and nanotechnology are currently employed to modify the characteristics of bitumen binder and asphalt mixtures. The high surface area and effective network created in the modified bitumen increases their stiffness, improving the asphalt mixtures' resistance to permanent deformation (Hasaninia and Haddadi 2017; Taherkhani and Afroozi 2016).

Nano-silica has several applications in the medical and engineering sectors. In the building material and concrete industry, silica plays an important role in the adhesion and cohesion of concrete. In road and pavement materials, nano-silica exhibits a promising potential for improving the mechanical and engineering properties of asphalt mixtures. Nano-silica can be used in bitumen and asphalt modification owing to its several advantages, including low-cost production and practical characteristics. Nano-silica is a novel material that has many useful features such as a high surface area, high absorption, high distribution, high stability, high purity, and a cost-effective nature (Hasaninia and Haddadi 2017).

To the best of the author’s knowledge, nano-silica has not been used to modify bitumen C320 in the past, which is the most comment bitumen used to design wearing courses in Australia. This chapter is aimed at investigating the rheological and ageing properties of nano-silica on the C320 bitumen, and to determine the ideal type of nano-silica to be used as a hybrid additive for waste plastic-nano-modified asphalt. The flow chart in Figure 6.1 shows the methodology of this chapter, indicating the strategies and testing methods used.

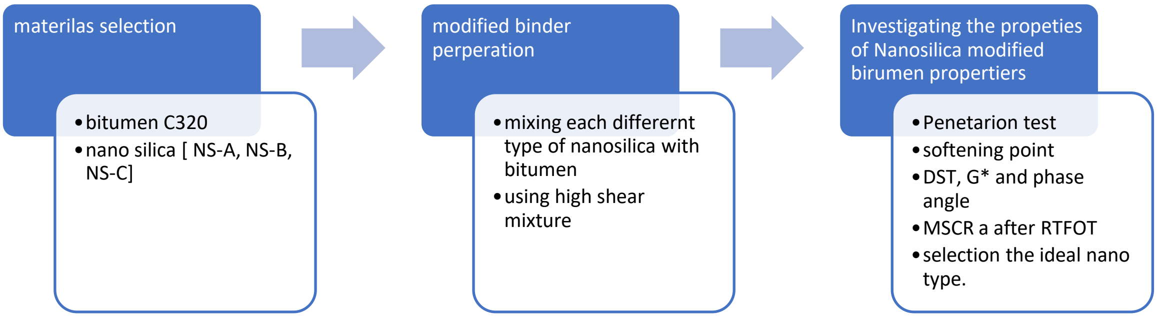

Figure 6.1: Flow chart of research process conducted in this chapter

6.2 Parameters of materials and mixing samples

In this chapter, three different sizes of nano-silica were used, as shown in the SEM image in Figure 6.2. Generally, three types of nano-silica have been used in this study, two of which were coated with Silan coupling agent, which is used to improve the compatibility between the nano-silica and bitumen binder and to modify the silica's surface. Table 6.1 illustrates the properties of the three different types of nano-silica. The nanomaterial was supplied by US Research Nanomaterials Inc., Houston, United State of America. The high-shear mixer was used to create nano-silica-modified bitumen with various contents: 0%, 2%, 4%, 6%, and 8% by weight of bitumen for each sample of NS-A, NS-B, and NS-C, which refer to the types of nano-silica used, as illustrated in Table 6.1. The mixing conditions included a high shearing rate of 4000 rpm, a blending time of 2 hours, and a temperature of 180 ± 0.5°C. The prepared samples of the modified bitumen were stored in a 1-litre container to be used for testing the physical, viscoelastic, oxidation, and durability properties.

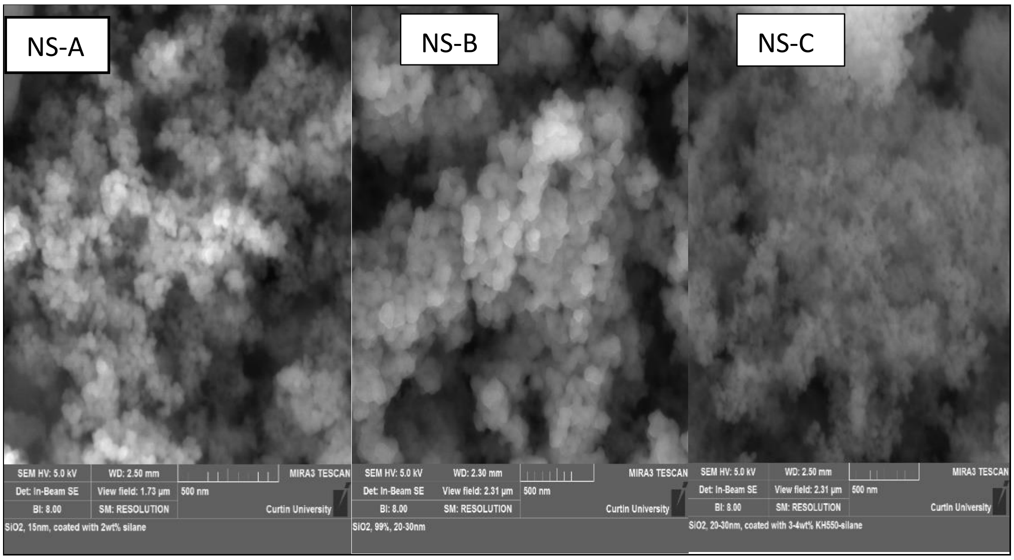

Figure 6.2: Different types of nano-silica used as shown in SEM

Table 6.1: Properties of different types of Nano-silica

Nano name/	Sample name	Service area	size	colour	Bulk Density	True density	Loss of weight in drying	Loss of weight on ignition	Purity
SiO2, 15nm, coated with 2wt% KH550-Silane Coupling Agent.	NS-A	600 m2/g	15nm	White powder	<0.056 g/cm3	2.4 g/cm3	5.3	9.4	97.3 %
SiO2, 99+%, 20-30 nm (no coating agent)	NS-B	180-600 m2/g	20-30mm	White powder	<0.10 g/cm3	2.4 g/cm3	Not given	Not given	99%
SiO2, 30 mm coated with 3-4wt% KH550-Silane Coupling Agent.	NS-C	130-600m2/g	30mm	White powder	<0.10 g/cm3	2.4 g/cm3	Not given	Not given	96.3%

6.3 Physical properties of nano-silica modified C320 bitumen

Figure 6.3 shows the penetration results of nano-silica at 25°C. The addition of different sizes of nano-silica leads to a considerable improvement in the penetration results for all contents of nano-silica, ranging from 2–8%. However, NS-A has better results at 6–8%, which could be attributed to the role of the small size of 15 nm and the use of KH550-Silane as the coupling agent. The use of KH550-Silane significantly improves the compatibility and interaction between the bitumen and nano-silica. In addition, a similar trend was observed in terms of the softening point, as shown in Figure 6.4. The optimum physical properties could be achieved using NS-A, which is nano-silica with a size of 15 nm coated with the coupling agent. However, all nano-silica modified samples have higher softening points than the non-modified C320 bitumen.

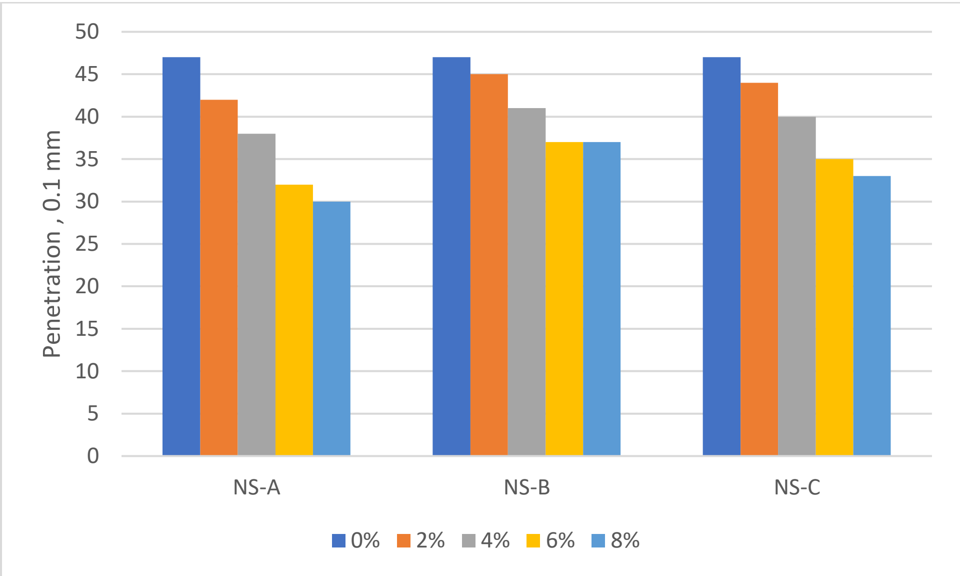

Figure 6.3: Penetration results

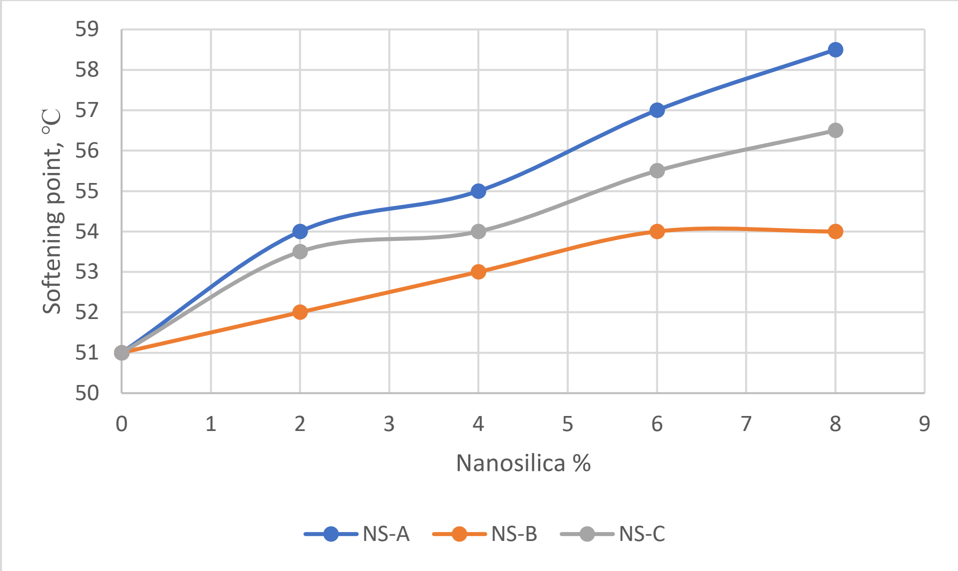

Figure 6.4: Softening point results

6.4 Rheological properties of nano-silica modified C320 bitumen

To examine the visco-elastic behaviour at high temperatures and the bitumen's resistance to rutting and fatigue, both treated and non-treated binder samples were subjected to the dynamic shear rheometer (DSR) test following the AASHTO 315 standards. This test focuses on determining the shear stress and linear viscoelastic properties of the bitumen tested in oscillatory shear using parallel plates. The main aim of the test is to measure the complex shear modulus, which is known as the stiffness indicator G*, and measure the phase angle, which is known as the elasticity indicator. Tables 6.2, 6.3, and 6.4 illustrate the stiffness properties in terms of the complex shear modulus for all the different types of nano-silica. At different temperatures – of 50℃, 58℃, 60℃, 64℃, 70℃, and 76℃ – Tables 6.2, 6.3, and 6.4 show the effect of nano-silica content on the complex shear modulus of the modified bitumen.

Table 6.2: Complex shear modulus of NS-A

	50℃	58 ℃	60 ℃	64 ℃	70 ℃	76 ℃
0%	14.2	3.87	3.2	2.76	0.8	0.4
4%	15.89	7.6	5.4	2.9	1.9	0.42
6%	16.66	5.9	4.3	2.5	2.1	0.5
8%	18.6	7.1	4.8	4.2	2.78	0.5

Table 6.3: Complex shear modulus of NS-B

	50℃	58 ℃	60 ℃	64 ℃	70 ℃	76 ℃
0%	14.2	3.87	3.2	2.76	0.8	0.4
4%	14.89	5.6	4.4	1.9	1.9	0.42
6%	16.66	5.9	4.3	1.5	2.1	0.5
8%	18.6	9.1	5.8	1.2	0.78	0.15

Table 6.4: Complex shear modulus of NS-C

	50℃	58 ℃	60 ℃	64 ℃	70 ℃	76 ℃
0%	14.2	3.87	3.2	1.76	0.8	0.4
4%	16.89	5.6	4.4	2.9	1.9	0.42
6%	16.66	4.9	3.3	2.5	2.1	0.5
8%	19.6	6.1	4.8	3.2	2.78	0.5

6.5 DSR Rutting of nano-silica modified C320 bitumen

The rutting factor (G*/sin δ) has been used as a rutting indicator and the results of various samples modified with different nano-silica sizes are shown in Figure 6.5. At 64℃, the 8% NS-A and NS-C samples had a higher rutting resistance than the unmodified bitumen. The rutting factors of the NS-A and NS-C samples were 7.1 kPa and 5.88 kPa, respectively, whereas the rutting factor of NS-B was only 2.45 kPa. Although the NS-B and NS-C samples both had the same size, of 20–30 nm, using a

2% coating of silane coupling on NS-C resulted in an increase in the rutting resistance in comparison to NS at 20–30 nm without a coupling agent coating.

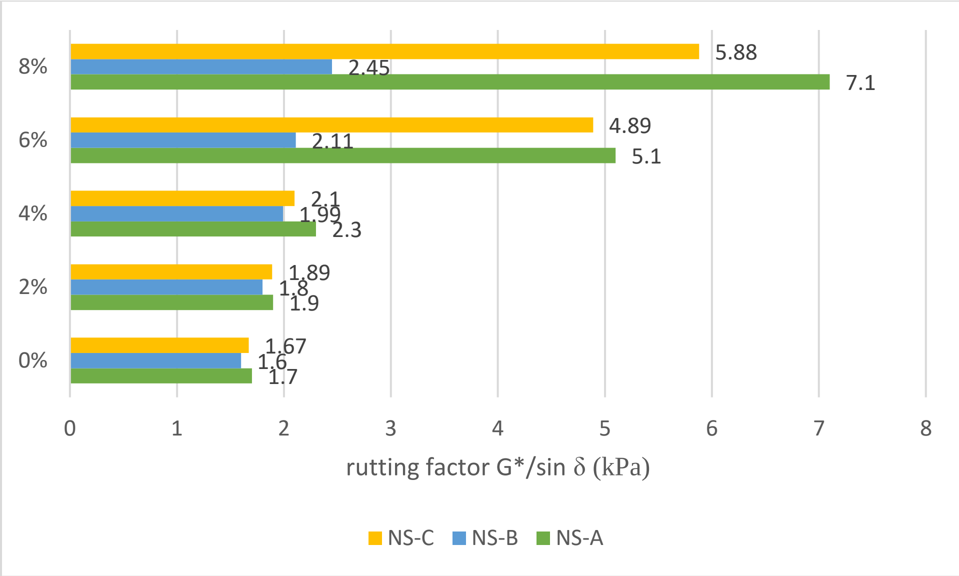

Figure 6.5: Rutting factor of nano-silica-modified bitumen

6.6 MSCR Rutting of nano-silica modified C320 bitumen

Figure 6.6 shows the recovery percentage of nano-silica-modified bitumen C320 and the non-modified bitumen with three different nano-silica sizes for high and low stress levels after RTFOT aging; this can help evaluate the rutting deformation. From the results shown in Figure 6.6, adding nano-silica as a modifier results in an increase in the elastic properties and the recovery performance of the modified binder at high temperatures. All nano-silica-modified bitumen has a higher percentage of recovery in comparison to the non-modified bitumen. Figure 6.7 shows the non-recovered strain for nano-silica-modified bitumen C320 and the non-modified bitumen with three different nano-silica sizes for high and low stress levels. Most of the modified samples exhibit a decrease in Jnr at high stress levels. Since non-recovered strain is considered as a sensitivity indicator against rutting deformation, it is clear that – in comparison to non-modified bitumen – all nano-silica modified bitumen samples have a lower susceptibility for the accumulation of non-recoverable strain under creep loading and recovery (Enieb and Diab 2017).

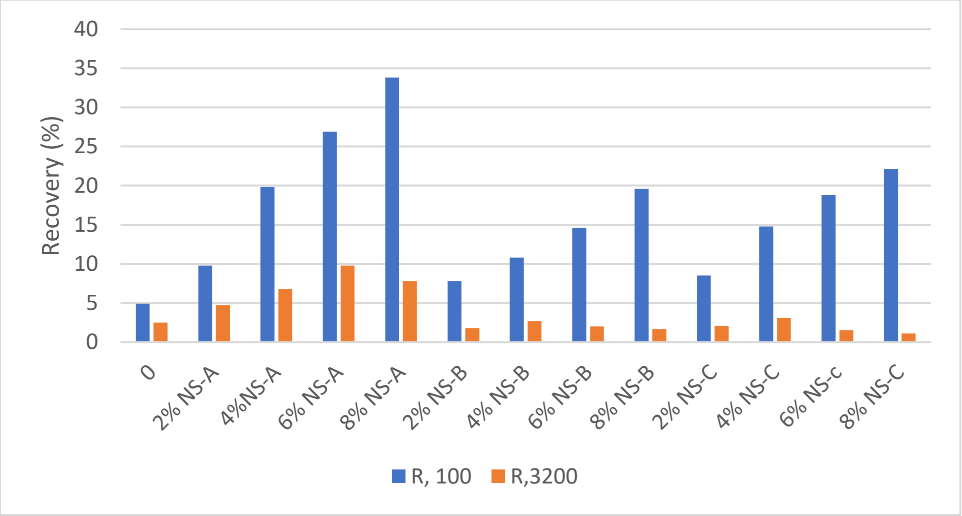

Figure 6.6 : Recovery percentage of nano-silica-modified bitumen

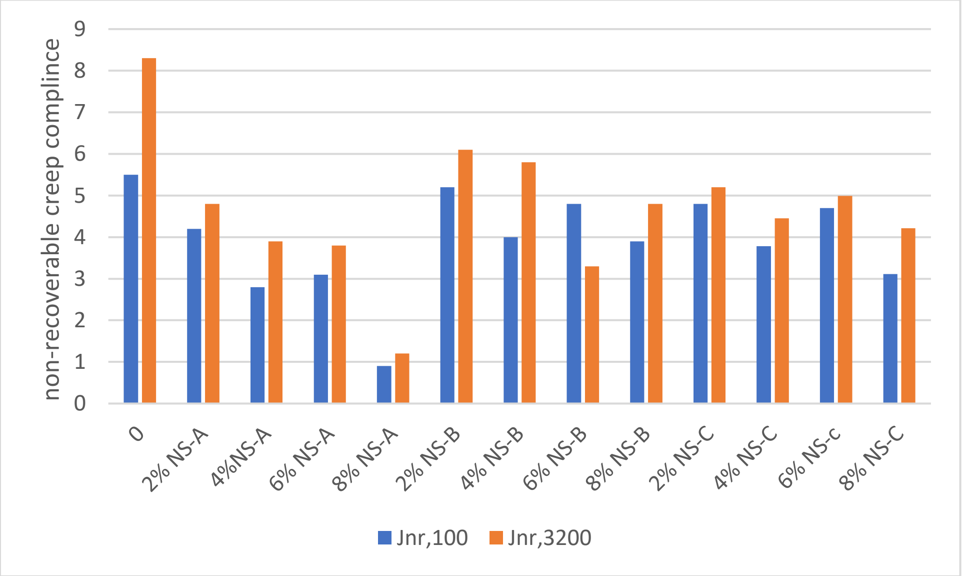

Figure 6.7: Non-recovered strain for nano-silica-modified bitumen

6.7 Summary

a- Using polymers for bitumen modification has some disadvantages in terms of storage stability, bitumen–polymer phase separation, and elevated costs. Therefore, researchers have attempted to find alternative additives to improve the bitumen properties. Nanomaterials and nanotechnology are currently employed to modify the characteristics of bitumen binders and asphalt mixtures. The high surface area and effective network created in the modified bitumen increases the stiffness of the modified bitumen and improves the asphalt mixtures' resistance to permanent deformation.

b- The results exhibit an increase in the stiffness properties by lowering the penetration, increasing the complex shear modulus of all nano-silica modified bitumen samples. The higher the percentage of nano-silica, the higher the rutting resistance; however, the trend followed by the rutting factor was not consistent, as the rutting resistance was impacted by the size of the nano-silica coated with the silane coupling agent.

c- The non-recovered strain for nano-silica-modified bitumen C320 and the non-modified bitumen at three different nano-silica sizes for high and low stress levels were found. Most modified samples exhibited a decrease in Jnr at high stress levels. Therefore, using NS-A leads to a reduction in the levels of rutting deformation. All nano-silica-modified bitumen has a higher percentage of recovery in comparison to the non-modified bitumen.

d- Based on the results of this chapter, NS of 15 nm coated with the silane coupling agent is selected for further research in the next chapter on producing the hybrid PET-nano-silica-modified bitumen. Several tests on binders and asphalt mixtures will be conducted. It seems that adding nano-silica as a modifier results in an increase in the elastic properties and the recovery performance of the modified binder at high temperatures.

Chapter 7

Performance of waste plastic and Nano-Silica Modified Asphalt Mixtures

7.1 Introduction

The construction of hundreds of kilometres of roads around the world every year results in the consumption of tonnes of raw materials and the impoverishment of natural resources in different parts of the globe. In addition, as an outcome of a consuming society, developed countries are currently facing a major problem from the huge waste materials produced daily by their citizens. The disposal of these waste materials has turned into one of the critical issues of municipalities in modern cities. The worst part of the problem is that the major portion of the produced waste materials remain intact in nature for a long time or is expected to decompose at some time in the distant future, which, in turn, results in long-term environmental contamination obliging the authorities to find solutions, most of which are temporary, such as dumping the waste in landfills around large cities (Wen 2007). Currently, using waste materials in civil and construction engineering is of great interest for researchers and industry. In specific, using waste materials as recycled polymer in bitumen modification. Polymer modified bituminous mixture has a wide range of applications nowadays in most of the developed and developing countries (Casey et al. 2008). Adding polymer to the bituminous mixture increases its stiffness and improves its non-susceptibility to temperature variations in different regions and climates.

Elastomer and plastomer have been used as popular polymers in asphalt pavement modification. However, these polymers are costly and have less storage stability. Thus, recycled plastic polymer with nanomaterials might produce sustainable and cost-effective pavement with high performance properties. Nanomaterial displays novel properties and profound attributes as an additive in asphalt binder modification which can overcome the drawbacks of recycled polymers (Mashaan, Chegenizadeh, and Nikraz 2022c).

Nanomaterial displays special characteristics as compared to normal material and have showed novel properties and excellent performance because of small size nature, which makes nanomaterial has vital feature that can be applied in asphalt pavement modification (Li et al. 2017). The properties and characteristics of nanomaterials, like its bulky surface area and lesser size, that distinguish it from more commonly used in construction, make it an idealistic material to be applied as an additive in asphalt pavement. Also, nanomaterials possess tremendous abilities that include self-cleaning and self-healing abilities. The fundamental properties of nanomaterials successfully meet the requirements and standards of present-day highway pavement. Therefore, engineers and scientists consolidated the nanotechnology in pavement materials, utilizing nanoparticles to enhance the efficiency of asphalt (Li et al. 2017; Mashaan, Chegenizadeh, and Nikraz 2022c).

Stone Mastic Asphalt (SMA) has shown a fabulous involvement in pavement engineering research and industry. SMA is a bituminous mixture made up of a skeleton of coarse aggregate and a binder rich mortar with as much as 6% to 8% liquid bitumen. SMA consists of crushed coarse mixture, crushed fine aggregate, asphalt binder, mineral filler, and a stabiliser such as cellulose, mineral fibers, or a polymer for the binder (Chiu and Lu 2007). It has been approved by various studies that the application of SMA to road surfacing noticeably improves the durability of the mixture and rutting resistance. The levels of rutting resistance of SMA is considerable high as compare with rutting of dense graded mixtures. The reason could be attributed to the coarse aggregate framework. In simple explanation, such strong framework offers the contact of stone on stone amongst the structural particles of coarse aggregate (Moghaddam et al. 2011). Due to the climate changes and load conditions variations, using specific additives in SMA is required. Thus, it is essential to utilize a modern mixture with a high capacity to survive the high traffic loads. The current study aims to use the combination of waste Polyethylene terephthalate (PET) and Nano-silica (NS) as a newly developed hybrid additive in SMA modification, which could improve the rutting and stiffness performance.

7.2 Using polymers with nanomaterials as a hybrid polymer

According to the literature, nano-silica is an excellent additive in pavement modification. There was a new approach to using polymers with nanomaterials as a hybrid polymer to overcome some disadvantages of using a single polymer. Table 7.1 illustrates the different types of polymers and nanomaterials used in asphalt modification and the major findings (Enieb and Diab 2017; Zhang et al. 2016; Yusoff et al. 2014; Yao et al. 2013). The application of combining 2–4% of Nano-silica with 5% of SBS polymer resulted in improving the asphalt mixture's performance concerning better rutting and fatigue resistance (Ghasemi et al. 2012; Yusoff et al. 2014; Yao et al. 2013). The combination uses 1% Nano-silica with waste 5% polyvinyl chloride (PVC) and emphasises that the modified SMA mixture would have the best performance concerning high stability, good moisture failure resistance, and high rutting resistance (Nguyen et al. 2021). Obaid characterised and evaluated the asphalt mixture modified with nano-silica/waste polypropylene polymer (PP). The addition of 5% Nano-silica with 3% PP positively impacts moisture sensitivity, fatigue life, and rutting resistance (Obaid 2020).

In summary, most of the literature of previous studies focuses on the application of nano-clay/polymer in asphalt modification. Additionally, previous studies mostly highlighted the rheological and physical properties of the bitumen binder modified by Nano-silica. The application of Nano-silica with SBS polymer is well investigated, as discussed in the literature review. Nevertheless, no investigation on the combination of Nano-silica and waste PET plastic modified C320 bitumen has been conducted. As such, it is necessary to investigate and evaluate the engineering, mechanical, and deformation performance properties of combining Nano-silica and waste PET plastic polymer as a 'sustainable hybrid additive'. The study aims to investigate, evaluate, and find the ideal mixing contents to produce the sustainable hybrid additive, which can be effective in both sectors of asphalt modification engineering and the polymer recycling industry.

Table 7.1: Polymer and nanomaterials in asphalt modification

Studies	**Hybrid polymers Nano-polymer binders' content and mixing condition (temperature, time, and shear mix)**	**Binder testing**	**Mixture testing**	**Major findings**
Nguyen et al. (2021)	1%, 2%, 3% NS with 5% waste PVC. Mixing condition of Temperature 170˚, time 45–60 minutes, and 3,500–4,000 rpm.	Penetration, softening point, viscosity, multiple stress creep recovery (MSCR), dynamic shear rheometer	Marshall stability Water stability Rutting tests	SMA mixtures modified with 5% PVC and 1% Nano-silica showed the best performance concerning high stability,

		(DSR), and standard rolling thin film oven (RTFO) aging		good moisture failure resistance and high rutting resistance.
Obaid (2020)	2-5% Nano-silica 3% PP waste. Mixing condition of temperature 150˚ at 3,500 rpm.	No tests.	Indirect tensile strength test, rutting and fatigue tests	The addition of 4% and 5% Nano-silica with 3% PP showed better fatigue life and rutting.
Ganjei and Aflaki (2019)	0.5, 1, 2% of Nano-silica with 1%, 3%, 5% SBS. Mixing condition of Temperature 170˚, time 60 minutes, and high shear rpm.	No tests.	Fatigue and indirect tensile tests	The ideal combination was using 4% SBS, and 2% Nano-silica, which showed improved fatigue resistance.
Bala, Napiah, and Kamaruddin (2018)	1%, 2%, 3% & 4% Nano-silica with 5% virgin polypropylene polymer. Mixing condition of Temperature 150˚, at 4,000 rpm.	No tests.	fatigue test, Drain down test and Indirect tensile strength test (ITS).	Using nano-silica and PP polymer showed better fatigue life with 3% Nano-silica, high tensile strength.
Sun, Xin, and Ren (2017)	0.5 & 1% Nano-silica 3,4,5% Bentonite With 1–5% of SBR and PE. Mixing condition of Temperature 170˚, time 30 minutes, and 5,000 rpm.	The softening point, ductility, viscosity, bending beam rheometer (BBR), DSR, and RTFOT aging tests.	Rutting test, low temperature bending test, Marshall stability tests.	0.5% Nano-silica+5% SBR+ 1% PE shows better aging resistance and rutting depth.

7.3 Rheological properties of PET-NS-bitumen

To evaluate the linear rheological properties of hybrid additive of PET-NS-modified bitumen with different content of nano-silica, the temperature sweep tests, stress sweep tests and frequency sweep tests were conducted in this stage. The most eminent parameters and rheological factors which are obtained from the temperature sweep tests using the DSR tests were the dynamic shear modulus (G*), phase angle (δ), storage shear modulus (G´), loss shear modulus (G´´), and loss tangent (tan δ). The reason to measure these parameters is because these parameters are used as to examine and evaluate the elasticity and viscosity characteristics of the modified bitumen binders. Other important rheological factors that obtained from the DSR tests are the rutting factor (G*/sinδ), which is applied to assess the rutting resistance of the modified bitumen binders at high temperatures. On the other hand, the fatigue factor (G* sinδ) are applied to examine and assess the fatigue resistance of the modified bitumen binder at low temperatures. During the DSR tests, 24 mm diameter and 1 mm thickness were the dimensions of the bitumen samples.

7.3.1 Temperature sweep test results

The temperature sweep tests are performed at various temperatures of 31 ˚C, 33 ˚C, 25 ˚C, 37 ˚C,39 ˚C, 41 ˚C, 43 ˚C,45 ˚C,47 ˚C,49 ˚C,51 ˚C, 53 ˚C, 55 ˚C, 57 ˚C, 59 ˚C, 61 ˚C, 63 ˚C, 64 ˚C, 68 ˚C, 70 ˚C, 72 ˚C,74 ˚C, 76 ˚C, 78 ˚C, and 80˚C. The test was a controlled strain test using the frequency of 10 rad/s. Six different percentages of modified binders were added to the C320 bitumen to assess the viscous-elastic behaviour of bitumen; 0%, 6% PET, 6%PET 2%NS, 6%PET 4%NS, 6%PET 6%NS, and 6%PET 8%NS by weight of bitumen. The results of temperature sweep test are presented in Figures 7.2-7.8. As anticipated and shown in Figure 7.2, the modified bitumen binders demonstrated higher values of dynamic complex shear modulus (G*) in comparison to the non-modified bitumen binders. The complex shear modulus (G*) is used to reflect and indicate the stiffness and resistance to deformation of the bitumen binders. Based on the results of Figure 7.2, the more additive added to the modified binders tend to increase the complex shear modulus (G*) showing the trend of elastic improvement, and enhancement in resistance to deformation at high temperatures. The use of hybrid modifier of 6%PET 8%NS resulted in the high performance in terms of better stiffness of the modified bitumen binders, for instance, at temperatures of 35˚C and 70˚C by about 35% - 48% improvement as compared to the non-modified binders. At 64℃, the use of single polymer of only 6%PET results in an improvement in complex shear modulus (G*) by about 30% as compared to the non-modified bitumen binders. All the modified bitumen samples were higher than the non-modified bitumen at all testing temperatures. At temperature of 76˚C, for instance, the complex shear modulus of 6% PET, 6%PET 2%NS, 6%PET 4%NS, 6%PET 6%NS, and 6%PET 8%NS modified bitumen increase 255.7%, 883.9%, 938.5%, 950.7%, and 1,605.7 % more than that of the non-modified bitumen, respectively.

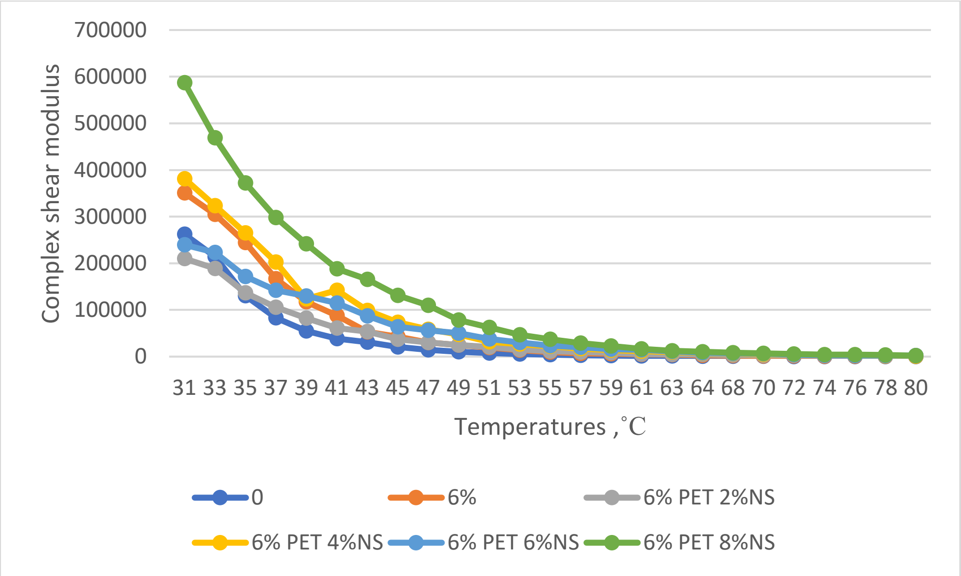

Figure 7.2: Complex shear modulus results

Similar trend has been found in Figure 7.3, showing the improvement in phase angle of all modified bitumen binders in comparison to the non-modified bitumen binders. The phase angle is defined as the ability of bitumen binder to resist the shear deformation in the visco-elastic zone. All the modified bitumen samples were higher than the non-modified bitumen at all testing temperatures. At temperature of 76˚C, for instance, the complex shear modulus of 6% PET, 6%PET 2%NS, 6%PET 4%NS, 6%PET 6%NS, and 6%PET 8%NS modified bitumen decrease 101.5%, 85.6%, 88.4%, 80%, and 77.2 % less than that of the non-modified bitumen, respectively. Therefore, the hybrid additive of 6%PET 8%NS modified bitumen exhibit better rutting resistance as it has the better value of phase angle of 65.44 degree. According to Bala, Napiah, and Kamaruddin (2018) the phase angle is "*the lag of the strain with respect to the stress*". When phase angle value is 0 degree this referred to the absolute elastic material, however, phase angle of 90 degree referred to the absolute viscous material (Mashaan and Karim 2013).

The decrease in phase angle with the increment of nano-silica in the hybrid polymer indicated the building of exfoliated nanostructure within the polymer-nano-bitumen phase, which resulted in an improvement in binder's resistance to deformation. Figure 7.3 indicates that a higher temperature causes in a longer strain hysteresis and as such elevated phase angle. The phase angle of bitumen binder is meaningfully greater than that of the modified bitumen, which signifies that the modifier constrains the movement of the bitumen molecule. Therefore, enhancing the elastic element of the bitumen, and develops the stability, and deformation resistance of the modified bitumen (Mashaan, Chegenizadeh, and Nikraz 2021b).

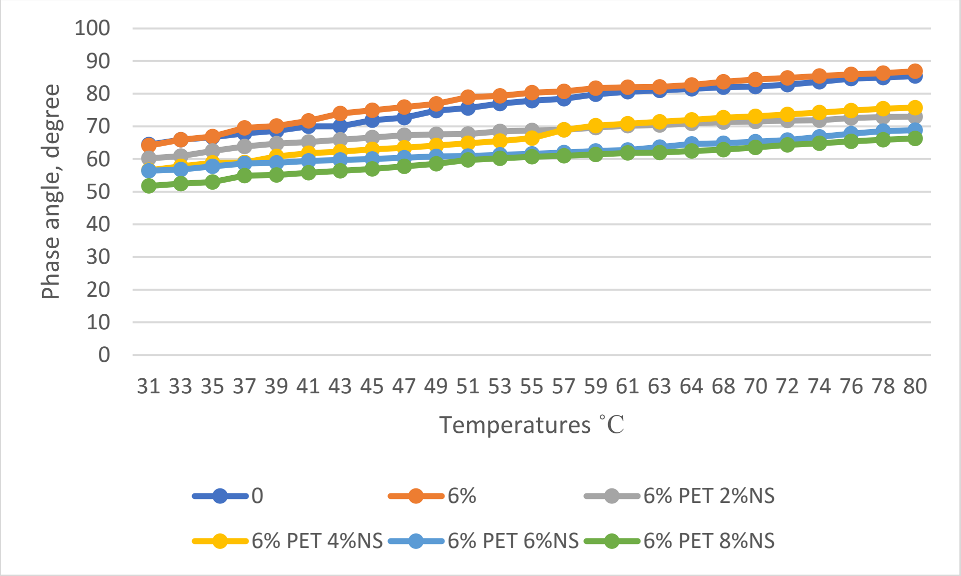

Figure 7.3: Phase angle results

Bitumen performs from elastic to viscous based on the variation of temperatures and loading stresses. This phenomenon led to elastic deformation including viscous behaviour during the mixing and construction of the bitumen binder and aggregate mixtures. To better understand the viscous to elastic behaviour of bitumen, the two elements of storage modulus (elastic modulus) G´, and loss modulus (viscous modulus) G´´ are investigated.

Figures 7.4 and 7.5 show the storage modulus and loss modulus results. as shown that six different percentages of modified binders were added to the C320 bitumen to assess the viscous-elastic behaviour of bitumen; 0%, 6% PET, 6%PET 2%NS, 6%PET 4%NS, 6%PET 6%NS, and 6%PET 8%NS by weight of bitumen. Figures 7.4 and 7.5 show the storage modulus and loss modulus are increases as the percentage of nano-silica increased in the hybrid polymer. However, the single polymer of only 6%PET plastic shows high values of storage modulus and loss modulus in contrast with the non-modified bitumen binders at all testing temperatures. For example, at 64˚C, the storage modulus and loss modulus are about 250 Pas and 2678 Pas, which show that 6%PET binders show high loss modulus and low storage modulus, meaning at 64C the binder will be high in viscous property.

Isacsson and Lu (1999) advised that the binder should have a high storage modulus (G') at high temperature to resist the deformation, therefor, the storage modulus is a measure of binder's elasticity. The current results storage modulus and loss modulus are of In line with Mashaan, Chegenizadeh, and Nikraz (2021a) findings, showing the significant increase in both modulus as results of using waste PET. It is important to point out that the storage modulus displays the element of complex shear modulus that is storing the energy through the loading cycle. Figure 7.4 shows that the storage modulus of the modified bitumen binders is effectively higher than that of the non-modified bitumen at 30℃-80℃, indicating that the modified binders would operate in more elastic region.

On the other hand, Figure 7.5 shows the substantial increase in loss modulus at temperature of 30˚C-˚58C than that of the non-modified, after increasing the temperature up to 80℃, the increase in loss modulus was sufficient. Meaning, the variation in loss modulus at high temperature was less, however, the loss modulus was highly different at low temperatures below 58℃. The increase in both of storage modulus and loss modulus could be explained by the increase in dissolving and swelling rate of the PET-nano-bitumen through belonging processes. In addition, because of the large service area of nano silica, the performance of PET-bitumen phase would be improved by adding the nano-silica to the bitumen. Consequently, physical, and chemical properties of the modified binders are improved, hence the mechanical properties of the hybrid polymer would be developed.

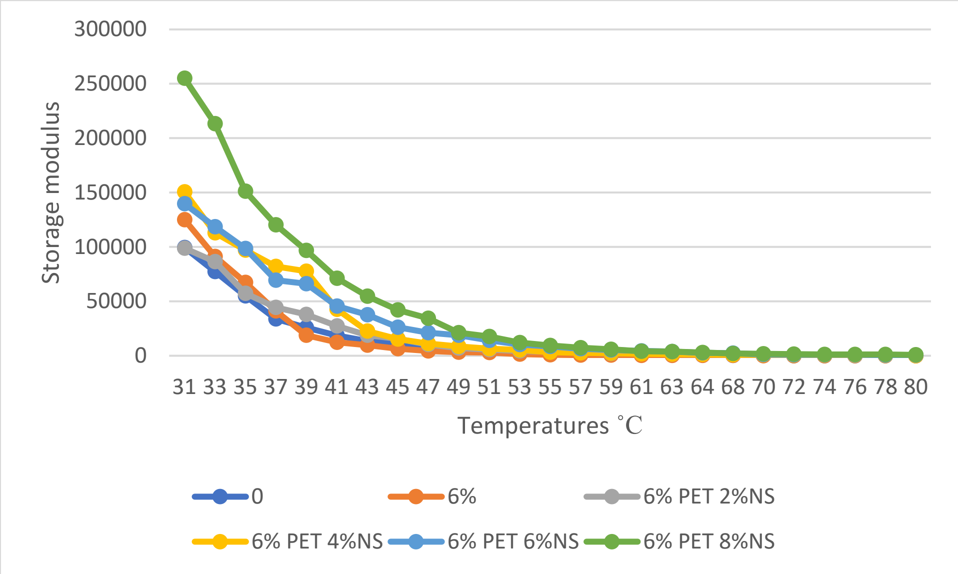

Figure 7.4: Storage modulus results

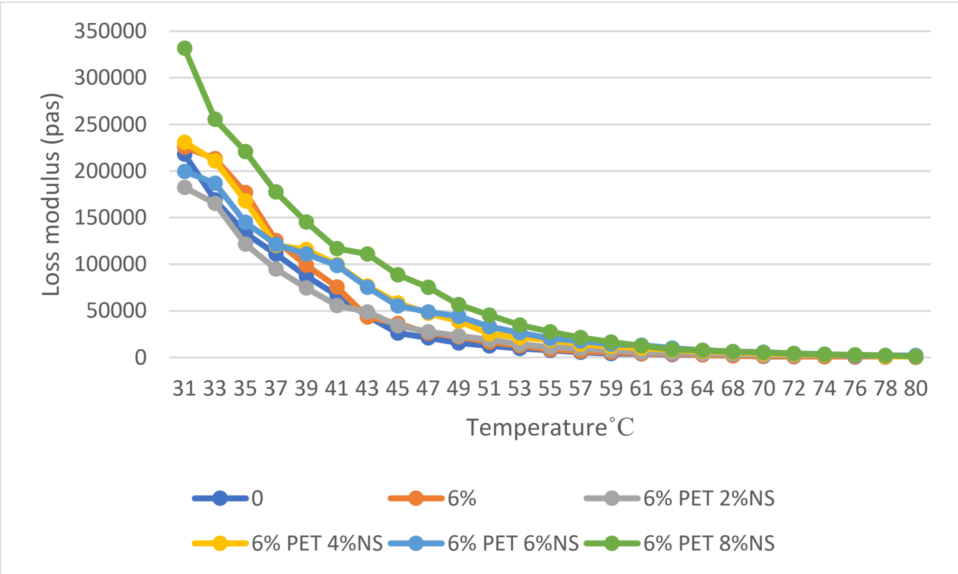

Figure 7.5: Loss modulus results

Figure 7.6 shows the loss tangent of the modified bitumen binders and non-modified bitumen binder. As can be seen from Figure 7.6 the loss tangent increase with increase in temperature and most significant increase could be noticed after temperature of 45˚C. The results of loss tangent are in line with results of phase angle and in same order, and the phase angle of various binders is being increased gradually closer towards the higher temperatures and tend to be the equivalent. Nevertheless, the loss tangent of the binders is being increased deviating with more temperature and have the tendency to be greatly different.

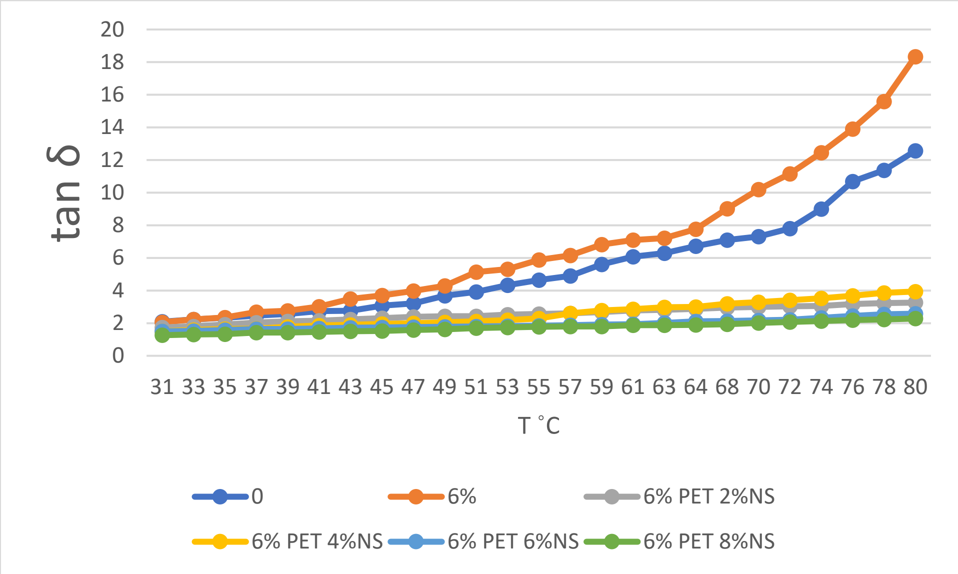

Figure 7.6: Loss tangent results

Figure 7.7 shows the rutting factor (G*/sin δ) of C320 bitumen (non-modified bitumen), single polymer of 6%PET, and four hybrid polymer modified bitumen. The results of rutting factor are in trend that is similar to the complex shear modulus (G*). At temperatures of 31-41℃, the hybrid additives of 6% PET 4%NS and 6% PET 8%NS showed the highest values of rutting resistance, and then after temperature of 43C-80℃, the 6% PET 8%NS binders show the highest value of rutting resistance and improvement by about 92% at 76℃ as compared to the non-modified bitumen binders. The figure displays the essential role of the combined use of PET and nano-silica in improving the rutting resistance by enhancing the elastic component of the bitumen. Therefore, modified binders are highly resistance to shear deformation, which could be attributed to the tremendous mechanical-engineering strength of nano-silica.

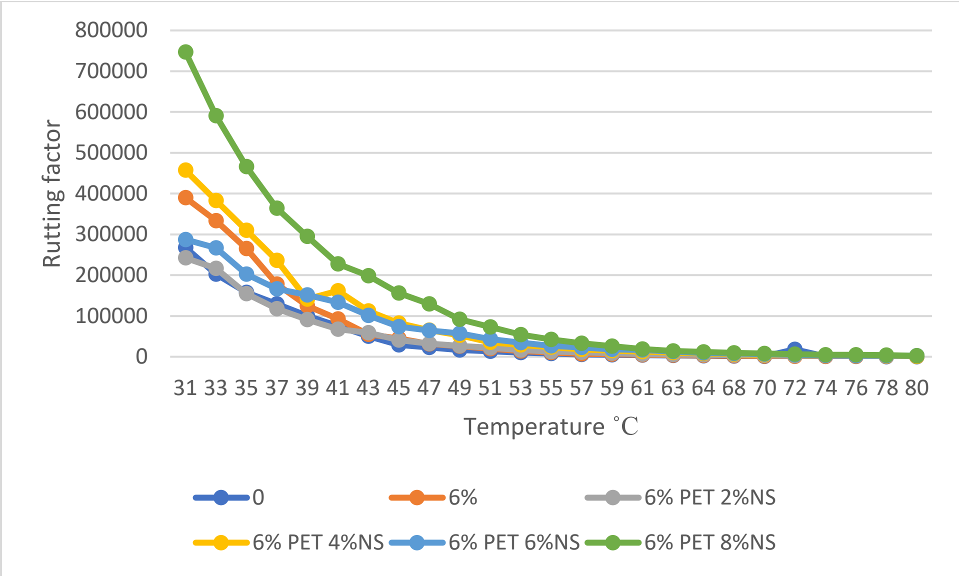

Figure 7.7: Rutting factor results

The fatigue life and fatigue resistance are presented in fatigue factor (G*sin ẟ) of different modified bitumen binders, as show in in Figure 7.8. The trend of the fatigue factor was overall same as the trend of complex shear modulus and storage modulus. As such, the results indicate that the fatigue factor (G*sin ẟ) of all modified binders is proportional to the energy of work used by bitumen per loading cycle. Therefore, the smaller the fatigue factor amount, the smaller the energy spent. On the other hand, the more elastic (high storage modulus) the modified bitumen, the higher ability to resist deformation and the higher capability to rebuild the original structure after deformation of the bitumen. The increased in binder's elasticity could be related to the increasing of bond strength between the plastic and nano particles in the new phase of PET-Nanao-Bitumen structure and the order of molecules and their organization with each other.

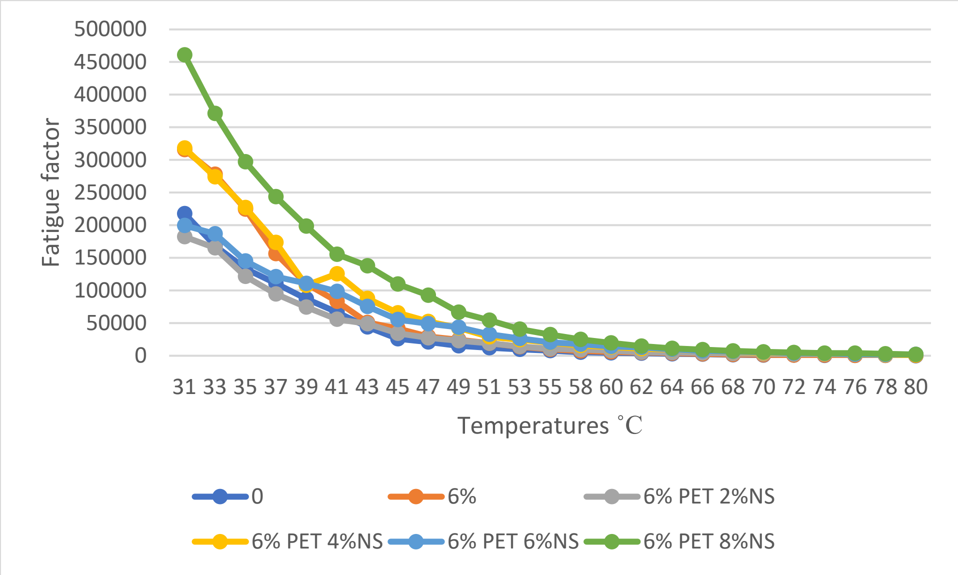

Figure 7.8: Fatigue factor results

7.3.2 Stress Sweep tests

The oscillation stress sweep test was used to determine a material's linear viscoelastic range. The oscillatory test has been used to measure the stress- strain reaction of the asphalt binder. It is possible by utilizing this test to determine the difference in viscoelastic behavior according to the asphalt binder reaction. Amplitude stress sweep parameters and conditions are stress 100-10000 Pa, Temperature 25℃, frequency 10Hz.

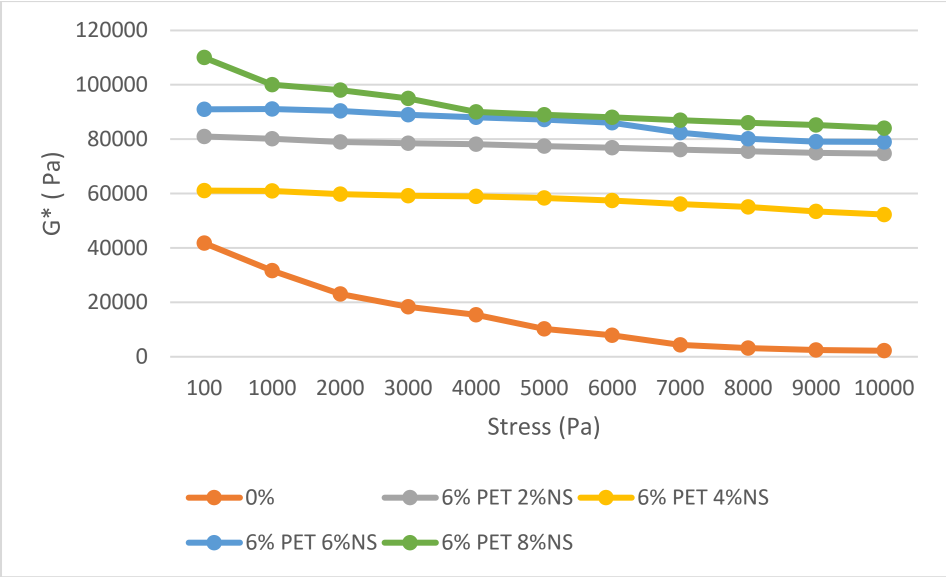

Figure 7.9: Complex shear modulus results

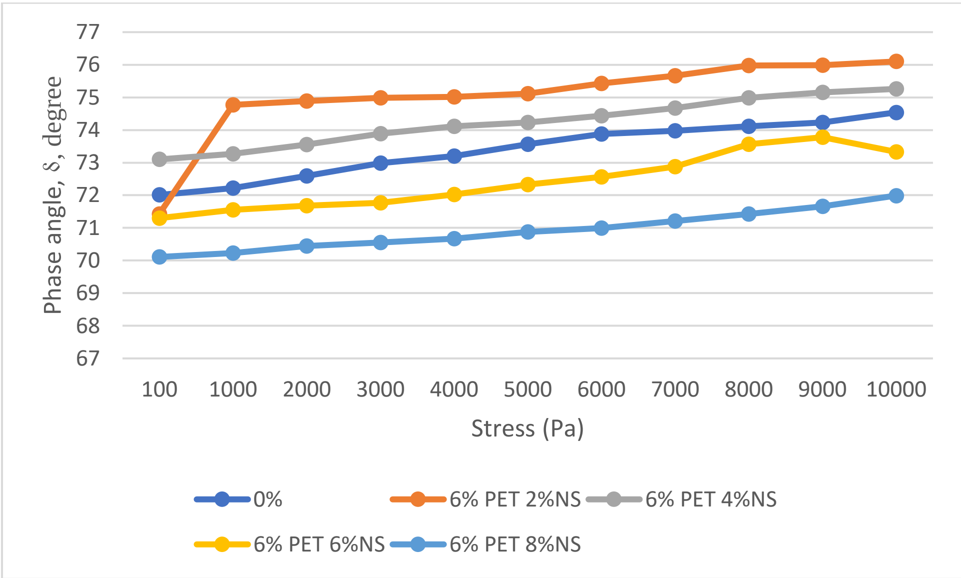

Figure 7.10: Phase angle results

7.3.3 Frequency sweep test

Once the road pavement introduced to the traffic load, the layers of pavement are subjected to dynamic loading effect. And as such, the bitumen is demonstrated different viscous-elastic properties under various load frequencies. The current frequency sweep test is used to indicate the behaviour of the bitumen under the speed of various types of vehicles driving on the road surface. As such, the test can be used to simulate the speed of driving vehicles. The frequency of 10Hz is used to simulate the impact of 60 Km/h speed, and the frequency of 15Hz is used to simulate the impact of 90 Km/h speed. Six different percentages of modified binders were added to the C320 bitumen to assess the viscous-elastic behaviour of bitumen; 0%, 6% PET, 6%PET 2%NS, 6%PET 4%NS, 6%PET 6%NS, and 6%PET 8%NS by weight of bitumen. The frequency sweep test conducted at 25℃at controlled stress of 1000 pascal. The frequency sweep test was performed at various frequencies of 1Hz to 50 Hz. The results of frequency sweep test are shown in Figures 7.11 and 7.12. As can be seen from Figure 6.11, the complex dynamic shear modulus G* of hybrid additives of 6%PET 4%NS, 6%PET 6%NS, and 6%PET 8%NS by weight of bitumen, were all higher in comparison with the 6%PET and 6%PET 2%NS, at different frequencies.

Adding extra nano-silica into waste plastic-bitumen samples showed an increase in complex shear modulus, which indicates less temperature susceptibility to stress/strain deformation. This can result in better rutting resistance. Another result support the ability of the PET-Nano additive in improving the rutting resistance is shown in Figure 7.12, which displays the phase angle after frequency sweep test. In general, the phase angle values are decreased in a substantial rate with frequency increasing by using various content of nano-silica in the combination polymer. For instance, the phase angle of 6% PET, 6%PET 2%NS, 6%PET 4%NS, 6%PET 6%NS, and 6%PET 8%NS are 83.87, 81.82, 77.56, 72.56, 65.11, respectively.

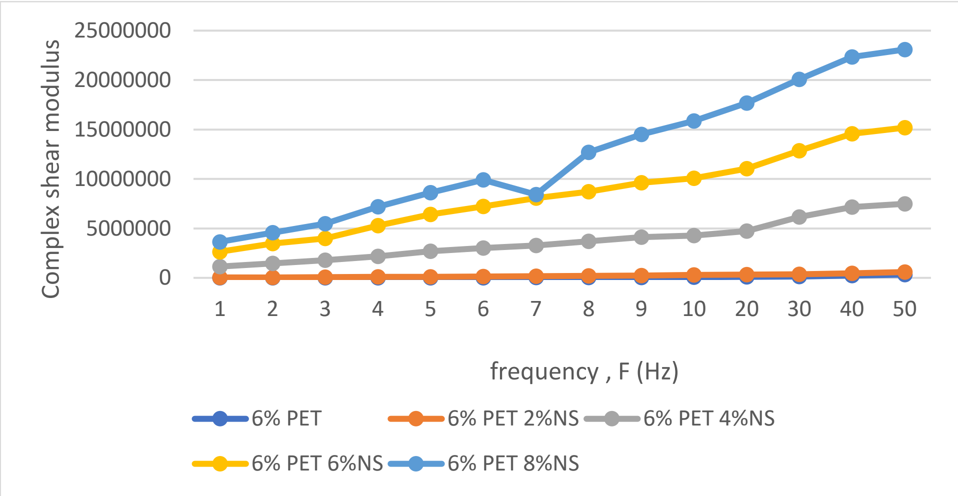

Figure 7.11: Complex shear modulus after frequency sweep test

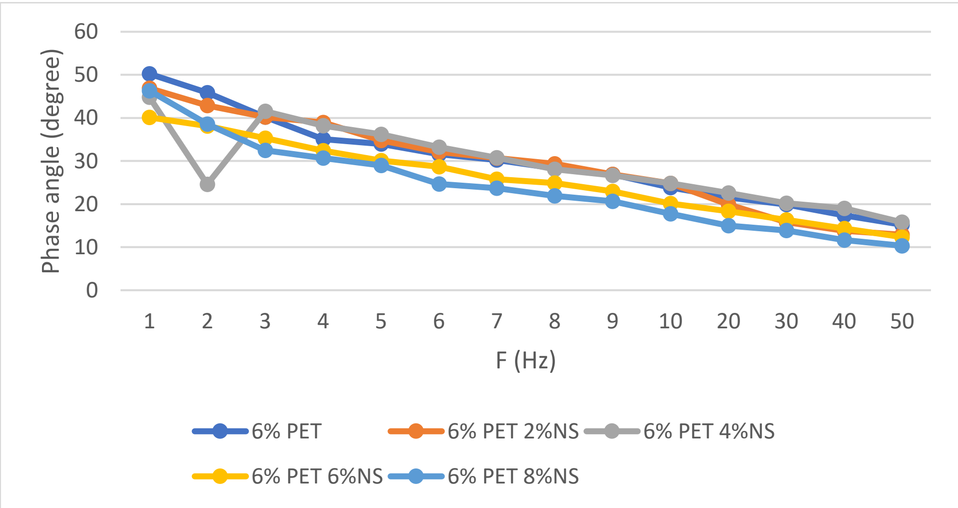

Figure 7.12: Phase angle after frequency sweep test

7.4 Marshall Properties of PET-Nano-silica-modified asphalt

Marshall test has been conducted to investigate and assess the ability of SMA mixture to withstand substantial loads of traffic and subsequent failure and rutting deformation. Figures 7.13,7.14, and 7.15 display the results of Marshall stability, Marshall flow, and Marshall quotient. Marshall quotient can be defined as the rutting resistance indicator and can be calculated as the ratio of Marshall stability to Marshall flow (Mashaan, Chegenizadeh, and Nikraz 2021a). As can be seen from Figures 7.13 and 7.14, the increases in different Nano-silica content along with 6%PET has shown increment in Marshall stability and Marshall quotient, however, Marshall flow shows declined results. Studies have indicated that Marshall stability values are an essential indicator of asphalt resistance to shear stress, displacement, and rutting deformation. Adding 8%NS and 6%PET could produce the ideal stability and strength properties of SMA mixture with high Marshall stability and Marshall quotient of 20.1 kN and 8.7 kN/mm, respectively.

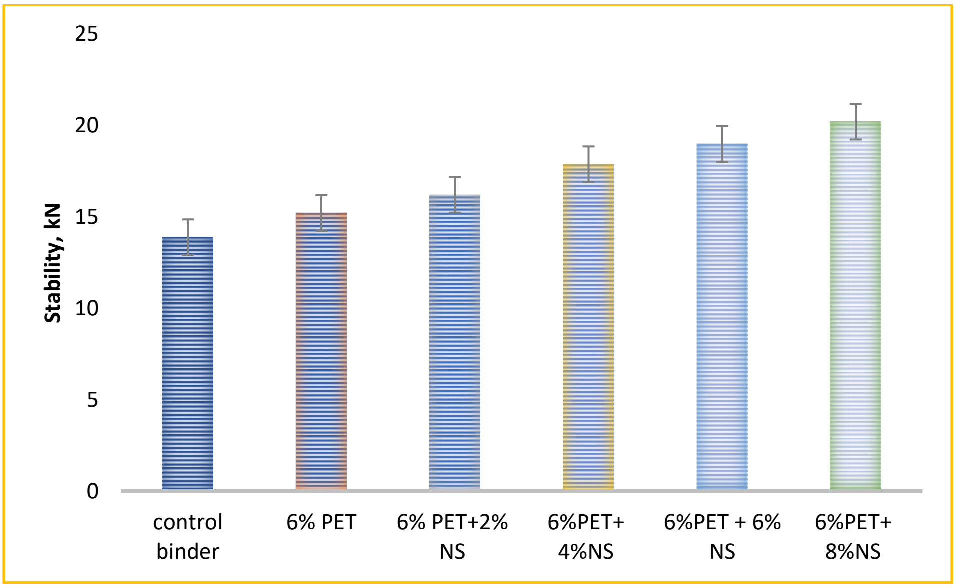

Figure 7.13: Marshall stability

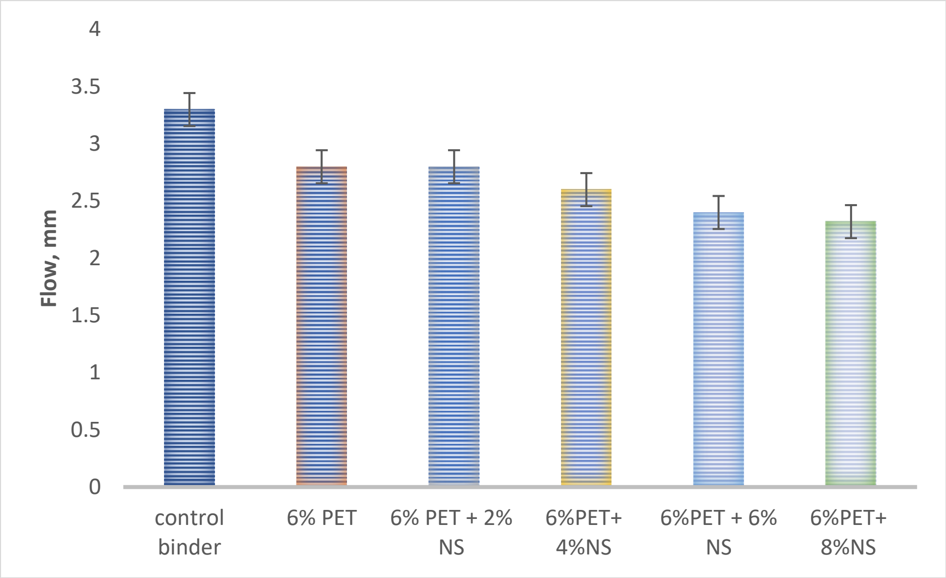

Figure 7.14: Marshall flow

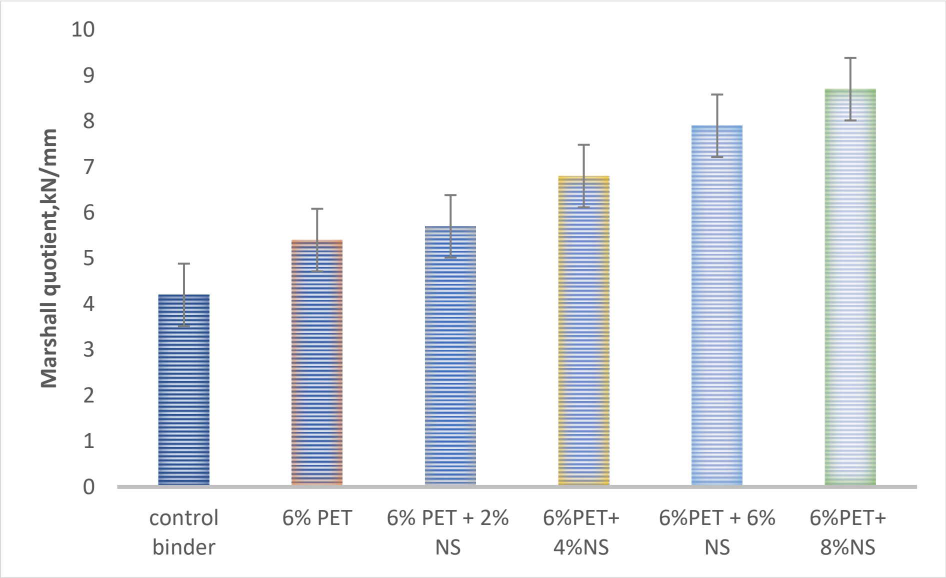

Figure 7.15: Marshall Quotient results

7.5 Rutting resistance of PET-Nano-silica-modified asphalt

Rutting is mainly the most important distress which can result in the deformation of road pavement, specifically in high-temperature climates. Unsuitable mixture design, such as higher bitumen content, a higher percentage of coarse aggregate, and unreasonable filler amount could potentially consequence in rutting defamation. Thus, investigating the effect of the modified mixtures to explain the rutting resistance is essential.

The rutting test was conducted as per AG: PT/T231. Figure7.16 displays the rutting depth antonymous the different modified mixtures, and the data of the rutting test have used the average of three readings for each mixture type and content. Adding PET and NS results in a considerable decrease in rut depth to 1.2 mm and 2.4 mm for mixtures modified with 6% PET/6% NS and 6% PET/8% NS, respectively. The results indicate the positive effect of NS and PET plastic on rutting resistance. The reason behind this improvement results is the growing adhesion force between bitumen binder and aggregate. Thus, forbid aggregate from slithering due to the influence of compressive loads, and as such, the rutting deformation decreased (Bala, Napiah, and Kamaruddin 2018). This result shows that using more nano-silica in the mixture reduces the rutting depth as compared to non-modified SMA (control binder) and 6% PET-modified SMA. However, the result of 6%PET is of concern as compared to the non-modified SMA. The results indicate that adding NS and PET results in SMA mixture stiffness and strength have been enhanced. This demonstrates a rise in the capability of the modified stone mastic asphalt to withstand and resist accumulative deformation under heavy traffic loads. Therefore, by utilizing PET and NS, the rutting resistance of the SMA mixtures are enhanced (Mashaan, Chegenizadeh, and Nikraz 2022c).

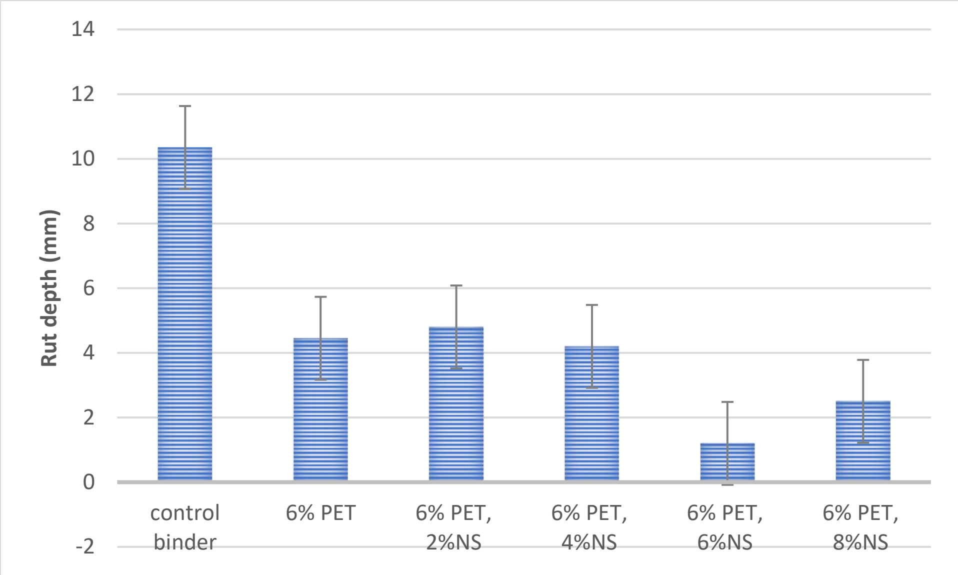

Figure 7.16: Results of rutting resistance

7.6 Resilient Modulus of PET-Nano-silica-modified asphalt

Resilient modulus considers as one of the most important tests to mechanistic design method for asphalt pavement. This test is used to measure the asphalt consequence regarding the dynamic stress and related strains. Therefore, the major objective of conducting this test was to determine if adding nano-silica would bring momentous change in the stiffness properties of SMA modified mixtures.

Figure 7.17 shows the stiffness modulus results using different content of nano-silica and waste PET. As can be seen that the hybrid binder modified SMA mixture have a comparatively higher stiffness resilient modulus than the control binder (non-modified). The stiffness modulus values are noted to increase from 5010 MPa of 6%PET samples to 5345 MPa, 5788 MPa, 5897MPa and 6100MPa for the hybrid additive of 6PET/2NS, 6PET/4NS, 6PET/6NS and 6PET/8NS, respectively. This implies that the modified mixture would come up with greater load spread ability (Bala et al., 2018), high load-bearing capacity, and more resistance to pavement deformation in comparison to non-modified mixtures. This increase in stiffness resilient modulus is attributed to the role of nanomaterial in improving the binder performance and as result improve the mixture resistance to high temperature and high traffic load. Another reason behind the increase in stiffness modulus is the increase in viscosity, this, in turn, improves the adhesion between the aggregate and bitumen and prevent the mixture from sliding easily (Nguyen et al. 2020).

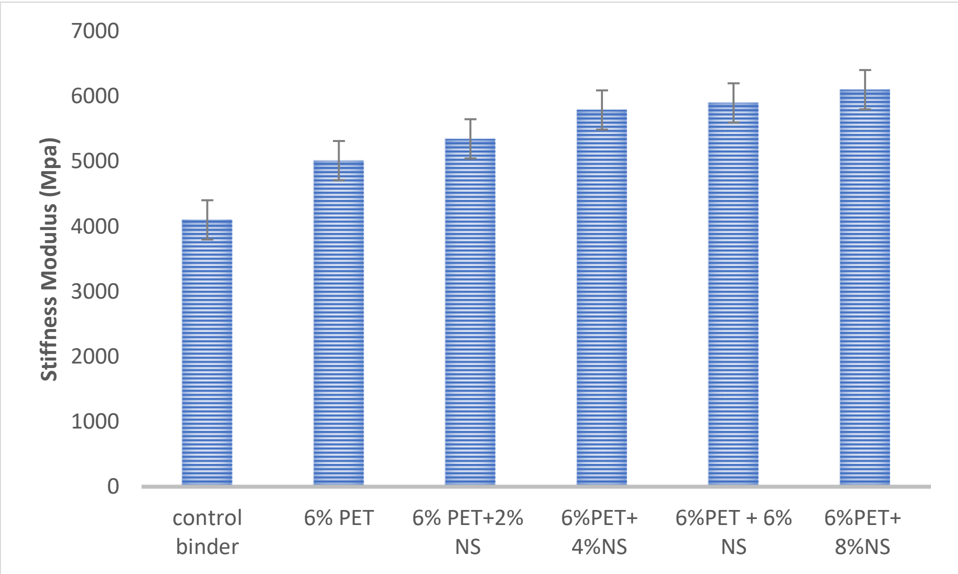

Figure 7.17: Stiffness modulus (resilient modulus) results

7.7 Moisture damage resistance of PET-Nano-silica-modified asphalt

Permanent deformation, cracking, moisture susceptibility, and stripping can be evaluated by conducting the indirect tensile strength test (ITS). The results of ITS and tensile strength ratio (TSR) are illustrated in Figure 7.18. As shown that the non-modified-SMA mixture has a lower tensile strength value, as compared to the high values of the plastic and nano modified SMA. The results show that the more nano-silica content added to the SMA mixture, the further resistance to stripping and less moisture susceptibility will be established. The results displayed that the TSR % of non-modified SMA and highest sample modified with 6PET4NS were 84 % and 96%, respectively. Nano silica possesses very small fragment sizes and a bigger surface area so that it can absorb more binder and increase the structurally modified binder. The TSR values of all modified SMA samples increased. This indicates that PET and nano-silica working significantly to improve the tensile strength resistance by developing strong bonding forces between bitumen binder and aggregate, and, as such they develop better resistance to stripping and moisture damage (Mostafa 2016).

Figure 7.18 also shows that the tensile strength ITS of conditioned samples is less than that of un-condition samples which is like previous findings (Mostafa 2016; Enieb and Diab 2017; Zhang et al. 2016; Yusoff et al. 2014; Yao et al. 201). The reason behind this reduction of ITS conditioned samples possible would be ascribed to less cohesion in the mixtures, which is resulted from the long coverage to moisture and wet conditions. Due to the improvement of connection bonds between aggregate and bitumen (Zhang et al. 2016; Yusoff et al. 2014). Figure 7.18 shows that all PET/NS modified SMA samples have satisfactory resistance against moisture damage and showing the ability to increase the bond strength between the aggregate and the bitumen binder. As displays in Figure 9 that the mixture modified with 4% NS display the highest growth in ITS. This increase is about 50% higher than that the un-modified SMA mixture. On the other hand, as can be seen, that mixtures with further nano of 6% and 8% result in a slight reduction of the ITS values about 1.4 - 1.2, respectively. The reason for this could be associated with stiffness reduction during adding high percentages of nanoparticles. However, all PET and NS modified mixtures exhibited a fundamental improvement of the modified mixtures in terms of better resistance to rutting and fatigue cracking.

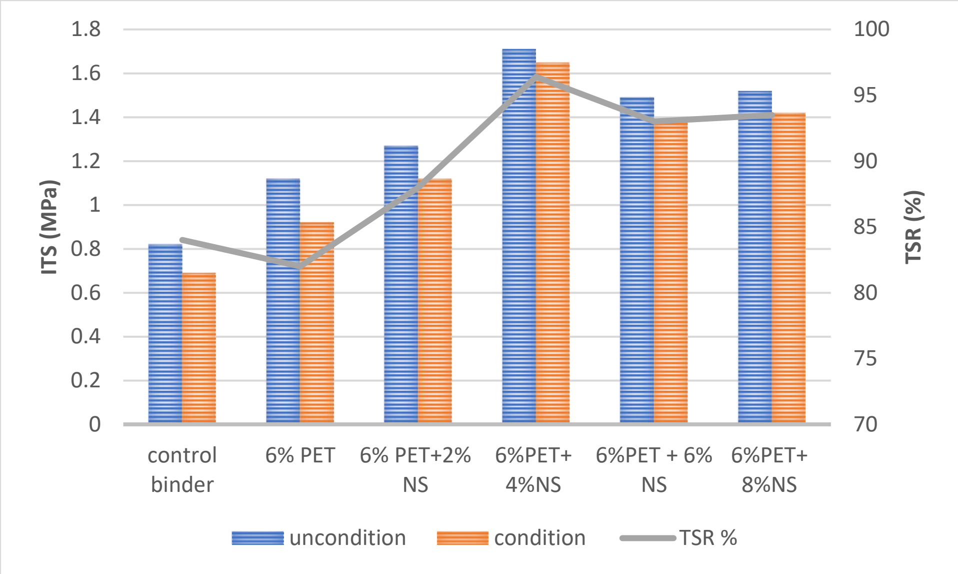

Figure 7.18: Indirect Tensile strength and TSR % results

7.8 Drain- off properties of PET-Nano-silica-modified asphalt

SMA is identified as a mixture of gap-graded aggregate, which minimises the fine and medium-sized aggregate. Specific weakness is distinguishable in the SMA structure, such as drain down, which ensues from the absence of mid-sized aggregate in the gap-graded mixture, which has a high asphalt binder content instead. As such, it is very important to test the drain down of the mixtures. Austroads AG: PT/T235 drain-off test was followed used for this purpose. Figure 7.19 shows the results of the drain-off test. As can be seen, there is a tremendous improvement to the varied SMA mixtures in comparison to the non-modified mixture. The drain-off value of the non-modified SMA mixture produced a drain-off approximation of 0.22%, which is within the standard boundary. The addition of the only 6%PET resulted in a decrease of drain off about 0.9%. at 6%PET with 8%NS substance, the drain off effectively lessened to

0.04%. As shown in Figure 10, adding NS and PET as a hybrid additive in the SMA mixture results in lower the drain-off, and, as such improved, resistance to deformation of the SMA modified mixture. A limit of 0.3% binder drain-off was recommended as the maximum value. The results of these findings were contrary to (A Mirsepahi et al. 2020; Obaid 2020), where the drain off of PP plastic showed a decrease in adjustment with the adequate limits (Mashaan, Chegenizadeh, and Nikraz 2022c).

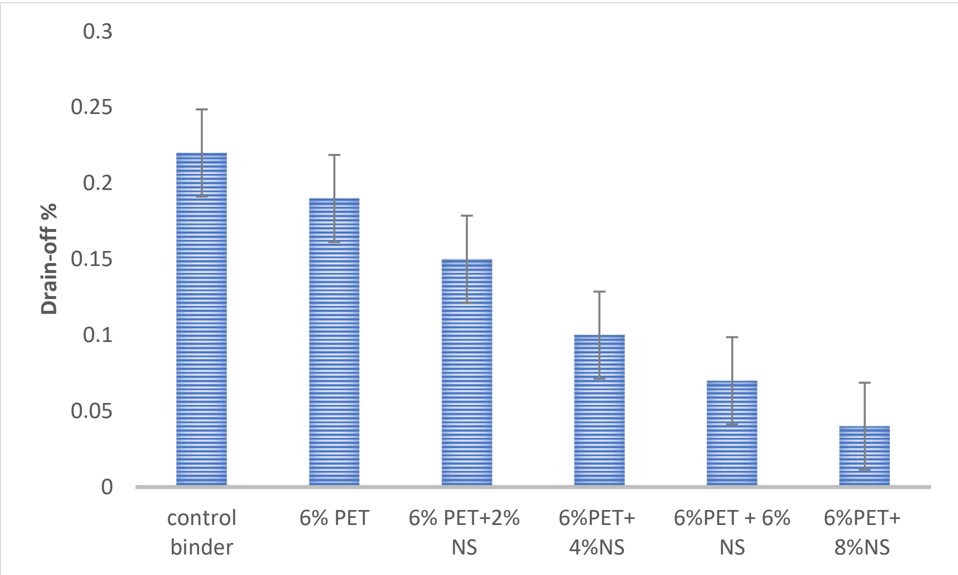

Figure 7.19: Binder drain-off results

7.9 Fatigue resistance of PET-Nano-silica-modified asphalt

The fatigue strength and fatigue life of the PET-Nano-silica-modified asphalt was measured using the four-point bending fatigue test in accordance with Austroads AGPT/233 method. The results show that the increase in nano-silica content with PET plastic increased the fatigue to highest level of fatigue life up to 220490 of hybrid additive of 6PET6NS mixtures, and then declined slightly to 215070 of 6PET6NS mixtures. All the modified mixtures were higher than the non-modified mixture which has the lowest fatigue life of only 67680, as shown in Figure 7.20. The use of nano-silica with different content of 2%, 4%, 6% and 8% has better fatigue life in comparison to samples of using only 6% PET, which can explain that the nano-silica enhanced that the polymer-bitumen phase.

This signifies that nano-silica particles have a substantial consequence on fatigue life of the mixtures. This result could be ascribed by the of nano-silica's surface energy, which to some extents reduces the aggregation of PET fragments during the mixing. By this means improving elasticity, stiffness and connection of binder-aggregates structure (Obaid 2020; Mashaan, Chegenizadeh, and Nikraz 2022c).

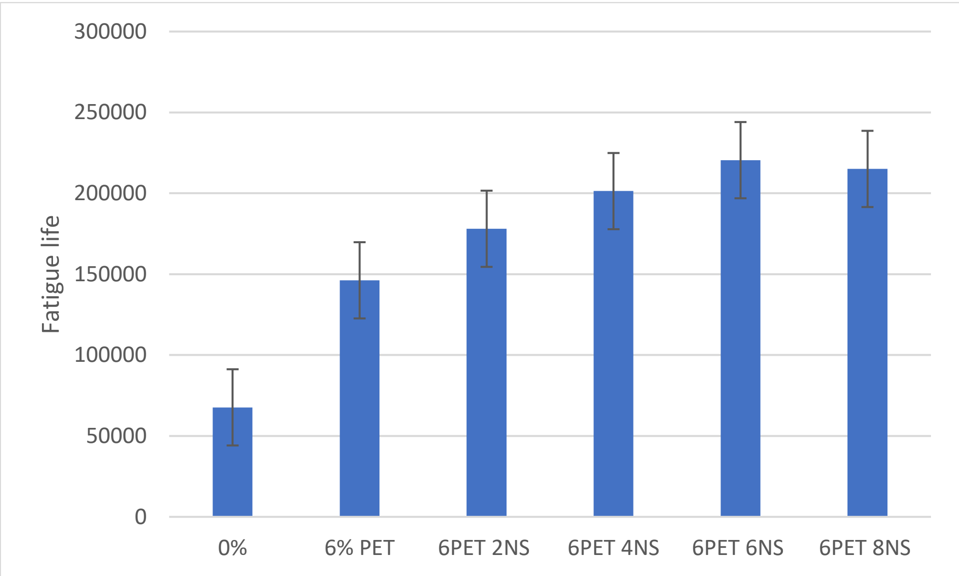

Figure 7.20: Fatigue life of different binders

Figure 7.21 shows the initial flexural strength of PET-Nano-silica-modified asphalt. As can be seen that flexural strength of all modified asphalt mixtures samples was high in comparison to the non-modified asphalt mixtures, which has 5441 MPa. Then by adding 6% PET plastic, the flexural strength increases slightly to only 5997 MPa, however, by introducing the nano-silica to the 6% PET plastic binder, the flexural strength has improved and show an obvious increase of about 6234 MPa, 6641 MPa, 6818 MPa at using 2, 4% and 6% NS.

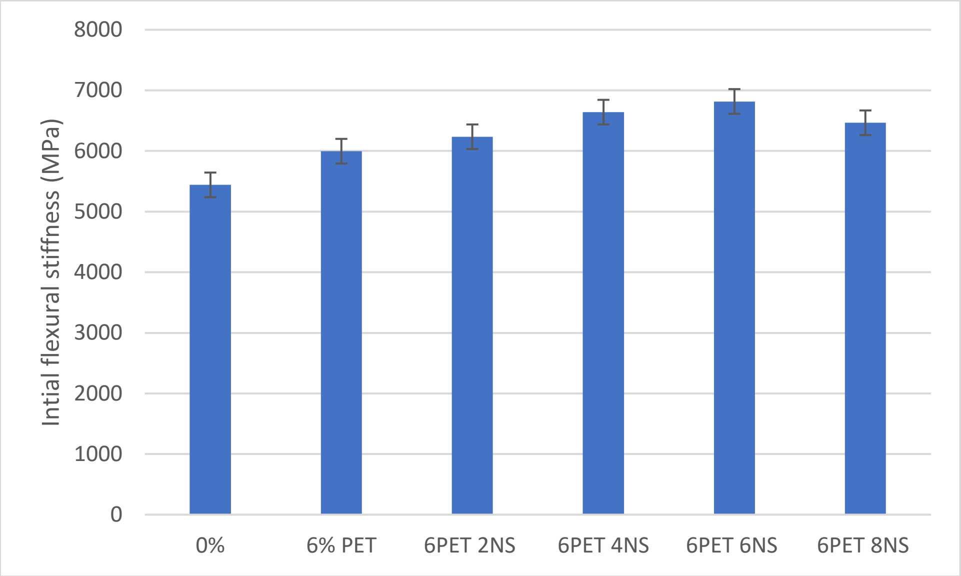

Figure 7.21**:** Initial flexural strength of PET-Nano-silica-modified asphalt

Figure 7.22 shows the initial modulus of elasticity of PET-Nano-silica-modified asphalt. The increase in initial modulus of elasticity of treated PET-bitumen plastic samples and treated PET-NS- bitumen samples was higher than that of the untreated samples. The highest amount of hybrid additive of 6 % PET 8%NS resulted in the highest initial modulus of elasticity of about 7137 MPa. The figure shows fluctuation increases in initial modulus of elasticity.

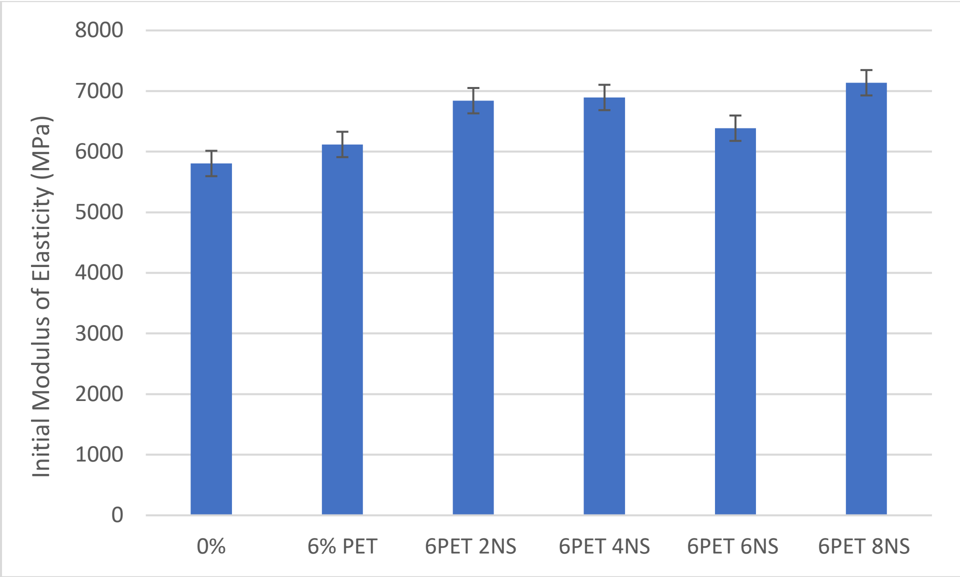

Figure 7.22: Initial modulus of elasticity

Figure 7.23 shows phase angle of PET-Nano-silica-modified asphalt using the fatigue tests. The phase angle of the hybrid additive of 6 % PET 6%NS shows the better elasticity of about 26.7, as compared to the single additive of 6 % PET of about 28.2. The combination of nano silica to the waste PET plastic creates more stable and strong coupling and bonding between the particles of plastic and nano, and this in turn enhance the bonding of polymer-nano phase dispersion in bitumen particles. As results, the mixtures modified with plastic-nano polymer would have high resistance to deformation.

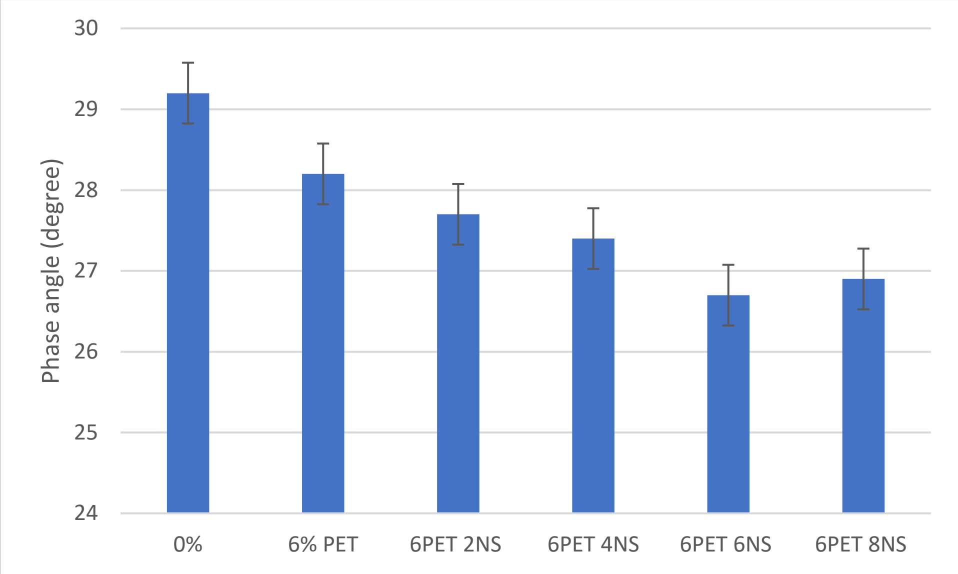

Figure 7.23: Phase angle of PET-Nano-silica-modified asphalt

Figure 7.24 demonstrates cumulative dissipated energy of PET-Nano-silica-modified asphalt. As can be seen that untreated samples and 6% PET treated samples have the high value of dissipated energy of about 1.952 kPa and 1.981kpa, respectively. By adding 2% ,4% and 6% nano-silica to the plastic and produced the hybrid polymer, the dissipated energy decreases to 1.88, 1.79 and 1.716, however the dissipated energy then increaser to 1.85 by adding 8% nano-silica.

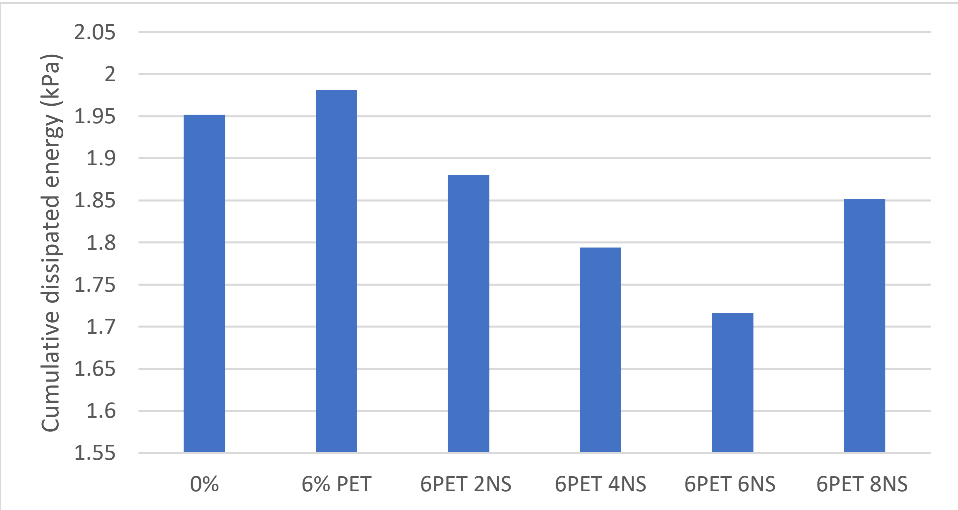

Figure 7.24: Cumulative dissipated energy

6.10 Summary

In this study, the influence of nano-silica (NS) and waste PET on the rutting resistance and permanent deformation of asphalt mixtures were investigated and evaluated. By application of wet mix process, NS and PET were blended with C320 binder and SMA mixtures were fabricated. Various contents of NS of 2% to 8% with 6%PET were used as a hybrid combined polymer/additive. The mechanical and engineering properties were examined and assessed through Marshall stability, Marshall flow, wheel tracking test, indirect tensile strength ratio test, stiffness modulus test, and drain-off tests. To sum up, given tests consequence, the below conclusions can be drawn:

1- The study shows an innovative approach to recycling plastic in asphalt modification and industry. This thesis demonstrates the influence and the possibility of using waste plastic with/without nano-silica as an alternative cost-effective recycled polymer for the modification of bitumen binder C320 and asphalt mixtures following Australian standards. As 6% PET mixtures has the comparative ability to the mixtures with addition of 2% nano-silica, in term of stability and rutting resistance performance.

2- The raises in different Nano silica substances alongside with 6%PET has demonstrated an obvious increase in Marshall stability and Marshall quotient, however, Marshall flow shows declined results. The higher Marshall stability values indicate that the hybrid additive of NS/PET samples have become stiffer and, as such modified SMA mixtures are more resistant to deformation.

3- NS results in a sustainable decrease in rut depth to 1.2 mm and 2.4 mm for mixtures modified with 6% PET/6% NS and 6% PET/8% NS, respectively. The results imply the positive effect of NS and PET plastic on rutting resistance.

4- The resilient modulus values were increased up to 6100MPa for the hybrid additive of 6PET/8NS. In addition, the results displayed TSR % of SMA modified with 6PET4NS has the highest value of 96%. This implies that the modified mixtures are more resistant to rutting deformation in comparison to non-modified mixtures.

5- The drain-off of modified SMA mixtures confirmed a decrease in values in comparison with non-modified mixtures. The addition of the only 6%PET resulted in a decrease of drain off of about 0.9%. At 6%PET with 8%NS, the drain off effectively diminished to 0.04%. The results demonstrated that the inclusion of NS with PET successfully decreased the drain-off rates.

6- In addition, it is recommended to do more tests at different stress and temperatures to take into account the rutting resistance and fatigue performance. After all, it is recommended to test the fatigue life and fatigue deformation of the different percentages of the hybrid additive using the SMA mixture.

Chapter 8

Conclusions and Recommendations

8.1 Introduction

Due to the recent rapid industrial growth in Australia, the volume of waste plastic generated has observed an unprecedented boost. As a consequence of this economic growth, road pavement has weakened rapidly due to significant increases in the traffic load. To ensure that a bituminous pavement surface be capable of surviving deformation, modification is needed. Asphalt concrete is vital to modern life in Australia, particularly in infrastructure and consumer products; therefore, it is crucial to consider its durability and safety. The design and construction of most asphalt concrete pavement structures reflect that their stability depends on their construction, what materials are used, and the environmental conditions. Generally, asphalt damage is associated with the bitumen and asphalt performance. Therefore, improving the binders' properties is vital in terms of improving the rheological, mechanical, and aging performance.

Polymer-modified asphalt mixtures and polymer concrete are commonly used in civil engineering and construction projects. The addition of polymers to the pavement mixtures improves their stiffness and significantly enhances their robustness against temperature fluctuations. This modification, in turn, enhances the mixture resistance to pavement cracking (due to fatigue and rutting damage), which is one of the most common problems affecting pavement in hot or tropical regions. In such cases, adding polymers to the mixture create a softer base binder, which can provide better high-temperature performance. The addition of polymers to the binder results in a significant increase in its cohesiveness and adhesiveness, binding the mixture of components together effectively and strongly. In addition, polymers play another important role in generating an aggregate coating substance to improve the irregularity of the aggregate surfaces, producing superior pavement mixtures. However, the application of virgin polymers is expensive. Thus, waste polymers, such as waste plastic, are inexpensive substitutes. Furthermore, using waste polymers yields a new effective bituminous mixture from the unwanted residue, which is commonly referred to as ‘greening asphalt’. In addition, the better engineering of complex materials like asphalt pavement at the nano level can help impart advanced and smart characteristics. The practicality of adding nanomaterials to asphalt pavement is that nanomaterials’ large surface area and small size impart several advantageous properties.

8.2 Research significance and environmental impact

This study aimed to offer a revolutionary eco-friendly method of manufacturing asphalt wearing courses with optimal resistance to mechanical failure. This aim is achieved through the use of recycled polymer modified with nano-silica. The recycled polymer is obtained from waste plastic through the modification of asphalt binder and asphalt concrete. Broad laboratory investigations are conducted to ascertain the rheological, mechanical, durability, and engineering properties of nano silica-polymer-modified asphalt. The modification of bituminous mixes with waste plastics seems to have great potential for use in flexible pavements to enhance their active service life or minimise the layer thickness of its wearing course or base layer. The application of waste plastic in asphalt modification increases the stability and service life of the pavement, in addition to improving its ability to tolerate high traffic loads, reducing its susceptibility to deformation, and imparting better ageing resistance. In addition, waste plastic asphalt can meet the requirement for design, coating, and construction, and seems to be a substantial, practical, and economical alternative to other commercial polymers. The results show an improvement in the properties of the asphalt mixture, and the use of this material will be significantly advantageous in Australia. Further, this would support reduction the amount of waste plastic, protecting the environment. The consideration of such issues, along with the systematic design of asphalt concrete for highway applications, is of utmost significance as this type of concrete represents a high percentage of interstate highway systems with heavier activity loads. Accordingly, reusable plastic items are preferred since they can help save the resources and money of the consumers. Therefore, multi-trip plastic containers have gained more appeal among manufacturers and consumers. This, in turn, contributes to a reduction of plastic waste materials in the environment.

8.3 Effect of waste plastic on modified bitumen properties

This research was divided into several stages to analyse the impact of incorporating waste plastic polymer and nano-silica on the rheological, durability, stiffness, and engineering properties of modified bitumen C320 and modified asphalt mixtures.

In the first stage of the study, the possibility of using waste plastic as a viable modifier in C320 bitumen was investigated, and several testing methods were conducted. The results of long-term aging indicate that nearly all waste PET samples had longer fatigue life, a lower aging index, and a higher resistance to fatigue and cracking in comparison to C320 bitumen. Adding 2% and 4% HDPE and LDPE are recommended as ideal contents to ensure good performance in the penetration tests before and after aging. As for the DSR tests, a similar trend found that a high content of 6–8% is not significant in terms of improving the stiffness and elasticity. In terms of the aging properties, the modified binder becomes more susceptible to aging and, as such, samples became more vulnerable to permanent deformation. Finally, 6–8% PET is selected as the ideal material to produce waste plastic modified bitumen with the best resistance to permanent deformation.

8.4 Effect of waste plastic on asphalt mixtures

Waste plastic has been used as a modifier to improve the mechanical and stiffness properties of asphalt mixtures. According to the results of this study, the essential role of waste plastic in improving the stiffness and rutting resistance should be noted. The Marshall stability, Marshall flow, and MQ of the Marshall tests exhibit good improvements through the use of PET in modified SMA and AC mixtures. A similar trend is found in PET-modified SMA and AC mixtures, which could resist plastic deformation and shear stresses, reducing the rutting depth of the modified mixtures. However, the highest results in terms of Marshall stability and rutting resistance were achieved for PET-modified SMA mixtures.

Furthermore, the high content of 6% and 8% can make the SMA mixtures more stable and durable. As such, from the engineering point of view, this study has demonstrated the application of waste plastic as a modifier in bitumen in an economically and environmentally friendly manner. Recycling plastic can yield several advantages such as preservation of limited fossil resources, reducing in energy consumption, reduction of Carbon-dioxide, Sulphur-dioxide, Nitrogen-oxide emissions. Reflecting the points above, recycling plastic waste materials contributes to a large reduction in disposed plastic materials in the environment, as well as helping to preserve the natural fossil resources that form the main source of plastic production and manufacturing around the world.

8.5 Effect of Nano-silica as single modifier in bitumen

Nano-silica has several applications in the medical and engineering sectors. In the building materials and concrete industry, silica shows an essential role in the adhesion and cohesion of concrete. In road and pavement materials, nano-silica has the potential for improving the mechanical and engineering properties of asphalt mixtures. Nano-silica is considered to be a novel material for use in bitumen and asphalt modification owing to its low-cost production and practical characteristics.

The results exhibit an increase in the stiffness properties by lowering the penetration, increasing the complex shear modulus of all nano-silica modified bitumen. The higher the proportion of nano-silica, the better the rutting resistance. Nevertheless, the trend observed by the rutting factor was not steady as the rutting resistance was impacted by the size of the nano-silica coated by the silane-coupling-agent. The non-recovered strain for nano-silica-modified bitumen C320 and the non-modified bitumen with three different nano-silica sizes for high and low stress levels were determined; most of the modified samples exhibited a decrease in Jnr at high stress levels.

8.6 Effect of plastic-nano-silica-modified asphalt as a hybrid modifier

Increases in the content of different nano-silica substances in 6%PET demonstrated an obvious increase in Marshall stability and Marshall quotient; however, the Marshall flow reduced. The higher Marshall stability values indicate that the hybrid additives of the NS/PET samples have become stiffer and, as such, modified SMA mixtures be more resistant to deformation. NS results in a sustainable decrease in rut depth to 1.2 mm and 2.4 mm for mixtures modified with 6%PET6%NS and 6%PET8%NS, respectively. These results reflect the positive effect of NS and PET plastic on the rutting resistance.

The resilient modulus values were increased to 6100 MPa for the hybrid additive of 6%PET8%NS. In addition, the results showed that the TSR% of SMA modified with 6%PET4%NS has the highest value, of 96%. This implies that the modified mixtures are more resistant to rutting deformation than non-modified mixtures. The drain-off of the modified SMA mixtures confirmed a decrease in value in comparison to non-modified mixtures. The addition of the only 6%PET resulted in a decrease in the drain-off of about 0.9%. For 6%PET8%NS, the drain-off effectively reduced to 0.04%. These results demonstrate that the inclusion of NS with PET successfully decreased drain-off rates.

8.7 Recommendations

This study aimed to examine the application of waste plastic as a single modifier and a hybrid modifier combined with nano-silica in asphalt SMA mixtures using the wet mix method. Improvements to the physical characteristics, rheological properties, stiffness, mechanical properties, rutting resistance, and fatigue resistance of these mixtures were assessed. Some recommendations for future research are as follows:

1- Examine the use of different types of bitumen binders, such as C170 and C600, and other types of bitumen in other areas of Australia. In addition, it is important to use different types of asphalt mixtures and different aggregate gradations such as AC10, AC14, SMA 14, SMA 20.
2- The use of dry mix methods should also be addressed, following Australian standards, emphasising the differences between the dry and wet mixtures in terms of rutting and fatigue resistance.

3- The low-temperature properties of the modified bitumen should be further researched, particularly in areas with lower temperatures.

4- To better understand the physical reaction between plastic, nano-silica, and bitumen blends, advanced testing methods should be used, such as Fourier transform infrared spectroscopy and other tools of chemical analysis.

5- In addition, it is recommended to conduct more tests at different stresses and temperatures to consider the rutting resistance and fatigue performance. Furthermore, the fatigue life and fatigue deformation of different percentages of the hybrid additive using the SMA mixture should also be assessed.

6- Field trial sections using this research optimum mixes would be beneficial to check the actual environmental and loading impact on the modified asphalt.

7- Recycling plastic waste materials contributes to a large reduction in disposed plastic materials in the environment, as well as helping to preserve the natural fossil resources that form the main source of plastic production and manufacturing around the world. It is important a comprehensive leachate analysis is recommended for the new products incorporated with waste plastic materials.

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“Attribution statement”

1- Mashaan, N.S, Chegenizadeh, A., Nikraz, H., Rezagholilou, A. (2021). Investigating the engineering properties of asphalt binder modified with waste plastic polymer. Ain Shams Engineering Journal 12(2); 1569- 1574.

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Paper 2

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Laboratory Properties of Waste PET Plastic-Modified Asphalt Mixes

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Abstract

Commercial polymers have been used in pavement modification for decades; however, a major drawback of these polymers is their high cost. Waste plastic polymers could be used as a sustainable and cost-effective additive for improving asphalt properties, attaining combined environmental–economic benefits. Since 2019, in Australia, trial segments of roads have been built using waste materials, including plastic, requiring that laboratory evaluations first be carried out. This study aims to examine and evaluate the effect of using a domestic waste plastic, polyethylene terephthalate (PET), in modifying C320 bitumen. The assessment of several contents of PET-modified bitumen is carried out in two phases: modified bitumen binders and modified asphalt mixtures. Dynamic shear rheometer (DSR) and rolling thin film oven tests (RTFOT) were utilised to investigate the engineering properties and visco-elastic behaviour of plastic-modified bitumen binders. For evaluating the engineering properties of the plastic-modified asphalt mixtures, the Marshall stability, Marshall flow, Marshall quotient and rutting tests were conducted. The results demonstrated that 6–8% is the ideal percentage of waste plastic proposed to amend and enhance the stiffness and elasticity behaviour of asphalt binders. Furthermore, the 8% waste PET-modified asphalt mixture showed the most improvement in stability and rutting resistance, as indicated by increased Marshal stability, increased Marshall quotient and decreased rut depth.

Figure 1

Paper 3

Open Access Article

A Comparison on Physical and Rheological Properties of Three Different Waste Plastic-Modified Bitumen

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Abstract

This study aims to investigate the effect and the possibility of using waste plastic as a sustainable cost-effective polymer to modify bitumen binders. Different types of waste plastic have been used in this modification, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), and low-density polyethylene (LDPE). The modification targets the physical characteristics, rheological properties, and binders' resistance to ageing. Both long- and short-term ageing are investigated to determine the durability and ageing resistance of the modified binder using rolling thin film oven tests (RTFOT) and pressure ageing vessels (PAVs). Penetration tests and dynamic shear rheometer (DSR) tests were conducted to investigate and evaluate the complex shear modulus, stiffness, elasticity, and viscous properties. The results show that 2% and 4% of HDPE and LDPE are recommended as ideal contents for good performance, as reflected by the penetration tests before and after ageing. However, higher contents, such as 6% and 8% HDPE and LDPE, are not significant in improving the stiffness, elasticity, and ageing resistance. Therefore, samples of 6–8% HDPE and LDPE are more vulnerable to permanent deformation. Furthermore, using waste PET exhibits obvious improvements in terms of the physical characteristics, rheological properties, stiffness, elasticity, and ageing resistance with up to 8% PET-modified bitumen. Based on the results, the ideal type and content is 6–8% PET waste plastic. View Full-Text

Keywords: waste plastic; PET; HDPE; LDPE; penetration; DSR; ageing

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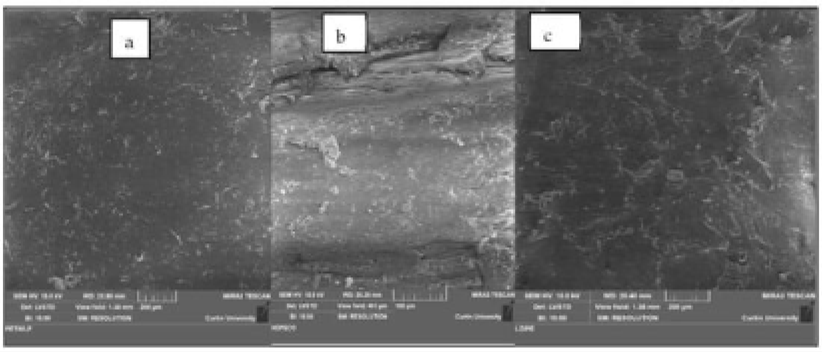

Figure 1

Paper 4

Open Access Article

Evaluation of the Performance of Two Australian Waste-Plastic-Modified Hot Mix Asphalts

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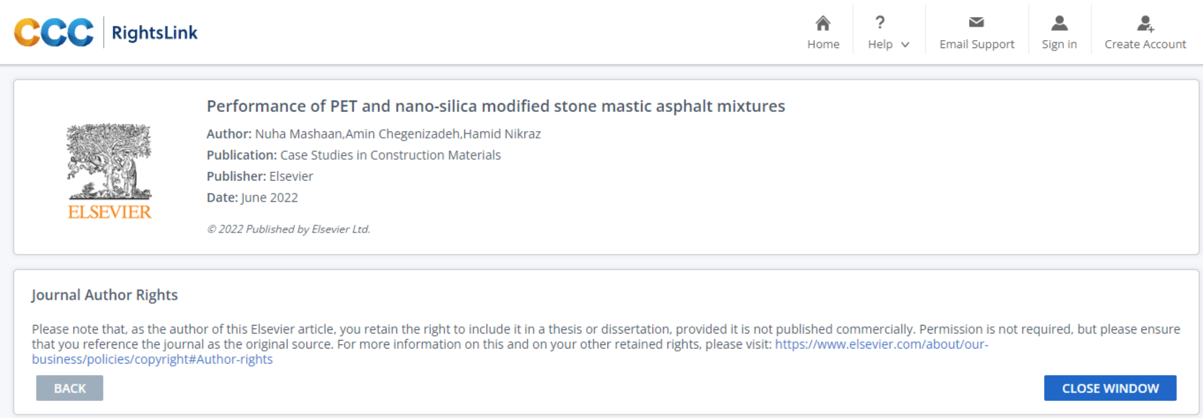
Abstract

The construction of hundreds of kilometres of roads around the world every year results in the consumption of large amounts of raw materials and the depletion of natural resources. In addition, technologically advanced countries such as Australia are currently facing a major issue regarding the waste materials produced daily by their citizens. The disposal of these waste materials is a critical issue faced by municipalities in modern cities. Currently, using waste materials in civil and construction engineering is of great interest to researchers and industry. This study investigates the impact of using waste polyethylene terephthalate to modify asphalt mixtures following Australian design guidelines and criteria. Different types of asphalt are used to investigate and determine the mechanical properties of modified asphalt mixtures. The Marshall stability, Marshall flow, Marshall quotient, and wheel-tracking tests were tested. The Marshall stability, Marshall flow, and MQ of the Marshall test results exhibited significant improvements when using PET in modified SMA and AC mixtures. It can be seen that the 8% PET produced a mixture with the highest stability of 19.78 kN. The lowest rut depth was about 2.08 mm for samples modified with 8% PET.

Keywords: waste plastic; asphalt modification; stability; rutting

Paper 5

5. Mashaan, Nuha S., Amin Chegenizadeh, and Hamid Nikraz. 2022c. "Performance of PET and Nano-silica Modified Stone Mastic Asphalt Mixtures". *Case Studies in Construction Materials*, 16: e01044.



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