Optimization of the Use of Post-Industrial Recycled Multilayer Plastic Packaging (MPP) as Asphalt Modifier

by

Ali Qabur

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Civil Engineering

Waterloo, Ontario, Canada, 2023

Examining Committee Membership

The members of the Examining Committee for this dissertation are listed below. The committee's decision is determined by a majority vote.

External Examiner Dr. Leila Hashemian
Civil and Environmental Engineering, University of Alberta

Supervisor Dr. Hassan Baaj
Civil and Environmental Engineering, University of Waterloo

Supervisor Dr. Mohab El-Hakim
Civil and Environmental Engineering, Manhattan College

Internal Member Dr. Susan Tighe
Civil and Environmental Engineering, University of Waterloo

Internal Member Dr. Shunde Yin
Civil and Environmental Engineering, University of Waterloo

Internal-External Member Dr. Tizazu Mekonnen
Chemical Engineering, University of Waterloo

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.
I understand that my thesis may be made electronically available to the public.

Abstract

The quality of road infrastructure significantly impacts the safety and comfort of road users and the country's economy. In Canada, 15% of roads are rated poor or very poor, with 108,000 km in poor condition, costing drivers CAD 3 billion annually. The cost of pavement maintenance and repairs can be high while investing in sustainable pavement design and maintenance is crucial to ensure longevity and safety. Researchers have investigated using thermoplastic additives, including recycled plastics, to improve pavement performance. Using multi-layer packaging plastics (MPP) additives has become a potential solution to enhance asphalt pavement materials. The primary components of MPP are Polyethylene (PE), Polyester (PET), Nylon (NY), and Metalized Polyester (METPET). Incorporating MPPs into asphalt mixtures minimizes plastic waste generation while conserving virgin aggregate and asphalt cement. The MPP stream from the plastic industry can contribute significantly to this endeavour, allowing for a more controlled and superior output than post-consumer plastics. This approach provides a sustainable solution for both the plastic and asphalt industries with the added benefit of enhanced pavement performance.

In Canada and the rest of the world, MPP waste is a growing concern due to its increasing volume over the past two decades, resulting in significant environmental and economic consequences. Recent studies have shown that the individual components of MPP, such as PE and PET, can be successfully used as asphalt modifiers, highlighting the potential for MPP to be used as an asphalt additive. However, a comprehensive study is lacking to evaluate MPP as a viable asphalt additive. This study aims to address this gap in the literature by evaluating the feasibility of using MPP as an asphalt modifier through wet and dry methods., Several sub-objectives were set to achieve this objective. These sub-objectives included the development of a laboratory-scale method for producing MPP powder, which can provide significant benefits for research, development, and education. The study then evaluates the physical, thermal, rheological, and storage properties of the MPP-modified binder at different MPP concentrations in asphalt cement (PG 58–28). The following tests were used: Differential Scanning Calorimeter (DSC), Thermogravimetric Analysis (TGA), Superpave Dynamic Shear Rheometer (DSR), Rotational Viscosity (RV), and Environmental Scanning Electron Microscopy (ESEM). The results from thermorheological testing indicate that incorporating MPP has a solid potential to improve permanent deformation resistance at high temperatures. Concentrations of less than 4% of MPP additives also offer adequate permanent deformation.

The study also uses the wet method to investigate the effect of MPP additives on the low-temperature performance of asphalt binders and mixtures. As thermal cracking may have a significant impact on the structural integrity of asphalt pavements, the following tests were used to evaluate the low-temperature properties of modified materials: Thermal Gravimetric Analysis, Differential Scanning Calorimeter, Dynamic Shear Rheometer, Bending Beam Rheometer (BBR), Tensile Strain Restrained Specimen test (TSRST), and Complex Modulus test. It was observed that the chemical composition of MPP influenced the asphalt binder's physical and performance properties. At low temperatures, results show that MPP additives at all dosages increase stiffness, affecting the Superpave Continuous PG and BBR ΔT_c parameter. While MPP additives can increase asphalt mixtures' stiffness, they may also reduce their resistance to thermal cracking, demonstrating that the MPP modification percentage should be limited to below 4% by the weight of the binder.

Moreover, the study investigated the potential of using a high concentration of MPP pellets to enhance asphalt mixtures using the dry method. The following tests were used: Complex Modulus Test, Moisture-Induced Damage Test, British Pendulum Skid Resistance Tester, Indirect Tensile Cracking Test (Ideal-CT), and Hamburg Wheel Tracking Test (HWTT). The results show that incorporating MPP additives significantly improves resistance to softening at higher temperatures, fracture resistance, rutting resistance, load-carrying capacity, and skid resistance while reducing susceptibility to moisture damage. A more sustainable solution can be promoted by incorporating MPP additives into asphalt mixtures using wet and dry methods.

The study highlights the need for increased efforts to address the growing MPP waste issue and promote sustainability and circular economy principles. The research has demonstrated that MPP waste can be upcycled to reduce plastic waste and conserve virgin materials such as asphalt cement, aggregate and plastic additives. The study's findings provide valuable information for policymakers and industries to develop sustainable strategies and regulations to address the MPP waste issue. Thus, repurposing plastic waste and promoting a circular economy is possible through a holistic approach and stakeholder collaboration. However, further research and testing are needed to determine MPP additives' long-term durability and effectiveness in asphalt mixtures under various environmental and traffic conditions. In summary, this study offers valuable insights into the potential of repurposing plastic waste to enhance pavement performance through a comprehensive evaluation of MPP as an asphalt modifier. The laboratory-scale method for producing MPP powder presents significant benefits for research and education.

Acknowledgements

I want to express my profound gratitude to Prof. Hassan Baaj for his exceptional guidance, unwavering care, and insightful comments throughout my research journey. His invaluable support made this thesis possible, and I am grateful for the chance to pursue graduate studies at the Centre for Pavement and Transportation Technology (CPATT). His mentorship has significantly shaped my academic and professional development, and I cannot thank him enough for being an exceptional supervisor. I would also like to convey my deepest appreciation to Dr. Mohab El.Hakim for his outstanding collaboration and co-supervision assistance throughout this thesis. His willingness to help and his invaluable contributions are greatly appreciated.

Additionally, I extend my heartfelt thanks to Professors Leila Hashemian, Susan L. Tighe, Shunde Yin, and Tizazu Mekonnen for their valuable contributions and feedback as members of the review committee for my thesis. Their expertise and constructive criticisms have substantially improved the quality of my research.

I am grateful to my friend Dr. Eskedil Melese and Dr. Rob Aurilio for their support and encouragement during my Ph.D. journey.

This project would not have been successful without the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC) through the NSERC Discovery Grant program (ALLRP 558326 20). I am also grateful to Jazan University in Saudi Arabia for their generous financial assistance during my master's and Ph.D. studies, allowing me to concentrate on my research without financial concerns.

I would also like to acknowledge the following partners who supported this research:

- The Centre for Pavement and Transportation Technology (CPATT), Norman W. McLeod Chair, University of Waterloo.
- The Civil and Environmental Engineering Department's technical staff are Richard Morrison, Peter Volcic, and Rob Kaptein.
- Peel Plastic Products Ltd., Yellowline Asphalt Products Ltd., and Steed & Evans Ltd. for their crucial in-kind contributions and support in this project, particularly Mike Aurilio and Richard Marco. Their assistance has been critical in the successful completion of my research.

Dedication

I dedicate this dissertation to my family, who has been an unwavering source of support and love throughout my academic journey. I am grateful for my parents, Hussain and Fatimah, who have always encouraged me to pursue my dreams and have provided me with the necessary resources and opportunities to achieve my goals. I also extend my heartfelt gratitude to my brother, Ahamed, who passed away during my first year of the Ph.D. journey. His constant encouragement and belief in me motivated me to keep going and reach new heights.

To my sisters, Norah, Kholod, and Nazik, and my brothers, Mohammed, Tariq, Khaled, Fahad, and Abdullah, I am grateful for their unconditional love and support. Also, to my beloved Noof. They have been my pillars of strength throughout my academic journey and have always been there to provide a listening ear or a shoulder to lean on.

Moreover, I dedicate this work to my beloved grandmother, who has been a constant source of inspiration and strength in my life. Her wisdom, guidance, and unconditional love have shaped my character and values.

This dissertation would not have been possible without the love and support of my family. Their encouragement and belief in me have motivated me during challenging times; I am forever grateful for that. I hope this work makes them proud and is a testament to their unwavering support and belief in me.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AASHTO: American Association of State Highway and Transportation Officials
AC: Asphalt Cement
ASTM: American Society for Testing and Material
BBR: Bending Beam Rheometer
BPNs: British Pendulum Numbers
BRD: Bulk Relative Density
CPATT: Centre for Pavement and Transportation Technology
CTR: Crumb Tire Rubber
DSR: Dynamic Shear Rheometer
EBA: Ethylene Butyl Acrylate
ELT: End-Of-Life Tyres
EMA: Ethylene Methyl Acrylate
ESEM: Environmental Scanning Electron Microscope
EVA: Ethylene-Vinyl Acetate
FTIR: Fourier Transform Infrared
GHG: Greenhouse Gas
HDPE: High-Density Polyethylene
HMA: Hot Mix Asphalt
HWTT: Hamburg Wheel- Tracking Test
IDEAL-CT: Indirect Tensile Asphalt Cracking Test
ITS: Indirect Tensile Strength
LAS: Linear Amplitude Sweep
LDPE: Low-Density Polyethylene
LVE: Linear Viscoelastic
MEPDG: Mechanistic-Empirical Pavement Design Guide
METPET: Metalized Polyester
MPP: Multilayer Plastic Packaging
MSCR: Multiple Stress Creep Recovery
MTO: Ministry of Transportation Ontario
MTS: Material Testing Systems

NY: Nylon
OMMT: Organophilic Montmorillonite
PAV: Pressure Aging Vessel
PE: Polyethylene
PET: Polyethylene Terephthalate ‘Polyester’
PF: Polyester
PG: Performance Grading
PMA: Polymer Modified Asphalt
PP: Polypropylene
PS: Polystyrene
PVC: Polyvinyl Chloride
RAP: Reclaimed Asphalt Pavement
RPE: Reclaimed Low-Density Polyethylene
RTFO: Rolling Thin Film Oven
RV: Rotational Viscometer
SARA: Saturates, Aromatics, Resins, and Asphaltene
SBR: Styrene-Butadiene Rubber
SBS: Styrene-Butadiene-Styrene
SGC: Superpave Gyratory Compactor
SMA: Stone Mastic (Matrix) Asphalt
TSRST: Thermal Stress Restrain Specimen Test
TTS: Time-Temperature Superposition
Va: Air Voids
VECD: Viscoelastic Continuum Damage
VFA: Voids Filled with Asphalt
VMA: Voids in Mineral Aggregate
WLF: William-Landel-Ferry
WMA: Warm Mix Asphalt
WPE: Polyethylene Packaging Waste
WTR: Waste Tire Rubber

1. Introduction and Background

1.1 Introduction

Road pavements and other infrastructure have been crucial to the development and growth of every society. The World Health Organization (WHO) reported that road infrastructure quality and conditions significantly impact fatal and severe traffic accidents [1]. Ensuring that road infrastructure meets minimum safety standards have become more critical due to the increasing traffic volumes and demands. The latest data reveals that a considerable proportion of Canadian roads are suboptimal, as shown in Figure 1-1. Specifically, 15% of roads are rated as poor or very poor, while another 28% are considered fair. Although over half, approximately 52%, of roads are in good or very good condition, the number of poor-quality roads is concerning [2]. Canada has 108,000 km of roads in poor condition and 48,000 km in very poor condition. Poor roads in Canada cost drivers CAD 3 billion per year in higher operating costs or an additional CAD 126 per year per vehicle, equating to over $1,250 over a 10-year car lifespan [3]. By prioritizing the maintenance and rehabilitation of the worst roads or avoiding their deterioration in the first place, Canadians may save a substantial amount of money. Spending one dollar on pavement preservation today can prevent or delay spending $6-$10 on costly rehabilitation or reconstruction in the future. As such, high-quality and deliberate pavement design is crucial for ensuring durability, safety, and efficient transportation. Therefore, investing in sustainable and effective pavement design and maintenance is essential to ensure the longevity and safety of our transportation infrastructure.

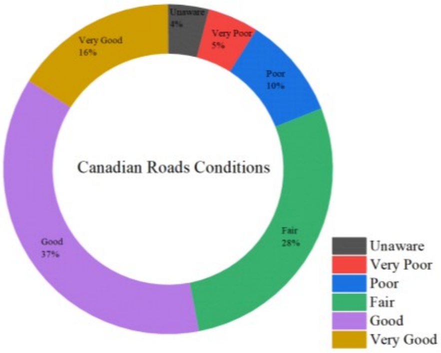


Figure 1-1 Overall Canadian road network condition, 2020 [2]

Waste plastic has become a pressing concern in Canada and globally due to its alarming scale. In recent years, an emphasis on reducing and recycling waste plastic has increased to tackle this persistent challenge. The Recycling Council of Ontario organized a Circular Procurement Summit to raise awareness about the role of circular procurement in managing Canada's plastic waste problem [4]. The summit highlighted the urgent need for Canada to transition from a linear to a circular economy to improve waste plastic management, as illustrated in Figure 1-2 [5]. A circular economy emphasizes better design, reduced waste, and increased sustainability in resource utilization as it moves beyond the traditional linear model of make, take, and waste. This circular system maximizes value and minimizes environmental, economic, and social costs.

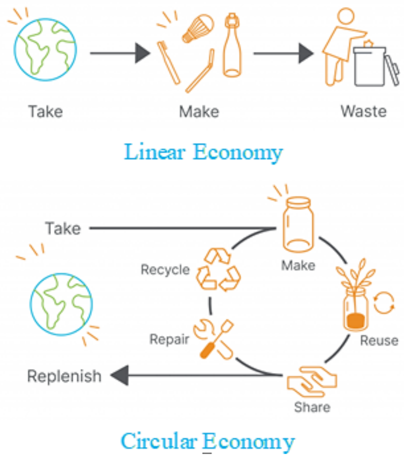


Figure 1-2 Linear versus circular economy [5]

According to Environment and Climate Change Canada (ECCC), Canada produces an estimated 3.3 million tons of waste plastic per year, of which approximately 2.8 million tons end up in Canadian landfills every year; about 86% of all waste plastic is comprised of polypropylene (PP), polyethylene terephthalate (PET), polyamide (or nylon), polyethylene (PE), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) [6]. The residual plastic waste in Canada represented a lost opportunity cost of almost CAD 7.8 billion in 2016 alone and is projected to increase to CAD 11.1 billion by 2030 [6]. Multi-Layer Plastic Packaging (MPP) significantly contributes to the Canadian plastic waste dilemma. However, a significant portion of MPP waste comes from plastic industries, which generate high-quality and easily manageable MPP waste sources that can be repurposed to modify asphalt using appropriate pre-processing procedures.

The demand for asphalt materials in road pavement production and other applications has risen over the last decade, resulting in a surge in asphalt prices. To achieve high-quality road serviceability and long-term performance, including low-cost, high-performance alternative additives in the asphalt mix or binder [7]. Since the quality of asphalt cement is constrained by the availability of only a limited number of crude oil yields. However, using more efficient coking technologies, refineries have been able to diminish the amount of residual crude oil (e.g., the primary component in asphalt production), thus, enabling more crude oil to be transformed into synthetic fuels. This coking technology has slowly led to a reduction in the quantity and quality of residual crude oil that is accessible for asphalt production [8]. Polymer modification is a common tool used to improve asphalt pavement performance. Elastomers such as styrene-butadiene-styrene (SBS) have been used to enhance asphalt's high, intermediate and low-temperature performance [7], [9]. Previous studies have shown that thermoplastic additives can reduce pavement deformation, increase the fatigue resistance, and improve adhesion between asphalt and pavement aggregate [10]–[12]. Although thermoplastics do not increase strength during initial loading as elastomers do, thermoplastics can increase asphalt binder viscosity and enhance its resistance to rutting at high temperatures. The successful use of elastomers, plastomers, and thermoplastic polymers in asphalt modification has led researchers to explore alternative additives that can enhance the durability and longevity of asphalt pavements [10], [13], [14]. However, these traditional polymer modifiers can be expensive and prone to aging and degradation during use. Research on alternative additives, such as those from plastic waste streams, has been proposed [15]–[18]. High-quality waste streams composed of multi-layer plastic packaging (MPP) are an innovative additive that can offer improved rheological and physical properties of asphalt binder and mixtures. MPP additives have the potential to enhance the permanent deformation resistance and durability of asphalt pavements while also contributing to sustainable plastic waste management. It is vital to explore innovative materials such as MPP additives to ensure the long-term performance of pavements.

The road construction and maintenance industries consume significant amounts of natural resources such as asphalt binders, aggregates, and asphalt modifiers to produce asphalt pavement material. Due to its high natural resource consumption, pavement production has the potential to significantly reduce waste plastic disposed of in landfills by incorporating recycled materials. However, the road industry still faces barriers to using recycled and alternative materials for road construction. The preference for traditional materials can be attributed to a lack of practical experience, insufficient positive evidence, and inadequate performance data, all of which contribute to this tendency. Therefore, it is necessary to investigate solutions to overcome our reliance on primary materials from pits and quarries and increase the potential use of secondary sources.

1.1.1 Problem Statement

As previously mentioned, a significant proportion of Canadian roads - almost 40% - are categorized as being in poor, very poor, or fair condition. This condition necessitates an annual expenditure of approximately CAD 7 billion by Canadian provinces to maintain serviceability and safety standards [19], [20]. This research project aims to develop a cost-effective material that can provide superior performance on Canadian roads, thus reducing the frequency of rehabilitation and the total maintenance cost. Polymer-modified asphalt binders are a popular material for improving the performance of asphalt mixtures. However, the cost of virgin polymer additives is relatively high, increasing the cost of hot mix asphalt (HMA) production [21]. Due to budgetary constraints, virgin polymer additives cannot be the sole binder modifier for improving asphalt performance on a large scale to improve Canadian roadway conditions. Reducing pavement deterioration and enhancing long-term performance must be ensured to mitigate this expenditure. Therefore, using abundant waste plastic additives, which have shown promising results, provides a viable alternative [14], [22]–[24].

The literature review indicates a significant amount of research focused on polyolefin-modified asphalt binders' high and intermediate-temperature performance. However, limited research is available on their low-temperature performance. Furthermore, no studies have evaluated the suitability of MPP additives for use in asphalt modification. Therefore, this study aims to assess the potential of MPP additives to modify a local asphalt binder and determine its overall performance characteristics at high and low temperatures. To address the gaps in current research, this study takes a comprehensive approach to evaluate the feasibility of using MPP in asphalt pavement mixtures to improve their performance and durability.

1.1.2 Motivation

In Canada, managing plastic waste has become a crucial concern due to its significant environmental impact. The plastic industry by-products can be utilized in asphalt modification manufacturing to find alternative uses for plastic waste and reduce its disposal in landfills. Elastomer, plastomer and thermoplastic polymers have already shown success in asphalt modification. Thus, the use of waste plastic modifiers could provide an efficient solution for both asphalt production and waste plastic management [10], [25], [26]. However, the thermal cracking resistance at low temperatures appears to be the greatest challenge for adopting waste plastic polymers [27], [28]. Given the extreme climate conditions in most regions of Canada, a viable solution must perform well in moderate, warm, and cold periods of the year. Thus, the primary objective of this study is to investigate the use of waste plastic in road pavement to improve Canadian road performance under various conditions while reducing the amount of plastic waste that ends up in landfills. As Yotam Ottolenghi stated, ***"One person's garbage could be another person's treasure"*** [29].

1.1.3 Research Hypothesis

In the last two decades, a significant amount of research has investigated the use of waste plastic for modifying asphalt. The overall findings of this research suggest that recycled/waste plastic can be used as a substitute for aggregates, as an aggregate coating, as an asphalt cement modifier, or some combination of the three [28], [30]–[33]. Incorporating waste plastic additives into asphalt cement and/or asphalt mixture can improve road pavements' physical and mechanical properties in terms of fatigue and rutting. However, some types of waste plastic are incompatible with asphalt cement, which can reduce mix performance. The current study examines MPP additives to determine whether they enhance the mechanical properties and improve the overall serviceability of flexible pavement.

Several studies have incorporated various types of waste plastics into both asphalt cement and mixes using dry or wet methods. These waste plastics, added to different types of asphalt cement (e.g., soft or hard binder types), had different shapes, sizes, and chemical compositions [13], [24], [34]. As a result, there is uncertainty about the method that should be followed to obtain the maximum benefit regarding future road serviceability and cost. Furthermore, extant studies have raised the possibility that using waste plastics could reduce pavement construction and maintenance costs because it is less expensive than virgin polymers [25], [33], [35], [36]. Additionally, using waste plastic in road construction may assist in waste management by reducing waste going into landfills by incorporating the waste plastic in road pavement. Therefore, more investigation is required to determine a standard protocol for adding recycled plastics to binders and mixes.

The current study hypothesizes that MPP additives are feasible for asphalt mixtures when coupled with an appropriate pre-processing procedure, as determined by their shape, size, and chemical makeup. Specifically, the hypothesis is that adding MPP powder to low-viscosity asphalt cement can improve bituminous pavements' durability and mechanical performance. In conclusion, the current research is based on the following hypotheses:

- Incorporating MPP additives into asphalt cement and/or asphalt mixture would improve the mechanical properties of the asphalt mixes (e.g., intermediate and high temperatures).
- Adding MPP powder (as opposed to the larger, conventional pellets) with low-viscosity asphalt cement would enhance damage resistance, particularly at low-temperature cracking.
- Improving the blending efficiency of MPP additives and virgin asphalt cement could hypothetically offer a solution to enhance the durability and performance of MPP mixtures.
- The dry process, which incorporates the MPP additive directly into the asphalt mixes, would provide a better outcome when compared to the wet method in terms of the larger size and amount of particles added.

1.1.4 Research Goal and Objectives

The main goal of the current research is to provide a logical framework and method for choosing the best MPP additive dosage and application technique for modifying asphalt cement and mixes. This framework shall provide asphalt manufacturers and the paving industry with a clear methodology and reliable way to assess if adding MPP additives to asphalt mixes is feasible. Presently, there is no standardized procedure for these evaluations, which are often conducted using an empirical and trial-and-error methodology. Laboratory testing resources and technical know-how to accomplish this goal were provided by the Centre Pavement and Transportation Technology (CPATT) at the University of Waterloo. The necessary materials were supplied by industry partners, namely Peel Plastic Products Ltd., Yellowline Asphalt Products Ltd., and Steed & Evans Ltd. The primary goals of the present research work are:

- Develop a cost-effective and reliable plastic powder production process to help researchers studying plastic additives in asphalt in a laboratory setting,
- Examine the use of MPP powder as a binder additive and its effect on the physical, thermal, rheological, and storage properties of the MPP-modified binder,
- Determine how the incorporation of MPP affects the modified binder's rheological and mechanical characteristics under high-temperature conditions using both wet and dry processes,
- Evaluate the effect of adding MPP additives on the properties of the asphalt binder and mixture, specifically at lower temperatures, and
- Provide recommendations for determining the optimum dosage of MPP additives that can be integrated into the asphalt binder or mixture using statistical analysis, thus, achieving better asphalt mix performance.

Finally, the study shall answer the question: "Is the use of Multilayer Plastic Packaging (MPP) waste in asphalt modification ***beneficial or detrimental?"*** The study's findings and conclusions will guide plant mixing trials to produce HMA with MPP additives. Furthermore, the testing framework and data analysis methods developed during the study can be employed to evaluate similar materials. The test results can be utilized as input for mechanistic empirical pavement design.

1.2 Dissertation Organization

This manuscript-based dissertation is composed of eight chapters, which are organized as illustrated in Figure 1-3:

Chapter 1
Introduction and Background

The Introduction outlines the research project's context, motivation, and goals. The Background offers an in-depth review of flexible pavements and related distresses.

Chapter 2
Literature Review

This chapter reviews polymer modified asphalt and waste/recycled plastic additives, emphasizing research gaps and potential innovative solutions for asphalt industry challenges.

Chapter 3
Lab-Scale Protocol for Multilayer Plastic Packaging Powder Production and Its Integration in Asphalt Modification

The chapter concentrates on lab-scale MPP powder production and integration into modified asphalt binder, stressing experimentation, quality control, and potential environmental solutions.

Chapter 4
Incorporation of the Multi-Layer Plastic Packaging in the Asphalt Binders: Physical, Thermal, Rheological, and Storage Properties Evaluation

This chapter assesses MPP as an asphalt modifier, examining its properties at various concentrations. Findings indicate MPP's potential to improve pavement performance, especially in high temperatures, offering insights for sustainable MPP waste solutions.

Chapter 5
Exploring the Low-Temperature Performance of MPP Modified Asphalt Binders and Mixtures Using Wet Method

The chapter examines MPP additives' potential in enhancing asphalt binders' low-temperature performance, testing doses and analyzing thermoanalytical and rheological properties. The results inform guidelines for MPP use in asphalt modification, improving durability, sustainability, and reducing plastic waste.

Chapter 6
The Influence of Multi-Layer Plastic Packaging (MPP) on the High-Temperature Performance of Asphalt Binders and Mixtures through Wet and Dry Mixing Methods

This chapter explores MPP's potential in enhancing asphalt cement and pavement performance. It compares wet and dry mixing processes, highlighting MPP's effectiveness in improving high-temperature performance, with the wet method being superior.

Chapter 7
A Laboratory Study on Enhancing Asphalt Mixture Properties through Dry Mixing with High Dose Multi-Layer Plastic Packaging (MPP) Additives

This chapter explores MPP additives in asphalt pavement materials to reduce plastic waste and enhance performance. It investigates MPP pellet dosage effects on asphalt mixtures, revealing improved durability and safety.

Chapter 8
Conclusions, Contributions, and Recommendations for Future Research

This chapter outlines conclusions, contributions, and future research recommendations, addressing limitations and gaps. It emphasizes insights, research design improvements, and applying findings to various contexts.

Figure 1-3 Overview of dissertation chapters

1.3 Background

1.3.1 Flexible Pavement

The main function of a pavement structure is to provide a smooth wearing surface that provides acceptable resistance to skidding while redistributing vehicle loading to the underlying soil foundation. There are two main types of road pavement: flexible asphalt pavement and rigid Portland cement concrete pavement. However, this research focuses only on flexible asphalt pavement materials [37]. Flexible pavements consist of an asphalt mixture and granular layers. The pavement structure of flexible pavement (see Figure 1-4) is composed of asphalt-bound layers over unbound drainage layers and natural or prepared subgrade. The function of this type of pavement structure is to decrease and distribute the downward stress generated by traffic volume. The thickness of the pavement structure must be suitable to adequately redistribute the downward stress on the underlying soil foundation in different seasonal environmental conditions.

Figure 1-4 Typical structure of flexible pavement

Flexible pavements are a suitable choice for projects that require less impact and better friction, such as roads, highways, bridges, and airport runways. There are many benefits to using flexible pavements, including cost-effectiveness, reduced construction time, and easier maintenance and repair [38]. However, there are also some limitations in using asphalt mixtures due to environmental concerns. Despite these concerns, flexible pavement materials have continued to develop extensively over the last eight decades in response to engineering needs. One of the major factors that affect flexible pavement is load distribution. To adequately design a flexible pavement that maintains structural integrity, it is essential to properly determine the expected loads that the pavement structure will carry. The primary purpose of the pavement structure is to support wheel loads that create horizontal tensile stresses and strains caused by repeated traffic loads [37]. As shown in Figure 1-5, the bottom of the surface layer has the highest tensile stress and strain of all the pavement layers [37], [39]. Due to these typical traffic loads and environmental conditions, pavement experience deterioration, such as permanent deformation, fatigue cracking, low-temperature cracking, and moisture damage, which will occur over time, decreasing serviceability.

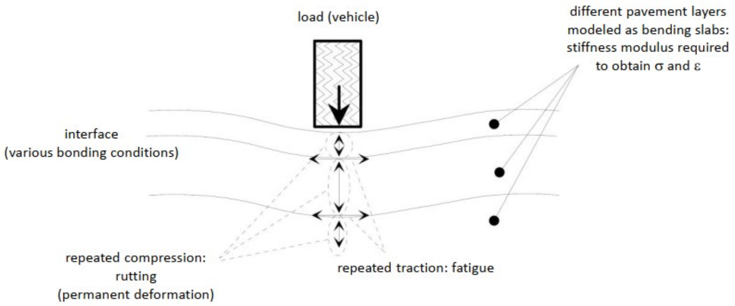


Figure 1-5 Scheme of traffic loads and corresponding flexible pavement response [40], [41]

1.3.2 The Surface Layers

The surface layer in a flexible pavement is typically composed of a compacted asphalt concrete material, which can generally fall under one of the four categories: hot mix asphalt (HMA), warm mix asphalt (WMA), half warm asphalt, and cold mix asphalt; defined based on the mixing and construction temperatures [42]. The mixing temperature range for hot mix asphalt ranges typically between 120°C and 190°C, while it is between 100°C and 150°C for WMA, between 70°C and 100°C for half warm asphalt, and below 40ºC for the cold mix asphalt, which is produced with unheated aggregate and bitumen emulsion or foamed bitumen [42], as shown in Figure 1-6.

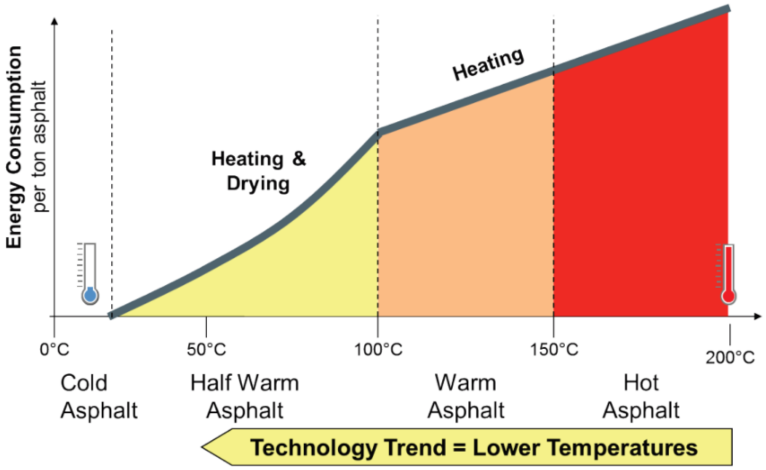


Figure 1-6 Temperature range of asphalt mixture [42]

1.3.3 Hot Mix Asphalt

Hot mix asphalt (HMA) is a preferred option for road construction due to its exceptional durability, resistance to deformation/rutting, and cracking [43]. HMA comprises a combination of mineral aggregates, which usually account for 94 to 96% of the mixture, such as crushed stone, gravel, or sand, and asphalt cement, which typically accounts for 4 to 6%.

Asphalt cement or binder is a viscoelastic material made from natural hydrocarbons that are highly viscous, sticky, and black or dark brown [44]. It is usually derived from oil sands, gilsonite, lakes, and rock formations. Most asphalt cement is a complex mixture of hydrocarbons that differ in molecular weight, viscosity, and boiling temperature. This cement comes from crude petroleum oil with the heaviest part of crude oil, straight-run asphalt binder (also known as liquid asphalt), the residue found after vacuum distillation [38]. Straight-run asphalt cement is usually soft and requires additional processing, including air rectification, mild oxidation, blending, and adding additives such as polymers, to produce suitable grade asphalt binders for road construction in various conditions [38]. Asphalt has many applications, with approximately 85% of total production being used in road construction, 10% used for roofing applications, and the remaining 5% used in a variety of other applications such as sealing, waterproofing, paints, and bonding agents [37], [38], [44]. In Canada, there are two major natural deposits of bituminous sands: one in the Athabasca River valley in Alberta and the other in the Peticodiac River valley in New Brunswick [45].

The mineral aggregates used in HMA are meticulously selected based on their strength and durability, ensuring that the resulting pavement can withstand projected traffic loads and environmental conditions. The asphalt cement acts as a binding agent, holding the mineral aggregates together and endowing the pavement with its waterproofing and adhesive qualities. However, aggregates play a crucial role in carrying loads in HMA by forming a skeleton of the asphalt mixture. They are essential for carrying traffic loads on HMA. The shape, toughness, and abrasion resistance of the aggregate particles determines the performance of HMA. For instance, flaky or elongated aggregates are easier to crush when traffic loads are applied to the pavement, affecting performance and service life. Various types of aggregates can be used to produce HMA, such as natural aggregates, processed aggregates, synthetic aggregates, and waste aggregates.

Natural aggregates, mainly found in a river or glacial deposits, can be used to manufacture HMA without further processing. When natural aggregates are processed to enhance the performance characteristics of the HMA, they are known as processed aggregates. Processed aggregates are often found in quarries and involve crushing and sizing the aggregate particles. Synthetic aggregates are primarily industrial by-products, such as blast furnace slag. More recently, waste products, like scrap tires and glass, have been used more widely as replacements for aggregates in pavement structures [46]. Regardless of their source, processing method, or mineralogy, aggregates are expected to provide a strong stone structure that can resist repeated load applications. Rough and cubical-shaped aggregates are preferred over smooth and rounded aggregates because they provide more strength to the HMA. Cubical aggregate particles tend to lock together better than rounded particles, resulting in a stronger mass of material [47], [48].

The thickness of the HMA layer varies depending on the level of traffic on the road. Thicker HMA layers are necessary for roads with high traffic volumes to endure the increased load. The HMA layer thickness is typically between 40 and 75 mm, although it can be customized to meet specific project requirements [37]. HMA is a versatile material that can be adjusted to meet diverse project specifications. The composition of the mixture can be modified to suit different traffic levels and environmental conditions, guaranteeing that the resulting pavement will perform well throughout its design life [44].

1.3.4 Viscoelastic Material Behaviour

1.3.4.1 Mechanical Behaviour of Asphalt Cements

As depicted in Figure 1-7, asphalt cement is a temperature-dependent viscoelastic material. At higher temperatures, it exhibits a viscous behaviour; at intermediate temperatures, it behaves rubber-like and semi-solid. At colder temperatures, it becomes stiff and brittle. The behaviour of asphalt cement is influenced by the type of loading and temperature conditions it is subjected to. It should be noted that under faster loading rates, asphalt cement exhibits a stiffer response [41], [49], [50].

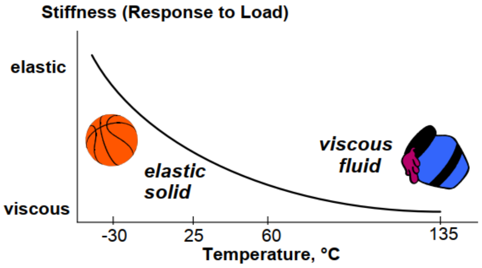


Figure 1-7 Asphalt cement behaviour [51]

Asphalt cement, at a macroscopic level, is assumed to be a continuous, homogeneous, and isotropic material [40], and its behaviour is influenced by: temperature (T), strain amplitude (ε), and number of loading cycles (N). Figure 1-8 demonstrates the mechanical behaviour domains of the asphalt cement binder dependent on temperature and strain amplitude [40], [41].

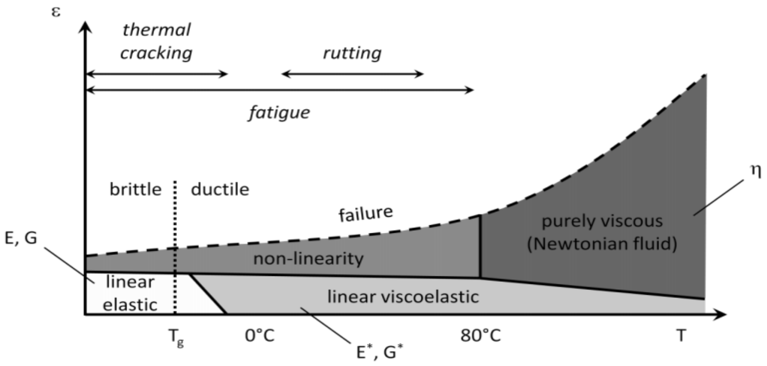


Figure 1-8 Typical mechanical behaviour domains of asphalt cement [40], [41]

In determining the linear viscoelastic limit of asphalt cement, the asphalt material and the test temperature play important roles. However, when asphalt cement is subjected to a large amplitude strain, the mechanical behaviour becomes non-linear. This is not the case at lower temperatures below the glass transition temperature (T_g), in which case, asphalt cement can be treated as a linear elastic material since the viscous aspect of mechanical behaviour can be largely ignored. Fatigue cracking is the typical mechanical mode of failure of asphalt cement when a higher number of cycles and large strain amplitudes are applied at controlled intermediate temperatures, as shown in Figure 1-9. In addition, when the number of cycles increases, and the asphalt binder material is subjected to larger strain amplitude (and/or increased temperature), permanent deformation is more likely to occur [40], [41], [49].

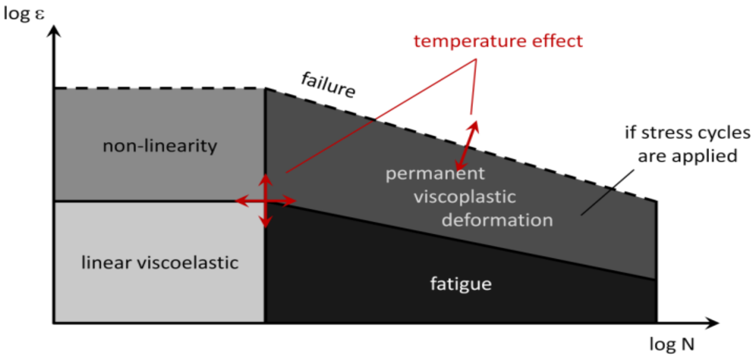


Figure 1-9 Typical mechanical behaviour domains of asphalt cement [40], [41]

At a lower number of cycles, the asphalt cement response will vary according to strain amplitudes. Lower strain levels with a lower number of cycles lead to linear viscoelastic behaviour. On the other side, higher strain levels under a lower number of cycles can lead to non-linearity. This means that strain levels and the number of cycles play an important role in determining the mechanical behaviour of asphalt cement. In other words, permanent viscoelastic deformation occurs when both an increased number of cycles and high strain levels are present. In contrast, fatigue failure occurs when the number of cycles is increased, regardless of whether strain amplitude is increased [40], [41], [49].

1.3.4.2 Mechanical Behaviour of Asphalt Mixtures

In terms of asphalt mixtures, strain amplitude and the number of cycles have the greatest impact on their viscosity and are proportionately related to temperature (for example, high, intermediate and low temperatures). In Figure 1-10, the mechanical behaviour of the asphalt mixtures is presented in terms of the changes in strain amplitude and the number of cycles (note: the Y-X axis scale uses a logarithm base 10) [40], [41], [49].

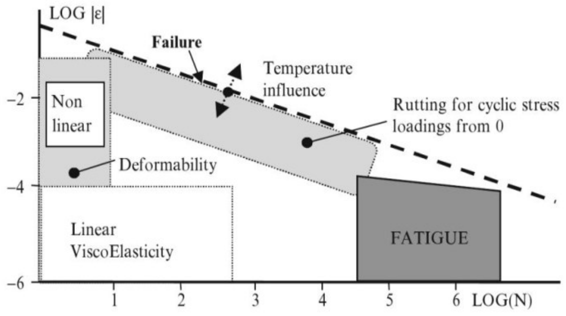


Figure 1-10 Typical mechanical behaviour domains of asphalt mixtures [40], [41]

The unique characteristic of pure elastic solid materials is the immediate deformation corresponding to sinusoidal loads. However, viscous fluids are characterized by the occurrence of a phase lag angle of 90˚ from the moment the load is applied to the time deformation begins. The phase lag (phase angle-φ) for viscoelastic materials ranges between 0˚ and 90˚, Figure 1-11.

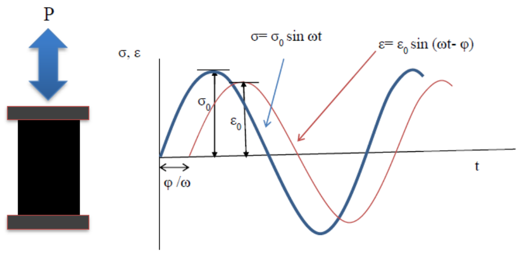


Figure 1-11 Viscoelastic material stress-strain response [27]

1.3.5 Pavement Distresses

Premature pavement deterioration leads to reduced service life and is caused by the applied loads and different environmental conditions to which the pavement is subjected. Mechanical loading induced by heavy traffic and thermal loading induced by thermal changes is external loads faced by road pavement. Pavement damage can take different forms, such as permanent deformation (surface rutting), fatigue failure and low-temperature cracking [39], [46], [52].

1.3.6 Permanent Deformation

Permanent deformation is defined as rutting, see Figure 1-12, which is caused by the sum of repeated traffic loading in each pavement structure layer [37], [53]. The two main factors for permanent deformation are the ambient temperature and loading magnitude. High temperature accelerates permanent deformation in heavy and slower-moving traffic [54]. Permanent deformation is further associated with the type of road construction, which determine the pavement structure layers, the rheological properties of the asphalt cement binder, such as viscosity and penetration, and air voids in the asphalt mix [54]–[57].

Figure 1-12 Permanent deformation damage [58]

1.3.7 Fatigue Cracking

Fatigue cracking is one of the predominant forms of failure experienced in flexible pavement and occurs when traffic load is repetitive over an extended period of time, see Figure 1-13 [51], [59]. Several factors affect the fatigue life of flexible pavement; these factors include asphalt cement binder properties, temperature, air voids content, and aggregate composition and graduation [40], [60]–[62]. Typically, the initiation of fatigue cracking occurs at the bottom of the surface layer of hot mix asphalt, where the maximum tensile strains occur and propagate toward the surface due to repeated traffic load [52].

Figure 1-13 Fatigued cracking in pavement (Waterloo, Canada)

Fatigue cracking has three stages: crack initiation, stable fatigue crack growth, and unstable fatigue crack growth [63]. According to National Cooperative Highway Research Program (NCHRP) publication in 2011, fatigue cracking can be categorized into two types: top-down and bottom-up, as shown in Figure 1-14. In addition, improper pavement drainage has been identified as one of the primary reasons for fatigue cracking and premature pavement failure [43].

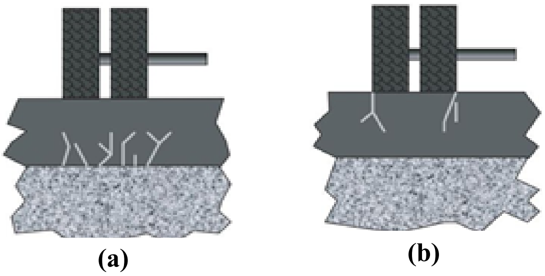


Figure 1-14 a) Bottom-up fatigue cracking b) Top-down fatigue cracking [64]

1.3.8 Low-Temperature Cracking

Low-temperature “thermal” cracking, see Figure 1-15, primarily occurs in regions with cold climate conditions [65]. This temperature is referred to as the fracture or cracking temperature. In regions such as Canada, where low temperatures extend over longer periods and fluctuate, thermal cracking is more severe [39], [66]. The tensile thermal stresses in the asphalt layer result in the shrinking of the restrained asphalt mixture at a critical point where the crack initially forms. In other words, transverse cracking appears on the pavement surface when the accumulation of the tensile stresses is greater than the tensile strength of the asphalt pavement materials [39].

Figure 1-15 Low-temperature (transverse) cracking (Waterloo, Canada)

1.3.9 Asphalt Mix Design

Over the last few decades, the Hveem, Marshall, and Superpave design methods have been the most common methods for asphalt mixes worldwide. In North America, the Superpave method is widely used due to its integrated approach to addressing traffic load and climate. Superpave was established by the United States Department of Transportation Federal Highway Administration (FHWA) in the late 1980s as part of the Strategic Highway Research Program (SHRP). It is still considered an improvement over the Hveem and Marshall methods [48], [51].

The Superpave asphalt mix design follows four steps: (1) material selection, (2) selection of the aggregate design structure, (3) selection of the design asphalt cement content, and (4) evaluation of moisture sensitivity in the mixture [48]. Two main mechanistic aspects make the Superpave mixture design method more beneficial than the other aforementioned methods. These two features are:

(1) An asphalt-grading system, Performance Grading (PG), matches the physical binder properties to the desired level of pavement distress, including resistance to rutting, fatigue, and low-temperature cracking; and

(2) A design for the aggregate structure based on volumetric analysis and requirements [48].

In 1987, the Council of Deputy Ministers Responsible for Transportation and Highway Safety introduced and later adopted the Superpave asphalt design method for Canadian roads under the Canadian Strategic Highway Research Program (C-SHRP). The Canadian pavement industry began using the Superpave system in Canada, which has become the standard procedure for designing asphalt mixtures (C-SHRP, 2013). Therefore, the Superpave asphalt design system is used in this research.

1.3.9.1 Asphalt Binder Performance Grade

Asphalt binders' physical properties and performance depend on the traffic volume and climate conditions in the roadway location. Asphalt binders are typically classified based on their physical properties and performance. When low-temperature asphalt binder cement properties are required, the preferred method for asphalt design is Superpave [51], [68], [69]. Although conventional grading tests can determine the physical properties of asphalt cement, such as penetration, softening point, and viscosity at high and intermediate temperatures, they cannot determine these properties at low temperatures, which is why Superpave is used in Canada.

Superpave not only considers the climate conditions and applied load stress but also determines performance in terms of aging behaviour. Superpave simulates critical stages of binder life, including transport, mixing production and construction (simulated by a rolling thin-film oven or RTFO), and long-term pavement serviceability (simulated by a pressure-aging vessel or PAV). The Superpave binder test and standards are summarized in Table 1-1. The grades of asphalt can be presented as Performance Grade (PG) or Performance Grade Asphalt Cement (PGAC) XX-YY, according to Superpave specifications (see Figure 1-16). XX represents high-temperature service in degrees Celsius, and YY represents low-temperature service in degrees Celsius. For example, if the PG binder designation is PG 58-28, 58°C represents the high-temperature working limit of the asphalt cement, and -28°C represents the low-temperature limit based on the Superpave test methods [48].

Table 1-1 Superpave Binder tests [48]

Superpave Binder Tests	**Purpose of Use**	**Standard Designation**
Dynamic Shear Rheometer (DSR)	Determine asphalt binder properties at high and intermediate temperatures	AASHTO T 315 AASHTO R 29
Rotational Viscometer (RV)	Determine asphalt binder properties at high temperatures	AASHTO T 316
Bending Beam Rheometer (BBR) Direct Tension Tester (DTT)	Determine asphalt binder properties at low temperatures	AASHTO T 313 AASHTO T 314
Rolling Thin Film Oven (RTFO) Pressure Aging Vessel (PAV)	Simulate hardening (aging)	AASHTO T 240 AASHTO R 28

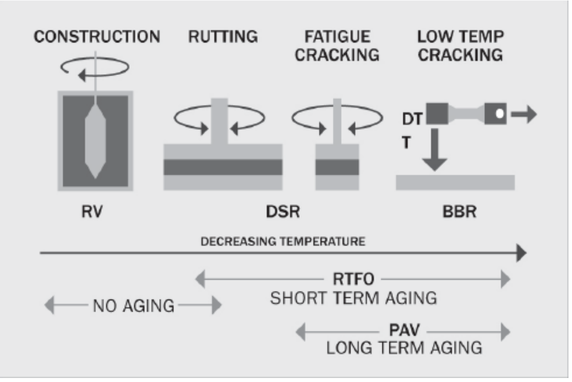


Figure 1-16 Performance grade asphalt cement [70]

1.3.9.2 Mixture Performance Tests

After preparing HMA samples based on the Superpave design criteria outlined in AASHTO R 30, it is recommended that the asphalt mixture undergo a series of performance testing experiments to quantify its mechanical properties. This data is crucial for better understanding the asphalt mixture's potential field performance. Therefore, the asphalt mixture performance testing protocols are designed to simulate various loading and environmental conditions, summarized in Table 2-1. To fabricate test specimens for Complex (Dynamic) Modulus, Hamburg Wheel Rutting Tester, Indirect Tensile Strength, and Tension-Compression Fatigue tests, samples are prepared using AASHTO PP 60 and the Superpave Gyratory Compactor (SGC). For Four-Point Bending Fatigue and Thermal Stress Restrain Specimen Test, specimens are prepared using a Shear Compactor. After preparing HMA samples based on Superpave design criteria, AASHTO R 30, the recommended asphalt mixture, should be tested through a series of performance testing experiments to quantify the mechanical properties of the asphalt mixture.

Table 1-2 Mixture Performance Tests

Performance tests	**Purpose of Use**	**Standard Designation**
Complex (Dynamic) Modulus (CM)	Characterize stiffness for the asphalt mixtures at different temperatures and various load frequencies	AASHTO T 342
Indirect Tensile Strength (ITS) Creep Compliance Test (CCT)	Evaluate the moisture susceptibility of the asphalt mixtures Evaluate the low-temperature resistance of the asphalt mixtures	AASHTO T283 AASHTO T 322

Hamburg Wheel Tracking Test (HWTT)	Examine the rutting resistance of the asphalt mixtures	AASHTO T 324
Four-Point Bending Fatigue (4PBF) Tension-Compression Fatigue (TCF)[1]	Determine the fatigue life of the asphalt mixtures	AASHTO T 378 AASHTO T 321
Thermal Stress Restrain Specimen Test (TSRST)	Evaluate the low temperature cracking of the asphalt mixtures.	AASHTO TP 10

---

[1] If applicable

2. Literature review

2.1 Polymer Modified Asphalt

Using polymer modification in asphalt binders is a major advancement in constructing flexible pavements. It offers numerous benefits to the functional properties of pavements, including resistance to various forms of distress such as rutting, fatigue, low-temperature cracking, stripping, wear resistance, and aging [10]–[12]. Engineers and material researchers have been modifying binder properties to mitigate these challenges to create an ideal mix, as shown in Figure 2-1 [24]. Various polymers have been successfully attempted in research, but only a few have shown high overall performance in terms of pavement service life. Some examples of these polymer modifiers include styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR), ethylene-vinyl acetate (EVA), as well as virgin or waste polyethylene modifiers. However, the selection of the appropriate polymer type for a specific application depends on several factors, such as the desired physical and mechanical properties of the composite mixture of the asphalt pavement, its availability, and production cost [34], [49], [54], [59], [71]–[73]. The type of polymer most suitable for achieving long-term pavement service life will depend on several other factors such as local climate, traffic volume, road construction method, and the roadway's functional class. The polymer type must be selected carefully to ensure that the pavement is durable, resilient, and able to withstand the challenges of heavy traffic and harsh environmental conditions, leading to longer-lasting, safer, and cost-effective roadways [13], [14], [74], [75]. Engineers and material researchers need to consider all these factors before selecting the appropriate polymer type to create an ideal mix for constructing long-lasting pavements.

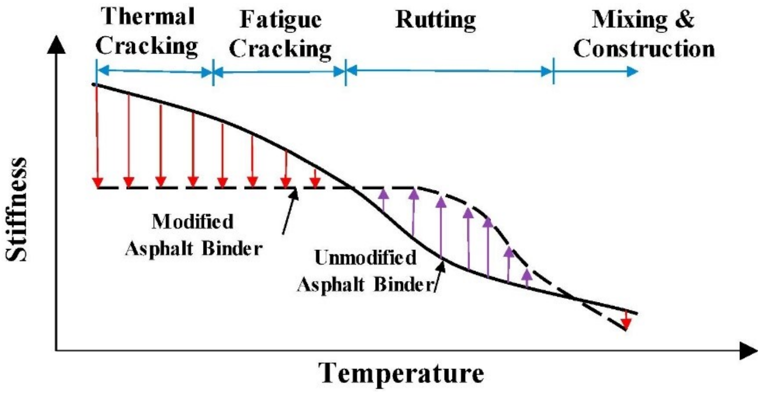


Figure 2-1 The expected behaviour in the rheological properties of modified asphalt binders[24]

2.2 Polymer Structure

Polymers have a larger chain of repeating monomer molecules. These larger chains can have different forms, such as simple straight chains or variations of linked and cross-linked chains (as shown in Figure 2-2). The chain's structure and chemical composition influence the polymer's behaviour. Although different kinds of polymers have been used in asphalt modification, the most commonly used are thermoplastic elastomers, plastomers, reclaimed tire rubbers and, to a lesser extent, viscosity modifiers and reactive polymers [14], [24], [75]. For example, due to the cross-linking of the SBS molecules into a 3-D network, the asphalt binder becomes stronger and more elastic, according to Airey [71]. Table 2-1 summarizes the most common polymers used in asphalt modification showing their advantages and disadvantages [34]. Due to the scope of this research, only by-product plastomer type polymers will be examined as an alternative additive for asphalt pavement modification.

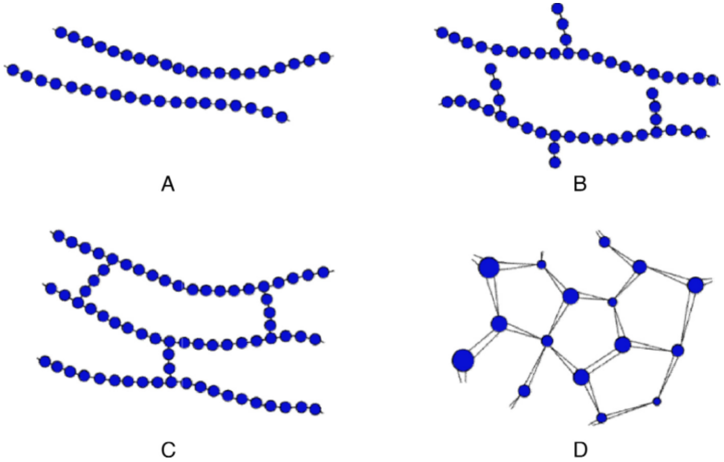


Figure 2-2 Schematic of different polymer molecular structures: (A) linear, (B) branched, (C) crosslinked, and (D) network polymers [76]

Table 2-1 Common polymers used in asphalt modification [34]

Groups	Examples	Advantages	Disadvantages
Plastomers	Polyethylene (PE) Polypropylene (PP)	Good performance at high temperatures, and it is relatively inexpensive	Limited improvement in elasticity, low temperatures and issues with phase separation
	Ethylene-vinyl acetate (EVA) Ethylene-butyl acrylate (EBA)	Good storage stability and a high level of resistance to rutting	Slight improvement in elastic recovery, and it does not significantly enhance low-temperature properties

Thermoplastic elastomers	Styrene-butadiene-styrene (SBS) Styrene-isoprene-styrene (SIS)	Enhanced stiffness, reduced sensitivity to temperature changes, and improved elastic response	Face compatibility issues with certain bitumen, and it has lower resistance to heat, oxidation, and ultraviolet radiation. Additionally, it tends to be relatively expensive
	Styrene ethylene/butylene-styrene (SEBS)	Exhibits excellent resistance to heat, oxidation, and ultraviolet light.	Storage instability issues, lower elasticity, and expensive.

2.3 Plastomers

Thermoplastics soften when heated and harden when cooled. Primary examples of thermoplastic plastomers that increase the stiffness and viscosity of asphalt binder at normal service temperatures include Polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polystyrene (PS) and various ethylene copolymers (semi-crystalline polymers), such as ethylene vinyl acetate (EVA), ethylene butyl acrylate (EBA) and ethylene methyl acrylate (EMA) [28], [77]. These polymers tend to influence the penetration of the asphalt binder more than its softening point. In recent decades, the main plastomers used in asphalt modification have been polyethylene, polypropylene, polyvinyl-chloride, polystyrene and ethylene-vinyl acetate copolymer [77]. Overall, the use of thermoplastic plastomers in asphalt binder modification has shown promise in increasing the stiffness and viscosity of the binder at normal service temperatures. This increase enhances the pavement's resistance to rutting, which is a significant challenge in road construction [28], [77]. While plastomers may not be as effective in resisting thermal cracking at low temperatures, they are still a viable option for improving asphalt pavement performance, especially in warmer climates [10]. Engineers and material researchers should consider all these factors before selecting the appropriate thermoplastic plastomer to create an ideal mix for constructing long-lasting pavements.

2.4 Incorporation Methods of Polymers

Incorporating polymers into asphalt mixes can be accomplished using two common methods: the dry process and the wet process [13], [24], [78]. The wet method involves using unmodified asphalt cement and adding solid polymer additives directly to the hot asphalt cement, then mixing with the aggregate to produce modified asphalt mixtures. The mixing time and temperature depend on the properties of the asphalt binder and additives. The use of waste plastic polymers as a modifier has been studied in terms of their thermal stability and the degradation of the rheological properties of the asphalt binder [27], [28], [79]. To preserve the desired rheological properties of the asphalt binder and prevent fire, the mixing temperature should not exceed 180°C or 185°C, as suggested by Garcia-Morales et al. and Read et al., respectively [27], [38]. These studies also emphasize the need for sufficient mixing and shearing time to effectively disperse the waste additive polymers into the asphalt cement matrix.

On the other hand, the dry method involves adding a mixture of solid polymers and aggregates directly to the asphalt cement mix without any prior modification. The dry method has been used in various studies, including Awwad and Shbeeb, to mix high-density and low-density polyethylene, which improved the adhesion between the asphalt binder and the aggregate, resulting in better pavement deformation and fatigue resistance [80].

The dry and wet methods for incorporating polymer into asphalt mixes have advantages and disadvantages. To ensure long-term pavement service life, engineers and material researchers must consider several factors, such as the availability of the polymer and its production cost. Selecting a suitable polymer for the specific road construction project is essential. However, it is important to remember that the chosen polymer may not be compatible with the local climate, traffic volume, road construction method, and the roadway's functional class. Choosing the right polymer and incorporation method is crucial in achieving an optimal mix for constructing durable pavements.

2.4.1 Influencing Factors on PMA Properties

Several factors in the literature strongly influence binder properties when virgin or waste polymers modify the asphalt cement. The main factors are discussed below:

2.4.1.1 Chemical Composition of Asphalt Cement

The characteristics of the base asphalt cement play a crucial role in determining the properties of the resulting modified asphalt binder due to its complex chemical composition. When asphalt cement is modified with a polymer, its chemical composition undergoes significant changes that can alter the overall molecular structure of the binder. These changes can significantly impact the durability, hardening, and viscoelastic properties of the modified asphalt binder [81], [82].

Asphalt cement (Bitumen), a complex mixture of hydrocarbons, sulfur, oxygen, nitrogen, and trace amounts of metals such as vanadium, iron, nickel, calcium, and magnesium, can be divided into two main chemical groups: asphaltenes and maltenes, with maltenes having three subcategories: saturates, aromatics, and resins. Techniques such as chromatography, molecular distillation, and solvent extraction are commonly used to separate bitumen into fractions, with the SARA method being the most widely used for analysis.

Asphaltenes are amorphous solids that are brown or black and not soluble in h-heptane. They contain oxygen, sulfur, hydrogen, nitrogen, and carbon and have high molecular weight and complex aromatic materials with high polarity. The rheological properties of bitumen are significantly affected by the amount of asphaltene content, which typically ranges from 5% to 25%. Asphaltenes have a molecular weight ranging from 600 to 30,000, and an increase in asphaltene content leads to higher viscosity, higher softening point, and lower penetration in bitumen. Resins are primarily composed of carbon and hydrogen, are soluble in n-heptane, and have a molecular weight ranging from 500 to 50,000. The ratio of resins to asphaltenes determines if the bitumen is gelatinous (GEL) or a solution (SOL). Aromatics are viscous solids that are dark brown to black, making up approximately 40% to 65% of bitumen. They have a molecular weight ranging from 300 to 2000 and possess high dissolving power and non-polarity compared to other hydrocarbons with higher molecular weight. Saturates, non-polar viscous oils, are either straw or white-coloured and account for 5% to 20% of bitumen. Saturates contain waxy and non-waxy saturates and mainly consist of straight and branched-chain aliphatic hydrocarbons.

The Gaestel Index, also known as the colloidal index (CI), measures the ratio of asphaltenes and saturates to resins and aromatics, indicating the stability of the colloidal structure in bitumen. A lower CI indicates a more stable colloidal structure, indicating an SOL-type bitumen, while a higher CI indicates a GEL-type bitumen. The mechanical, rheological, and physical characteristics of asphalt binders depend on the chemical composition and physical properties of the molecules[38], [83], [84].

The modified binder's viscoelastic properties are critical for predicting its performance in pavement applications, and the changes in its chemical composition after polymer modification can significantly impact these properties. These changes include increases in the stiffness and softening point of the binder and improvements in its resistance to rutting and fatigue cracking [81], [82]. These modifications can lead to increased durability and longevity of the pavement. Overall, the complex chemical composition of asphalt and its modification with polymers necessitates careful consideration of several factors, such as the type and amount of polymer used, the mixing conditions, and the aggregate properties, to achieve the desired performance characteristics of the modified binder.

2.4.1.2 PMA Viscoelastic Behaviour

The Glass Transition Temperature (T_g) is widely recognized as a crucial factor in determining the viscoelastic properties of amorphous polymer materials [85]. T_g refers to the temperature at which a reversible transition occurs in the amorphous domain of the material, resulting in a shift from a rubbery or viscous state to a hard, brittle, and glassy state [86]. Figure 2-3 illustrates the typical behaviour of high molecular weight, viscoelastic polymers over time and temperature. Polymer-modified asphalt (PMA) displays time and temperature dependence in all four regions: glassy, transition, plateau, and flow. In contrast, unmodified asphalt binders do not exhibit this rubber-like behaviour and transition directly from the glassy region to the flow region [24], [79], [87], [88]. The T_g becomes a critical parameter for studying the rheological properties of the modified asphalt binder at low temperatures [89]. Adding polymer to the asphalt mixture can reduce thermal cracking at low temperatures, fatigue cracking at intermediate temperatures, and permanent deformation at high temperatures. In special low-temperature situations, the polymer can be used to modify the soft-grade base asphalt binder, demonstrating that the polymer directly impacts the softening of asphalt binders [90], [91].

Several parameters can impact the glass transition and phase stability in asphalt binders, including molecular weight, functional and structural groups, cross-linking and molecular interactions, crystallinity, and dilution [24], [86], [92], [93]. The molecular weight of the polymer can influence the degree of chain entanglement. At the same time, the presence of functional and structural groups can affect the intermolecular forces and bonding in the polymer matrix. Cross-linking and molecular interactions can also impact the properties of the polymer-modified binder, leading to changes in stiffness and viscosity. Crystallinity and dilution can affect the polymer distribution and stability within the binder, which can influence the overall performance of the asphalt mixture. Overall, understanding the T_g and its impact on the viscoelastic properties of polymer-modified asphalt is critical for designing asphalt mixtures with desired performance characteristics. The selection of appropriate polymer types, molecular weights, and mixing conditions can be optimized to achieve the desired stiffness, viscosity, and resistance to deformation and cracking.

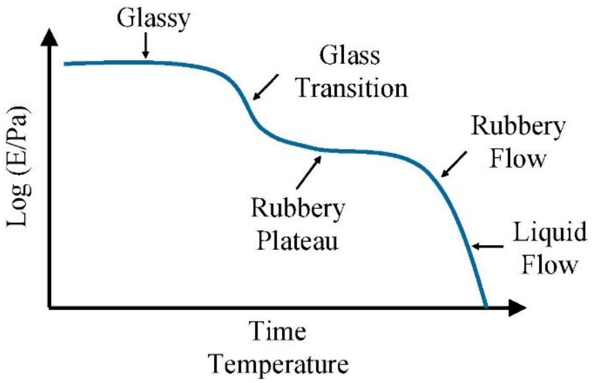


Figure 2-3 Typical behaviour of Viscoelastic PMA[24]

2.4.1.3 Compatibility of Modified Asphalt

Several studies have established that adding polymers to asphalt binder can enhance its rheological properties. However, achieving a homogeneous mix between the binder and the polymer can be challenging due to the large number of molecules involved, their weight, density, and viscosity [13], [94]. The particle size of the polymer additives also plays a significant role in achieving a stable blend. The physical mixing of thermoplastic polymers with asphalt binder can occur in two phases: swollen polymers and non-interaction of the polymer components. Increasing the percentage of polymer in the asphalt blend can significantly improve the physical properties of the mix, such as plasticity interval, tensile strength, and elasticity while reducing thermal sensitivity [13], [24]. The chemical composition of the polymer also plays a crucial role in the chemical stabilization of the asphalt binder via the formulation of chemical cross-linking. For instance, Figure 2-4 shows the interaction between malleated asphalt binder and recycled Low-Density Polyethylene (LDPE) [95].

In contrast, other types of polymers may undergo similar linkage. Ali et al. noted that at low temperatures, the mechanical properties of the asphalt mixtures are affected by the original grade asphalt binder, leading to cracking. However, polymer modification can reduce low-temperature cracking [96].

The challenges associated with achieving a homogeneous mix must be addressed to ensure the optimal performance of polymer-modified asphalt binders. Various methods, including high-shear mixing, ultrasonic mixing, and chemical modification of the polymer, have been explored to improve the homogeneity of the mix. In addition, selecting the appropriate polymer type, dosage, mixing temperature and time, and aggregate type and gradation can also help achieve a more uniform and stable mix. The chemical crosslinking of the polymer and binder can also improve the stability of the mix and enhance its long-term performance. By carefully considering these factors, engineers and material researchers can develop polymer-modified asphalt mixtures with superior performance and improved durability.

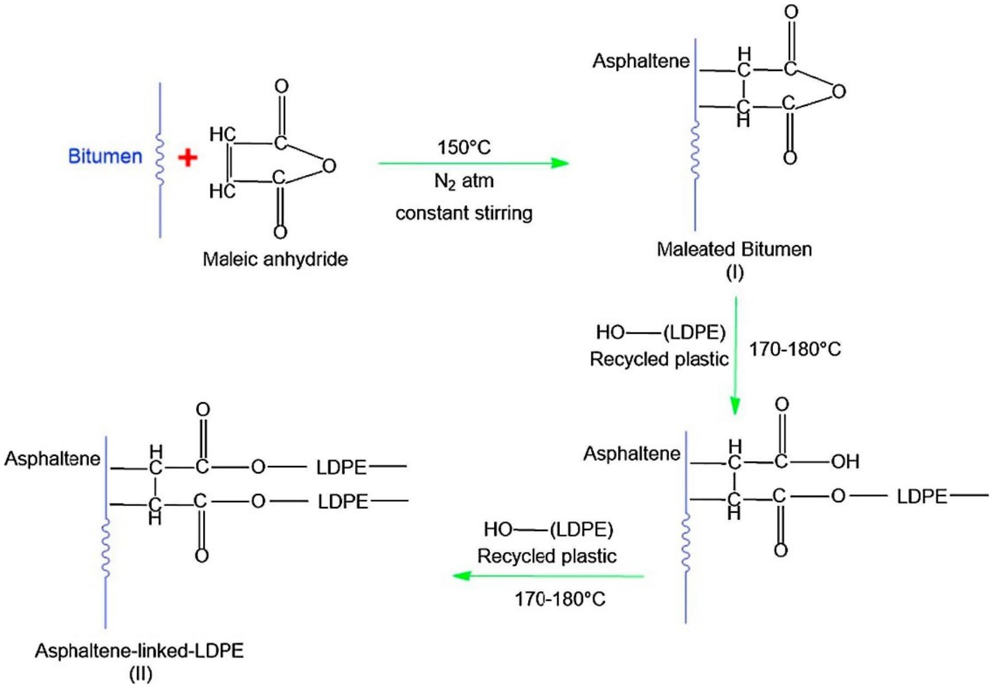


Figure 2-4 Schematic of interaction between maleated (Bitumen) asphalt binder and recycled LDPE[24], [95]

Fluorescence microscopy is one of the common techniques that can be used to verify the micro-structure and the compatibility of the modified asphalt polymer blend. According to Fang, the recommended amount of waste polyethylene (WPE) should be kept below 10% due to an increase in particle aggregation when an increase in the content of WPE is more than 10% [97], as shown in Figure 2-5.

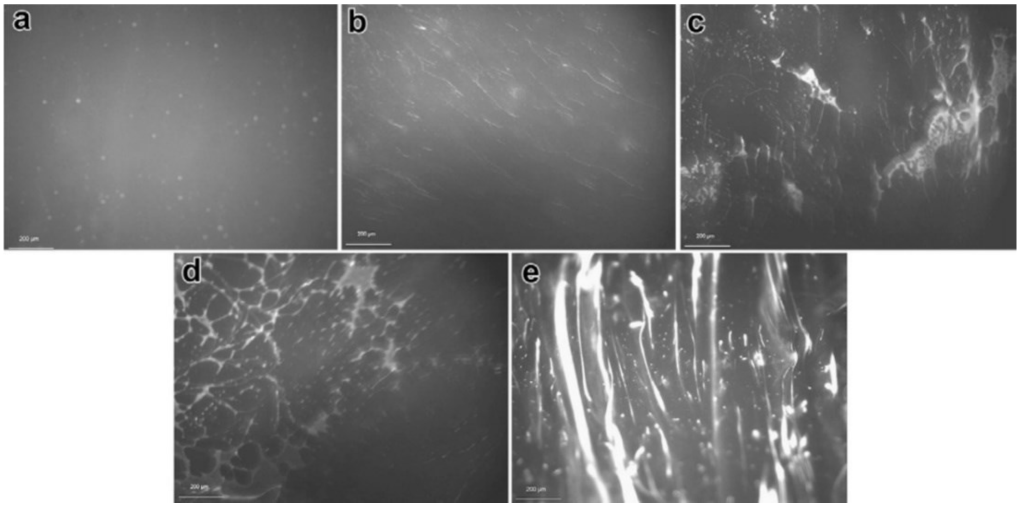


Figure 2-5 Microstructure of waste polyethylene-modified asphalts with (a) 2 wt%, (b) 4 wt%, (c) 6 wt%, (d) 8 wt%, (e) 10 wt%[24], [97]

2.4.1.4 Mixing Conditions

Several parameters influence mixing conditions, including the polymer's nature and form, the asphalt cement's physical properties, and the mixing method, time, and temperature. It is crucial to know the physical properties of the polymer, such as molecular weight, size, shape, and chemical composition, because they play a significant role in determining the mixing time [13], [38]. Additionally, the physical and chemical composition of the asphalt binder determines the binder's viscosity, which affects the selection of an appropriate polymer additive. Finally, the mixing method, time, and temperature should be based on the chemical composition of the binder and polymer being mixed.

Although high mixing temperatures can increase the incorporation of polymer particles into the asphalt binder mix, unreasonably high temperatures should be avoided because they negatively impact the thermal resistance of the polymer and asphalt structures [98], [99]. Therefore, the lowest mixing temperature for the shortest possible mixing time should be used to ensure that the polymer particles are fully incorporated into the asphalt binder blend. Mixing polymer particles into the binder mix can be difficult at high temperatures due to the large difference in viscosity between the asphalt and polymer [24]. Hence, high-shear or low-shear methods should be used depending on the size of the polymer particles. For example, high-shear mixing is preferable for large particles to reduce their size, while low-shear mixing is preferable for powder and liquid modifiers. Colloidal mills are preferable in the mixing plant as they allow small polymer particles and asphalt binder to flow through narrow clearances and gaps at high temperatures [24].

2.4.2 Mitigating the Drawbacks of PMA

Not all Polymer Modified Asphalts (PMA) have the same characteristics; using some polymers, PMA may have several drawbacks that can impact their performance, including aging, oxidation, cracking, and rutting. However, several techniques and materials can be used to mitigate these drawbacks and improve the long-term performance of PMA. Antioxidants, such as phenolic antioxidants, amine antioxidants, and hindered amine light stabilizers, can improve the aging and oxidation resistance of PMA, thereby increasing the pavement's service life. Adding fibers to PMA can also improve its strength, toughness, and durability while reducing cracking and rutting. Nanomaterials, such as nanoclay or carbon nanotubes, can improve the stiffness, strength, and durability of PMA, reducing thermal cracking and rutting [24], [100]. Warm mix asphalt (WMA) is an alternative to hot mix asphalt (HMA) that can reduce energy consumption and greenhouse gas emissions [101]. Using WMA can also improve the workability and compaction of PMA, as well as its long-term performance. Incorporating crumb rubber from waste tires into PMA can improve its elasticity, durability, and resistance to cracking and rutting while reducing its temperature susceptibility. Rejuvenators can also be used to restore the aging properties of PMA, improving its flexibility and resistance to cracking [102]. By employing these techniques and materials, it is possible to mitigate the drawbacks of PMA and improve its long-term performance. This can lead to more durable and sustainable pavement solutions, reducing the need for frequent maintenance and repairs and ultimately providing greater value for transportation agencies and road users.

2.5 Waste/Recycled Plastic Additives in Asphalt Modification

While virgin polymers have been shown to improve the properties of asphalt binder, their high cost and limited compatibility with the binder in larger amounts have led researchers to explore waste polymers as an alternative. Not only does using waste polymers as asphalt modifiers offer similar performance improvements, but it also provides an economical and environmentally friendly solution for waste plastic disposal. This has been the focus of studies for the past 40 years, with polypropylene (PP) being a commonly used recycled additive in asphalt mixtures. Polyethylene (PE), found in a range of applications, including plastic bottles, packaging, and single-use bags, is also being explored as a potential additive [24], [103]. The use of waste polymers as an asphalt modifier has the potential to provide a more sustainable and cost-effective approach to road construction and maintenance [13], [104], [105].

Hinisliglu and Agar found that using waste plastic of HDPE as a polymer modifier, with different mixing times (5 min, 15 min, and 30 min), temperatures (145°C, 155°C, and 165°C), and percentages of HDPE (4%, 6%, and 8% of the weight of asphalt binder), resulted in binders with higher stability and strength. Additionally, these binders had a higher Marshall quotient value, which improved their resistance to permanent deformation. In addition, the optimum result for Marshall stability was found when 4% of HDPE was added and mixed for 30 minutes at 165°C [72]. Garcia-Morales et al. [27] found a similar result to that of Hinsisliglu and Agar in their study of the rheology of recycled polymer-modified asphalt binder. The Garcia-Morales et al. study used flow behaviour of 60/70 penetration grade asphalt binder modified with 5% and 9% waste EVA/LDPE at low, intermediate and high temperatures. Their study showed the modified recycled EVA/LDPE asphalt binder had improved mechanical properties resulting in an improvement in the overall performance of road service life. In addition to these improvements, adding waste plastic contributed to the disposal of waste plastic.

Awwad and Shbeeb [80] experimented by adding two types of polyethylene (i.e., LDPE and HDPE) with two shapes (i.e., ground and unground) to modify bitumen in HMA mixes. The Marshall mix design was used to determine the optimum binder content and the properties of the modified mixtures. After adding seven different portions of 6%, 8%, 10%, 12%, 14%, 16% and 18% in both the ground and unground state, the mix showed better resistance against rutting. In Awwad and Shbeeb's study, fatigue and permanent deformation were improved by modifying the asphalt with polyethylene due to the better adhesion between the aggregate and asphalt [80]. According to Casey et al., 2008 [106], when 4% of the waste HDPE was added to modify the binder, the optimum fatigue and rutting resistance performance were achieved.

Hadidy and Yi-qiu [73] confirmed the findings of the aforementioned studies, namely, that the improvement of the softening point was directly related to an improvement in permanent deformation. Furthermore, adding LDPE in the modified asphalt binder improved the ductility at both high and low-temperature regions. According to Fang, when modified asphalt binder with both polyethylene packaging waste (WPE) and organophilic montmorillonite (OMMT), the fundamental properties of the modified asphalt binder significantly improved high-temperature performance, and low-temperature cracking resistance [107].

In their study, Maharaj concluded that the particle size and the amount of the waste polyethylene terephthalate (WPET) used impacted the asphalt binder in terms of fatigue cracking and rutting resistance [108]. Wang's study on the use of WPET and rubber modification found that the rheological properties of the asphalt binder were enhanced after modification at different temperature ranges. The density difference must be reduced to acquire stable modified asphalt binder, and the interaction must be enhanced [109]. However, there was a slight difficulty in the compatibility between PE and asphalt binder due to the crystalline property of WPET when mixed with an asphalt binder [97]. Furthermore, there was no improvement in asphalt binder performance at low temperatures when only WPET particles were added [110]. According to Kim, WPET particles separate from asphalt binder when improperly stored, thus restricting WPET-modified asphalt binder[111]. According to Dalhat et al., PETs that have been processed to have finer dimensions (sieves No. 8 to No. 40) have superior moisture resistance when compared to PETs with sizes ranging from passing No. 8 to No. 10 [112]. Researchers have also found that incorporating 12% PET into asphalt mixtures can significantly improve pavement service life, extending it 2.81 times while reducing the required thickness of the asphalt layer by approximately 20% [113].

According to Ho et al., waste LDPE as an asphalt modifier is influenced by molecular properties such as molecular weight (Mw) and its distribution, which can affect the low-temperature properties, hot storage stability, and polymer phase morphology of the asphalt. The study found that LDPE with lower Mw and broader molecular weight distribution (MWD) is more appropriate for asphalt modification. Figure 2-6 illustrates that waste LDPE particles are more uniformly dispersed in the asphalt at higher MWD when Mw is similar. The same trend is observed for lower molecular weights with similar MWDs [114], [115].

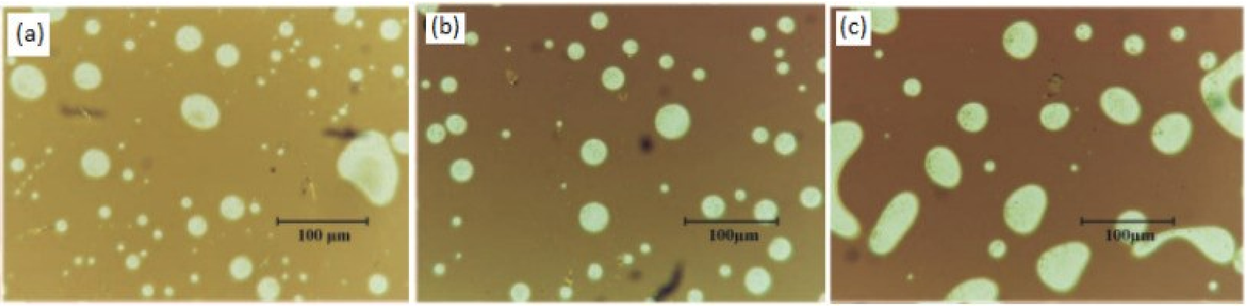


Figure 2-6 Phase morphology of waste LDPE (2 wt.%) as asphalt modifier: (a) Mw=736764, molecular weight distribution (MWD, Mw/Mn)= 3.73; (b) Mw=82715, MWD =6.13; (c) Mw=128165, MWD =6.49 [114], [115]

According to [33], the addition of polypropylene, high- and low-density polyethylene (PP, HDPE and LDPE)-recycled plastic wastes (RPW) to asphalt can enhance its rutting performance and increase its upper PG limit by at least one grade for every 2% rise in RPW. Additionally, a correlation was established between the resilient modulus (MR) of asphalt concrete and the non-recoverable creep compliance (J_{nr}) of the asphalt binder. By leveraging the viscoelastic attributes of RPW-modified binder, a typical pavement segment was simulated using AASHTO MEPDG software, which forecasts considerable improvements in rutting and fatigue performance. In laboratory tests, Baghaee Moghaddam et al. evaluated the impact of waste polyethylene terephthalate WPET on the stiffness and permanent deformation of asphalt mixtures. The results showed that the temperature variation, WPET content, and stress level significantly influenced the stiffness of the asphalt mixture. In addition, he found that WPET modification decreased permanent strain, resulting in excellent resistance to permanent deformation [52], [54]. However, given the application area of this study, low-temperature cracking and moisture damage were not of concern and hence were not evaluated. As a result, more in-depth research into using waste plastic polymer additives is required.

Lu et al. focused on evaluating the future recyclability of plastic-modified asphalt at the end of its service life (P-RAP) through mechanical testing. The study used three different mixing methods to produce P-RAP and incorporated it into a new hot mix at 30% before testing its various properties. The study's findings revealed that P-RAP produced through all three mixing methods was completely recyclable and performed similarly to standard RAP mixes. The study's results provide practitioners with the confidence that P-RAP can be recycled and reused as conventional RAP after its service life instead of being discarded as waste [116].

2.5.1 Incorporation of MPP in Asphalt

As mentioned in Section 2.4, the dry and wet processes are the two most common methods to incorporate polymer into the asphalt mix. Thus, it has been adopted to incorporate waste plastic into asphalt materials. The addition of waste plastic into asphalt binders and mixtures has been added as powder or fiber [78]. Waste plastic has been added to HMA, WMA, and stone matrix asphalt (SMA). The percentage of waste plastic in asphalt binder was roughly from 0.5 to 10% of the total weight of the asphalt binder and can be added as a powder or fibrous form. In the asphalt mixture, waste plastic is roughly 0.3 to 20% of the total weight of the mixture and can be added as a replacement for a fine aggregate or as a filler in powder or fibrous form. Using waste plastic in asphalt mixtures directly with the dry method has demonstrated several advantages compared to modifying the asphalt binder. This leads to cost benefits and ease of use because no further modification is required, enabling conventional equipment to process the asphalt mixtures. In addition to performance, cost, and ease of production benefits, using waste plastic in asphalt mixtures also has significant environmental benefits due to the larger amounts of waste plastic which can be used in road construction. This section summarizes the differences between the wet and dry methods for incorporating MPP additives in asphalt binder modification. In-depth information on both of these techniques (wet and dry) can be found in the subsequent chapters.

2.5.2 Waste Plastic in Road Application

The potential benefits of using waste plastic polymers as an alternative modifier for asphalt pavement materials have been identified in various studies. However, most of these studies have focused on laboratory tests, leaving a lack of information on the effectiveness of waste plastic polymers in field conditions. Several field projects have been conducted to investigate the use of waste plastics in asphalt pavement. In India, Vasudevan et al. incorporated plastic wastes with PE, PP, and PS into the pavement. Field monitoring showed that plastics in the pavement are suitable for heavy traffic, resulting in an improved binder, increased strength, and increased strength better surface condition of asphalt mixtures [117]. Canada has used waste plastic in warm mixed asphalt since 2012 [118], and the Netherlands used recycled plastic in road construction in 2015.

Similarly, in a field trial by White and Reid (2018), over 200,000 plastic bags, 63,000 glass bottles, and over 4500 printer cartridges were added to asphalt pavement, showing improved rutting and fatigue resistance compared to unmodified asphalt roads [119]. Another project conducted by Chin and Damen incorporated HDPE, LDPE, and PET in asphalt pavement. Field tests showed that incorporating plastics in the pavement could improve moisture resistance, enhance binding properties, and facilitate high-temperature performance without increasing construction costs or releasing toxic gases [120]. Despite these promising results, the long-term performance of asphalt pavement containing waste plastics requires further monitoring and investigation. Therefore, there is a need for more field projects to validate the pavement performance of incorporating waste plastics.

The literature suggests that incorporating waste plastic into asphalt mixes has great potential for improving road performance in terms of resistance to fatigue cracking and permeant deformation. This highlights the need for more research into the standardized use of waste polymers in asphalt modification. For waste plastic modifiers to be practical and cost-effective, they must be readily available at a lower cost than virgin polymers, blend well with the asphalt mix, and resist degradation at mixing temperatures. Additionally, they must improve durability at high and low temperatures once placed and be compatible with conventional equipment used in asphalt production. Effective polymer modifiers must also improve binder cohesion and adhesion properties, and the resulting asphalt mix must remain physically and chemically stable during storage, transportation, application, and in-road service. Overall, the potential benefits of using waste plastic in asphalt modification underscore the importance of further research to realize their potential in constructing and maintaining roads fully.

2.6 Research Gaps

Although a considerable amount of research has been carried out on the efficacy of incorporating plastic waste materials into asphalt pavement materials, there is still a lack of comprehensive information on how to use these materials effectively. The incomplete understanding of the value and benefits of using waste plastic as an alternative modifier for asphalt pavement materials is a critical issue that needs to be addressed. The modified binder properties are highly dependent on several polymer characteristics, such as type, size, and physical and chemical properties. Therefore, no clear approach has been developed to assess the effectiveness of using waste plastic.

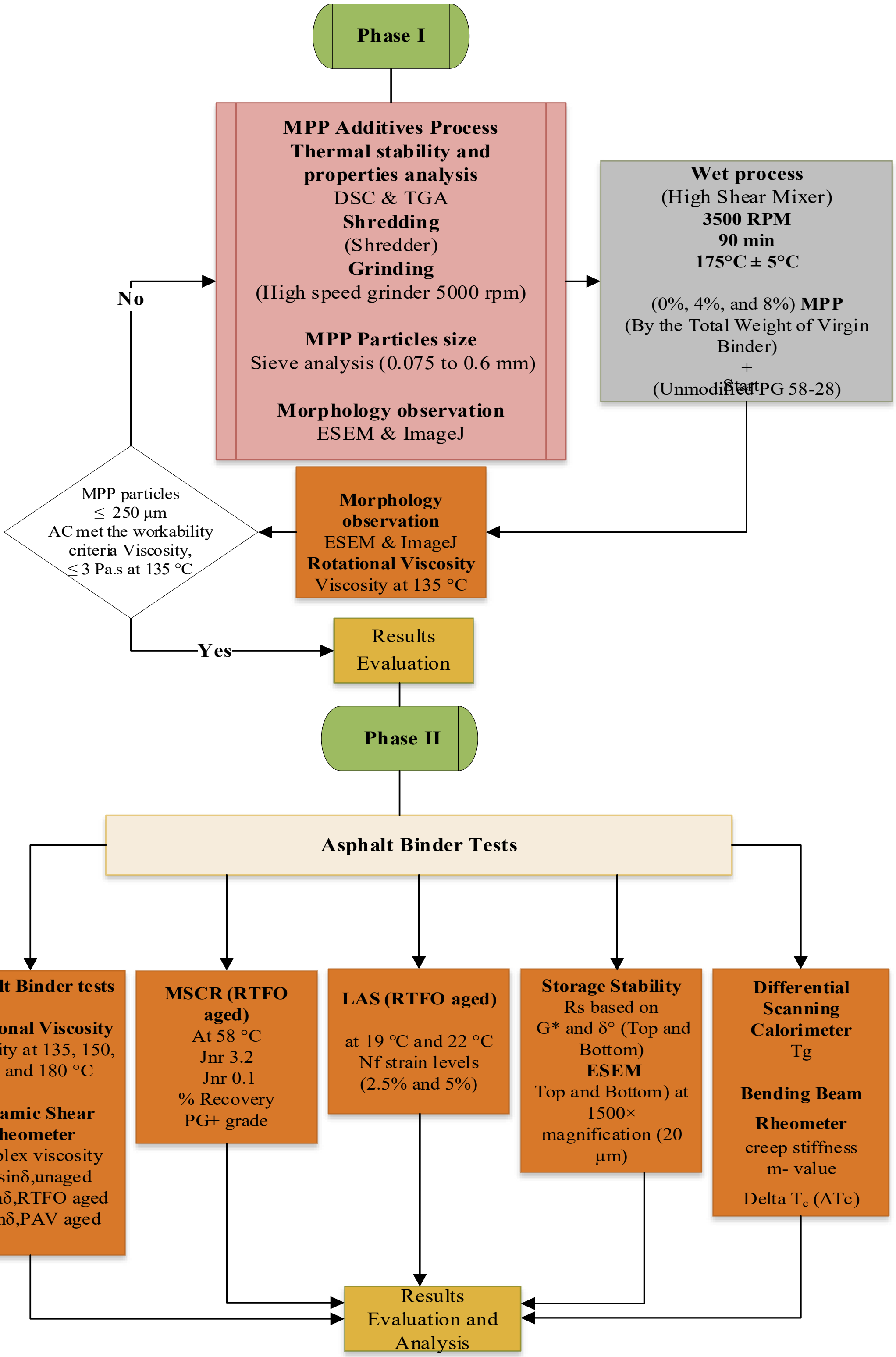
In addition, it is crucial to consider the binder source, blending conditions, and polymer dosage to ensure optimal performance of the modified binder. Before incorporating them into the asphalt blends, physical, thermal and chemical verification of the waste plastic is also necessary. Despite the ongoing efforts to investigate the use of waste plastic, several research gaps still exist, including the characterization of Multi-Layer Plastic Packaging (MPP) that combines several polymer layers. To date, no clear approach has been developed to assess these MPP additives effectively.

Moreover, the effectiveness of waste plastic in improving the mechanical performance of asphalt mixes in Canadian conditions is still unknown. Therefore, there is a need for further investigation to determine the efficacy of waste plastic in these conditions. Field trials are also necessary to better understand how modified pavements will behave in actual fieldwork. As such, extensive investigation into the design of asphalt mixes is necessary to identify the optimal MPP dosage, blending conditions, and binder source to ensure that waste plastic polymers can be used practically, effectively, and at a lower cost than virgin polymers.

2.7 Methodology

This research aims to investigate the feasibility of using MPP as an additive in asphalt modification. A comprehensive review of recent studies on using recycled plastics in asphalt mixtures was conducted to achieve this goal. The review aimed to identify research gaps and comprehensively understand waste plastic in asphalt binder and mixture performance. MPP additives will be prepared with various polymers, including Polyethylene (PE), Nylon (NY), Polyester (PET), and Metalized Polyester (METPET), with different structures and treatment processes processed by shredding and grinding. MPP-modified binders were analyzed using DSC and Environmental Scanning Electron Microscope (ESEM) to verify MPP-modified asphalt binder's compatibility, microstructure, and whether its physical and chemical properties change due to modification. The impact of MPP additives on the thermal, rheological, and stability properties of asphalt binders was evaluated using Rotational Viscometer (RV), Dynamic Shear Rheometer (DSR), Storage Stability (SS), and Bending Beam Rheometer (BBR).

Additionally, the mechanical properties of asphalt mixture performance are determined when waste plastic additives are used in wet or dry processing using Complex (Dynamic) Modulus, Hamburg Wheel Tracking Test (HWTT), Thermal Stress Restrained Specimen Test (TSRST), British Pendulum Skid Resistance Tester, and Indirect Tensile Strength (ITS). Experimental results from PG and mixture performance and characterization tests were statistically analyzed to investigate the effects of various MPP contents and identify optimal ones. Finally, some guidelines and recommendations for best practices when handling and using MPP additives in asphalt modification have been developed. The framework outlined that demonstrates the above steps is shown in Figure 2-7. Each chapter has been meticulously structured to include a method section and a materials section, which allows readers to follow a logical and seamless progression of the research or experiment. The method section outlines the step-by-step processes used in the study, describing the approach and techniques employed. Along with the method section, the materials component clarifies the resources and tools used, providing essential context and enabling the replication of the study. Additionally, a flow chart has been incorporated into each chapter to improve understanding and facilitate navigation.


Phase I
MPP Additives Process
Thermal stability and properties analysis
DSC & TGA
Shredding
(Shredder)
Grinding
(High speed grinder 5000 rpm)
MPP Particles size
Sieve analysis (0.075 to 0.6 mm)
Morphology observation
ESEM & ImageJ
Wet process
(High Shear Mixer)
3500 RPM
90 min
175°C ± 5°C
(0%, 4%, and 8%) MPP
(By the Total Weight of Virgin Binder)
+
Start
(Unmodified PG 58-28)
No
MPP particles
≤ 250 µm
AC met the workability criteria Viscosity,
≤ 3 Pa.s at 135 °C
Morphology observation
ESEM & ImageJ
Rotational Viscosity
Viscosity at 135 °C
Yes
Results Evaluation
Phase II
Asphalt Binder Tests
Asphalt Binder tests
Rotational Viscosity
Viscosity at 135, 150, 165, and 180 °C
Dynamic Shear Rheometer
Complex viscosity
G*/sinδ,unaged
G*/sinδ,RTFO aged
G*sinδ,PAV aged
MSCR (RTFO aged)
At 58 °C
Jnr 3.2
Jnr 0.1
% Recovery
PG+ grade
LAS (RTFO aged)
at 19 °C and 22 °C
Nf strain levels
(2.5% and 5%)
Storage Stability
Rs based on
G* and δ° (Top and Bottom)
ESEM
Top and Bottom) at 1500×
magnification (20 µm)
Differential Scanning Calorimeter
Tg
Bending Beam
Rheometer
creep stiffness
m- value
Delta Tc (ΔTc)
Results Evaluation and Analysis

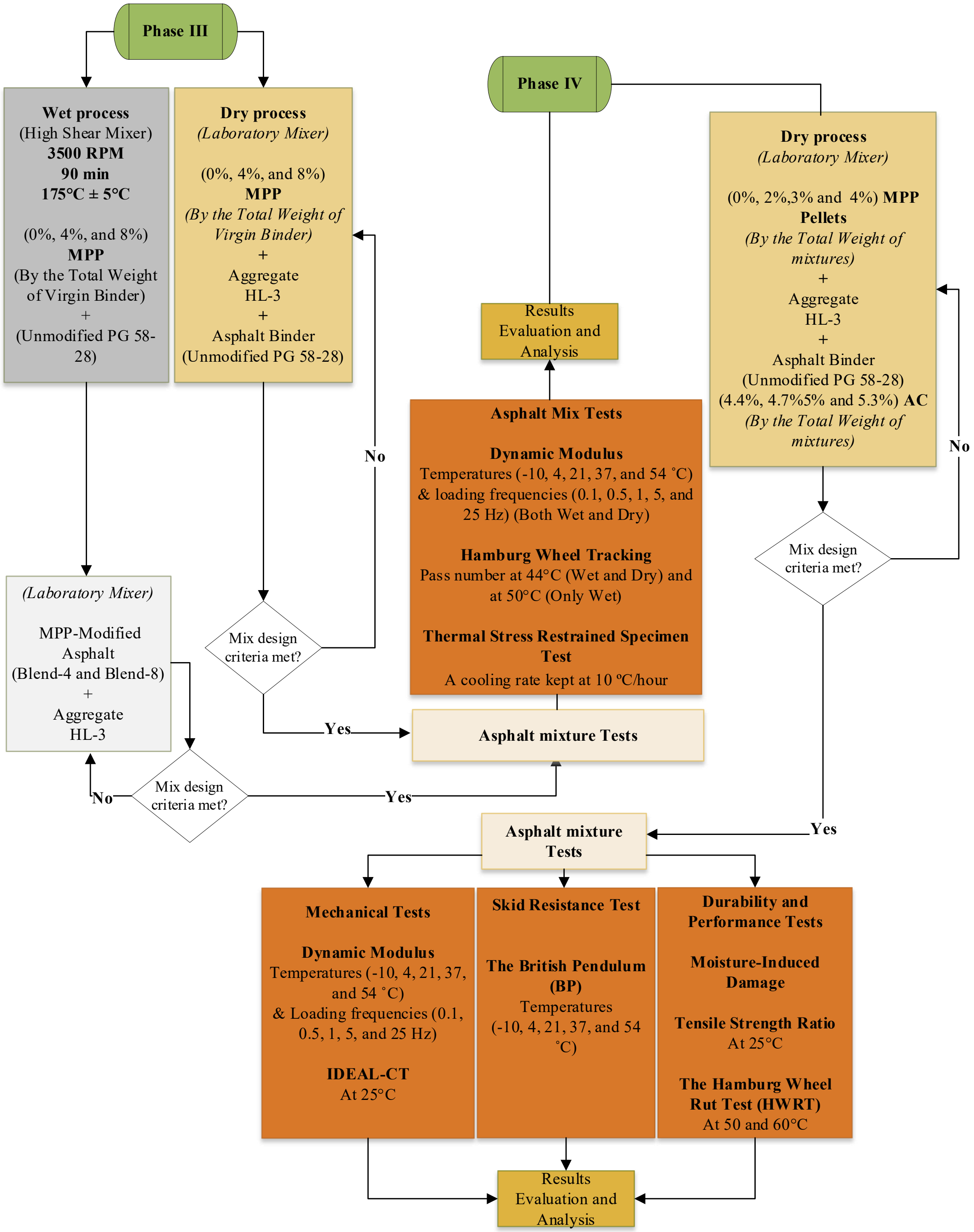


Figure 2-7 Flowchart of the Research Methodology

3. Lab-Scale Protocol for Multilayer Plastic Packaging Powder Production and Its Integration in Asphalt Modification

The chapter focuses on lab-scale MPP powder production and integration into modified asphalt binders, stressing experimentation, quality control, and potential environmental solutions.

Abstract

Performing experiments in a laboratory setting is of utmost importance for advancing new technologies, process optimization, risk reduction, cost savings, and safety assurance. Recycling Multilayer Plastic Packaging (MPP) into asphalt materials offers waste volume reduction and natural resource conservation benefits. Existing plastic powder production methods, such as cryogenic milling, can be expensive and impractical for laboratory-scale use, significantly limiting research opportunities. Therefore, lab-scale production facilitates the testing and development of new recycling technologies and processes, leading to more efficient and cost-effective solutions for recycling in the future.

This protocol paper presents a laboratory-scale method for producing MPP powder and incorporating it into a modified asphalt binder. The process involves collecting, drying, shredding, and grinding plastic packaging waste into fine powder. The quality of the powder is confirmed by Thermal Gravimetric Analysis (TGA), Differential Scanning Calorimeter (DSC), and Environmental Scanning Electron Microscopy (ESEM) by assessing purity, thermal properties, and stability, as well as morphology and size distribution. The asphalt binder is modified using a high-shear mixer, and the morphology of the modified binder is again analyzed using ESEM. Overall, this laboratory-scale method contributes to the field of sustainable materials and recycling for the asphalt industry.

Keywords: Multi-layer Plastic Packaging (MPP), Powder production, Protocol, Asphalt modification

3.1 Introduction

Producing plastic powders from plastic waste is a promising solution for asphalt modification[78], but it remains challenging and expensive, especially at a lab scale. The typical process involves pulverization, classification, and sieving, which are costly and time-consuming. Efficient and cost-effective methods of producing plastic powders at a lab scale are essential for researchers to conduct their studies on asphalt modification effectively. However, the high cost of producing these powders can limit their ability to develop sustainable and efficient asphalt materials. Exploring new and innovative methods of producing plastic powders at a lab scale would significantly benefit research and development with plastic materials. Therefore, the study aims to develop an efficient and cost-effective method for producing plastic powders at a lab scale for asphalt modification purposes. This method would provide researchers with a reliable and steady supply of plastic powders for research, accelerating the development of more sustainable asphalt materials. The study also aims to contribute to the advancement of the plastic industry by exploring sustainable and efficient methods of producing plastic powders, leading to a more sustainable future.

3.1.1 Objective

Develop a cost-effective and reliable plastic powder production process to aid researchers studying plastic additives in asphalt in a laboratory setting.

3.1.2 Laboratory-Scale Production of MPP Powder

The laboratory-scale production of MPP powder involves a series of steps: collecting, drying, shredding, and grinding. The MPP waste is collected, and the layers are separated by heat and pressure. The separated layers are dried to remove moisture, shredded into small pieces and ground into a fine powder. The powder's purity, thermal, and stability properties are tested using Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimeter (DSC). In contrast, Environmental Scanning Electron Microscopy (ESEM) determines morphology and size distribution. The tests ensure the quality and consistency of the MPP powder for subsequent use.

3.1.3 Incorporation of MPP Powder into Modified Asphalt Binder

The modified asphalt binder is created by mixing the MPP powder with the asphalt binder using a high-shear mixer. The high-shear mixer creates a homogeneous mixture that ensures consistent distribution of the MPP powder in the modified asphalt binder. The morphology of the modified binder is analyzed using ESEM, which confirms the successful incorporation of the MPP powder into the asphalt binder.

3.2 Materials and Methods

3.2.1 Materials

Polyethylene terephthalate (PET), polyamide (commonly known as nylon and referred to as NY in this study), polyethylene (PE), and metallized polyester MET PET are all widely used materials in various industries. To determine their characteristics and assess their suitability for different applications, it is crucial to thoroughly comprehend their physical, thermal, and chemical properties, as illustrated in the following Table 3-1. A recycled Low-density polyethylene (LDPE) was also investigated in this project as the second alternative for recycled plastic material. The MPP and LDPE were used in the study based on their approximate total mass percentages presented in Table 3-2.

Table 3-1 The following table provides a summary of the typical properties of MPP materials [78], [121], [122]

Property	PET	Nylon	PE	MET PET	LDPE
Melting Point (°C)	250-260	220-280	120-135	260-270	105–115
Density (g/cm^3)	1.38	1.13-1.15	0.91-0.97	1.3-1.5	0.910–0.940
Tensile Strength (MPa)	55-75	50-80	20-40	70-100	20-40
Glass Transition Temperature (°C)	76	47-67	-120 to -80	-	–125 to –110
Young's Modulus (GPa)	2-4	2-7	0.1-1.2	2-4	0.1-1.2
Water Absorption (%)	(Less than 0.8)	(Up to 10)	(Less than 0.1)	(Less than 0.5)	(Less than 0.1)
Chemical Formula	$(C_{10}H_{8}O_{4})\ n$	$(C_{12}H_{22}N_{2}O_{2})\ n$	$(C_{2}H_{4})\ n$	$(C_{10}H_{8}O_{4})\ n$ with a metal layer	$(C_{2}H_{4})\ n$
Molecular Weight (g/mol)	192.17	226.31	28.05	Varies	28.05

Table 3-2 The MPP and LDPE were used in the study based on their approximate total mass percentages

Bag Structure	% PE	% METPET	%NY	% PET	%LDPE	Total
PE-METPET-PET	**87**	**8**	**---**	**5**	**---**	**100**
PE-PET	**94**	**---**	**---**	**6**	**---**	**100**
PE-NY-PET	**86**	**0**	**8**	**6**	**---**	**100**
Blend *	**89**	**3**	**2**	**6**	**---**	**100**
LDPE	**----**	**---**	**---**	**---**	**100**	**100**

This study used unmodified (virgin) asphalt cement (AC) PG 58–28. Similar AC was used in previous studies at the University of Waterloo [78], [123]. The fundamental binder properties of asphalt cement are presented in Table 3-3. The unmodified PG 58–28 was blended with MPP additives at concentrations of 2, 4, and 8 percent (by binder weight) to produce four different binders. The weight of MPP additives that needs to be added to asphalt cement can be calculated using the following Equation 3-1:

Equation 3-1

$$\boldsymbol{W_{MPP} = (P_{MPP} / (1 - P_{MPP})) \times W_{AC}}$$

where: W_{MPP} = weight of polymer to be added (kg) P_{MPP} = percentage of polymer to be added (%) W_{AC} = weight of asphalt cement (kg). Each binder was tested at the appropriate test temperatures designed by AASHTO standards. Before modification, binders were required to meet the AASHTO M320 standards. A series of dynamic shear rheometer (DSR) tests were carried out, following AASHTO T315, on the asphalt binders to characterize and determine the effect of MPP on the modulus at the high and intermediate performance grade temperatures.

Table 3-3 Properties of asphalt cement PG 58-28

Asphalt Properties	Test Method	Value	Units
Ash Content	ASTM D2939–09	0.03	%
Viscosity at 135°C	AASHTO T316	0.266	Pa.s
G*/sin(δ°)	AASHTO T315	1.18	kPa
RTFO Residue	**AASHTO T240**		
Mass Loss	AASTHO T240	0.37	%
G*/sin(δ°)	AASHTO T315	3.05	kPa
PAV Residue	**AASHTO R 28**		
G*sin(δ°)	AASHTO T315	3550	kPa
m-Value at Pass Temperature	AASHTO T313	0.358	
Stiffness at Pass Temperature	AASHTO T313	187	MPa
m-Value at Fail Temperature	AASHTO T313	0.294	
Stiffness at Fail Temperature	AASHTO T313	385	MPa
True Grade	**AASHTO M320**	**59.4-31.4**	
Appearance	N/A	Black viscous material	
Odour	N/A	Petroleum odour	
Physical state	N/A	Liquid or semi-solid	
Melting point/freezing point	ASTM D3418	31	°C
Initial boiling point/boiling range	ASTM D86	228	°C
Flash point	ASTM D92	243	°C
Relative density	ASTM D1298	1.020-1.045	@21.1°C
Solubility	ASTM D2042	Insoluble in water	

3.2.2 Methods

Figure 3-1 shows the systematic approach used to produce the MPP additives and MPP-modified binder.

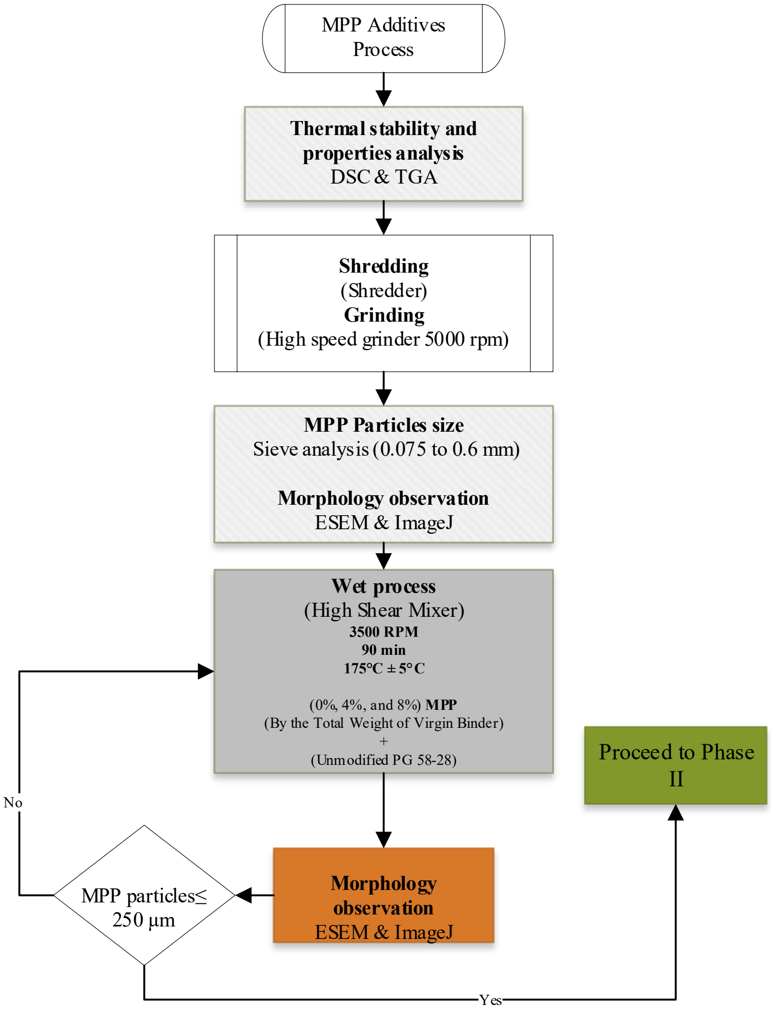


Figure 3-1 shows the systematic approach used to produce the MPP additives and MPP-modified binder

The process started by producing MPP additives from multi-layer packaging plastic bags. This process involved shredding the MPP into small particles using a Micro-Cut electric shredder, which helped break the plastic into manageable pieces. After the MPP was shredded, the next step was to grind it into a fine powder using an Electric Grain Mills Grinder. This grinding process was essential in creating a uniform size and texture for the MPP powder, which is crucial for its effectiveness as an additive in asphalt binder. The grinder speed was set to 5000 rpm to ensure getting particles ranging from 0.075 to 0.595 mm. The grinding process was repeated multiple times until the desired quantity of powder was obtained, as shown in Figure 3-2. However, it is important to note that the grinding process can generate high noise and dust levels, which can be hazardous to health if proper safety precautions are not taken.

Therefore, to ensure the safety of the personnel involved in the grinding process, it is mandatory to wear all necessary safety equipment, including goggles, an N95 mask (at minimum), gloves, and a lab coat. Additionally, the grinding process should be conducted under a fume hood to contain any dust or fumes generated during the grinding process, making the environment safe for the personnel involved by minimizing the inhalation of harmful dust particles.

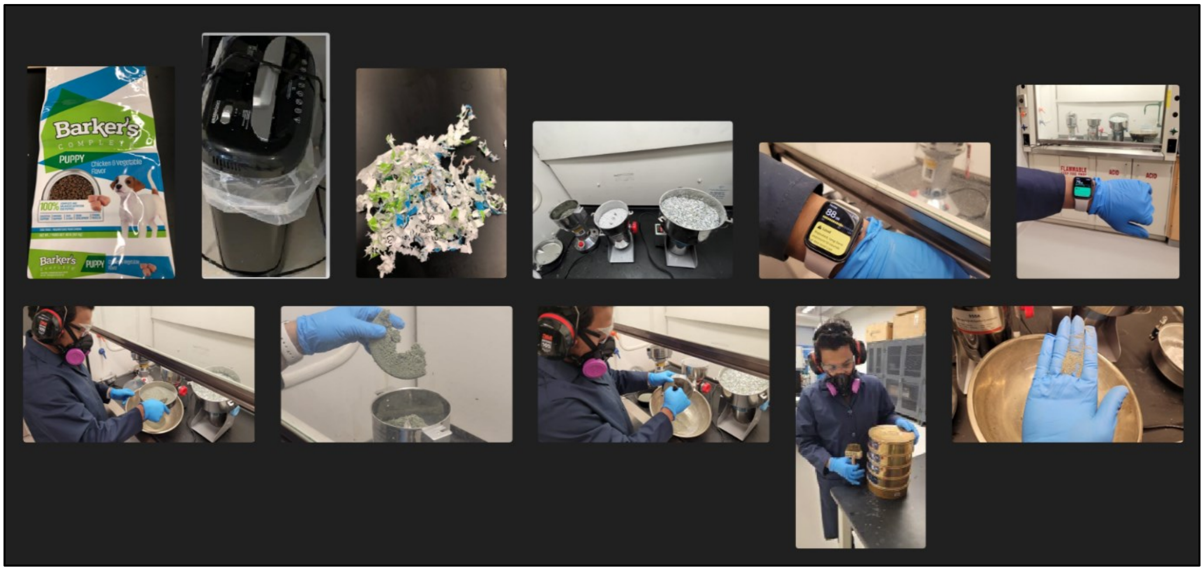


Figure 3-2 Steps for producing MPP additives at the CPATT lab

The MPP powder was then sieved and screened to ensure the powder was of the right size and distribution. This screening process allowed for the selection of particle sizes that ranged from 0.075 to 0.595 mm, which was suitable for adding to the asphalt binder. The particle size distribution was critical in the effectiveness of the MPP additive as a modifier for the asphalt binder. A uniform particle size distribution ensured that the MPP additive would be evenly dispersed throughout the asphalt binder, which is essential for achieving the desired properties. Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) tests were performed to analyze the thermal properties and stability of the MPP additives and AC. Differential Scanning Calorimetry (DSC) is a widely used technique for measuring the thermal properties of materials. The DSC Q2000, shown in Figure 3-3, was used in this study. The laboratory testing was performed on the MPP and LDPE samples according to the ASTM D3418 standard. In this study, the samples utilized for DSC analysis ranged from 10 to 20 mg in weight. The sample pans used for this analysis were Tzero Aluminum and sealed with a DSC encapsulation press to ensure accurate and precise measurement of thermal properties, as shown in Figure 3-4. The encapsulation process helped to prevent contamination of the samples and minimize the effects of any external factors during heating and cooling cycles. This method allowed for measuring the samples' melting, crystallization, and glass transition temperature information, per the ASTM D3418 standard[124]. Each cycle started by maintaining the sample temperature at -90°C for 2 minutes, then increasing the temperature to 260°C and maintaining it for 2 minutes. The heating and cooling rates were conducted at 10°C per minute. The data obtained from the DSC measurements provide crucial information on the thermal behaviour of the MPP additives and how they may affect the properties of the asphalt binder.

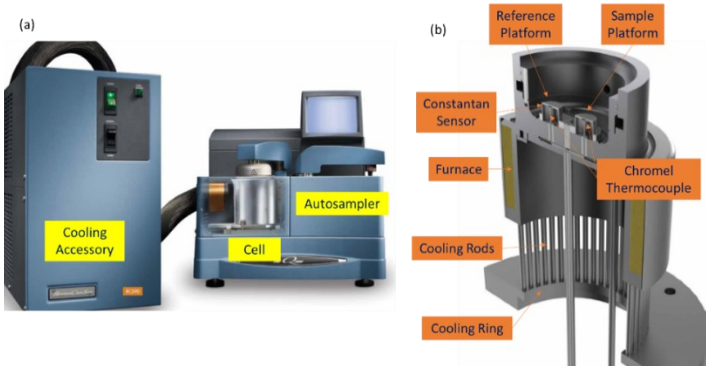


Figure 3-3 Main components of DSC at Analytical Laboratory / Department of Chemical Engineering: (a) overview, (b) cell

Figure 3-4 DSC encapsulation press

Thermogravimetric Analysis (TGA) was also used to measure the amount and rate of weight change of the MPP and MPP-modified asphalt samples (Figure 3-5). TGA is a technique that measures the weight change of materials as the temperature increases (up to 1000°C if desired) and can detect any phase changes resulting from decomposition, oxidation, or dehydration. This study used the TGA results to determine the thermal stability of the MPP additives and the asphalt cement samples. The heating rate used in the TGA was 10°C per minute, and the data obtained provided important information on the purity of the MPP additives and the thermal degradation behaviour of the MPP additives and how they may affect the properties of the asphalt binder. The TGA results can also be used to evaluate the effectiveness of the MPP additives in improving the thermal stability of the asphalt binder.

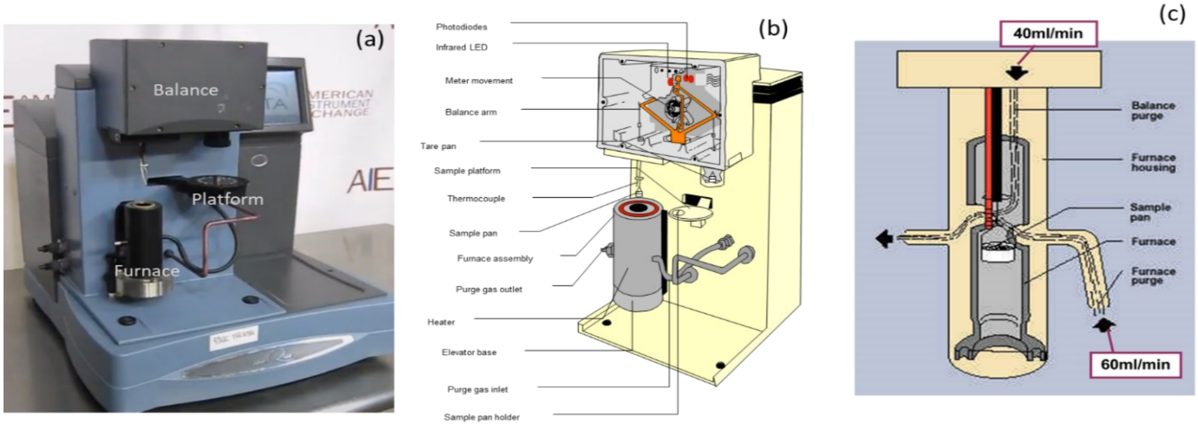


Figure 3-5 Main components of TGA: (a) overview, (b) thermobalance, and (c) furnace

The preliminary analysis of the MPP showed that the melting point of the PE was approximately 120°C, while the melting points of NY, PET, and METPET films ranged from 248 to 254°C. The TGA results confirmed no significant changes in the MPP or asphalt cement samples up to 320°C. These results helped to determine the mixing temperature for the MPP additives. A production temperature of 175°C ± 5°C was selected to ensure the PE material entered the melting phase and blended with the liquid asphalt cement. The remaining unmelted components of the MPP acted as fillers due to their high melting points. Environmental Scanning Electron Microscopy (ESEM) was used to determine the size of the MPP before and after blending. To prepare the MPP-modified binder for observation, approximately 10 milligrams of it should be carefully placed into sample holders from the container using a spatula, as shown in Figure 3-6. The ESEM can then be used to examine the morphology and structure of the MPP-modified binder at high resolution and under various environmental conditions. The observation parameters were carefully selected to optimize the images. The observation parameters were as follows: the selected acceleration voltage was 20 keV, the spot size was 3.0, and the chamber pressure was 0.8 mBar in low-vacuum mode. The observations were conducted at room temperature using an FEI Quanta 250 FEG ESEM, with a magnification of 1000x in SE mode, which was ideal for clearly observing the bitumen microstructure. The electron gun was maintained at a distance of 15 mm from the sample's surface to ensure accurate imaging. A lower acceleration voltage of 10 keV was found to produce images that were not sufficiently clear, as reported by Mikhailenko et al. [125]. After determining the MPP powder's exact size, the asphalt cement was modified, and the modified binder was evaluated using ESEM at the microstructural level for subsequent MPP-binder blends.

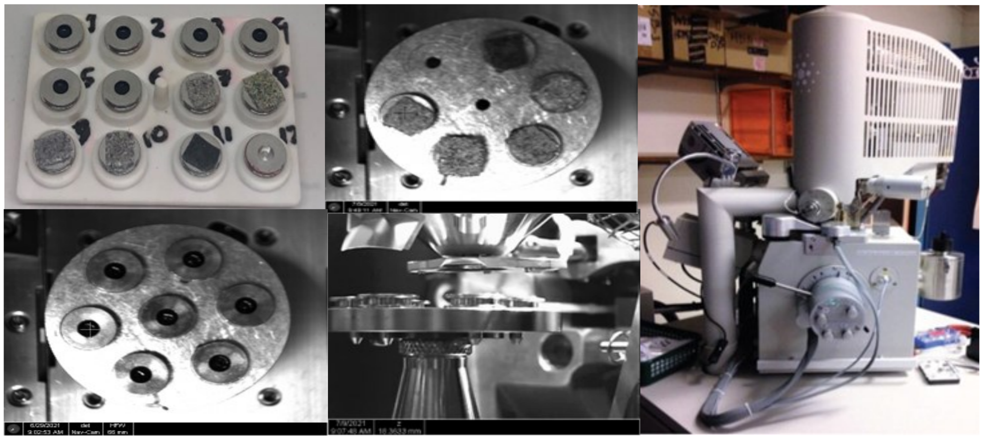


Figure 3-6 Setup of ESEM corresponding samples at (FEI Quanta 250 FEG)

3.3 Discussion and Conclusions

3.3.1 Laboratory-Scale Production of MPP Powder

After grinding, the MPP powder was sieved to determine its grain size distribution. Before being used to modify the asphalt cement, the selected MPP particles were examined using ESEM to ensure that they met the selected size requirements. The particle size distribution of the MPP powder to be added to the asphalt binder was selected to be between 0.075 to 0.595 mm. An ESEM image of MPP powder at 40x magnification (1 mm) was obtained to verify the size and shape of the particles (Figure 3-7). ImageJ software was used to perform a size analysis of the MPP particles. The particle distribution of the MPP powder was determined, as shown in Figure 3-8.

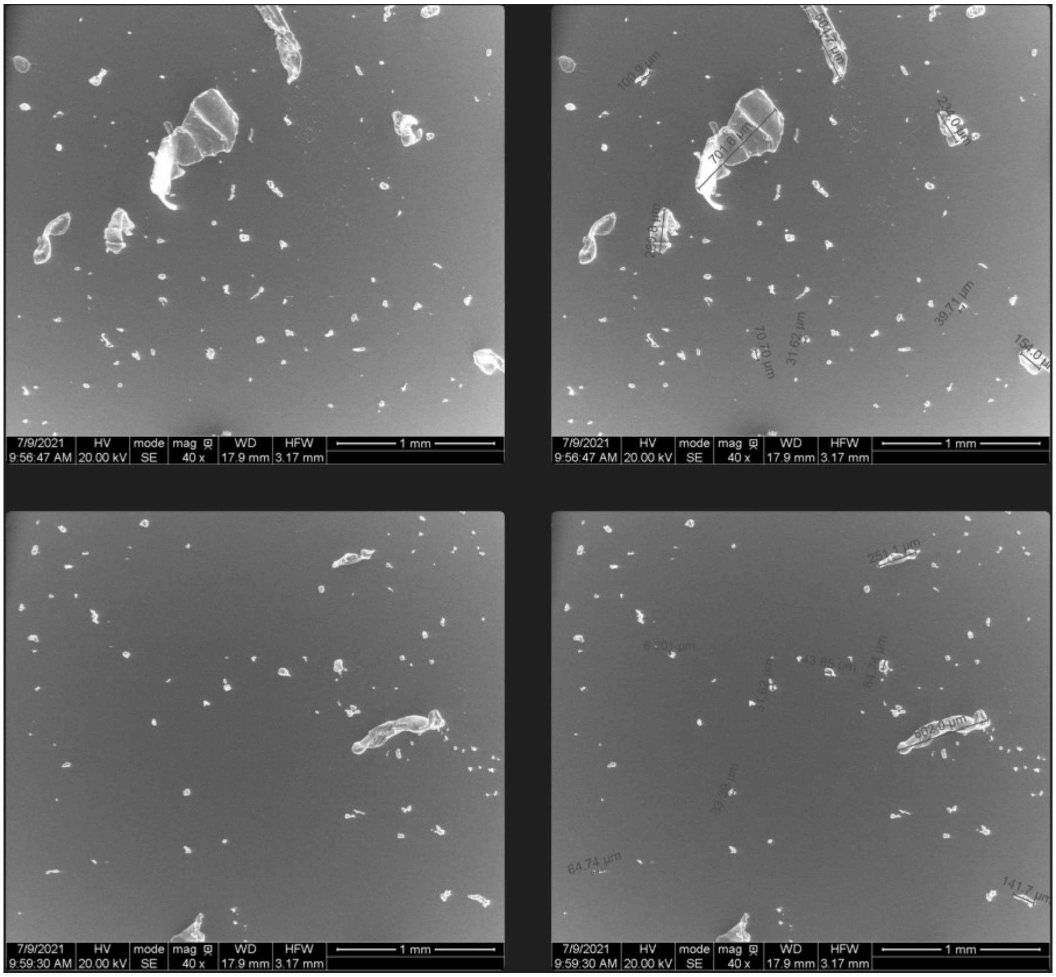


Figure 3-7 MPP particles were examined using ESEM

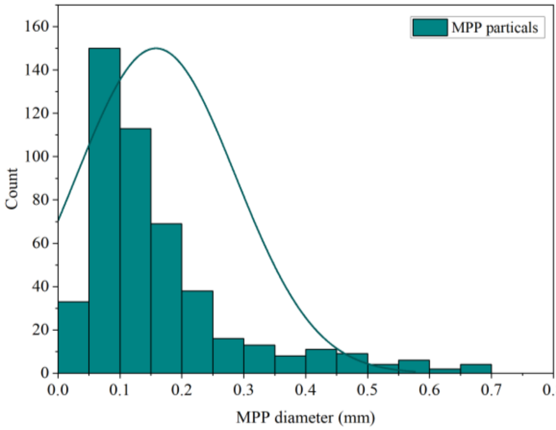


Figure 3-8 The particle distribution of the MPP powder

3.3.2 Water Absorption

The water absorption test was conducted on an MPP plastic material according to ASTM D570. The test required a plastic specimen, distilled water, a container, a balance, an oven, and a desiccator. To conduct the test, the plastic material sample was cut to size, weighed using the balance, and submerged in distilled water maintained at 23°C for 24 hours Figure 3-9. The specimen was removed, dried with a clean cloth, and weighed again. The final mass was recorded.

Figure 3-9 The water absorption test on an MPP plastic material at the CPATT lab

The specimen was dried in an oven until its mass became constant and then weighed again to determine its dry weight. The water absorption of the plastic material was calculated as shown in Figure 3-10 using Equation 3-2 below:

Equation 3-2

$$\boldsymbol{Water\ absorption} = \left[\frac{(\boldsymbol{final\ mass} - \boldsymbol{initial\ mass})}{\boldsymbol{initial\ mass}}\right] \boldsymbol{x\ 100}$$

The results were reported to the nearest 0.1% of the initial mass. Since some of the polymers used in asphalt mixtures, such as Nylon, PET, and METPET, exhibit hygroscopic behavior, it is essential to measure their water absorbance before further use. This factor must be taken into account in wet climate conditions.

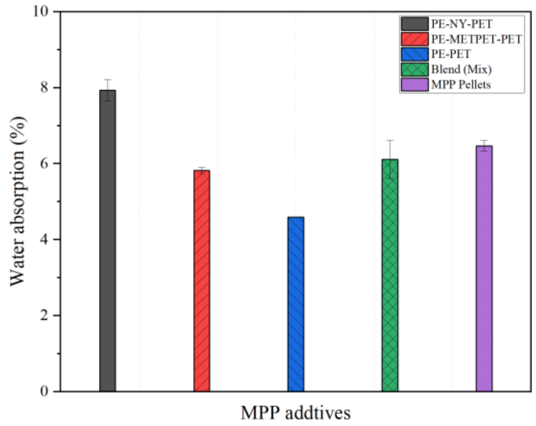


Figure 3-10 Water absorption of MPP materials

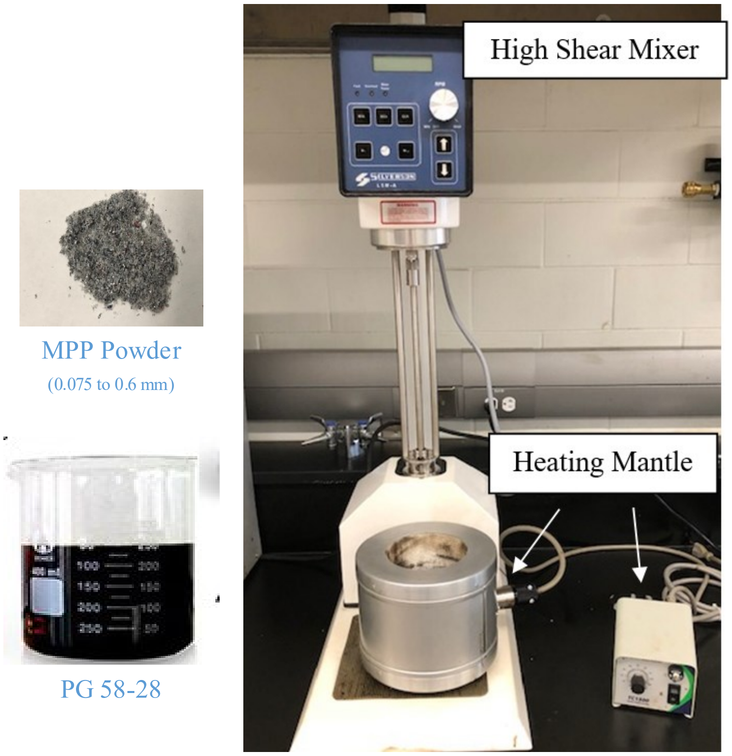
3.3.3 Incorporation of MPP Powder into Modified Asphalt Binder

The virgin binder used in this experiment was PG 58–28. The MPP and LDPE modifications were performed at concentrations of 2%, 4%, and 8% of the total weight of asphalt cement. The concentrations were selected based on the literature and the relative proportion of PET in each plastic product, as shown in Table 3-2. The smallest addition of 2% was selected for each plastic to produce blends with similar overall PET content, and 8% was selected as the maximum based on previous research. Table 3-4 lists the identified blends and their corresponding modifier and concentration percentages.

Table 3-4 List of modified asphalt binders

Asphalt Cement	Modifier	Modifier Tested (%)	ID in the Graphs
PG 58–28	None	0	Unmodified (PG58–28)
	LDPE	4, 8	LDPE-4 and LDPE-8
	Blend	4, 8	Blend-4 and Blend-8
	PE-METPET-PET	4, 8	PE-METPET-PET-4 and -8
	PE-NY-PET	2, 8	PE-NY-PET-2 and -8
	PE-PET	2, 4	PE-PET-2 and -4

MPP-modified asphalt was blended in two primary steps. In Step 1, the hot asphalt binder was mixed with the additives using a stirring bar. In Step 2, a high-shear mixer was used to enhance the homogeneity of the blend at a temperature of 175°C (±5°C) and a rotational speed of 3500 rpm for one hour as shown in Figure 3-11. It should be noted that the same blending procedure was applied to the virgin asphalt to avoid any inconsistencies that may occur due to the blending process.



MPP Powder
(0.075 to 0.6 mm)

PG 58-28

Figure 3-11 The high-shear mixer at CPATT lab

The mixing temperature was selected based on the thermal properties obtained from the DSC and TGA tests, which showed that the melting points of all MPP and LDPE additives were 110 to 270°C. The amount of residue (purity 96.39%) and thermal degradation of MPP powder were measured using TGA, as shown in Figure 3-12, which involved subjecting them to temperatures ranging from ambient to 600 °C. TGA was also employed to examine the magnitude and rate of mass change of asphalt cement samples, with PG 58-28 binder exhibiting high thermal degradation temperatures, as displayed in Figure 3-13. The selected mixing temperature of 175 ± 5°C effectively prevented significant thermal degradation.

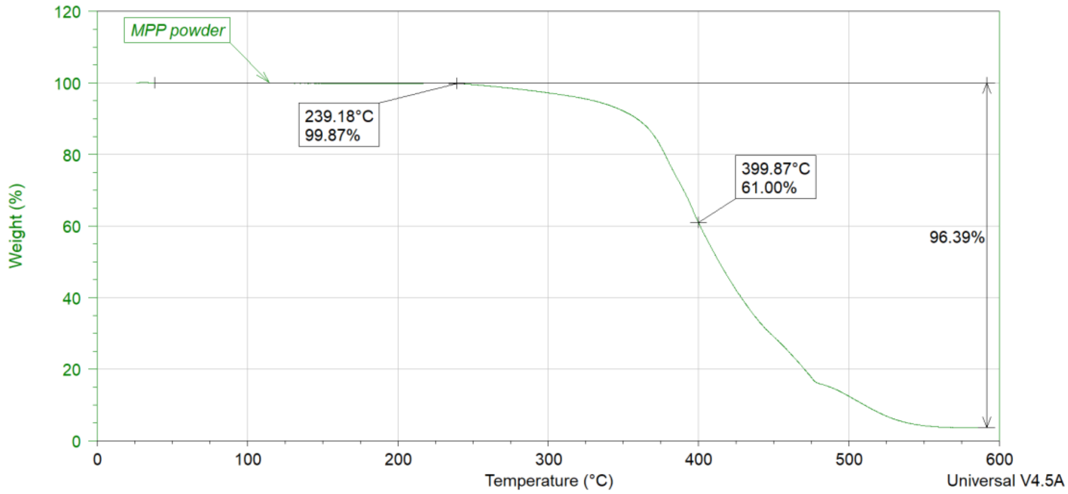


Figure 3-12 The amount of residue and thermal degradation of MPP powder

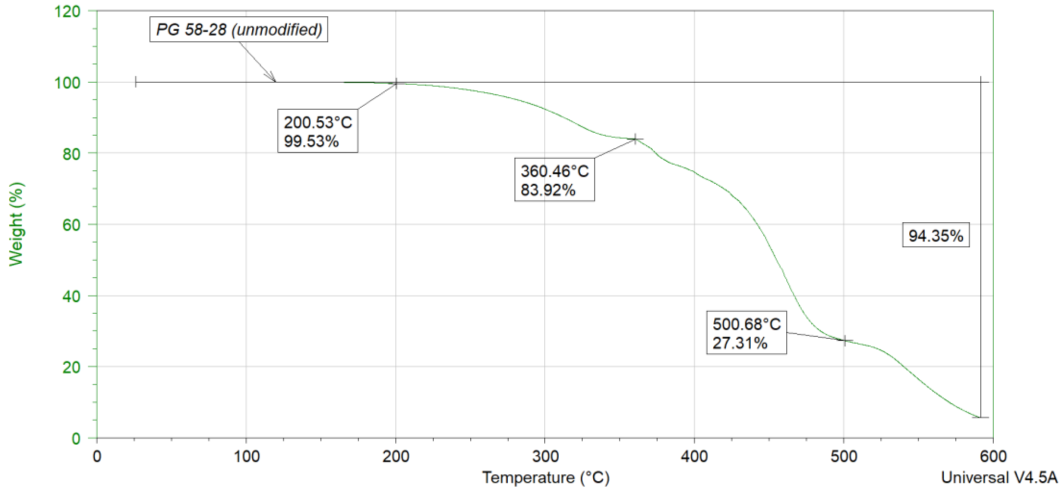


Figure 3-13 The amount of residue and thermal degradation of PG 58-28 (unmodified)

Again, ESEM was utilized to ensure that the MPP powder size met the particle size recommendation (below 250µm) in the modified binder before the DSR test. The test results showed that the MPP additive powder size was reduced after binder modification, with particles melting and integrating into the asphalt binder. The particles with higher melting points were reduced to a size below the recommendation of AASHTO T 315 and ASTM D7175 standards[126], [127] (less than 250 µm), as shown in Figure 3-14.

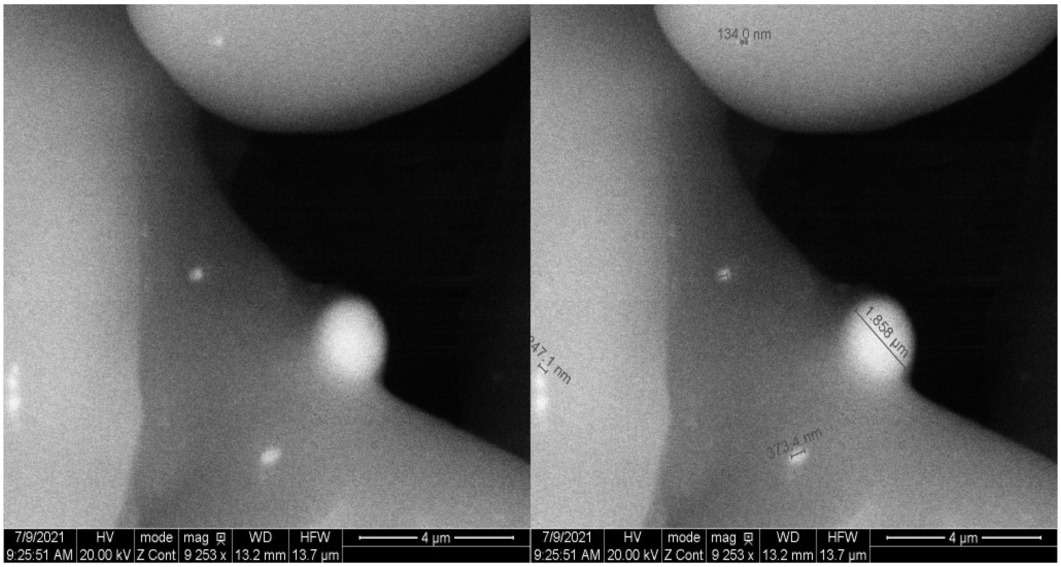


Figure 3-14 ESEM images of (a) MPP modified PG 58–28 binder (Blend−8) at 9253× magnification (4 μm scale bar)

In conclusion, this study has successfully developed a cost-effective and simple laboratory-scale process to produce MPP powder. The process includes sourcing suitable MPP plastic materials powder, pre-treating them, grinding them to a fine powder, and ensuring that the powder meets the necessary specifications to be used as additives in asphalt.

The laboratory-scale process can provide significant benefits and opportunities for research, development, and education and contribute to sustainable materials and upcycling by addressing the environmental challenges of plastic disposal. The success of this laboratory-scale method opens up possibilities for exploring new recycling technologies and processes to upscale production.

4. Incorporation of the Multi-Layer Plastic Packaging in the Asphalt Binders: Physical, Thermal, Rheological, and Storage Properties Evaluation

This chapter is based on the article "Qabur A, Baaj H, El-Hakim M. Incorporation of the Multi-Layer Plastic Packaging in the Asphalt Binders: Physical, Thermal, Rheological, and Storage Properties Evaluation. *Polymers*. 2022; 14(24):5396. https://doi.org/10.3390/polym14245396" published in the Polymers Journal. The study's main goal is to evaluate the feasibility of using MPP as an asphalt modifier through the wet method. The evaluation involves examining the physical, thermal, rheological, and storage properties of MPP-modified binders at different MPP concentrations (2%, 4%, and 8%) in asphalt cement (PG 58-28).

Abstract

The amount of residual Multi-layer Plastic Packaging (MPP) in Canada has greatly increased in the last two decades, which has economic and environmental consequences. MPP is primarily made up of two or more layers of Polyethylene (PE), Polyester (PET), Nylon (NY), and Metalized Polyester (METPET). While MPP has not been used as an asphalt modifier, some of the materials commonly found in MPP, such as PE and PET, have also been successfully used as asphalt modifiers. Nevertheless, a few recent studies have demonstrated the potential for reusing MPP as an asphalt modifier to improve asphalt pavement performance. Recycling post-industrial MPP instead of using raw polymers could lead to economic and environmental benefits. However, a comprehensive study to evaluate MPP as a viable asphalt additive is lacking. The main objective of this study is to evaluate the feasibility of using MPP as an asphalt modifier via the wet method, considering the physical, thermal, rheological, and storage properties of the MPP-modified binder at different MPP concentrations (2%, 4%, and 8%) in asphalt cement (PG 58–28). MPP-modified binders were evaluated using the following instruments: Differential Scanning Calorimeter (DSC), Thermogravimetric Analysis (TGA), Superpave Dynamic Shear Rheometer (DSR), Rotational Viscosity (RV), and Environmental Scanning Electron Microscopy (ESEM). Test results indicated that the incorporation of MPP has a strong potential to improve permanent deformation resistance at high temperatures. In addition, MPP shows a moderate impact on fatigue cracking performance at intermediate temperatures. Overall, in low-temperature climates, using less than 4% of MPP additives would offer higher fatigue damage resistance along with adequate permanent deformation. In high-temperature climates, higher concentrations of additives may be preferable to resist permanent deformation. Finally, MPP is a challenge for existing recycling systems, and its incorporation into asphalt applications may develop more sustainable materials that would contribute to circular economy principles.

Keywords: Multi-layer Plastic Packaging (MPP); recycling; asphalt cement; fatigue; permanent deformation; circular economy

4.1 Introduction

Canada produces 3.3 million tons of waste plastic per year, of which approximately 2.8 million tons end up in Canadian landfills every year [6]. The disposed plastic waste represents about 86% of all leftover plastic which mainly contains polypropylene (PP), polyethylene terephthalate 'Polyester' (PET), polyethylene (PE), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) [6]. The disposal of this waste plastic in landfills represented a lost opportunity of approximately CAD $7.8 billion in 2016 alone, and it will rise to CAD $11.1 billion by 2030 [6]. The development of a reliable method to reduce unrecovered plastic is essential. Plastic recycling should be performed in a cost-saving manner that reduces the carbon footprint of plastic production.

Elastomer/Plastomer or thermoplastic types of polymer are successfully used in asphalt modification [10]. Former research investigations reported that thermoplastic-based polymers are suitable for producing polymer-modified asphalt. In the last two decades, there has been a significant amount of research investigating the single-use plastic type of waste plastic polymers in asphalt modification such as LDPE, HDPE, PP, PE, and PET. Virgin polymers are known to improve asphalt binder properties. However, they are used in small modification percentages for financial constraints and due to a lack of knowledge of their impact on the mechanistic and rheological properties of the binder [103]. Using waste polymer as an asphalt modifier instead of virgin polymers has shown similar results in terms of improving mixture performance with reduced environmental and financial disadvantages. During the past four decades, studies focused on the use of waste plastic polymers in asphalt. Polypropylene (PP) was investigated by several scholars as a recycled additive in asphalt mixtures [13], [104], [128]. Polyethylene (PE) can be found in several applications, including low- and high-density polyethylene which is used in plastic bottles, packaging, and single-use plastic bags [129]. According to Hinisliglu and Agar, when the waste plastic of HDPE was used as a polymer modifier, using various mixing times (5 min, 15 min, and 30 min), temperatures (145 °C, 155 °C, and 165 °C), and percentages of HDPE (4%, 6%, and 8% of the weight of asphalt binder), the binders had higher stability, strength, and a higher Marshall quotient value which improved the resistance to permanent deformation.

In addition, the optimum result for Marshall stability was achieved at 4% HDPE binder modification by weight and mixed for 30 min at 165 °C [72]. Garcia-Morales et al. [27] found a similar result to that of Hinsisliglu and Agar's study of the rheology of recycled polymer-modified asphalt cement. The Garcia-Morales et al. study used flow behaviour of 60/70 penetration grade asphalt binder modified with 5% and 9% waste EVA/LDPE at high temperatures and linear viscoelasticity, and low and intermediate temperatures. The study showed the modified recycled EVA/LDPE asphalt binder improved the mechanical properties and overall performance of road service life. According to Casey et al., [106], the addition of 4% waste HDPE resulted in achieving the optimum performance in fatigue and rutting resistance. Hadidy and Yi-qiu [73] confirmed the findings of the aforementioned studies, namely, that the improvement of the softening point was directly related to an improvement in permanent deformation. Furthermore, the ductility result from the addition of LDPE in the modified asphalt binder showed an improvement in the cement performance in both high and low-temperature regions. According to Fang, binder modification using both polyethylene packaging waste (WPE) and organophilic montmorillonite (OMMT) significantly improved the fundamental properties of the modified asphalt, including the high-temperature performance, and low-temperature cracking resistance [107]. Maharaj concluded that the particle size and the amount of polyethylene terephthalate (PET) used had an impact on the asphalt binder in terms of fatigue cracking resistance and rutting resistance [108]. Xu et al. conducted a study on waste PET which is chemically treated by using triethylenetetramine (TETA) and ethanolamine (EA). This study also confirmed the capability of incorporating chemically treated waste PET into rubberized bitumen. The findings showed that waste PET improved the overall performance of rubberized bitumen [130].

Wang's study on the use of polyethylene (PE) and crumb tire rubber (CTR) found that the rheological properties of the asphalt binder were enhanced after modification at different temperature ranges. To acquire a stable modified asphalt binder, the density difference must be reduced, and the interaction must be enhanced [131]. However, there was a slight difficulty in the compatibility between waste polyethylene packaging (WPE) and asphalt cement when WPE exceeded 10% [132]. Furthermore, there was no improvement in asphalt binder performance at low temperatures through binder modification using waste tire rubber (WTR) and reclaimed low-density polyethylene (RPE) [110]. Table 4-1 summarizes some studies that investigated the use of waste plastic additives via the wet method (into asphalt binders).

The overall finding of this research suggested that recycled plastic can be included as: i) a substitute for aggregates, ii) an aggregate coating, iii) an asphalt binder modifier, or some combination of the three [28], [31]–[33], [119]. This incorporation of waste plastic additives in asphalt binder and/or asphalt mixture can improve the physical and mechanical properties of road pavements in terms of fatigue and rutting. The current study examined the use of MPP powder as a binder additive and its effect on the physical, thermal, rheological, and storage properties of the modified binder.

Table 4-1 Incorporation of Plastic Waste Additive to Asphalt Binder

							Mixing Conditions				
Origin	Plastic Type	Density (g/cm^3)	Tm [1] (°C)	Shape/Size (mm)	Binder Grade	OPT (%)	MT [2] (°C)	Mix Speed (RPM)	Time (min)	Notes	REF [3]
Computer parts	Electronic-Acrylonitrile Butadiene Styrene (ABS), Acrylonitrile Butadiene Styrene-Polycarbonate (ABS-PC) and High Impact Polystyrene (HIPS)	N/A	ABS = 105, ABS-PC = 125, HIPS = 180–260	Powder/0.3	PG58–28	5	N/A	5000 + 3000	45 + 15	E-waste plastics were treated with cumene hydroperoxide. The results showed untreated e-waste modified asphalt binders were stiffer and had more elastic behavior than the control binder; however, in treated e-waste plastics, the increases were significantly higher. Thus, treated e-waste modifiers have significantly improved the resistance to rutting of asphalt binders than untreated.	[133]
Waste petrochemical	Recycle Waste Polyethylene (RPE)	RPE = 0.92	RPE = 190	Powder/N/A	Aryl Hydrocarbon Bitumen AH-70	4	180	2000 + 5000 + <100	20 + 90 + 30	After adding 2% of RPE into asphalt binders, the performance grade changed and enhanced at the high-temperature performance, whereas at the low-temperature, the performance was kept unchanged after modification.	[36]
Waste packaging	Waste Polyethylene (WPE)	N/A	WPE = N/A	Powder/N/A	Non-waxy crude only A90	4	150, 175, 190, 205	3700	90	190 °C was the most suitable and recommended preparation temperature to mix WPE into the asphalt binder.	[134]
Waste milk packaging	Waste Packaging Polyethylene (WPE)	WPE = 1.8	WPE = N/A	Powder/N/A	A90	4	150	3750	90 min (with 10-min rest periods every half hour)	Organic montmorillonite (OMt) was mix with WPE modified asphalt. The results revealed that the addition of OMt improved the storage stability of WPE-modified asphalt, and meanwhile, OMt does not compromise WPE-modified asphalt's excellent high-temperature rheological properties.	[135]
Waste bottles	High-density polyethylene (HDPE)	N/A	HDPE = N/A	Powder/0.149–0.074	PG 64–16	10	180	4500	40	When 6 and 10% of HDPE were added to the asphalt binder, the fatigue life was improved.	[136]

Waste bottles	Waste rubber and polypropylene (PP), a blend of crumb rubber (CR) and PP powder by a ratio of 40:1 mixed with base asphalt to form plastic rubber asphalt (PRA)	PP = N/A, and CR = N/A	PP = N/A, and CR = N/A	PP and CR = Powder/Max 0.6 to 0.05	Shell 70	20	190	3600	N/A	Using plastic–rubber asphalt PRA mixture was matched with the SBS mixture for the low, high-temperature performances and water susceptibility, and it was more environmentally friendly in terms of energy consumption and greenhouse gas GHGs.	[137]
Waste pipe	Waste polyvinylchloride (PVC)	PVC = N/A	PVC = N/A	PVC = Powder/2–4	80/100	5	N/A	2000	120–180	The addition of waste PVC increased the rutting and fatigue life resistance of the asphalt mix.	[138]
Waste packaging	Waste polyethylene packaging (WPE)	WPE = N/A	WPE = N/A	WPE = Powder/4	N/A	6	N/A	3600	120	Modified asphalt with 10 wt% and below of WPE was the recommended percentage to obtain better service performances.	[97]
Waste packaging	Recycle polypropylene (PP), high- and low-density polyethylene (HDPE), and (LDPE)	PP, HDPE and LDPE = N/A	PP = 162, HDPE = 132 and LDPE = 110	PP, HDPE and LDPE = N/A	PG 64–22	4	PP = 190, HDPE = 180 and LDPE = 160	5000	PP = 50, HDPE = 60 and LDPE = 30	The recycled plastic wastes were pre-soaked in the asphalt for 60 min at 160 °C before mixing to ease the blending process.	[33]
N/A	Recycled polyethylene called PE1 and PE2	PE1 = 132.3 PE2 = 129.1	N/A	N/A	Trademark bitumen BNK 40/180	PE1= 5.4 PE2 = 3.9	180	420	180	When recycled polyethylene was introduced into the asphalt binder, the plasticity interval and viscosity of the asphalt binder increased significantly. The compatibility of asphalt binder and recycled polyethylene depends on the bulk properties of the polymer used. The Two mechanisms of the modifying action of recycled polyethylene were revealed: 1. Polyethylene with a higher melting temperature and narrow crystalline melting range does not interact with the dispersion medium of asphalt binder and serves as an inert filler, increasing the amount of disperse phase. 2. Polyethylene with a lower melting temperature and wide crystalline melting range combines with asphalt binder better.	[139]
Waste PET-based drinking bottles	Waste Polyethylene Terephthalate (PET)	PET = N/A	PET = 254 PET–TETA = <122, and PET–EA = 235	PET = Shredded/≤ 10, and CR = Powder/< 0.0232	60/70	CR = 18, PET–TETA = 2, and PET–EA = 2	180	3500	CR = 60, and 18CRMA2PET–TETA = 30 and 18CRMA2PET–EA = 30	The overall performance of rubberized bitumen improved when it was modified with treated waste PET. However, the incorporation of PET–TETA to modify the rubberized bitumen showed a significant increase in fatigue resistance. Whereas incorporation of PET–EA exhibited better resistance to permanent deformation.	[130]

[1] Melting temperature, [2] Mixing temperature, [3] Reference.

4.2 Materials and Methods

4.2.1 Materials

4.2.1.1 Asphalt Cement Properties

In this study, unmodified (virgin) asphalt cement (AC) PG 58–28 was used. Similar AC was used in previous studies at the University of Waterloo. The fundamental binder properties are presented in Table 4-2 [123]. The unmodified PG 58–28 was blended with MPP additives at concentrations of 2, 4, and 8 percent (by binder weight) to produce a total of four different binders. Each binder was tested at the appropriate test temperatures as designed by AASHTO standards. Prior to modification, binders were required to meet the AASHTO M320 standards. A series of DSR tests were carried out, following AASHTO T315, on the asphalt binders to characterize and determine the effect of MPP on the modulus at the high and intermediate performance grade temperatures.

Table 4-2 Properties of asphalt [123]

Property	Test Method	PG 58–28
Original Material		
Ash Content, %	ASTM D2939–09	0.03
Viscosity (Pa.s), At 135 °C	AASHTO T316	0.266
G*/sin(δ°), kPa	AASHTO T315	1.18
RTFO Residue	AASHTO T240	
Mass Loss (%)	AASTHO T240	0.37
G*/sin(δ°), kPa	AASHTO T315	3.05
PAV Residue		
G*sin(δ°), kPa	AASHTO T315	3550
m-Value at Pass Temperature	AASHTO T313	0.358
Stiffness, MPa at Pass Temperature	AASHTO T313	187
m-Value at Fail Temperature	AASHTO T313	0.294
Stiffness, MPa at Fail Temperature	AASHTO T313	385
True Grade	AASHTO M320	59.4–31.4

Complex shear modulus (G)

4.2.1.2 Multi-Layer Plastic Packaging

The MPP used in this project contained Polyethylene (PE), Polyester (PET), Nylon (NY), and Metallized Polyester (METPET) with different structures (PE-PETMET-PET, PE-PET, PE-NY-PET).

The MPP was provided by Peel Plastic Products Ltd. In addition to the MPP material, a recycled Low-density polyethylene (LDPE) was also investigated in this project as the second alternative for recycled plastic material. Table 4-3 illustrates the typical physical properties of the film materials used. After computing the total volume and mass for each bag, total bag structure percentages were calculated, and thus the total percentage composition of each polymer type was obtained, as summarized in Table 4-4.

Table 4-3 The typical physical properties of MPP and LDPE additives

Material	Melting Temperature (Tm °C) ASTM D7138-16	Transition Temperature (Tg °C) ASTM D7138-16	Density (g/cm^3)
Polyethylene (PE)	110–140	−120	0.9–0.95
Nylon (NY)	252–265	50	1.1–1.2
Polyester (PET)	240–255	75	1.4
Metallized Polyester (METPET)	240–255	75	1.4
Low-density polyethylene (LDPE)	110–140	−120	0.9–0.95

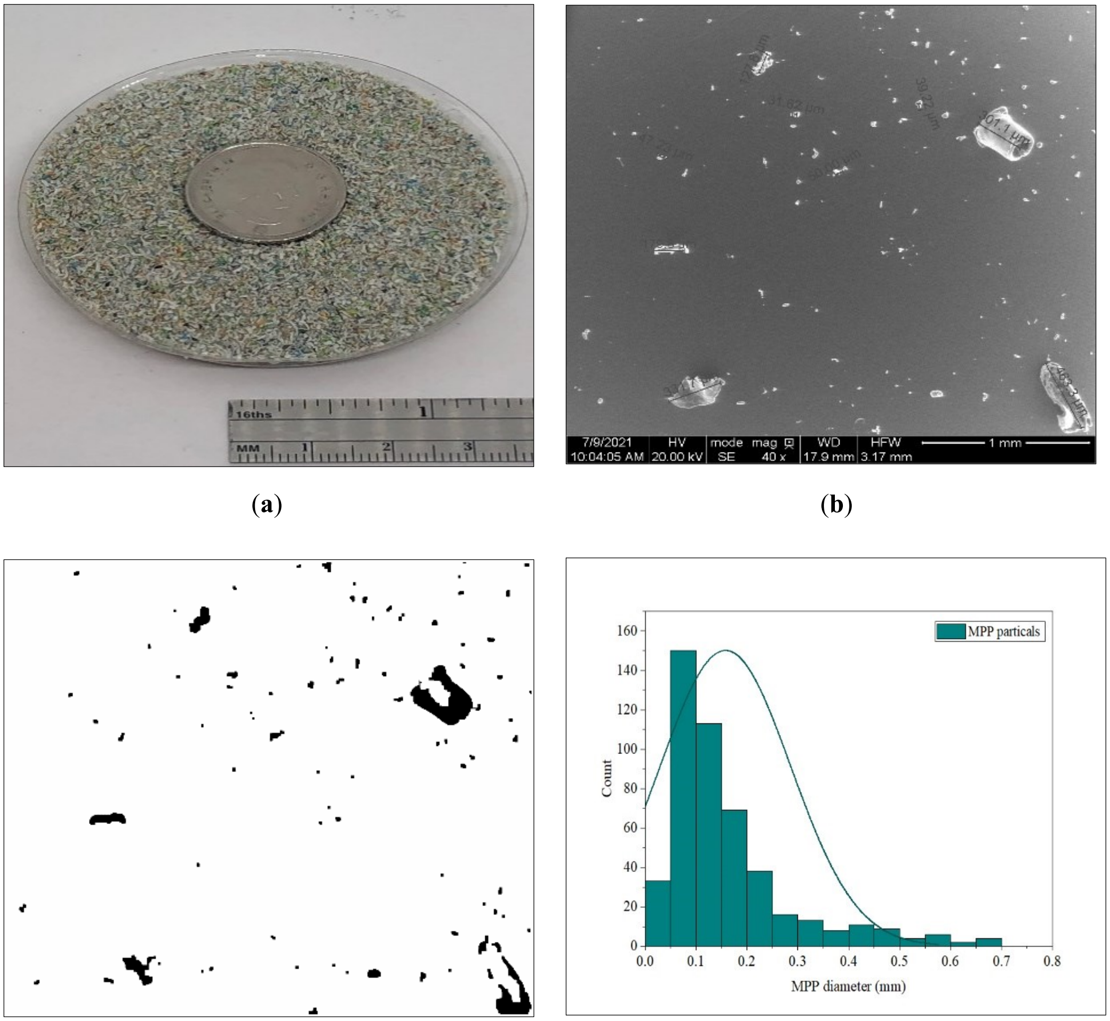
Table 4-4 The MPP and LDPE are based on the approximate total mass percentages

Bag Structure	% PE	% METPET	%NY	% PET	Total
PE-METPET-PET	87	8	---	5	100
PE-PET	94	---	---	6	100
PE-NY-PET	86	0	8	6	100
Blend *	89	3	2	6	100
LDPE	100	---	---	---	100

* Blend is a representative mix by mixing all MPP

4.2.1.3 The MPP Additives Preparation

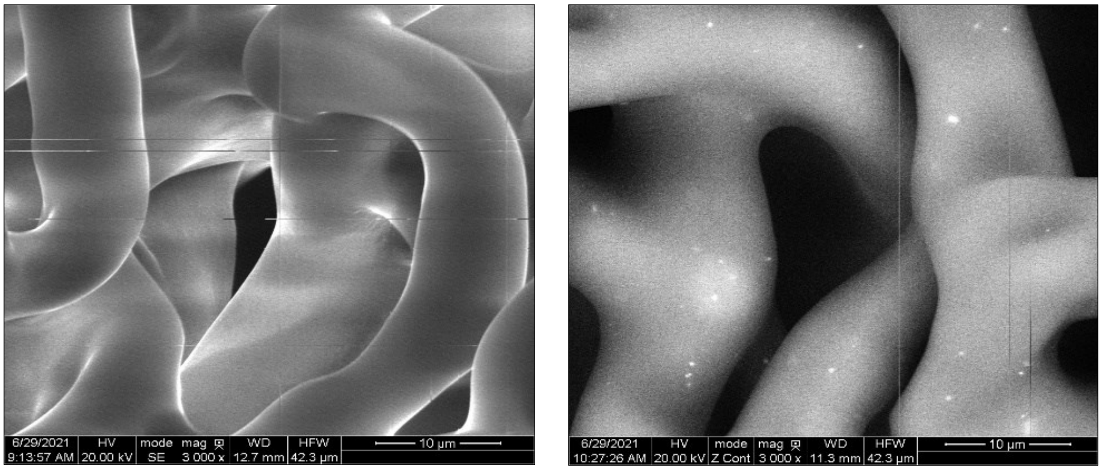
To prepare MPP powder additives, a Micro-Cut electric shredder was used to shred the MPP into small particles (2–6 mm). The shredded material was ground to powder using an Electric Grain Mills Grinder (Ultra Grinder Machine) and then sieved to determine the grain size distribution of the MPP powder. The particle size distribution of the MPP powder to be added to the asphalt binder was between 0.075 to 0.595 mm, see Figure 4-1. ESEM was utilized to ensure the MPP powder size meets the AASHTO and ASTM particle size recommendation below 250µm in the modified binder before the DSR test. The test results showed that the MPP additive powder size was reduced after binder modification. Most of these particles melted and integrated into the asphalt binder. Particles with higher melting points did not melt, but their size was reduced to a size below the recommendation of AASHTO T 315 and ASTM D7175 standards (less than 250 μm), as shown in Figure 4-2 below.



(**a**) (**b**)

(**c**) (**d**)

Figure 4-1 (a) MPP powdered form, (b) ESEM image of MPP at 40× magnification (1 mm), (c) MPP size analysis using ImageJ, and (d) MPP particle distribution (mm)



(a) **(b)**

Figure 4-2 ESEM images of (a) unmodified PG 58–28 binder and (b) Blend−8 at 3000× magnification (10 µm)

4.2.1.4 The MPP-Modified Asphalt Preparation

The virgin binder used in this experiment was PG 58–28. All MPP and LDPE modifications were performed at 2%, 4%, and 8% by the total weight of asphalt cement. Initially, the selected concentrations were determined based on the literature. Based on Table 4-4, the relative proportion of PET in each plastic product is different between PE-METPET-PET and PE-NY-PET. The smallest addition (e.g., 2% of PE-NY-PET) reflects the relatively higher proportion of ‘pure’ PET in that product, where it represents 6% compared to 5% in the PE-METPET-PET; thus, the 2 and 4% additions of PE-NY-PET and PE-METPET-PET were selected to produce blends with similar overall PET content. The 8% addition for both plastics was selected as a “ceiling” based on previous research that tended not to exceed 10% by weight of the binder. Table 4-5 shows the identified blends’ ID and their selected percentage additives for each blend used in this study. The mixing procedure was performed in two steps:

- Step 1: the hot asphalt binder was mixed with the additives using a stirring bar until the additives and asphalt binder produced a homogenous blend.
- Step 2: a high shear mixer was used to enhance the homogeneity of the blend at a temperature of 175 °C (±5 °C) at a rotational speed of 3500 rpm for one hour.

The mixing temperature was selected with respect to the thermal properties obtained from the DSC and TGA tests. The blend is a representative mix by mixing all the MPP types, as shown in Table 4-4 This blend will be further analyzed in the result and discussion section.

Table 4-5 List of modified asphalt binder blends

Asphalt Cement	Modifier	Modifier Tested (%)	ID in the Graphs
PG 58–28	None	0	Unmodified (PG58–28)
	LDPE	4, 8	LDPE-4 and LDPE-8
	Blend	4, 8	Blend-4 and Blend-8
	PE-METPET-PET	4,8	PE-METPET-PET-4 and PE-METPET-PET-8
	PE-NY-PET	2, 8	PE-NY-PET-2 and PE-NY-PET-8
	PE-PET	2, 4	PE-PET-2 and PE-PET-4

4.2.2 Experimental Methods

This section briefly describes the various laboratory experiments performed in this research investigation. A summary of the experiment's objectives and methods is stated herein. Detailed steps of these experiments could be obtained from the AASHTO or ASTM standard testing methods. The laboratory experiments were classified into experiments to perform thermal analysis, which is associated with a material-dependent response when heat is supplied to asphalt samples, and others for rheological analysis, which is associated with the flow and deformation characteristics of asphalt binder.

4.2.2.1 Thermal Analysis

4.2.2.1.1 Differential Scanning Calorimetry

The Differential Scanning Calorimetry (DSC) Q2000 is utilized to measure the thermal properties of MPP additives. The DSC laboratory testing was performed on the MPP and LDPE samples following ASTM D3418 to determine the melting, crystallization, and glass transition temperature information. Samples (weight range 10 to 20 mg) were subject to two cycles of cooling and heating. Each cycle started by maintaining the sample temperature at −90 °C for 2 min, followed by increasing the temperature to 260 °C and maintaining the temperature for 2 min. The heating and cooling rates were conducted at a rate of 10 °C per minute.

4.2.2.1.2 Thermogravimetric Analysis

Thermogravimetric Analyzer (TGA) is utilized to measure the amount and rate of change in weight of MPP and MPP-modified asphalt samples. TGA measures the weight change of materials from ambient temperatures up to 1000 °C and detects phase changes resulting from decomposition, oxidation, or dehydration. Results of TGA are correlated to the thermal stability of both the MPP additives and asphalt cement samples used in this study. The heating rate used in the TGA was 10 °C/min.

4.2.2.2 Morphology Observation

4.2.2.2.1 Environmental Scanning Electron Microscopy

Environmental Scanning Electron Microscopy (ESEM) is carried out to determine the MPP size before and after the blending process at a microstructural scale. In addition, ESEM is utilized to ensure random and homogenous distribution of the MPP particles in the asphalt cement prior to measuring the storage stability. The ESEM is used to assess the presence of segregation between the asphalt cement and MPP. ESEM setting was performed according to Mikhailenko et al., 's [140] recommendations.

4.2.2.3 Physical Properties

4.2.2.3.1 Rotational Viscometer

The viscosity of unaged asphalt samples is typically measured using the Rotational Viscometer (RV). The Strategic Highway Research Program (SHRP) stated a maximum viscosity of 3 Pa.s at 135 °C for workability purposes [48]. The binder's viscosity at mixing temperature is specified at 0.17 Pa.s ± 0.02. The binder's viscosity at compaction temperature is specified at 0.28 ± 0.03 Pa.s [141]. The ratio between the applied shear stress and the shear rate is referred to as viscosity. Viscosity measures the resistance of liquid material to flow (measured in Pascal-second, Pa.s). The test protocol used, according to AASHTO T 316 [141], specifies using an SC4-21 spindle at test temperatures of 135 °C, 150 °C, and 165 °C, and with speeds of 20, 50, and 100 rpm, respectively.

4.2.2.4 Rheological Performance

4.2.2.4.1 Dynamic Shear Rheometer

Dynamic Shear Rheometer (DSR) is performed to measure the binder's complex shear modulus (G*) and phase angle (δ°). G* is the parameter indicating the binder's total resistance to deformation when frequently shared, and the δ° measures the delay between the applied shear stress and the resulting shear strain. The phase angle shows the range of the behavior of binder cement material from 0° (perfectly elastic material) to 90° (perfectly viscous material). Temperature and loading frequency has a direct effect on the G* and δ° values. Virgin and MPP-modified asphalt binders were tested following the AASHTO 315 to determine the G* and δ°[142, p. 315].

4.2.2.4.2 Multiple Stress Creep Recovery

Multiple Stress Creep Recovery test is performed to measure elastic recovery, non-recoverable compliance (J_{nr}), and percentage recovery in virgin and MPP-modified asphalt samples at high temperatures. The test is performed based on (AASHTO MP19 and AASHTO M332) using the DSR equipment [143]. The testing mechanism includes the application of a specific load for one second followed by a 9-s rest period. The experiment starts with ten low-stress cycles (0.1 kPa) followed by ten high-stress cycles (3.2 kPa). The outcome of the test is used to estimate the permanent deformation of the asphalt cement by using the non-recoverable compliance (J_{nr}) to determine the corresponding traffic range in Equivalent Single Axle Loads (ESALs), as illustrated in Table 4-6. High creep resistance is reflected by achieving the low value of (J_{nr}), and high value of R. Based on recommendations stated in AASHTO MP19, the J_{nr} value corresponding to a 3.2 kPa load is used to determine the presence of a sufficient amount of elastomer in the modified asphalt. Finally, the standard curve can be developed to show the presence of a sufficient amount of elastomer in the modified asphalt. In this study, the MPP R-value did not exceed the standard curve due to its low elasticity.

The standard MSCR curve is the reference point to evaluate the elasticity of binders. If J_{nr} is higher than the MSCR curve, this indicates the binder has high elasticity, such as elastomeric polymers. If the J_{nr} results are below the reference MSCR curve, this indicates the binder has low elasticity, such as plastomeric polymers.

Table 4-6 MSCR grades depend on Jnr values (AASHTO M332)

Designation Traffic Level	J_{nr} Value at 3.2 kPa−1	ESALs Million and Load Rate
"E" refers to Extremely high traffic loading	0.0–0.5	≥30 and <20 km/h
"V" refers to Very high traffic loading	0.0–1.0	≤30 or <20 km/h
"H" refers to High traffic loading	1.0–2.0	10–30 or 20–70 km/h
"S" refers to Standard traffic loading	2.0–4.0	≤10 and >70 km/h

Note: ESAL = equivalent single-axle load.

4.2.2.4.3 Linear Amplitude Sweep

The linear amplitude sweep test (LAS) is used to determine the fatigue damage resistance of the asphalt cement according to AASHTO TP101. The LAS test uses cyclic torsion to increase strain amplitude steadily. Cyclic torsion results in the failure of the asphalt cement sample. The LAS test contains two tests, a frequency sweep and an amplitude sweep test. The frequency sweep test is performed by applying a constant strain of 0.1% and frequencies ranging from 0.2 to 30 Hz. The frequency sweep data is used to calculate the damage analysis "alpha" parameter. The linear amplitude sweep is performed by applying a linearly increasing strain within the range of 0–30% strain at a frequency of 10 Hz. The Viscoelastic Continuum Damage (VECD) model was used to determine the fatigue life of the asphalt binder as a function of strain, according to Hintz et al., [144]. Equation 4-1 was used to calculate the fatigue life of the modified binders. The LAS test was performed on the RTFO-aged samples at an intermediate temperature to evaluate fatigue damage resistance by conducting the number of cycles to failure (N_f). The N_f at 50% reduction from the initial modulus was selected to determine the peak stress failure as recommended by AASHTO TP101[145].

Equation 4-1

$$\boldsymbol{N_f = A\ (\gamma_{max})^B}$$

where *Nf* is the number of cycles to failure, γ_{max} is the maximum applied shear strain, and the parameters *A* and *B* are constants determined through the material characteristics.

4.2.2.4.4 Complex Shear Modulus under Frequency Sweep

The frequency sweep test applies a 0.5% strain rate at four low test temperatures of 5 °C, 15 °C, 25 °C, and 35 °C and uses an 8 mm parallel plate with a 2 mm gap. The high testing temperatures are 46 °C, 58 °C, 64 °C, 76 °C, and 82 °C and the experiment is performed using 25 mm parallel plate with a 1 mm gap and loading frequency sweep at 5% strain. The complex shear modulus (G*) and the phase angle (δ°) values were obtained for each MPP-modified asphalt sample. The G* and δ° were used to develop the master curve. A 2S2P1D model parameters were used to model the viscoelastic response of the MPP samples based on the recommendations of Nur et al., [146]. The data from the DSR test were modified by time-temperature superposition shift factors using the William–Landel–Ferry (WLF) Equation 4-2 to develop the master curve for the MPP-modified asphalt samples.

Equation 4-2

$$\log a_t = \frac{-C_1(T-T_{ref})}{-C_2+(T-T_{ref})}$$

where T_{ref} is the reference temperature and C_1 and C_2 are referred to as material constants.

The black space diagrams present complex modulus vs. phase angle. Black space diagrams were also developed using the frequency sweep test data.

4.2.2.5 Storage Stability

Storage stability in modified binders could be analyzed using several techniques. In this study, the separation ratio was used to evaluate storage stability. The storage stability test, commonly known as the cigar tube test (CTB), was used to determine the separation tendency of MPP-modified asphalt following the ASTM D 7173–11[147]. The CTB test uses an aluminum tube (25 mm diameter and 140 mm height) to hold the material during storage. The storage stability test was performed by filling tubes with 50 ± 0.5 g of MPP- modified asphalt binders. The tubes were sealed and stored vertically in an oven at 163 ± 5 °C for 48 h. The tubes were transferred to a freezer at −10 ± 1 °C for a minimum of 4 h until the material was completely solidified. Individual tubes with the solidified binder were split into three equal specimens, and the center specimen was discarded. The top and bottom specimens were used to determine the rheological properties of the binder, including G* complex modulus and phase angle δ°, and to test the morphology of the binder. Low compatibility between asphalt binders and polymers leads to a reduction in the storage stability of the modified binder. Low compatibility could result from differences in molecular structure, density, molecular weight, and viscosity of the polymer and asphalt components [148].

4.2.2.5.1 The Separation Ratio

In this study, the separation ratio was used to evaluate storage stability by applying Equations (3) and (4). The control, all MPP and LDPE modified binders were examined using DSR tests to obtain the rheological properties parameters (G^* and $\delta°$) at 58 °C. Separation ratios $R_s(G^*)$ and $R_s(\delta°)$ were calculated using Equation 4-3 and Equation 4-4 (NCHRP) 9–10 report recommended the values of the separation ratio within 0.8 to 1.2 to avoid binder separation[149].

Equation 4-3
$$R_s\,(G^*) = G^*\ separation\ ratio = \frac{[G^*]_{top}}{[G^*]_{bottom}}$$

Equation 4-4
$$R_s(\,\delta°) = \delta\ separation\ ratio = \frac{[\delta°]_{top}}{[\delta°]_{bottom}}$$

4.3 Results and Discussion

4.3.1 Differential Scanning Calorimetry

Table 4-7 summarizes the maximum endothermic peak integration, which refers to the melting points of all MPP and LDPE additives. The mixing temperature for all MPP and LDPE materials in this study was selected at 175 °C ± 5 °C to ensure the POLY and LDPE material enter the melting phase and blend with the liquid asphalt cement. The remaining components of the MPP materials used in this project (PET, NY, and METPET) represent less than 15% of the total MPP weight. These materials were treated as fillers due to their high melting points.

Table 4-7 Peak Integration by DSC for all MPP and LDPE

MPP	Start	Onset	Maximum	Stop	Area
	°C	°C	°C	°C	J/g
PE-PET	64.12	113.35	119.69	165.21	73.76
	233.27	237.91	249.08	267.97	4.435
PE-NY-PET	42.56	112.97	119.48	158.13	69.78
	185.08	237.32	251.14	269.65	25.24
PE-METPET-PET	62.1	111.11	120.5	151.39	55.04
	215.75	241.03	253.04	278.08	16.31
LDPE	46.6	101.74	109.42	141.96	103.7

4.3.2 Thermogravimetric Analysis

The magnitude and rate of change of MPP weight and asphalt cement samples were analyzed using TGA. Figure 4-3 demonstrates the thermogravimetric curve of the virgin PG 58–28 binder and MPP additives from 25 °C to 600 °C. Both MPP additives and PG 58–28 showed high thermal degradation temperatures. The degradation was limited to 5% for MPP additive up to 320 °C and almost 10% for PG58–28. The significant degradation occurred after 400 °C for the MPP additives, while the PG58–28 started rapid degradation around 320 °C. The selected mixing temperature of 175 ± 5 °C prevents the occurrence of significant thermal degradation to the mix.

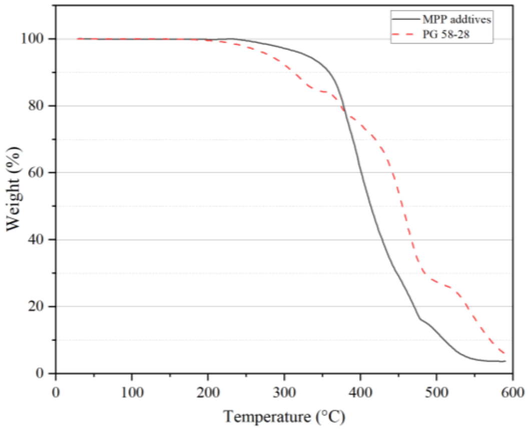


Figure 4-3 TGA curves of MPP additives and PG 58–28

4.3.3 Rotational Viscometer

The viscosity of modified asphalt binders using MPP and LDPE was measured to ensure the modified binder met the Superpave binder specification. Recommendations of Superpave specification stated that binder viscosity should not exceed 3 Pa.s when measured at 135 °C. Figure 4-4 presents the viscosity results measured at 135 °C. All the dosages 2%, 4%, and 8% showed a noticeable increase in the viscosity of all MPP-modified asphalt binders and LDPE-modified binders. However, all MPP-modified binders did not exceed the Superpave requirement. The viscosity of 2% MPP-modified binders was 50% higher than that of the control sample. The increase in viscosity was 100% higher in the 4% MPP-modified binder and 400% higher in the 8% MPP-modified binder.

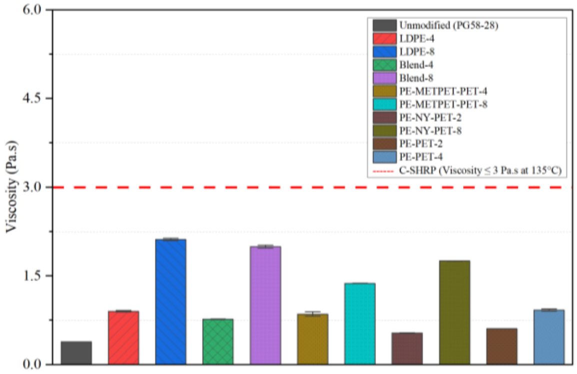


Figure 4-4 SHRP requirement 3.0 Pa.s at 135

Multiphase systems that occur when asphalt blends with polymers can lead to complex inter-molecular friction [150]. This complexity can lead to an increase in the applied shear stress, consequently increasing viscosity. In this study, the increase in viscosity values could be attributed to the effect of the non-dissolved particles and the difference in molecular structure, weight, and density of MPP additives [33]. To ensure the increment dosage showed the same trend even at different temperatures, changes were measured at 150, 165, and 180 °C, as presented Figure 4-5. The increase in the dosage subsequently increased the calculated mixing and compaction temperature range of all the modified binders, as presented in Figure 4-5 The increase in viscosity of modified binders resulted in an increase in mixing and compaction temperature ranges starting from 5 to 30 °C. This increase in viscosity could increase the resistance to high-temperature deformation. However, it has a high cost due to increased energy consumption and the production of additional greenhouse gases.

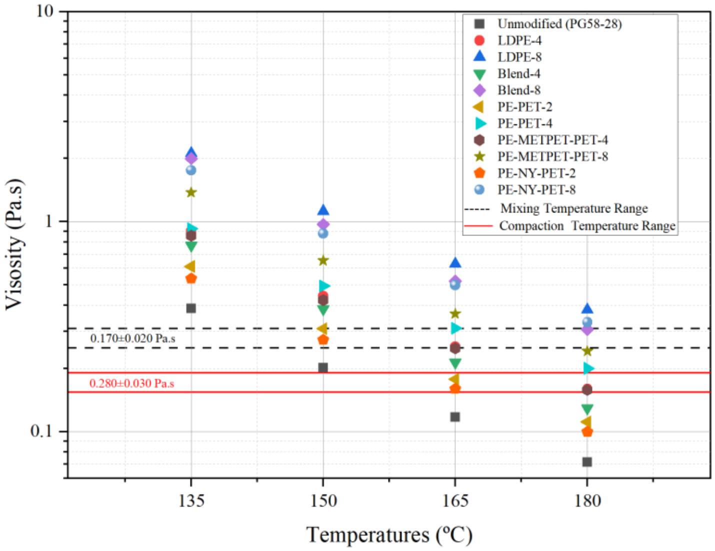


Figure 4-5 Temperature-viscosity curves of MPP and LDPE asphalt binders

4.3.4 Rheological Characterization

4.3.4.1.1 Dynamic Shear Rheometer

4.3.4.1.1.1 Rutting and Fatigue Parameters

The rheological properties of asphalt binders were characterized using the DSR test according to AASHTO M320 and M332. Superpave reported that G*/sin(δ°) factor for unaged and RTFO-aged asphalt binder samples indicates the potential resistance to permanent deformation at high temperatures. In this study, the G*/sin(δ°) increased by adding MPP and LDPE additives to the virgin asphalt, as shown in Figure 4-6. The addition of MPP or LDPE in any amount showed an increase of the G*/sin(δ°) for both unaged and RTFO-aged, modified binders when compared to the unmodified sample. The addition of 4% and 8% LDPE increased the G*/sin(δ°) from 1.8 to 3.0 KPa and 8.0 kPa, respectively. The addition of 4% and 8% MPP resulted in a higher increase of G*/sin(δ°) compared to the LDPE. The 8% MPP binder exhibited G*/sin(δ°) increase for unaged and RTFO-aged samples by more than 400% compared to the control binder. Binder modification using 8% PE-NY-PET resulted in an increase of G*/sin(δ°) from 1.8 kPa to 18.9 kPa and 62.6 kPa in unaged and aged binder samples, respectively. This noticeable change occurred due to the high elasticity and tensile strength of the NYLON.

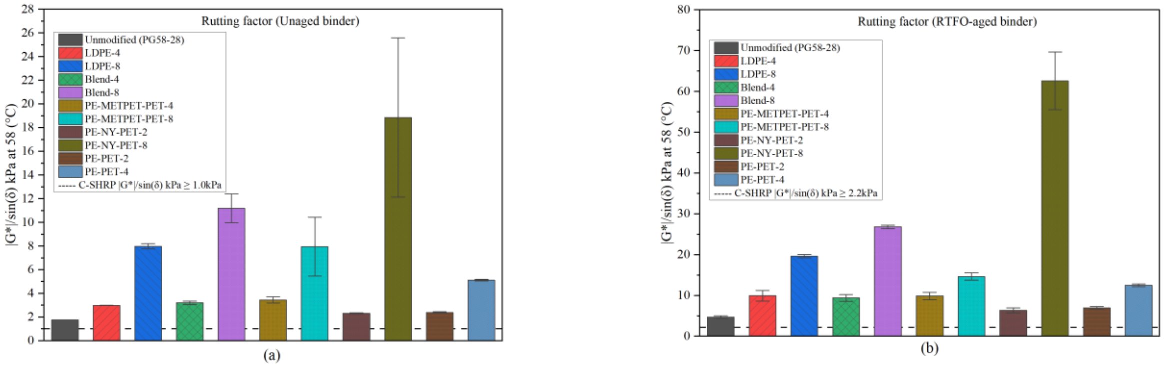


Figure 4-6 Rutting G*/sin(δ°) parameter for (a) unaged and (b) RTFO-aged binders

The noticeable increase in G*/sin(δ°) through LDPE and MPP binder modification indicates a change in the high-temperature grade of unaged and RTFO-aged samples. Therefore, LDPE- and MPP-modified binders would have high resistance to rutting at temperatures exceeding the virgin binder's PG high temperature. For example, the 8% MPP modified binders exhibited a shift in the high-temperature grade up to 100 °C while the virgin binder maximum high Superpave temperature for the virgin binder was 82° C according to Table 4-8.

Table 4-8 High-temperature continuous grade of MPP and LDPE modified binders for Unaged and RTFO aged binders

Asphalt Binder ID	Unaged Grading (°C)	RTFO-Aged Grading (°C)
Unmodified (PG58–28)	63	64
LDPE-4	67	70
LDPE-8	76	76
Blend-4	68	70
Blend-8	85 *	102 *
PE-METPET-PET-4	69	70
PE-METPET-PET-8	91 *	74
PE-NY-PET-2	65	67
PE-NY-PET-8	104 *	109 *
PE-PET-2	65	67
PE-PET-4	73	72

* Exceeds the maximum Superpave high temperature of 82 °C.

Figure 4-7 illustrates the difference between the fatigue parameter G*sin(δ°) for various virgin and modified binders. Generally, G*sin(δ°) reflects the linear viscoelastic properties of the MPP-and LDPE-modified binders. However, several studies concluded that the G*sin(δ°) fatigue parameter does not accurately measure the correlation between the asphalt binder fatigue resistance and pavement resistance to fatigue cracking as several parameters contribute to the mixtures fatigue resistance in addition to the binder's G*sin(δ°) [151]–[155]. In addition, the weak correlation between the binder's G*sin(δ°) and the mixture's fatigue cracking resistance is that G* and δ° are measured within the linear viscoelastic region. This region does not represent the actual variety of strains or stresses that occur in the nonlinear viscoelastic region of pavement loading. In other words, the pavement response in the higher stresses and strains exceeds the linearity of the viscoelastic region.

Superpave specification (AASHTO M 320) concluded that higher fatigue resistance of asphalt binder could be obtained using a lower G*Sin δ° parameter. Figure 4-7 presents the G*sin(δ°) of all virgin and modified binders. All MPP and LDPE-modified binders exhibited an increase in G*sin(δ°) values compared to the virgin binder. This concludes that MPP and LDPE binder modification would potentially result in a reduction in the binder's resistance to fatigue cracking within the linear viscoelastic material behavior. MPP- and LDPE-modified binders with a high percentage (exceeding 4% modification) exhibited G*sin(δ°) results that exceeded the Superpave maximum threshold of 5000 kPa at 19 °C. Since the G*sin(δ°) fatigue parameters cannot be used as an accurate performance measure to evaluate binder resistance to fatigue cracking and HMA resistance to fatigue cracking [43–46], these results are considered an indicator of the fatigue performance, but further testing on the HMA mixtures will be performed to develop a robust and comprehensive conclusion about the impact of MPP and LDPE binder modification on the fatigue resistance.

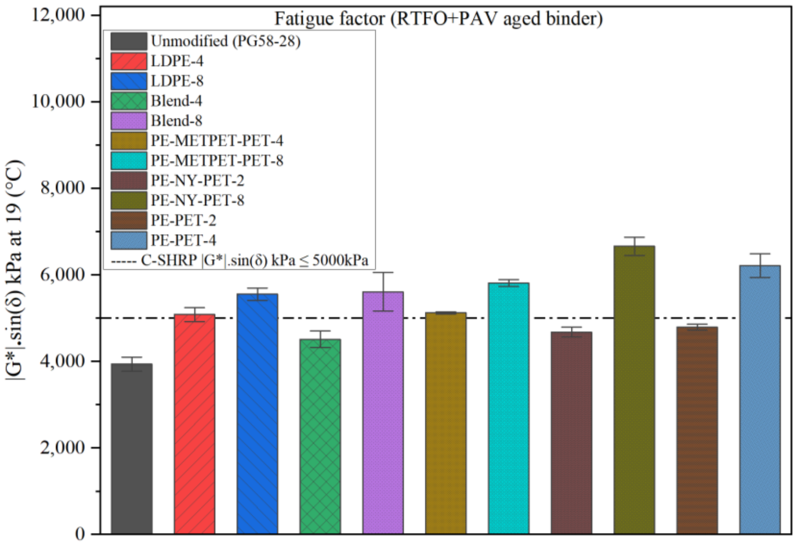


Figure 4-7 Fatigue parameter G*sin(δ°) for RTFO + PAV aged binders

The intermediate testing temperature of the virgin binder was 19 °C. The DSR results indicated that the intermediate temperature of MPP- and LDPE-modified binder exceeded 22 °C. This increase in the intermediate temperature is a direct result of the MPP- and LDPE-binder modification. Therefore, the MPP- and LDPE-modified binders should be tested at the intermediate temperature determined by the DSR rather than the recommended temperature based on the grade of the virgin binder. To set a consistent testing reference temperature in this project, all binder samples (virgin and modified) were tested at 19 °C as the intermediate testing temperature.

4.3.4.1.2 Multiple Stress Creep Recovery

Multiple Stress Creep Recovery (MSCR) test was performed according to AASHTO T350 to determine the following parameters J_{nr} 3.2, percent recovery, and J_{nr} difference. The test was performed at 58 °C based on Ontario's climatic conditions [156]. Figure 4-8 a presents the noticeable changes in J_{nr} 3.2 with the increase of all MPP and LDPE additives. The rate of change of J_{nr} 3.2 increased consistently by adding the binder modifiers leading to an increase in the binder modulus. An increase in binder modulus could be interpreted by the reduction of binder strain under traffic loads within the linear elastic range of the material properties when preventing permanent deformations. Figure 4-8 b presents the result of J_{nr} 3.2 versus the G*/sin (δ°). The figure concludes an inverse correlation that binder resistance to permanent deformations increases (i.e., increase in G*/sin (δ°)) by decreasing J_{nr} 3.2 (i.e., higher MPP and LDPE concentrations).

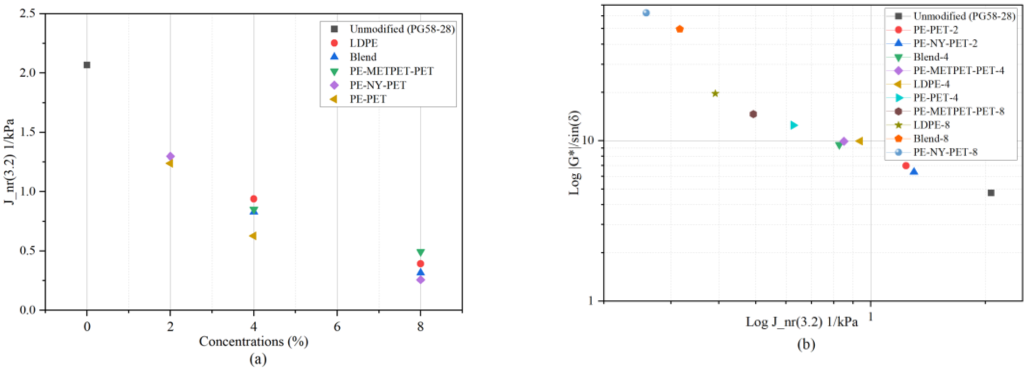


Figure 4-8 (a) Jnr (3.2 kPa) vs. additive concentration (%); (b) Log Jnr 3.2 vs. Log G*/sin(δ°)

Figure 4-9 demonstrates the relationship between the percentage recovery and non-recoverable compliance for virgin, MPP-modified, and LDPE-modified binders. Modified binders exhibited an improvement in traffic grades compared to virgin binders. The increase of MPP and LDPE modifiers from 2% to 8% led to a traffic upgrade in MSCR traffic grades from the standard traffic “S” to Extremely Heavy traffic “E”. The percent recovery results of the blends that contain NYLON (PE-NY-PET and Blend-8) had higher percentage recovery (i.e., reflecting more elastic behavior). The percentage recovery increased from 2.22% for the virgin binder to 14.68% and 21.68% for Blend-8 PE-NY-PET-8, respectively. This indicates higher resistance to permanent deformation of the modified binders.

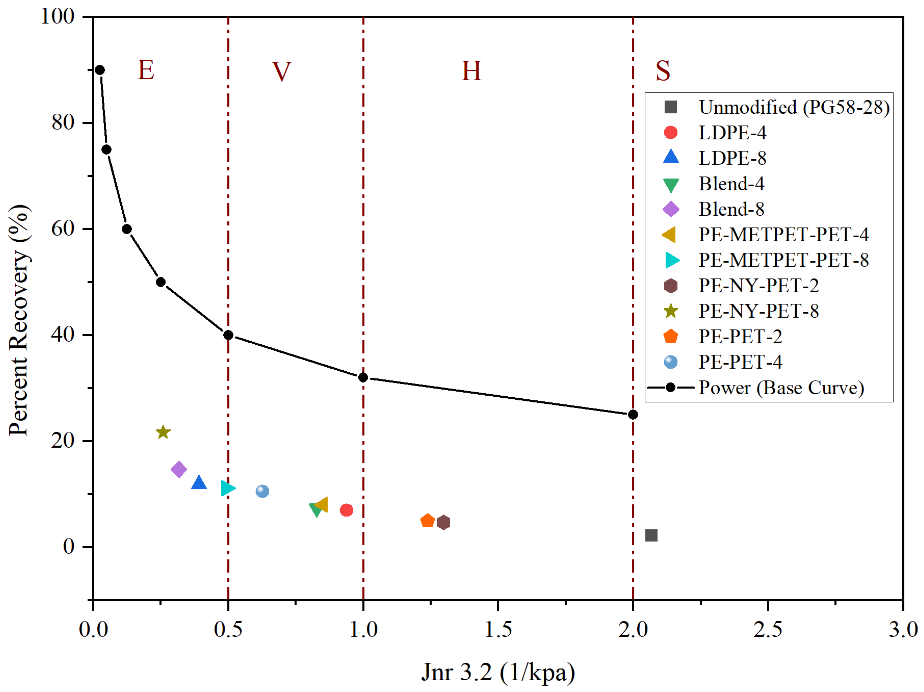


Figure 4-9 Relationship between R and Jnr for MPP- and LDPE-modified binders

4.3.4.1.3 Linear Amplitude Sweep

The LAS test is used to evaluate the fatigue damage resistance of the asphalt binder under standard AASHTO TP101. LAS is performed to determine the number of cycles to failure under fatigue cycles (N_f). The LAS test was performed at 19 °C and 22 °C and two strain levels (2.5% and 5%) representing the thick and thin pavements, respectively. Figure 4-10 presents the results obtained using a viscoelastic continuum damage (VECD) model at 50% damage levels. The results present the difference in LAS for all MPP- and LDPE-modified binders versus the virgin PG 58–28 binder. LAS performed at 19 °C, and 2.5% strain showed a slight increase of 7% in N_f for PE-NY-PET-8 and PE-PET-4 modified binders compared to the virgin binder. The LDPE-4, Blend-4, PE-METPET-PET-4, and Blend-8 modified binders exhibited a 10% increase in N_f compared to the virgin binder. PE-PET-2 was the only modified binder that exhibited lower N_f compared to the virgin binder. Other modified binders exhibited more significant increases in N_f, like PE-NY-PET-2, LDPE-8, and Blend-8, which increased by 50%, 70%, and 230%, respectively, compared to the virgin binder. LAS results at 22 °C generated similar trends as testing at 19 °C except that PE-METPET-PET-4 and blend-8, PE-NY-PET-8, and PE-PET-2 modified binders showed a smaller percentage of increase in N_f compared to the percentage of increases obtained at 19 °C.

The mobility of the polymer chains during fatigue loading results in early-stage brittle failure [148]. This phenomenon is associated with high molecular weight (Mw) and densifier-packed molecules. In contrast, low Mw increases chain mobility, which leads to an increase in resistance to shear yielding and ductile failure. Low Mw binders are expected to exhibit more N_f compared to binders with high Mw. The results of N_f for 8% LDPE at 5% strain level show an increase of 7% and 19% at 19 °C and 22 °C, respectively, compared to the virgin binder. On the contrary, a reduction of N_f is noticed in PE-NY-PET-2–8 and PE-PET-2-4 by comparing the N_f of modified binders to the virgin binder. This is because ductile-brittle transition occurs at an early stage with mixes containing higher PE concentration. This is justified by the high Mw of the PE and densely packed molecules [148]. Finally, the LDPE-8 and Blend-8 characterized by low molecular weights exhibited an increase in the N_f compared to other mixes.

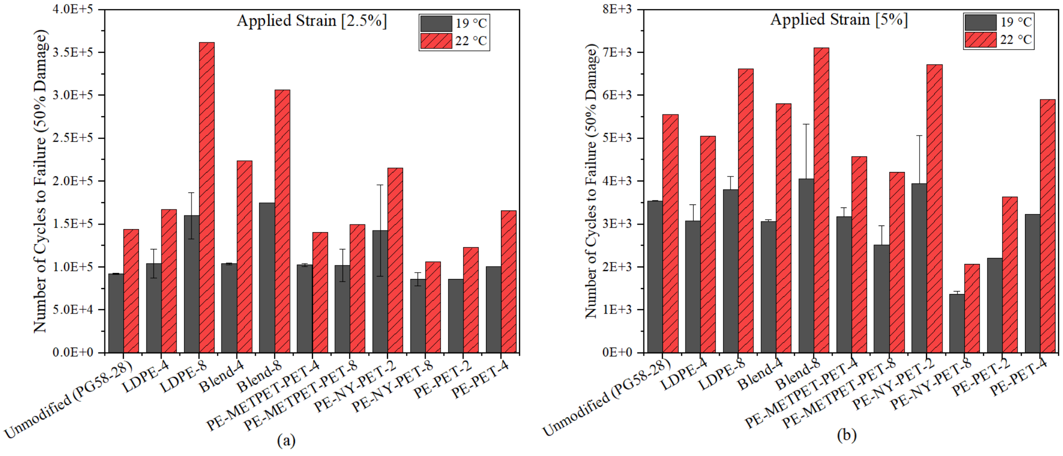


Figure 4-10 LAS results of MPP-LDPE-modified binders at 19 °C and 22 °C (a) 2.5% strain; (b) 5% strain

Results of the LAS test indicated that most of the modified blends exhibited an increase in N_f at 2.5% and 5% strain levels compared to the virgin binder. Since the LAS test considers the nonlinear viscoelastic behavior of asphalt binders, this experiment would offer a more accurate appreciation of the resistance to fatigue cracking compared to the fatigue factor G*sin(δ°) [157]. However, the discrepancy between the two tests confirmed the absolute need to use the mixture performance tests as a reliable evaluation when it comes to evaluating fatigue performance. Moreover, it confirmed the conclusions stated by Deacon et al., [151] that fatigue response in the pavement structure cannot be determined through testing asphalt binder only. Several factors significantly contribute to pavement fatigue performance, including mix characteristics, pavement structure, traffic, and environmental status[49].

4.3.4.1.4 Complex Shear Modulus under Frequency Sweep

The experimental matrix in this project included measuring the complex shear modulus and the phase angle δ° (◦) at a standard range of temperatures and frequencies for control virgin binder, MPP-modified, and LDPE-modified binders. The complex shear modulus includes a relative component of the elastic and viscous response to loading. Master curves were developed for all MPP- and LDPE-modified binders unaged samples. The results indicate a gradual increase of complex modulus at the high modified frequencies (representing low temperatures) and a reduction in modulus at low modified frequencies (representing high temperatures). The complex modulus significantly increased at all modified binders compared to the virgin binders, as expected from the MSCR test results. For example, MPP-modified binders, with 8% MPP, have shown a significant increase in the complex modulus that exceeded that of the virgin binder up to 10 times (at certain frequencies and testing temperatures). The LDPE-modified binder at an 8% modification rate has shown a more modest increase of complex modulus up to 3.5 times at certain frequencies and testing temperatures compared to the virgin binder. The increase in the stiffness aligns with the findings of the MSCR test and confirms the strong potential of improving the permanent deformation resistance using MPP- and LDPE-modification. The temperature range between 15 °C and 35 °C showed a change by +50%, +70%, and 100% of complex modulus for 2, 4, and 8% MPP- and LDPE- modified binders, respectively. Finally, at a low testing temperature (5 °C), the change of the complex modulus was less than 30% for 8% binder modification and less than 10% for 2% binder modification compared to the virgin binder, as presented in Figure 4-11 Therefore, a low modification percentage of MPP additives could maintain the low-temperature performance with a mild impact on the high-temperature properties. High binder modification that exceeds 4% could be used to resist higher stresses and severe temperature conditions.

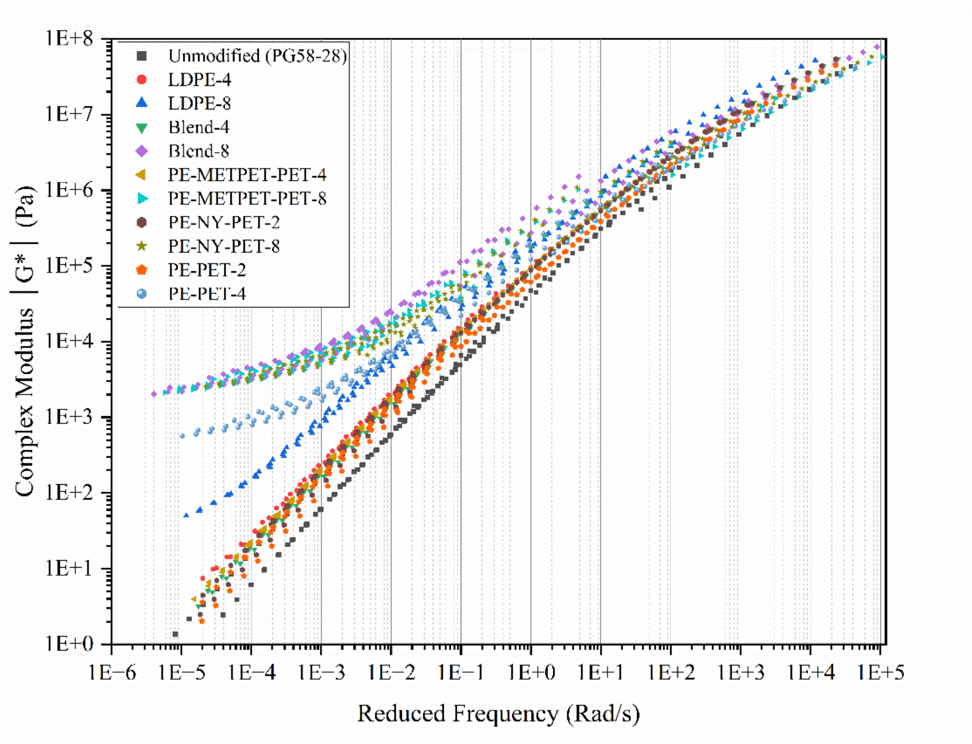


Figure 4-11 Modulus G* master curves for all MPP and LDPE modified asphalt original binders

According to Airey [71], black diagrams can provide a quick assessment of the simple thermo-rheological behavior of asphalt cement and any critical changes in rheological outcome. Therefore, the black space diagrams were developed to study the thermo-rheological behavior of all MPP- and LDPE-modified binders based on the shear complex modulus versus the phase angle δ°, as displayed in Figure 4-12 The black space diagram results showed that there is an obvious shift in the phase angle values of all MPP- and LDPE-modified binders at high temperatures for binder modifications exceeding 4% compared to the virgin binder. The effect of adding any type of MPP or LDPE modification at or above 4% concentration substantially increases the elasticity of the binder, particularly at higher temperatures, and leads to a reduction of the phase angle by more than 50%. The decrease in the phase angle is due to the elastomeric nature of the plastic. The presence of plastic with a high percentage changes the modified binder toward elastic behavior, confirming the positive impact at the high-temperature permanent deformation resistance. This phenomenon has a direct link to the ability of the polymer modifier to form a continuous elastic network between asphalt cement and the modifier when dissolved in the asphalt blend [158]. The remaining MPP particles characterized by higher melting points can dominate the rheological behavior when the high binder modification percentage of the MPP additive is used. Similar behavior was found with modified asphalt using crumb rubber and polyethylene (PE) [159], [160]. The Black space diagram results at the low temperatures show no obvious difference among all the modified binder blends with 4% or less of MPP and LDPE additives. Therefore, it can conclude that the presence of MPP and LDPE additives with 4% or less does not have a significant rheological impact at low temperatures. It would be beneficial to use a low percentage of MPP additives to maintain low-temperature performance.

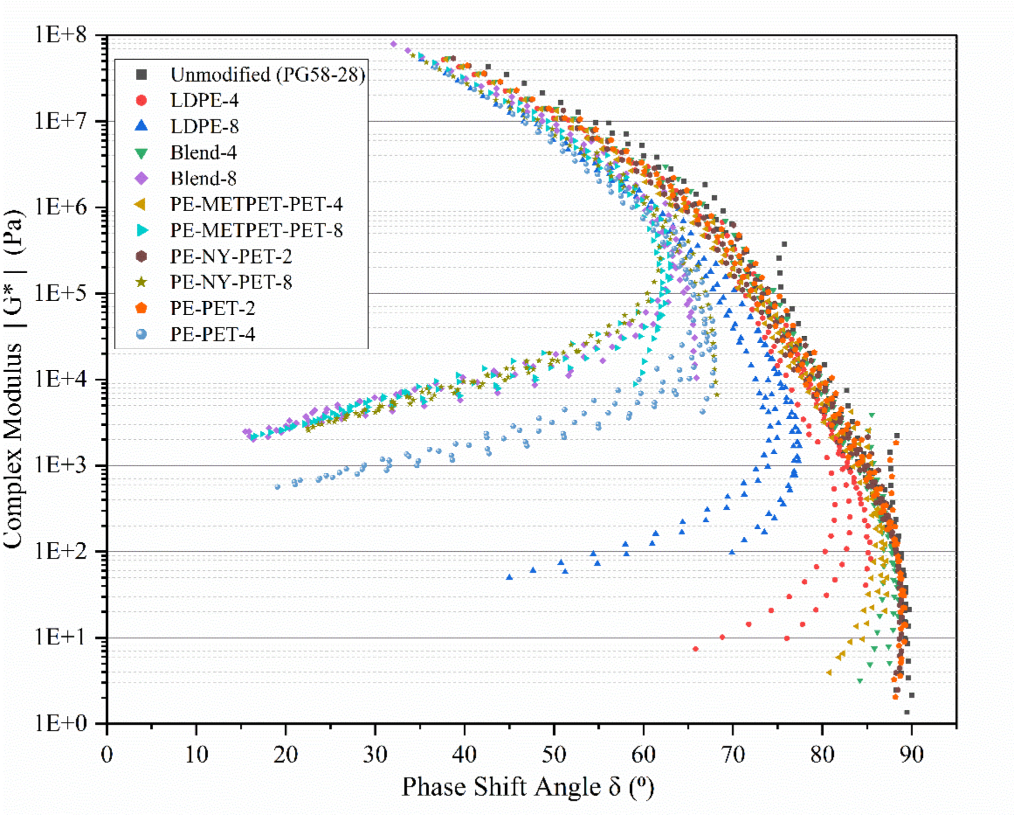


Figure 4-12 Black space diagrams for MPP- and LDPE-modified asphalt original binders

4.3.5 Storage Stability

4.3.5.1 The Separation Ratio

A common drawback of using polymers in asphalt modification is phase separation [132], [161]. Several approaches have been used to assess phase separation. The tube test, which has a better simulation of the storage conditions of the asphalt binder, is one of these tests. According to (NCHRP)

9–10 report, the separation ratio must be within the recommended values of 0.8 to 1.2 to avoid binder separation [149]. The results of the separation ratio Rs based on G* are shown in Figure 4-13a. The presented results confirmed that storage separation would be a concern with all MPP and LDPE additives and at all concentrations. However, the separation ratio Rs based on δ° (presented in Figure 4-13b) did not confirm the separation. Storage separation problems could not be identified through the determination of Rs based on *δ*° due to the DSR test limitations testing the modified binders. It was noticed that PE-NY-PET-8 and Blend-8 containing NY exhibited low separation compared to lower-concentration blends. LDPE-8 exhibited a high separation compared to LDPE-4. Roja et al., reported that the addition of polyethylene to asphalt binders tends to separate at high temperatures due to its non-polarity and non-aromaticity [149]. In this study, the presence of NY, METPET, and PET at high concentrations in MPP-modified blends resulted in a reduction in separation. This phenomenon is explained by the high polarity and aromaticity of NY, METPET, and PET materials [121]. This finding suggests that the results based on the G* and δ° are not the most accurate indicator to evaluate the storage stability of the modified binders. Therefore, examining the presence of the additive's particles at the microstructure level of the storge samples would be recommended.

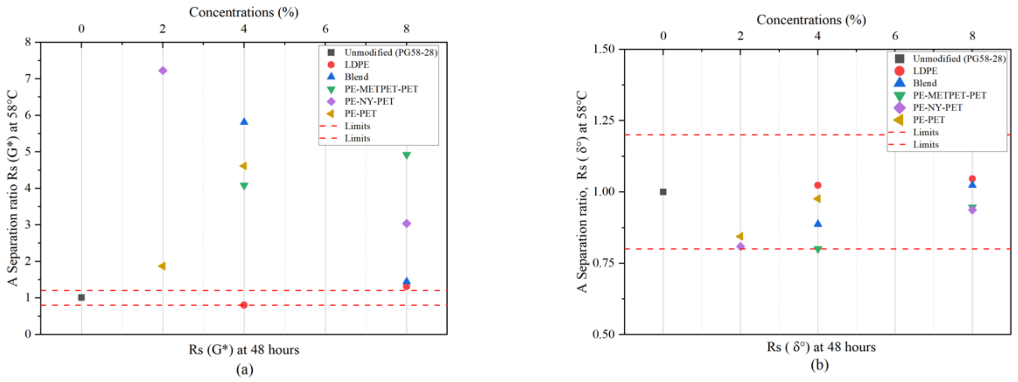
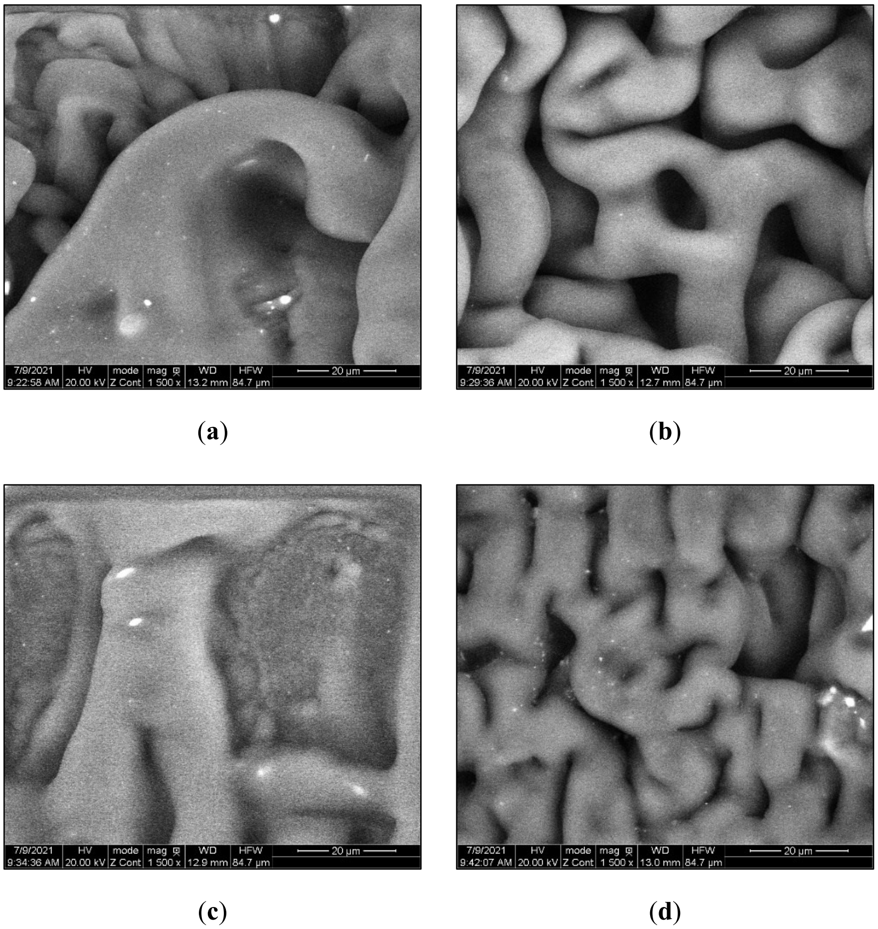


Figure 4-13 Separation ratio (Rs) (a) Rs based on (G*); (b) Rs based on δ°

4.3.5.2 Storage Stability using ESEM

ESEM test was performed on the storage stability samples to observe how the particles at the top and bottom of the samples of the Blend-4 and -8 modified binders dispersed, as shown in Figure 4-14. The presence of the MPP particles at both top and bottom samples were notable, with a higher concentration of 8% in comparison to Blend-4. This finding aligns with the results of the separation ratio outcome, which confirms that MPP with different densities, polarity, and molecular weight can reduce the mobility of the polymer to migrate from the bottom to the top. This finding indicates that increasing the quantity of NY, PET, and METPET could reduce the phase separation and alleviate the storage stability concerns for asphalt with polymer modifiers. This finding demonstrates the need for a more in-depth investigation of the use of analytical techniques to evaluate the storage stability issue of MPP-modified binders.



(**a**) (**b**)

(**c**) (**d**)

Figure 4-14 ESEM images of storage stability samples (Top and Bottom) at 1500× magnification (20 µm) (a) Blend-4 Top, (b) Blend-4 Bottom, (c) Blend-8 Top; (d) Blend-8 Bottom

4.4 Conclusions

The measurement of the virgin, MPP-, and LDPE- modified binders, including rheological, physical, morphological, thermal, and storage characteristics, were conducted in this study. The analysis assessed the impact of adding 2%, 4%, and 8% of MPP material and 4% and 8% of LDPE by the total weight of the asphalt cement. Based on the findings of laboratory investigation presented in this paper, the following conclusions are proposed:

- TGA results revealed multiple melting points ranging from 110 °C to 254 °C for all MPPs tested. Similarly, mass losses for asphalt samples and MPP additives, up to 320 °C, were negligible. These results, along with DSC, were used as criteria to determine the blending temperature.
- ESEM images showed that the MPP particle became significantly smaller after blending with the virgin asphalt and that most of the MPP additives were well integrated into the asphalt blend.
- The Brookfield viscosity test results confirmed that all MPP and LDPE additives would increase the viscosity and reduce the flow without exceeding the SHRP allowable limit (i.e., 3 Pa.s at 135 °C), resulting in acceptable workability performance.
- The rutting factor ($G^*/\text{Sin}\ \delta°$) exhibited an increase by adding the MPP and LDPE additives, which indicates the ability of asphalt binders to resist permanent deformation. Similarly, MSCR test results showed a noticeable reduction of $J_{nr\text{-}3.2}$ with the increase of all MPP and LDPE additives, which is also an indicator of higher resistance to permanent deformation. Blends that contain NYLON (PE-NY-PET and Blend-8) had a higher percentage recovery, reflecting more elasticity compared to other mixes.
- The temperature-sweep test showed that all MPP and LDPE-modified binders exhibited a shift from predominantly viscous to elastic behavior when the testing temperature increased from 46 °C to 82 °C, at a 4% modification rate and higher, which is a strong indication of an improved rutting resistance.
- The results of the Linear Amplitude Sweep (LAS) test exhibited an increase in the number of cycles to failure under fatigue cycles (N_f) in MPP- and LDPE-modified binders compared to the virgin binder. This indicates a potential improvement of fatigue cracking resistance in MPP-and LDPE-modified binders.
- MPP- and LDPE-modified binders would face some issues with storage stability. Due to their higher polarity, aromaticity, and density compared to PE, the blends that included NY, METPET, and PET have shown better stability and potential to reduce separation at high concentrations.

This study confirmed the feasibility of using MPP- and LDPE-modified binders to improve the fatigue and rutting behavior of asphalt pavements. Future work should include mixture tests to have a better understanding of the effect of MPP modifiers on the workability, rutting, fatigue cracking, and low-temperature resistance of asphalt mixtures.

5. Exploring the Low-Temperature Performance of MPP-Modified Asphalt Binders and Mixtures Using Wet Method

This chapter is based on an article prepared for submission to the Road Material and Pavement Design Journal. Qabur A, Baaj H, El-Hakim M. "Exploring the Low-Temperature Performance of MPP-Modified Asphalt Binders and Mixtures Using Wet Method. (2023).

Abstract

This study investigates the effect of using multi-layer plastic packaging (MPP) additives on the low-temperature performance of asphalt binders in cold regions, where thermal cracking may significantly impact the structural integrity of asphalt pavements. The literature review reveals limited research on the low-temperature performance of polyolefin-modified asphalt binders and no research evaluating the suitability of MPP additives. Therefore, the study aims to determine the potential of using MPP additives to modify a local asphalt binder (PG 58-28) and assess the low-temperature performance of MPP-modified asphalt mixes. The study tests various MPP doses (2%, 4%, and 8%) using the wet technique. Several thermoanalytical and rheological characterization techniques were used, including Thermal Gravimetric Analysis (TGA), Differential Scanning Calorimeter (DSC), Dynamic Shear Rheometer (DSR), and Bending Beam Rheometer (BBR). The Tensile Strain Restrained Specimen test (TSRST) and Complex (Dynamic) Modulus (CM) tests are also used to assess the characteristics of the MPP-modified mixture at low temperatures. The study findings indicate that the use of MPP additives at all dosages increased stiffness, affecting the Superpave Continuous PG and BBR ΔT_c parameter. The chemical composition of MPP was found to influence the physical and performance properties of the asphalt binder. While MPP additives can increase asphalt mixtures' stiffness, they may also reduce their resistance to thermal cracking, demonstrating that the MPP modification percentage should be limited to below 4% by the weight of the binder. TSRST experiment results indicate the MPP additive did not meet the lower PG grade criteria of -28°C for any tested mixtures; the trends observed from the TSRST were relatively consistent with results obtained from BBR tests on the modified binder. The findings from this study provide valuable information for developing guidelines for using MPP additives in asphalt modification, enhancing durability and sustainability while lowering plastic waste.

Keywords: Multi-layer Plastic Packaging (MPP), Polymer Modified Asphalt, Low-temperatures Performance, Stiffness

5.1 Introduction

Thermal cracking is one of the most prevalent destress modes of flexible pavements in cold regions, severely affecting Canadian provinces. Low temperatures cause the asphalt pavement to crack due to thermal contraction, and further degradation may occur due to water infiltration, ice expansion, and poor compaction [162]. The asphalt binders, which turn brittle and rigid in low temperatures, render the pavement vulnerable to cracking [38]. Various technologies have been developed to address this issue to enhance the performance of asphalt binders and mixtures in low temperatures. Researchers have spent the last four decades modifying asphalt cement by adding polymers to enhance its physical and rheological properties [7]. Polymer modification, specifically elastomers such as styrene-butadiene-styrene (SBS), is commonly used to improve asphalt's high and low-temperature performance [7], [9], [49], [123]. However, SBS modifiers are costly and prone to aging and degradation during use [15]–[18]. As a result, research on asphalt modification technologies has moved away from using a single material such as SBS to using multiple materials in compound modification, including SBS/crumb rubber (CR) [163], SBS/waste Polyethylene (WPE) [16], SBS/Fly Ash-Based Geopolymers [164], SBS/nanomaterials, and more [165]. Compound modification can improve the overall performance of asphalt binders to meet the multi-functional requirements of asphalt pavements. During the past four decades, studies have focused on waste thermoplastic polymers in asphalt. Thermoplastics are soft materials at high temperatures and act as hard materials at low temperatures. Polyethylene, Polypropylene, Polyvinyl chloride, Polystyrene, and Ethylene-vinyl acetate copolymer are the primary thermoplastics used in past research projects that studied asphalt modification using plastics [77]. Polypropylene (PP) is commonly used as a recycled additive in asphalt mixtures [13], [104], [105]. Polyethylene (PE), either low or high-density PE, is used in several applications, including plastic bottles, packaging, and single-use plastic bags; PE is also commonly used in asphalt mixtures [129]. Asphalt binders modified by thermoplastic materials are characterized by high stiffness and viscosity at high and moderate service temperatures [28], [77]. Although thermoplastics are not the same as elastomers in that they do not boost the asphalt binder strength during initial loading, they do improve the asphalt binder viscosity, which increases resistance to rutting at higher service temperatures.

Consequently, typical thermoplastic-modified binders have a low resistance to thermal cracking at low temperatures [27], [28]. Numerous studies have explored the efficacy of using various plastic additives in asphalt mixes to modify their low-temperature performance. For instance, Yousefi's study revealed that asphalt binder modified with High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE) plastic additives, and heavy vacuum slops (HVS) oil exhibited remarkable improvement in low-temperature performance [166].

Additionally, Al-Hadidy and Yi-qiu's research demonstrated that LDPE-modified asphalt mixtures had marginally higher stiffness and modulus of rupture than conventional asphalt mixtures, which reduced the potential for low-temperature cracking [167]. Attaelmanan et al. study suggested that HDPE could improve the low-temperature potential of modified asphalt binder [168]. Furthermore, Fang et al. observed that using Waste Packaging Polyethylene (WPE) as a plastic additive significantly improved the low-temperature characteristics of the modified asphalt mixture, making it viable for use in cold climate regions [169]. Similarly, Yu et al. research suggested that WPE could be treated with Organic montmorillonite (OMt); WPE/OMt-modified asphalt mixtures could enhance the low-temperature ductility and softening point of modified asphalt binder [135]. Hasan et al. study found that Electronic-Acrylonitrile Butadiene Styrene (ABS) and High Impact Polystyrene (HIPS)-modified binders increased creep stiffness at both test temperatures, indicating that the modified asphalt binder could perform better in low-temperature environments [133]. Lastly, a 2020 study showed that Recycled Polyethylene (RPE) alone or with reactive elastomeric terpolymers (RET) as plastic additives did not significantly alter the resistance to intermediate-temperature fatigue cracking, low-temperature thermal cracking, or reflective cracking. Still, it did enhance the modified asphalt binder's low-temperature potential [170].

Research conducted by the Strategic Highway Research Program (SHRP) has found that the low-temperature properties of asphalt binders significantly impact the performance of asphalt concrete pavement, with 80% of low-temperature cracking caused by low-temperature cracking of asphalt binders [171]. Table 5-1 summarizes experiments that investigated the impact of using recycled, waste, and virgin plastic additives via the wet technique on the low-temperature properties of modified asphalt. However, the literature review revealed limited research on the low-temperature performance of polyolefin-modified asphalt binders, especially those utilizing PET, PE, and polyamide (or nylon) or their combinations. Furthermore, few studies have explored the effects of using recycled or virgin plastic as asphalt modifiers on low-temperature properties. As a result, there is limited knowledge of the performance of plastic-modified binders and mixtures. Prior studies have suggested combining recycled plastics with additional additives such as heavy vacuum slops (HVS) oil, crumb rubber, or waste vegetable oils, along with treatments like organic montmorillonite (OMt) and cumene hydroperoxide, to improve resistance to fatigue and low-temperature cracking. However, some studies have demonstrated no change or slight improvement in low-temperature properties.

Utilizing waste plastic in the production of asphalt materials could be a valuable solution for countries like Canada. In Canada, the production of waste plastic is estimated to be 3.3 million tons annually, with approximately 2.8 million tons being deposited in landfills each year. This amount represents roughly 86% of all waste plastic in Canada, and it primarily consists of polyethylene terephthalate (PET), polyethylene (PE), metalized polyester (MET PET), and polyamide (or nylon) (NY)[172]. This potential modification presents a way to enhance the strength of asphalt while simultaneously addressing the environmental hazards associated with plastic waste. Failing to utilize this waste plastic represents a missed opportunity of around CAD 7.8 billion in 2016 alone, which is anticipated to increase to CAD 11.1 billion by 2030. Therefore, it is essential to identify a practical and cost-efficient solution for reducing unprocessed plastic waste while mitigating its environmental impact [172]. This investigation aims to evaluate the effect of adding MPP additives on the properties of the asphalt binder and mixture, specifically at lower temperatures. The research has the following specific goals:

- Measure the thermal properties and determine the MPP-modified binders' Superpave Performance Grading (PG).
- Conduct the low temperatures properties of MPP-modified binders using the BBR test.
- Examine the mechanical characteristics of MPP-modified mixtures using CM and thermal TSRST tests.
- Determine the optimal percentage of MPP modification required to achieve superior low-temperature properties in both asphalt binders and mixtures.

Table 5-1 Examples of current studies utilizing plastic additives to modify low-temperature properties of asphalt binder

Plastic types /Density (g/cm^3)	**Tm^1 (°C)**	**Shape/size (mm)**	**Binder Grade**	**OPT (%)**	**Test assessment**	**Test Temperature (°C)**	**Modified^4** **Yes** **No**	**Low-temperature properties (Effect)** **No Change - ◎ Low- ◔** **Moderate- ◓** **High- ●** **(↑↓)**	**REF**
LDPE =0.92, HDPE=0.955, and LLDPE=0.92	N/A	Powder/ N/A	Bitumen (40-penetration grade)	3	Frass breaking point	According to IP-80 standard	Yes heavy vacuum slopes (HVS) oil	High- ●↓	[166]
LDPE= 0.9205	LDPE = 113.2	Powder/ N/A	50/60-penetration grade	6	Flexural testing is called the flexural stiffness	-10	No	Moderate- ◓↑	[167]
HDPE = 0.9430	HDPE = 149	Pellets/ N/A	80/100-penetration grade	5	Flexural testing is called the flexural stiffness	0 & -10	No	Moderate- ◓↑	[168]
WPE = 0.93	WPE= 125	Flakes /15 in width, 20 in length and 0.1 in thickness	Asphalt (A-90)	10	LDDS-04^2	10 to -40	No	High- ●↓	[169]
PP = N/A, and CR =N/A	PP = N/A, and CR =N/A	PP and CR = Powder/ Max 0.6 to 0.05	Shell# 70	20	BBR (stiffness ≤ 300 MPa, m ≥ 0.3)	-12 & -18	Yes Crumb rubber (CR)	High- ●↑	[137]
N/A	N/A	Flake/> 10	Asphalt binder (40-penetration grade)	3TLPP 2 VPP ^{3}	BBR (stiffness ≤ 300 MPa, m ≥ 0.3)	-6, -12, -18	Yes Chemically derived from waste PET bottles	High- ●↓	[173]
WPE= 1.8	WPE = N/A	Powder/ N/A	A90	4	Ductility	5	Yes Organic montmorillonite (OMt)	Moderate- ◓↓	[135]
N/A	HDPE = N/A	Powder/0.149 - 0.074	PG 64-16	10	Indirect tensile stiffness modulus (ITSM)	5	No	Low- ◔↓	[136]
RPE=0.92	RPE= 190	Powder/ N/A	Aryl Hydrocarbon Bitumen AH-70	10% WTR & 2% RPE	BBR (stiffness ≤ 300 MPa, m ≥ 0.3)	-6, -12, -18, & -24	Yes Waste tire rubber (WTR)	No Change - ◎	[36]
N/A	ABS = 105, ABS-PC = 125,	Powder / 0.3	PG58-28	5	BBR (stiffness ≤ 300 MPa, m ≥ 0.3)	-18 & -21	Yes (Cumene hydroperoxide)	Low- ◔↑	[133]

	HIPS = 180-260								
N/A	N/A	N/A	PG 64-22	6	BBR (stiffness ≤ 300 MPa, m ≥ 0.3)	-6, -12, and -18	NO	High- ●↑	[174]
RPE =0.939	RPE= 120	Pellets/ N/A	PG 58-28	4	BBR (stiffness ≤ 300 MPa, m ≥ 0.3) Disc-shaped Compact Tension (DCT) Test	-18	Yes Reactive elastomeric terpolymers (RET)	No Change - ◎	[170]

[1] Melting temperature

[2] LDDS-04 is a multi-functional testing machine and computer-integrated control system developed by the Prevention of Seepage Research Institute of Xi'an University of Technology

[3] Thin Liquid Polyol PET (TLPP) and Viscous Polyol PET (VPP)

[4] Modified (using additional additives)

5.2 Materials and Assessment Methods

5.2.1 Materials

5.2.1.1 Asphalt Cement and Aggregate Properties

The virgin binder used in this study was a locally obtained PG 58-28 from the western crude. This AC has been used in a previous study [78], and its physical and chemical properties are presented in Table 5-2. The MPP-modified mixture investigated in this project is a modified HL3 (surface mixture). The unmodified HL3 mixtures are usually used for parking lots and residential driveways. The acceptance range of the volumetric properties of the unmodified HL3 mixtures is stated in the Ontario Provincial Standards Specification [156]. The sieve analyses of the unmodified and MPP-modified asphalt mixtures are presented in Table 5-3**.**

Table 5-2 Asphalt cement physical and chemical properties

Property	Values
Ash Content, %	0.03
Viscosity (Pa.s), at 135°C	< 3
Initial boiling point/Boiling range (°C)	228
Flash Point (°C)	243
Specific Gravity (at 21.1°C)	1.020-1.045
Solubility in water	None
True Grade	59.4-31.4

Table 5-3 Aggregate gradation

Sieve (mm)	Passing (%)	Retained (%)	Control Points	
			Minimum	Maximum
19	100.0	0		
12.5	95.0	5.0		
9.5	83.0	12.0	90	100
4.75	58.0	25.0	28	90
2.36	40.0	18		
1.18	19.0	21	28	58
0.6	12.0	7		
0.3	8.0	4		
0.15	4.5	3.5		
0.075	3.0	1.5	2	10

5.2.1.2 The MPP-Modified Asphalt and Mixtures Preparation

The study incorporated recycled bags made from multi-layer plastic packaging (MPP) containing various combinations of Polyethylene (PE), Polyester (PET), Nylon (NY), and Metallized Polyester (METPET) supplied by Peel Plastic Products Ltd. Different MPP combinations included PE-PETMET-PET, PE-PET, and PE-NY-PET. The earlier study presented the plastic materials' physical properties [78]. MPP additives were first derived from multi-layer plastic packaging bags, including PE as the primary component and less than 15% distributed among PET, NY, and METPET. These bags were used in the production of MPP additives. The MPP was shredded into small pieces that ranged in size from 2 to 6 mm using a Micro-Cut electric shredder. The small pieces were further processed to powder using an Ultra Grinder Machine. The MPP powder was sieved to determine the grain size distribution; only material within the 0.075 to 0.595 mm range was used for modification. Total bag structure percentages were calculated, and the composition of each polymer type was obtained, as summarized in Table 5-4. A recycled low-density polyethylene (LDPE) was also explored as a reference. MPP and LDPE were blended at 2%, 4%, and 8% by weight of virgin asphalt cement. Further information regarding the blending procedure can be found in a previous study [78]. Table 5-4 lists the mixes' IDs and the corresponding dosage used in the study.

Table 5-4 Lists the modified asphalt binder mixes and the approximate total mass percentages of MPP and LDPE used

Bag Structure	% PE	% METPET	% NY	% PET	Total	Asphalt Cement	Modifier	Modifier tested (%)	Mix Identifier
PE-METPET-PET	87	8	---	5	100	PG 58-28	None	0	Unmodified (PG58-28)
PE-PET	94	---	---	6	100		**LDPE**	4, 8	LDPE-4 and LDPE-8
PE-NY-PET	86	0	8	6	100		**Blend**	4, 8	Blend-4 and Blend-8*
Blend *	89	3	2	6	100		PE-METPET-PET	4,8	PE-METPET-PET-4 and PE-METPET-PET-8
LDPE	100	---	---	---	100		PE-NY-PET	2, 8	PE-NY-PET-2 and PE-NY-PET-8
*The Blend-4 and Blend-8, which comprises a mixture of all MPP types listed in Table 4							PE-PET	2, 4	PE-PET-2 and PE-PET-4

The thermal characteristics and stability of the MPP additives and AC were further examined using Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimeter (DSC) testing. The melting point of LDPE was determined to be below 120 °C. The melting points of NY, PET, and METPET films were between 248 and 254 °C, as demonstrated by the endothermic peak in Figure 5-1. The TGA data concluded that neither the MPP nor the asphalt cement sample exhibited appreciable change up to 320 °C. The TGA data concluded that neither the MPP nor the asphalt cement sample exhibited appreciable change up to 320 °C. These outcomes are crucial to determine the appropriate mixing temperature for the MPP additives. According to our previous study[78], to ensure proper melting and uniform blending with liquid asphalt cement, the PE material should be heated to a temperature of 175°C±5°C using the wet method. The limited quantity of MPP particles with higher melting points exhibited a reduction in their particle size, becoming smaller than 250 µm, thus, satisfying the recommendations of the AASHTO T 315[126].

The selected binders were evaluated using the DSR and BBR laboratory tests conducted following the Superpave PG testing. The representative mix, Blend-4 and Blend-8, which comprised a mixture of all MPP types (as listed in Table 5-4), were used to produce the hot mix asphalt (HMA) samples. The mixes were prepared for both the unmodified blend and the Blend-4-8 binder. For the neat asphalt, the mixing and compaction temperatures were determined using the equiviscosity method recommended by the supplier and described in AASHTO T312. The mixing temperature was determined to be 149°C and the compaction temperature was determined to be 137°C. On the other hand, the Blend-4-8 binder was chosen based on the equiviscosity method, and the recommended PMA mixing and compaction temperatures were determined by comparing Yellowline products to the PMAs [49]. The mixing temperature for Blend-4-8 was determined to be 160°C, and the compaction temperature was determined to be 150°C. Before testing, all mixes underwent a short aging period in a forced-draft oven, after which the HMA control mixtures were aged at 135°C for 4 hours and at field compaction temperatures for 2 hours as per AASHTO R30. The TSRST and CM tests were used to evaluate the performance of the representative mix (Blend-4 and Blend-8) in the asphalt mixture.

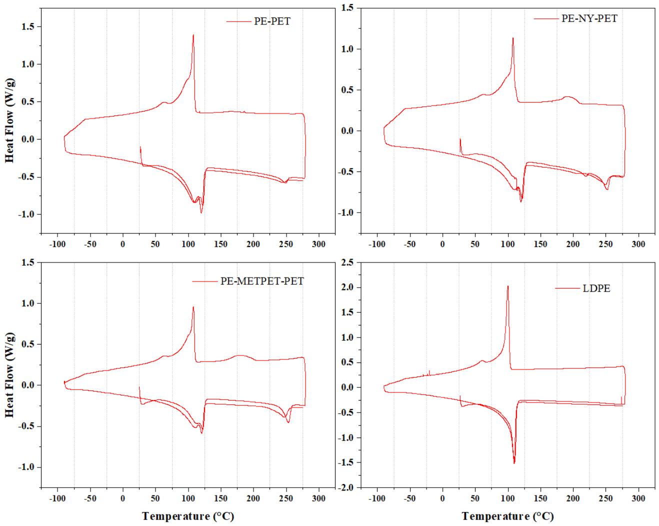


Figure 5-1 Heat flow versus temperature for MPP and LDPE additives

5.2.2 Assessment Methods

A flowchart of the experiments conducted is presented in Figure 5-2, and the subsequent sections briefly explain these tests. The mix design criteria used for the modified mixes, were the same as the control mix in terms of asphalt mix volumetrics.

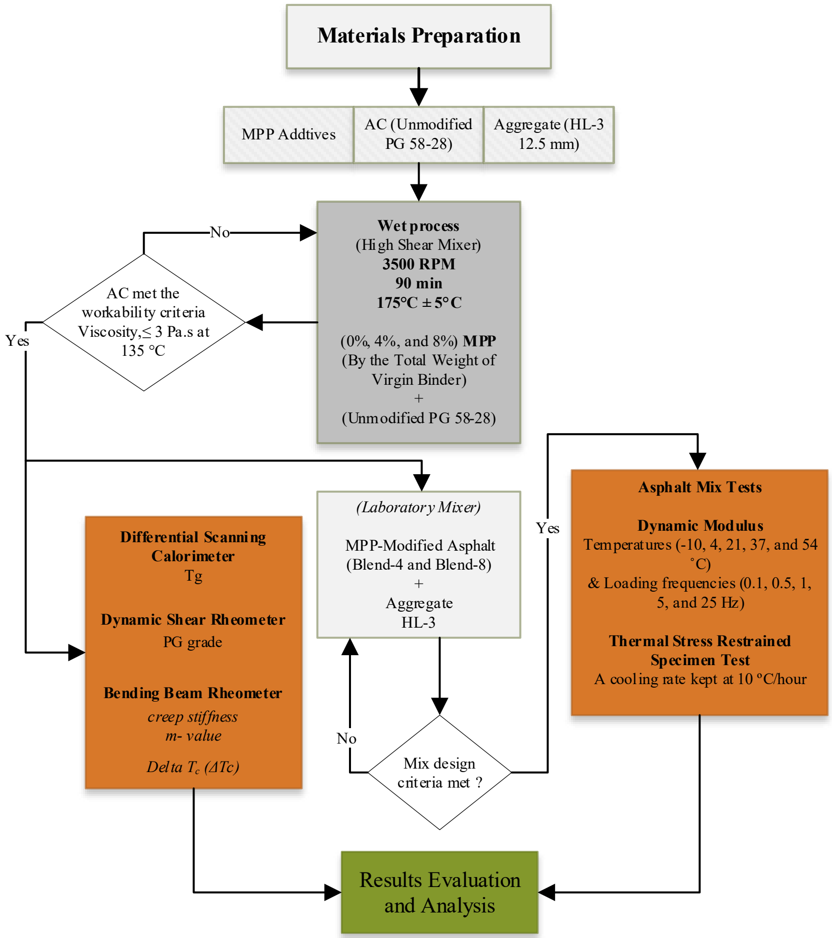


Figure 5-2 Flowchart of assessment methods

5.2.2.1 Thermal Analysis

5.2.2.1.1 Differential Scanning Calorimeter (DSC)

When amorphous and semi-crystalline polymers, such as thermoplastic polymers, are cooled and approach their glass transition temperature (T_g), they change from a rubbery to a hard-glassy state. The DSC is widely used to conduct a thermal assessment of plastic materials; homogeneous mixtures are characterized by one T_g value, while heterogeneous mixtures include multiple T_g values. The MPP additive's compatibility with the asphalt binder and its susceptibility to low-temperature cracking were examined through DSC testing. Using the DSC Q2000, samples weighing within 10 to 20 mg were treated with two cooling and heating cycles in the present study following ASTM D3418. The samples' temperature was held constant for two minutes at the start and finish of each cycle. The MPP additives were tested using a rate of 10°C per minute, from -90°C to 260°C, while MPP-modified binders were tested at the same rate from -90°C to 160°C.

5.2.2.2 Methods for Asphalt Binder Analysis

5.2.2.2.1 Superpave Performance Grading (PG)

The Strategic Highway Research Program (SHRP) established the Superpave mix design approach, which used standard rheology measures to analyze asphalt binder rutting and cracking performance as an indicator of asphalt mix performance. Superpave's mix design method addresses cracking using binder performance grade (PG). Most provinces and other highway agencies use the binder PG as the only criterion for choosing or accepting the asphalt binder for a specific traffic level and climatic condition. The high-temperature (PGH) for high-temperature is typically used as a rutting or permanent deformation indicator, the intermediate-temperature (PGI) is used for fatigue cracking, and the low-temperature PG (PGL) is used as an indicator of thermal cracking. Superpave simulates important binder life stages by aging asphalt binders. These stages include transportation (including storage and handling), mix production and construction, which is replicated by a rolling thin-film oven (RTFO), and long-term pavement aging, which is reproduced by a pressure-aging vessel (PAV). Superpave's asphalt grades are PG or PGAC XX-YY. Superpave specifications define high-temperature service as XX degrees Celsius and low-temperature service as YY [48]. AASHTO M 320 was utilized to evaluate the PGH, PGI, and PGL of virgin and MPP-LDPE-modified binder blends using the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) [175].

5.2.2.2.2 Bending Beam Rheometer

To evaluate PAV-aged asphalt binders versus loading time at low temperatures, the BBR test is used based on AASHTO T313 [142]. The two main thresholds for acceptance of asphalt binder are the creep stiffness and creep rate (also known as m-value). According to Superpave specifications, the creep stiffness should not exceed 300 MPa, and the m-value should exceed 0.300. The high value of creep stiffness indicates an increase in the brittleness of the asphalt binder and an increase in susceptibility to cracking. The m-value measures how the binder stiffness changes as the loads are applied. Since the binder creep stiffness changes rapidly and leads to increased thermal stress, a high value of the m-value is recommended to facilitate relaxation and mitigate low-temperature cracking. The outcome of the

BBR tests focuses on the low-temperature behaviour of the asphalt binder by measuring the stress relaxation when constant loading is applied on an asphalt beam [176]. The dimensions of the binder beam are 125 mm in length, 6.35 mm in width, and 12.7 mm in height. The creep stiffness is determined by applying a standard load to the beam and measuring the corresponding deformation. In this study, the load was designated as 980 ± 50 mN at three test temperatures, −12℃, −18℃, −24℃, and three duplicates were tested for each MPP and LDPE specimen. Then, the flexural creep stiffness *S(t)* data of specimens at loading times of 8.0, 15.0, 30, 60, 120, and 240 seconds were calculated using the following Equation 5-1:

Equation 5-1

$$\boldsymbol{S(t)} = \frac{\boldsymbol{PL^3}}{\boldsymbol{4bh^3\delta(t)}}$$

Where S(t) refers to time-dependent flexural creep stiffness, MPa, P is a constant load, N, δ(t) is the deflection of the beam, mm, b is the width of the beam, mm, h is the thickness of the beam, mm, and L is the span length of the beam, mm. Finally, δ(t) and S(t) refer to deflection and stiffness as time functions.

Since asphalt rheology depends on additives and age, the Delta T_c (ΔT_c) parameter assesses asphalt binder relaxation characteristics related to low-temperature thermal cracking. SHRP proposed this parameter in Project 06–01, supported by the Airfield Asphalt Pavement Technology Program (AAPTP). According to the study, the ΔT_c value directly affects block cracking and indirectly affects fatigue, edge, longitudinal, reflection, and transverse cracking [177].

The sign of ΔTc can be either positive or negative. The positive ($+\Delta T_c$) values are governed by creep stiffness S (S-controlled), while the negative ($-\Delta T_c$) values are governed by creep rate m (m-controlled). Creep stiffness (S) is critical in assessing asphalt binder performance at higher temperatures. In contrast, the creep rate (m) is the critical factor when assessing the performance of the asphalt binders at low temperatures. In North America, at least ten agencies adopted ΔT_c as a specification parameter with a minimum limit for ΔT_c of -5.0°C, using 20- and 40-hour PAV aging protocols. However, Utah DOT recommended a minimum limit for ΔT_c of -2.0°C for 20 hours of PAV. As a substitute for tensile strain failure and strength measured by the direct tension test, Utah DOT accepted the values from ΔT_c [178]. Although 40-hour PAV aging was recommended for a softer asphalt binder, the 20-hour PAV with a limit of ΔT_c of -2.0 and -5.0°C was adopted in this study. The ΔT_c can be determined by using the results of AASHTO T313 at multiple low temperatures until the BBR test is executed at temperatures that do not exceed the restricted values of S and m. Therefore, critical temperatures of both stiffness ($T_{c,s}$) and m-value ($T_{c,m}$) are calculated by interpolating between passing and failing temperatures using the following Equation 5-2 and Equation 5-3:

Equation 5-2

$$\boldsymbol{T_{c,s} = T_1 + \left(\frac{(T_1-T_2)*(Log300-LogS_1)}{Log\,S_1-Log\,S_2}\right) - 10}$$

Equation 5-3

$$\boldsymbol{T_{c,m} = T_1 + \left(\frac{(T_1-T_2)*(0.300-m_1)}{m_1-m_2}\right) - 10}$$

where S_1 is the creep stiffness at T_1, MPa, S_2 is the creep stiffness at T_2, MPa, m_1 is the creep rate at T_1, m_2 is the creep rate at T_2, T_1 is the temperature at which S and m passes, °C, and T_2 is the temperature at which S and m fails, °C. Finally, the ΔT_c can then be determined using the following Equation 5-4:

Equation 5-4

$$\boldsymbol{\Delta T_c = T_{c,s} - T_{c,m}}$$

5.2.2.3 Methods Asphalt Mixture Analysis

5.2.2.3.1 Complex (Dynamic) Modulus

The complex dynamic modulus |E*| of a Hot Mix Asphalt (HMA) can be determined using stress-controlled or strain-controlled laboratory procedures [179]. The development of master curves using dynamic complex modulus test data allows the comparison of the stiffness of asphalt mixes across a wide range of temperatures and frequencies through the generation of master curves.

MPP-modified (Blend-4-8) mixtures were subjected to a complex (dynamic) modulus test to determine their stiffness. The cylindrical samples with an air void content of 7±1% were compacted using a Superpave gyratory compactor. Specimens were adjusted to their final dimensions, measuring 150 mm in height and 100 mm in diameter and then tested using a sinusoidal axial compressive stress at five different temperatures (-10, 4, 21, 37, and 54 °C) and five different loading frequencies (0.1, 0.5, 1, 5, and 25 Hz) following AASHTO T342. A Material Testing System (MTS-810) equipment was used to conduct this test. The dynamic modulus and phase angle findings were then calculated by averaging the measured values from two specimens for each mix.

Rowe et al. [180] proposed a generalized logistic sigmoidal (GLS) model to describe the asymmetric sigmoidal master curves of filled polymer mastics materials. The model may be expressed as follows in Equation 5-5 and is relevant to asphalt binders as well:

Equation 5-5

$$\boldsymbol{log|E^{*}(f,T)| = \delta + \frac{\alpha}{(1+\lambda \exp^{\beta+\gamma(log_{fr}})^{1/\lambda}}}$$

Where E^{*}(f, T) is the dynamic modulus as a function of frequency and temperature, log *fr* is the logarithmic reduced frequencies, δ is the lower asymptote, α is the difference between the values of the upper and lower asymptotes, and λ is used to allow the curve to have a non-symmetrical shape, β and γ are the shape coefficients. Master curves can be developed using several models and shift factor equations to represent the linear viscoelastic characteristics of the asphalt mixture. The |G*| master curve has an asymmetric sigmoidal form as opposed to basic asphalt binders and conventional polymer-modified asphalt binders. Therefore, it is preferable to choose sigmoidal functions. The master curve generated using the sigmoidal fitting function for the dynamic modulus test data appears to fit the data well, according to Pellinen et al. [181], since it closely resembles the physical form of the observed data throughout a wide range of temperatures. According to Rowe et al., the generalized logistic sigmoidal model performs well for the studied samples. They recommended using it to produce a superior master curve for non-symmetric curves[180]. The AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) also utilizes a common sigmoidal logistic model [181], [182].

The development of the master curves for the rheological characteristics is facilitated by the time-temperature superposition principle (TTS), which enables the investigation of the material's rheological behaviour over a broad range of loading frequencies and temperatures. TTS shift factors have an inverse relationship with temperature which is a fundamental feature of materials accounted for by a few empirical relationships. Equation 5-6 describes the Williams-Landel-Ferry (WLF) shift factor as one of the most prevalent examples of this type of equation [183].

Equation 5-6

$$\boldsymbol{log a_T = \frac{C_1(T-T_{ref})}{C_2+(T-T_{ref})}}$$

Where C_1 and C_2 are constants and material specific, T is the temperature, T_{ref} is the reference temperature, and log a_T is the decadic logarithm of the TTS shift-factor. Equation 6, which uses the shift factor (a_T) from the WLF equation, and Equation 5, which uses the generalized logistic sigmoidal model, were applied in this study to produce the master curve for asphalt mixture at 21 °C, as shown in Figure 5-12. Microsoft Excel's spreadsheet and solver feature was used to develop the master curve. The coefficients of the sigmoidal model and shift factor equations for various additives at various temperatures are listed in Table 5-6.

5.2.2.3.2 Thermal Stress Restrained Specimen Test (TSRST)

In cold weather regions, low-temperature (thermal) cracking is responsible for most asphalt pavement failures [162]. To study thermal cracking failure under laboratory conditions, the TSRST was used to verify and simulate the mechanical properties of MPP-modified pavement materials throughout their service life. The rectangular-cross-sectioned specimen used in the test is 50 mm (width) × 50 mm (height) × 250 mm (length) with air voids of 7±1%. The sample was glued to two aluminum end platens and affixed in the test frame. At a cooling rate of 10 °C/hour, the specimen contraction was measured during the cooling process using two extensometers placed at 180° intervals and held by springs around the specimen, as presented in Figure 5-3. Finally, three thermistors were placed at the specimen's top, middle, and bottom to monitor the specimen surface temperatures.

As the specimen begins to cool, the thermal stress increases slowly as the asphalt mix relaxes. However, a transition occurs at the end of the stress relaxation phase, leading to a linear thermal stress increase. When the stress reaches its peak value, the fracture temperature is considered a failure temperature. The lower the fracture temperature, the better the resistance to low-temperature cracking, and vice versa. In addition, higher slope (DS/DT) values of the mixture lead to higher transition temperatures, which indicate higher susceptibility to low-temperature cracking. The transition temperature is calculated when the stress on the approximated straight line reaches 90% of the measured stress on the stress-temperature curve see Figure 5-4 [184].

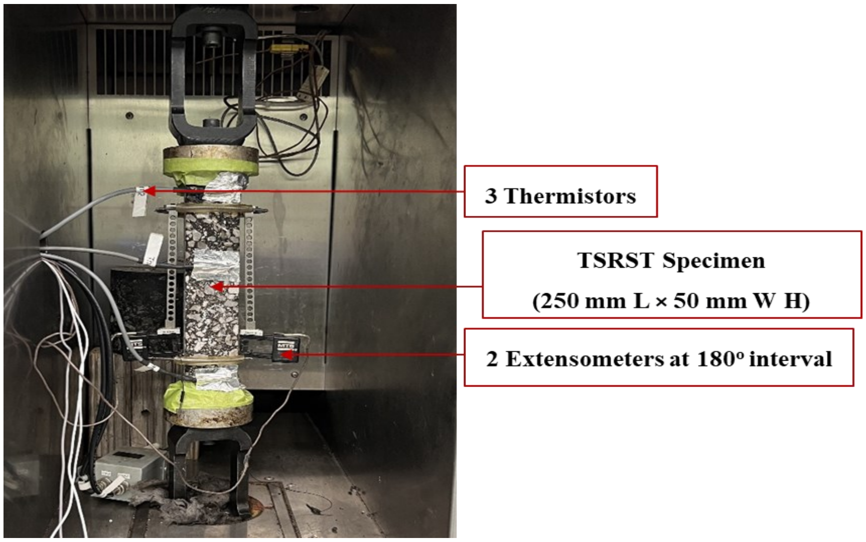


Figure 5-3 TSRST Specimen Test Set-up at CPATT

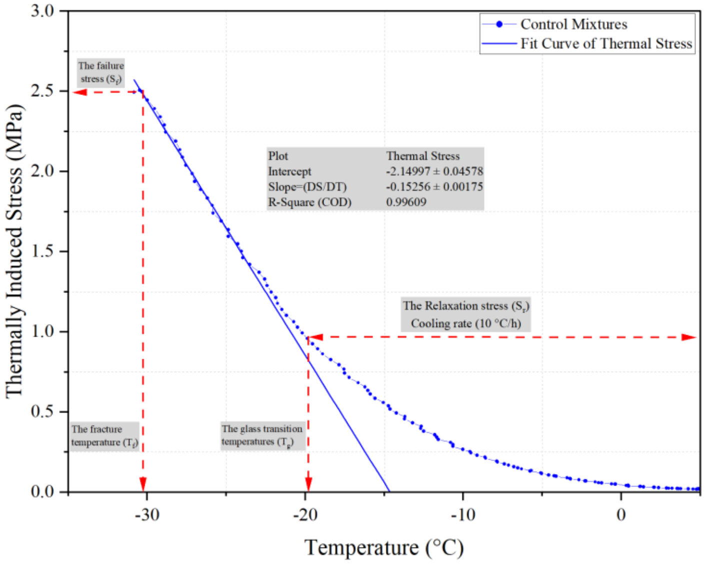


Figure 5-4 Typical TSRST Results of Control Mixture

5.3 Results and Discussion

5.3.1 Thermal Analysis

5.3.1.1 Differential Scanning Calorimeter

Figure 5-5 presents the heat flow curves of the Blend-4-8 modified binders compared to the unmodified PG 58-28. Pure PE has a melting onset temperature of approximately 110°C. Sharp PE melting peaks were observed in the DSC curves (T_m = 110 °C), which confirms that mix 4–8 contains PE components and that the MPP additives have been successfully integrated into the asphalt mix. According to Roja et al., polyethylene's non-polar and non-aromatic nature results in separation when added to the asphalt binder at high temperatures [185]. In this investigation, the high concentrations of NY, METPET, and PET in the MPP-modified blends decreased separation, improving compatibility with the binder. The high polarity and aromaticity of NY, METPET, and PET materials could explain this behaviour [186].

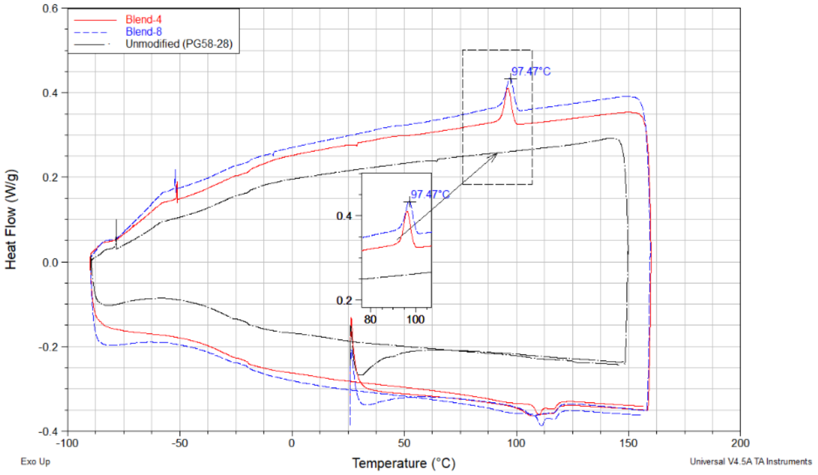


Figure 5-5 The DSC results of the unaged Blend-4-8 modified binders

The reversing and derivative heat curves were developed, as shown in Figure 5-6, demonstrating the occurrence of small melting peaks for low MPP content (up to 4%). In contrast, a larger melting peak is noticed at higher concentrations (up to 8%). The four different T_g's resulted from the bitumen saturates, aromatics, resins, and asphaltenes components, with a maximum at -20 °C, 10 °C, 60 °C, and 80 °C, respectively, according to the Kaya et al. study [18]. The DSC results further demonstrated that MPP does not change the T_g's for saturates and asphaltenes. However, aromatics and resins have been reduced for the Blend-4-8 compared to the virgin binder. This phenomenon may be related to the polymer's capacity to absorb and incorporate into the asphalt binder. In addition, a separate T_g was observed around 50 °C, the same T_g value of the Nylon [13].

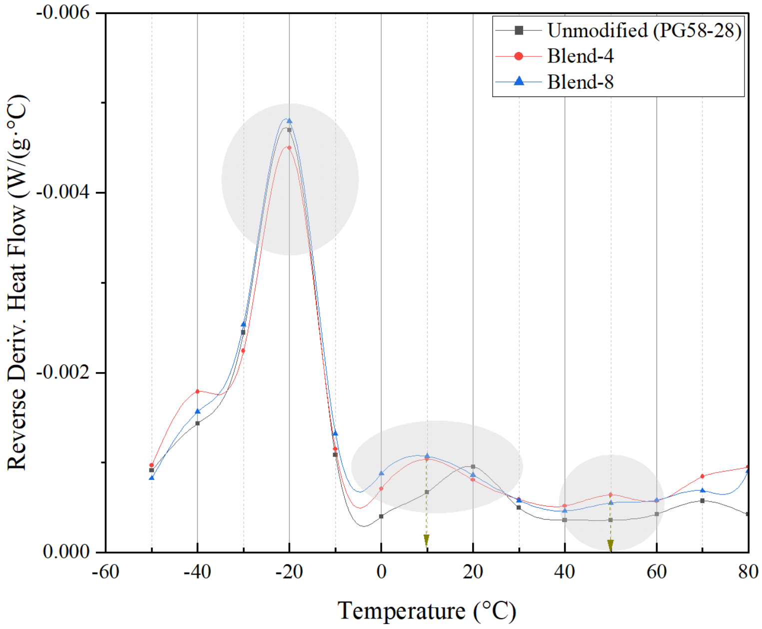


Figure 5-6 Reversing Deriv. Heat flow curves of unaged MPP-modified binders

5.3.2 Thermomechanical Behaviour of Modified Asphalt Binders

5.3.2.1 Superpave Performance Grading

Performance grading was used to evaluate the influence of the LDPE-MPP additives and determine the optimal dosage of MPP additives. Figure 5-7 presents the continuous grading results of the binder blends at high, intermediate, and low temperatures. Regarding the continuous PGH temperature, adding MPP has stiffened the asphalt binder, thus, bumping it up by at least one grade with the 2% dosages by the weight of the asphalt binder. The continuous PGH (62.7 °C) for the base binder PG 58–28 increased to 67.9 °C for Blend-4 and 84.9 °C for Blend-8. When the PE-NY-PET-8 was used, the PGH increased to 104.0 °C; likewise, with the PE-METPET-PET-8, the PGH was recorded at 91.0 °C. The PGH corresponded to a promising impact on high-temperature performance. Continuous PGI values were similar to, or higher than, the base binder (17.2 °C). The PGI increased by 0.8 °C for Blend-4 and 2.9 °C for Blend-8. Regarding PGL, the MPP modifiers with 4% or less did not change the low-temperature grades of the binders. The low-temperature grades remained the same as before the modification, although there were changes in the stiffness of the modified binders.

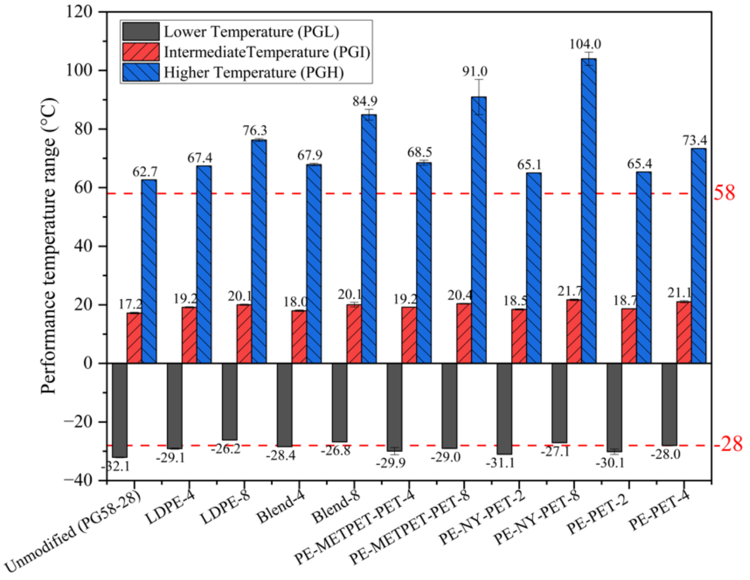


Figure 5-7 Continuous grading results of virgin binder and LDPE-MPP modified binders

Despite this modification, all MPP-LDPE modified binders had a greater useful temperature interval (UTI) than the virgin binder (86 °C), as shown in Table 5-5. From these results, it is recommended that the dosage of MPP as an additive does not exceed 4% by weight of the asphalt binder. A higher dosage of MPP produced very stiff binders based on the PGH values. The PGL values were generally negatively affected by more than half of the tested binder and met the requirement for a Low PG temperature of -28 °C.

Table 5-5 Performance grade of the MPP modified binders

Binder ID	PGH$^{\mathrm{I}}$ °C	SD	PGI$^{\mathrm{II}}$ °C	SD	PGL$^{\mathrm{III}}$ °C	SD	PG Nomenclature
Unmodified (PG58-28)	62.7	0.00	17.2	0.28	-32.1	0.14	PG58-28
LDPE-4	67.4	0.00	19.2	0.21	-29.1	0.21	PG64-28
LDPE-8	76.3	0.49	20.1	0.21	-26.2	0.07	PG76-22
Blend-4	67.9	0.42	18.0	0.28	-28.4	0.09	PG64-28
Blend-8	84.9	1.84	20.1	0.78	-26.8	0.01	PG82-22
PE-METPET-PET-4	68.5	0.85	19.2	0.00	-29.9	1.21	PG64-28
PE-METPET-PET-8	91.0	6.01	20.4	0.14	-29.0	0.11	PG88-22
PE-NY-PET-2	65.1	0.07	18.5	0.21	-31.1	0.04	PG64-28
PE-NY-PET-8	104.0	2.26	21.7	0.28	-27.1	0.10	PG88-22
PE-PET-2	65.4	0.07	18.7	0.07	-30.1	0.91	PG64-28
PE-PET-4	73.4	0.07	21.1	0.35	-28.0	0.11	PG70-28

[I]DSR unaged, [II] DSR PAV-aged, and [III]BBR PAV-aged. SD stands for "standard deviation"
Note that: any temperature reading of PGH that exceeds 88°C will be considered PG88.

5.3.2.2 Bending Beam Rheometer

Figure 5-8 depicts the influence of additives and temperature on the creep stiffness of unmodified and modified asphalt binders used in this study at -12 °C, -18 °C, and -24 °C. Adding LDPE and MPP enhanced the creep stiffness at the three temperatures. At -12 °C, the creep stiffness of the MPP-modified asphalt binder rose by up to 20% with 4% and by up to 30% with 8% for all MPP types indicating that the asphalt's resistance to low-temperature cracking was reduced. The PE-NY-PET-2 and PE-PET-2 modified binders exhibited the lowest creep stiffness among modified binders, increasing by less than 10% compared to the unmodified binders. At -12 °C and -18 °C, all LDPE- and MPP-modified binders with 4% or lower concentrations met the S-value limit values. However, at -24 °C, none of the unmodified LDPE and MPP-modified binders satisfied the Superpave criterion limit. To minimize the impact of plastic binder modification on thermal cracking resistance, the BBR stiffness results indicate that MPP concentrations of 4% or less (by weight of asphalt binder) could be recommended.

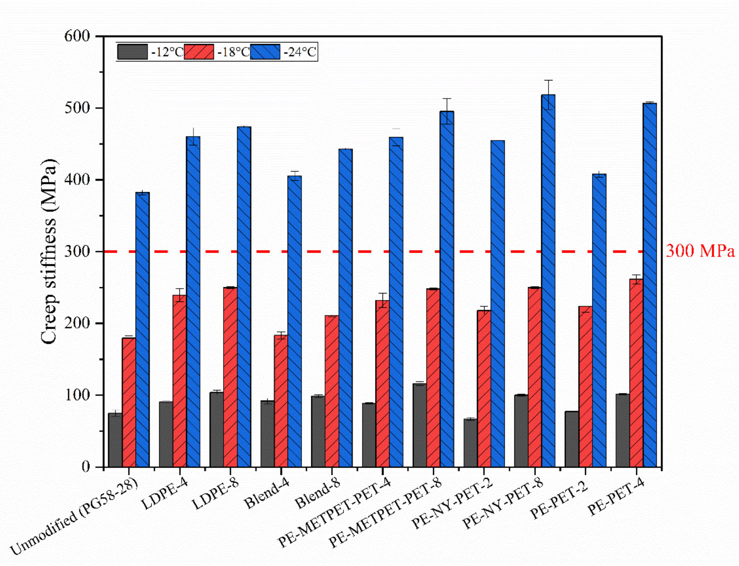


Figure 5-8 The creep stiffness of LDPE and MPP additives

The binder's stress relaxation capacity when the temperature drops is reflected in a higher m-value, which also demonstrates a lower susceptibility to cracking [187], [188]. Figure 5-9 illustrates the effect of LDPE and MPP additives on stress relaxation rate (m-value) at lower temperatures. The addition of LDPE and MPP additives negatively affected the m-value, particularly when the LDPE and MPP concentration exceeded 2%. At -12 °C, the m-value of LDPE-4 and Blend-4 declined by 10%, while those of LDPE-8 and Blend-8 decreased by 20%. This decrease in the m-value may indicate the capacity to relax under stress has been affected. While the addition of PE-NY-PET-2 and PE-PET-2 lowered the m-value by less than 7 percent at the three lower temperatures (-12 °C, -18 °C, and -24 °C). All LDPE and MPP-modified binders passed the m-value limits at -12 °C and -18 °C with 4 % or fewer concentrations. At -24 °C, however, none of the unmodified or LDPE-MPP-modified binders at any concentration level met the Superpave criteria limit. To avoid a substantial influence on the capacity to absorb stress, applying MPP additives at concentrations of 4% or less would be prudent.

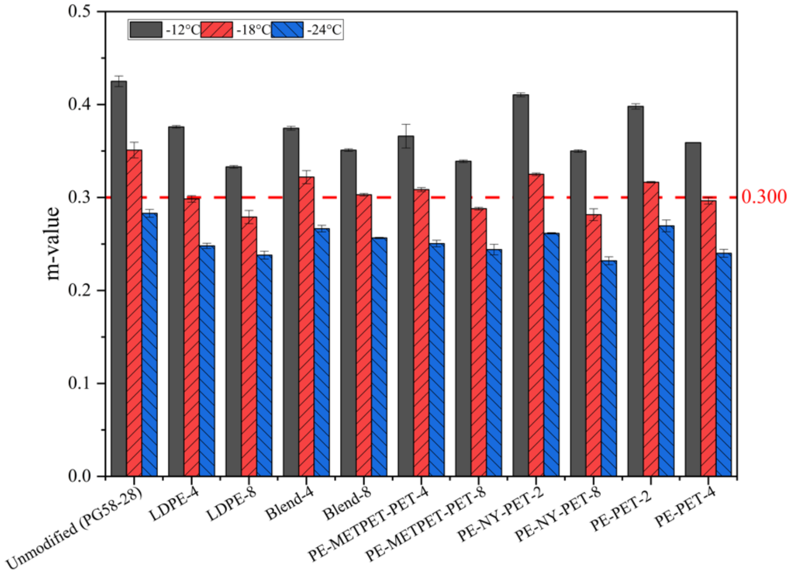


Figure 5-9 The m-value of LDPE and MPP additives

In previous research conducted through this investigation, BBR data was also plotted on a BLACK-space diagram to investigate the asphalt binders' and mixes' vulnerability to low-temperature cracking [189]–[191]. Romero [190] proposed plotting the stiffness vs m-value, which they considered equivalent to the BLACK-space diagram at low temperature, which was implemented in Figure 5-10.

The red-hued area shows the zone where the binder is susceptible to fracture at low temperatures. In comparison, the green zone represents the binder's acceptable performance range. This graph indicates that the tested binders separated into three distinct groups corresponding to the three testing temperatures, with the stiffness increasing and the m-value decreasing as the test temperature increases. In the case of the MPP modification, the figure verifies the prior finding of an increase in binder stiffness and a reduction in binder relaxation.

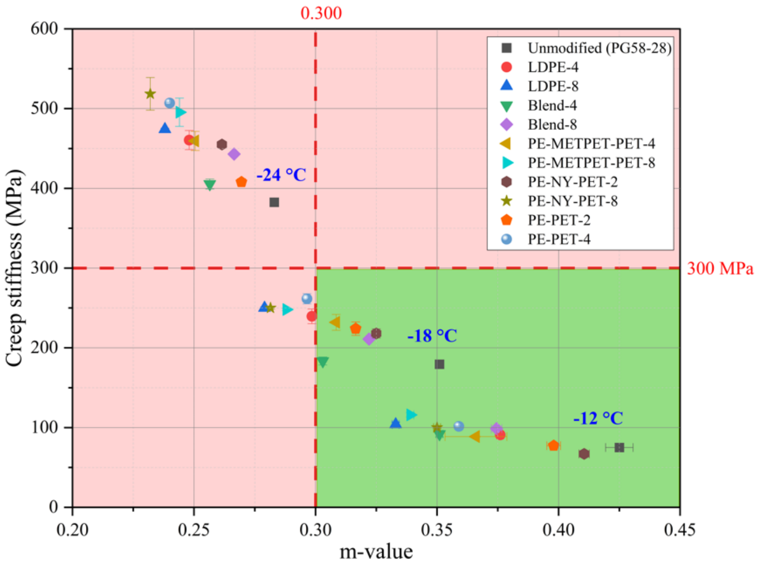


Figure 5-10 BLACK- space diagram of LDPE and MPP modified binders

5.3.2.3 Delta T_c Parameter

The ΔT_c values provide another indicator of crack development at low temperatures. Negative ($-\Delta T_c$) values are influenced by creep rate m (m-controlled). Positive ($+\Delta T_c$) values are determined by creep stiffness S (S-controlled). Positive values ($+\Delta T_c$) were only noticed for the unmodified binder. Figure 5-11 shows that LDPE and MPP-modified binders are more susceptible to failure at lower temperatures than unmodified ones. For instance, the ΔT_c decreased with Blends 4 and 8, respectively, from +0.4 °C to -3.2 °C and -4.1 °C. Compared to higher modification percentages, ΔT_c declined at a lower rate as the binder modification percentage increased. In this investigation, all LDPE and MPP-modified binders passed the Superpave threshold with a delta ΔT_c of -5.0°C, but only mixtures containing 2% MPP passed with a ΔT_c of -2.5°C. As a result, utilizing more than 2% of MPP is not recommended to retain the low-temperature performance since higher modification percentages cause the binder to stiffen at low temperatures.

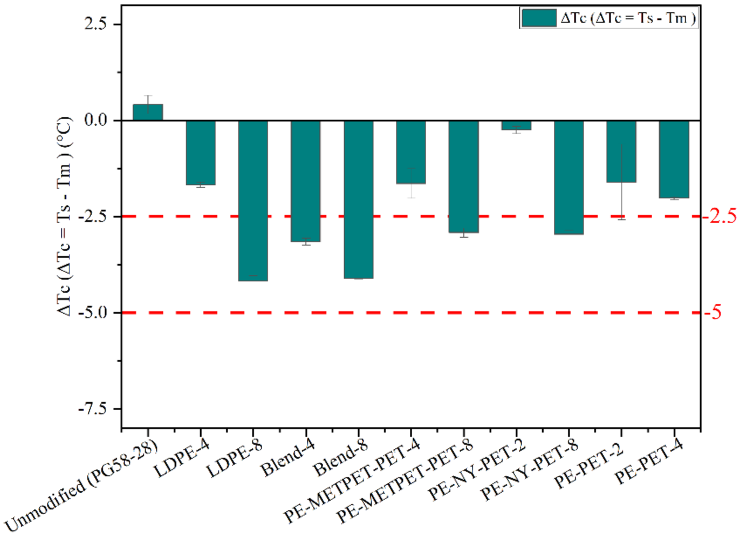


Figure 5-11 ΔT_c (20-hour) for MPP and LDPE modified binders

5.3.3 Asphalt Mixture Analysis

5.3.3.1 Complex (Dynamic) Modulus

Figure 5-12 demonstrates the master curves established of |E*| (norm of the complex modulus) at the reference temperature $T_{ref} = 21$ °C for MPP-modified. The findings show a slight increase in complex modulus at high frequencies, which correspond to low temperatures, and an increase at low frequencies (representing high temperatures). Compared to the virgin binder, the complex modulus for Blend-4-8 modified mixtures increased significantly at high temperatures (37°C and 54 °C). For instance, the modified Blend-8 mixture demonstrated a considerable increase in the complex modulus up to 50% greater than the virgin binder (at 25 Hz and 54 °C). The results of previous research concluded that binder tests (MSCR and G*/sin δ° tests) verified the high potential of using MPP modification to improve the permanent deformation resistance at high temperatures [78]. The previous study's finding is consistent with the increase in stiffness noticed by complex modulus testing in this paper.

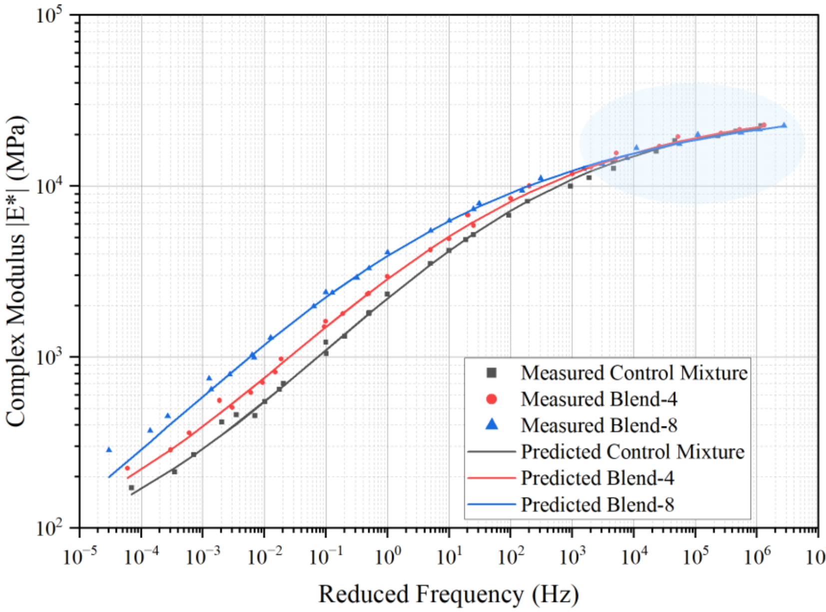


Figure 5-12 Master curve for MPP- asphalt mixtures modified modulus at 21 °C

The complex modulus of Blend-4 at frequencies of 25, 1, and 0.1 Hz changed by 13%, 27%, and 32%, respectively, at a temperature of 21 °C. At the same time, the Blend-8 mixture changed by, correspondingly, 40%, 75%, and 96%. At the low testing temperature (-10 °C), the complex modulus of both Blend-4 and Blend-8 exhibited insignificant change, as shown in Figure 5-12. Therefore, a lower modification concentration of MPP additives may preserve the low-temperature performance with little influence on the low and intermediate-temperature attributes. A high-binder modification that is more than 4% could be implemented to withstand greater pressures and harsher temperature conditions.

Table 5-6 Summary of sigmoidal model coefficients and shifting factors

Binder ID	Shifting Factors								
	C1	C2	α	β	δ	γ	λ	Tref	R²
Control Mixtures	16.7	142.3	2.918	-0.426	1.552	-0.439	1.142	21°C	0.983
Blend-4	17.4	145.1	2.816	-0.612	1.675	-0.385	0.714	21°C	0.9835
Blend-8	20.5	157.3	2.857	-0.947	1.648	-0.301	0.046	21°C	0.986

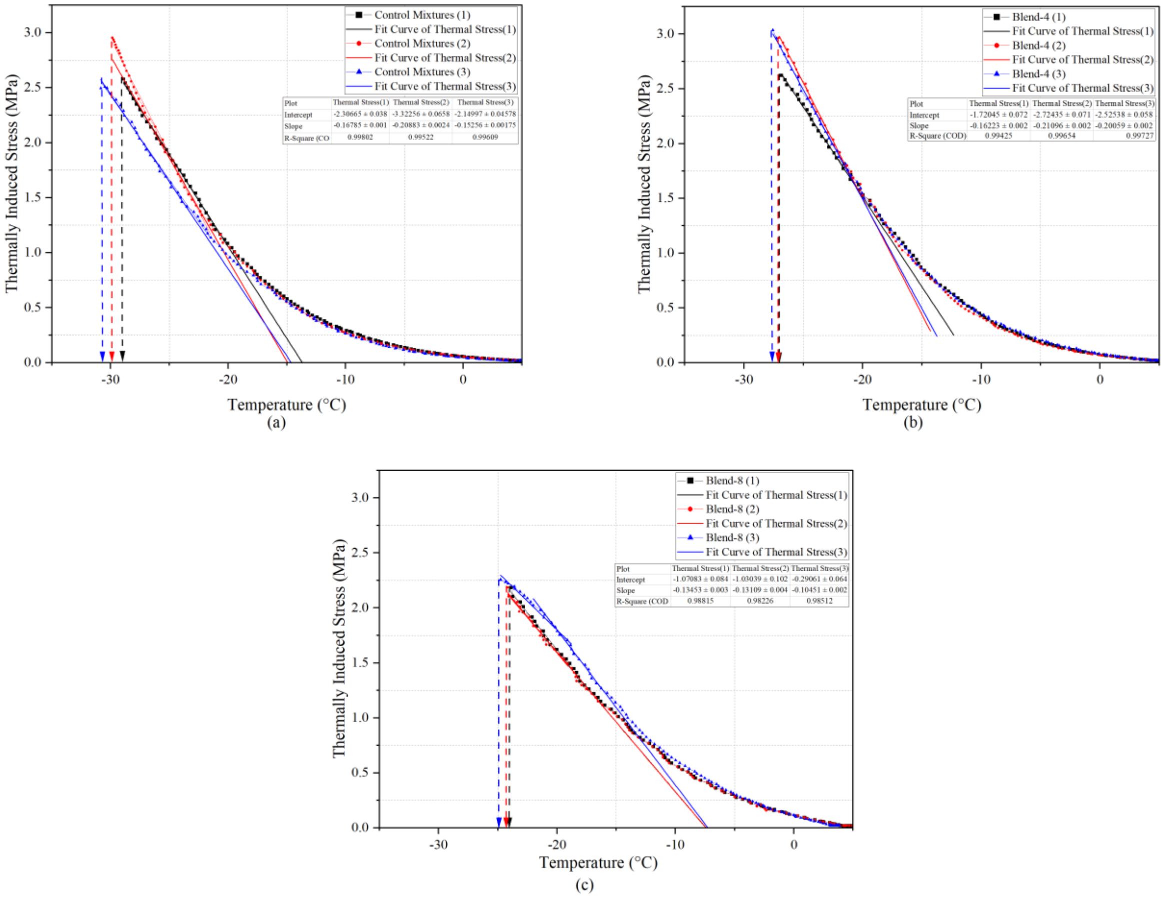
5.3.3.2 Thermal Stress Restrained Specimen Test

To assess the resistance to thermal cracking at lower pavement temperatures, the TSRST experiment was performed following AASHTO TP 10-93, "Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength," utilizing the same Multi-Testing System (MTS) loading frame and environmental chamber utilized for dynamic or complex modulus. Several parameters were measured by TSRST, including fracture temperature, fracture thermal stress, transition temperature, and the slope of the stress-temperature curve below the transition temperature, as presented in Figure 5-13. These parameters were determined by testing three samples of each mixture, as presented in Table 5-8.

The TSRST findings show that, compared to the Control Mixture mixture, the degree of resistance to thermal cracking decreased due to the presence of the MPP additive as the failure temperatures of Blend-4 and Blend-8 were used. The fracture temperatures increased by 3 °C and 6 °C for Blend-4 and Blend-8. Overall, TSRST findings show that all MPP mixes did not provide sufficient thermal cracking resistance to satisfy the lower PG grade criteria of -28 °C. To statistically analyze the thermal cracking test data, the null hypothesis was "Using MPP additives does not affect the thermal fracture temperature," The alternative hypothesis was the exact reverse. Table 5-7 findings indicate that the introduction of MPP resulted in a statistically insignificant influence on the thermal cracking temperature of Blend-4, as the observed P-value (P(T<=t) two-tail 0.026) was below the predetermined significance level of alpha = 0.05. Conversely, the results indicated a statistically significant impact on the thermal cracking temperature of Blend-8, as evidenced by the observed P-value (P(T<=t) two-tail 0.003).

Table 5-7 t-Test: Paired Two Sample for Means

Mixtures ID	Control Mixtures	Blend-4	Control Mixtures	Blend-8
Mean	-29.858	-27.225	-29.858	-24.268
Variance	0.944	0.084	0.944	0.218
Observations	3.000	3.000	3.000	3.000
Pearson Correlation	0.828		0.982	
Hypothesized Mean Difference	0.000		0.000	
df	2.000		2.000	
t Stat	-6.082		-18.595	
P(T<=t) one-tail	0.013		0.001	
t Critical one-tail	2.920		2.920	
P(T<=t) two-tail	**0.026**		**0.003**	
t Critical two-tail	4.303		4.303	



(a)

(b)

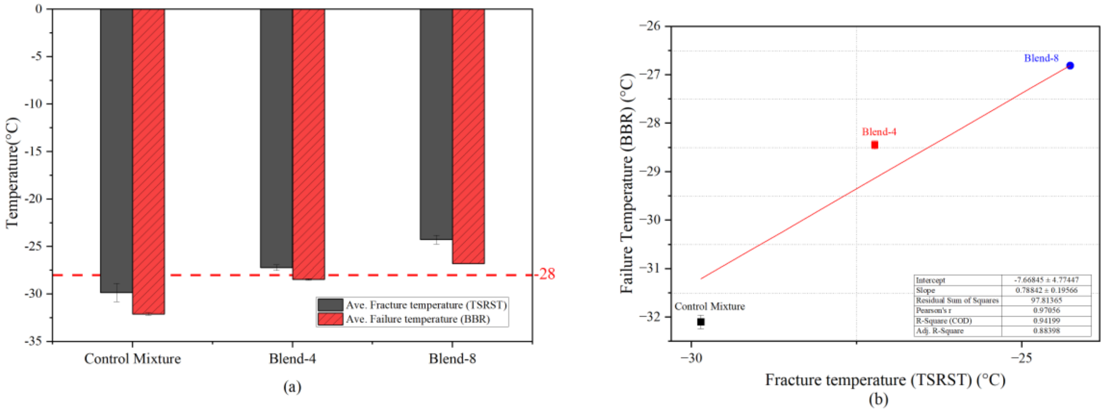
(c)

Figure 5-13 TSRST Results: (a)Control Mixture, (b)Blend-4, and (c) Blend-8

Table 5-8 Summary results of TSRST parameters

Mixture ID	FT^{I} (°C)	Ave.FT(°C)	SD	FT.S^{II} (MPa)	Ave. FT.S (MPa)	SD	Tg^{III} (°C)	Ave.T$_g$ (°C)	SD	Tg.S^{IV} (MPa)	Ave. T$_g$.S (MPa)	SD
Control Mixture	-28.90	-29.86	0.97	2.58	2.68	0.24	-16.53	-18.29	2.01	0.71	0.86	0.16
	-29.84			2.95			-17.85			0.84		
	-30.84			2.50			-20.48			1.03		
Blend-4	-27.08	-27.23	0.29	2.67	2.89	0.20	-13.86	-15.69	1.65	0.75	0.95	0.19
	-27.03			2.97			-16.16			0.98		
	-27.56			3.04			-17.05			1.13		
Blend-8	-23.87	-24.27	0.47	2.19	2.21	0.04	-11.47	-10.95	0.58	0.71	0.67	0.04
	-24.16			2.19			-11.06			0.66		
	-24.78			2.26			-10.33			0.64		
[I] Fracture temperature, [II] Fracture thermal stress, [III] Glass transition temperature, and [IV] Glass transition thermal stress												

The values of both fracture temperature (TSRST) and failure temperature (BBR) are presented in Figure 5-14 (a) to provide more insight into the low-temperature characteristics. It can be noticed that the TSRST values for the mixtures were 1 to 3°C higher (warmer) than the BBR results for the binder. Low-temperature cracking of an asphalt mixture may be affected by the mix parameters such as the air voids, aggregate-binder adhesion, and the additives used in the mix [192]. While the BBR test provides a reasonable understanding of the low-temperature characteristics of the asphalt binder, it often does not accurately reflect the mix's resistance to thermal cracking. The graphic in Figure 5-14 (b) shows the correlation between the TSRST's fracture temperature and the BBR's failure temperature. The deviation factor decides how two variables should be compared to the coefficient of variation (COV)—the COV findings for each examined material. R-Square (COD) for the TSRST and BBR tests, particularly for the reference mixes, is 0.94199. The TSRST testing was conducted only on Blend-4 and Blend-8 as they consist of all MPP plastic components and serve as tentative mixtures for mass production for industrial applications and construction of test sections.



Intercept	-7.66845 ± 4.77447
Slope	0.78842 ± 0.19566
Residual Sum of Squares	97.81365
Pearson's r	0.97056
R-Square (COD)	0.94199
Adj. R-Square	0.88398

(a)

(b)

Figure 5-14 Impact of MPP additives:(a) TSRST vs BBR (b) Correlation between the TSRST and BBR temperatures

5.4 Conclusions

The literature review found limited research on the low-temperature performance of polyolefin-modified asphalt binders, particularly those using polyethylene (PE) and its mixture. Furthermore, no research has been conducted on the suitability of MPP additives for modifying asphalt binders in terms of low-temperature performance evaluation. Therefore, this study aimed to investigate the feasibility of using MPP as an asphalt modifier via the wet method while considering the properties of asphalt binder and mixtures when MPP is modified at different percentages in asphalt cement (PG 58–28). Based on a series of laboratory experiments, the following conclusions were drawn and presented in this research paper:

- All mixes increased stiffness due to the MPP additives' presence. The Superpave Continuous PG (PGH, PGI, and PGL) and ΔT_c were influenced. However, the increase in asphalt stiffness (at low temperatures) was insignificant at lower MPP modification percentages. The incorporation of MPP made the asphalt binder stiffer, elevating it by at least one grade in the continuous PGH temperature with the 2% doses. Although there were some changes in the stiffness, using 4% or less MPP did not affect the low-temperature grades of the binders; the PGL remained the same as before the modification.
- The chemical composition of MPP influences the physical and performance properties of the asphalt binder. The DSC data revealed that the T_g's of saturates and the presence of MPP did not impact asphaltenes. However, the T_g's of aromatics and resins in Blend-4 and Blend-8 decreased compared to the virgin binder. This reduction is directly related to the polymer's ability to absorb and integrate into the asphalt binder.
- Only combinations containing 2% MPP passed delta ΔT_c of -2.5°C, whereas all LDPE and MPP modified binders passed with a ΔT_c of -5.0°C. Higher concentrations of MPP additives result in high binder stiffness at low temperatures. Thus, the authors recommend using MPP modification ideally up to 2% and not more than 4% by weight of asphalt binder to maintain the low-temperature performance.
- At low temperatures, the complex modulus of Blend-4 and Blend-8 mixtures exhibited insignificant changes compared to the virgin mixture. In addition, the small percentage of MPP modification can preserve low-temperature performance with little effect on the modulus at low and intermediate-temperature. However, high-binder modifications above 4% increased the mixtures' modulus at high temperatures.
- The TSRST experiment findings indicated the MPP additive did not meet the lower PG grade criteria of -28°C for any tested mixtures. Additionally, while the fracture temperatures of the Control Mixture increased by 3°C and 6°C for Blend-4 and Blend-8 mixtures, respectively, the presence of MPP additive reduced resistance to thermal cracking. Furthermore, statistical analysis revealed a statistically insignificant impact of MPP on the thermal cracking temperature of the Blend-4 mixture but a significant impact on the Blend-8 mixture.

Considering these findings, the feasibility of using MPP as an asphalt modifier is confirmed when coupled with an appropriate pre-processing procedure. The authors recommend limiting the MPP modification percentage to 4% of binder weight to avoid negatively impacting thermal cracking resistance in cold regions. A higher percentage could, however, be used if low-temperature cracking is not a concern or when a softer base binder is used. Further research is required to very this hypothesis.

6. The Influence of Multi-Layer Plastic Packaging (MPP) on the High-Temperature Performance of Asphalt Binders and Mixtures through Wet and Dry Mixing Methods

This chapter presents an expanded version of an abstract accepted for presentation at the 76th RILEM Annual Week and International Conference on Regeneration and Conservation of Structures (ICRCS 2022) in Kyoto, Japan. The conference presentation, Qabur A, Baaj H, El-Hakim M. titled "The Influence of Multi-Layer Plastic Packaging (MPP) on the High-Temperature Performance of Asphalt Binders and Mixtures through Wet and Dry Mixing Methods," explores the potential of MPP to modify asphalt cement, utilizing both wet and dry mixing techniques. The study takes a comprehensive approach to evaluate the feasibility of using MPP in asphalt modification, examining factors beyond simple rheological and mechanical analysis.

Abstract

Rising temperatures and heat waves are some of the consequences of climate change that represent a major challenge in pavement engineering. Higher temperatures, combined with heavy traffic loads, increase the risk of permanent deformation and reduce the useful lifespan of the pavement. These changes would increase the need for more pavement maintenance and rehabilitation activities during the pavement's service life, which contributes to higher carbon emissions and energy consumption, and increase the overall cost of the pavement during its life cycle. Researchers have been exploring various methods to improve pavement performance, including thermoplastic additives. Multi-Layer Plastic Packaging (MPP) materials, such as Polyester, Polyethylene, Nylon, and Metalized Polyester, contribute to global plastic waste and pose environmental and economic challenges. A substantial portion of MPP waste comes directly from the plastic industry as post-manufacturer waste, which typically has high quality and can be easily repurposed. Although the individual components of MPP have already been successfully used in asphalt modification, this study takes a comprehensive approach to evaluate the feasibility of using MPP to modify asphalt cement, going beyond simple rheological and mechanical analysis. Wet and dry mixing processes were investigated for MPP-modified mixtures. The results indicate that MPP improves the physical and rheological properties of modified binders at high temperatures, which enhances stiffness and resistance to deformation in asphalt mixtures, with the wet method being more effective than the dry method. Additionally, a strong correlation was observed between MSCR and HWTT tests providing insights into the rutting mechanisms of MPP-modified pavement materials. However, further research is required to optimize MPP modifiers, particularly regarding elastic recovery and moisture resistance. MPP could improve the performance of asphalt pavements and mitigate the environmental impact of plastic waste. The findings of this study provide valuable information for developing future guidelines for using MPP additives in asphalt modification, enhancing durability and sustainability while reducing plastic waste.

Keywords: Multi-layer Plastic Packaging, Climate Change, Recycling, Asphalt Modification, Permanent Deformation, Moisture Resistance.

6.1 Introduction

The primary function of a pavement structure is to carry wheel loads, which generate vertical, horizontal, and shear stresses in the bound layer's bottom, as well as compressive and tensile stresses in the unbound layers and subgrade soils [37]. However, rutting is one of the most significant distresses that directly affects the quality and serviceability of roads [44]. This type of damage is typically caused by repeated slow-moving traffic loads at high temperatures that result in irreparable permanent deformations. Rutting can be attributed to two main mechanisms: subgrade instability and inadequate asphalt mixture design properties[37],[53]. High temperatures, heavy traffic, and slow-moving vehicles can accelerate permanent deformation, resulting in wheel path rutting, the most prevalent form of permanent deformation [54]. The resistance to permanent deformation is mainly attributed to the internal friction and interlock formed by the aggregate skeleton and the cohesion provided by the asphalt binder. Additionally, permanent deformation is affected by several factors, such as the pavement structural layers, the rheological properties of the asphalt cement, and the volumetric properties of the asphalt mix [54]–[57]. Improving the resistance to permanent deformation is crucial in maintaining pavement durability and safety, which requires appropriate pavement design, construction techniques, and suitable materials.

Incorporating polymers, such as thermoplastic elastomers, into asphalt modification has demonstrated promising results in enhancing the mechanical characteristics, durability, and longevity of asphalt pavements [10]–[12]. Polymers, which are long-chain molecules, can be mixed with asphalt to create a polymer-modified asphalt (PMA). Although various polymers have been employed, only a select few have shown exceptional overall performance in terms of pavement service life. The most notable polymer modifiers include styrene-butadiene-styrene (SBS), which increases elasticity and rutting resistance; styrene-butadiene rubber (SBR), which enhances fatigue resistance and resilience; ethylene-vinyl acetate (EVA), which improves low-temperature performance and resistance to cracking; and both virgin and waste polyethylene (PE) modifiers, which provide improved resistance to permanent deformation and aging [10], [49], [72], [123], [193], [194]. The ideal polymer modifier type and dosage depend on the asphalt mixture's required physical and mechanical properties, availability, and production cost [75], [74], [14], [13]. The most suitable polymer type for designing long-lasting pavement service life considers local climate, traffic volume, road construction techniques, and the road's functional classification. Polymers can be introduced to asphalt in different forms, like pellets, powders, or liquids, and in varying amounts, based on the desired PMA properties [103]. Although virgin polymers are known to improve asphalt binder performance, their usage should be limited due to cost and compatibility challenges with binders at higher dosages. Instead, waste thermoplastic polymers have yielded similar enhancements in road performance at a lower environmental and economic cost [24], [103].

The wet and dry methods are two commonly used approaches to incorporate polymers into asphalt mixes [24]. In the wet method, solid polymer additives are mixed directly with hot unmodified asphalt cement to create a modified binder. Subsequently, aggregates are mixed with the modified binder to create asphalt mixtures. The mixing temperature and duration depend on the properties of the asphalt binder and additives [13], [195]–[197]. Studies have found that adding plastic waste as a modifier to asphalt binder improved its thermal stability, making it more resistant to oxidative aging at high temperatures [16], [198]. The presence of antioxidants in the plastic may help prevent the breakdown of the asphalt binder under these conditions. The mixing temperature should not exceed 185°C to prevent premature aging and loss of desirable rheological properties [38], [199], [200]. These studies also suggest sufficient mixing and shearing time is necessary to disperse the plastic additive polymers effectively into the asphalt cement matrix. In contrast, the dry method involves adding a mixture of solid polymers and aggregates directly to the asphalt mixture without requiring any prior modification of the asphalt cement. A study by Awwad et al., using the dry method to mix high-density and low-density polyethylene, showed improved adhesion between the asphalt binder and aggregate, improving pavement deformation and fatigue resistance [80].

Asphalt mixtures frequently incorporate both virgin and recycled forms of Polypropylene (PP), Polyethylene (PE), High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), and Polyethylene Terephthalate (PET) as additives [13], [104], [105]. PE is often used, as it is found in various products, including bottles, packaging, and single-use plastic bags [129]. Angelone et al. reported that using Recycled Polyethylene (RPE) to modify asphalt using the dry addition method improved Marshall's stability and flow, while modification using the wet method enhanced the asphalt binder's softening point and elastic recovery. Furthermore, the study demonstrated that RPE-modified mixtures possess better rutting resistance and reduced moisture susceptibility, making them a sustainable and high-performance alternative for asphalt pavement [195]. Reddy and Venkatasubbaiah conducted a study investigating the effects of adding High-Density Polyethylene (HDPE) and crumb rubber powder (CRP) to asphalt mixtures using wet and dry processes. The study reported an increase in rutting resistance at moderate to high temperatures. This improvement was accompanied by increased binder's softening point and the mixture's Marshall stability while decreasing the mixture's ductility and flow. Optimum modification percentages were determined to be 5% HDPE and 10% CRP (by weight of asphalt binder) [201]. Gibreil and Feng also reported that using HDPE and CRP improves asphalt's physical properties, temperature sensitivity, Marshall strength, Tensile Strength Ratio (TSR) values, and rutting resistance [202]. Nizamuddin et al. investigated using recycled linear low-density polyethylene (R-LLDPE) as a bitumen modifier. The addition of R-LLDPE increased the binder viscosity and softening point while decreasing the penetration value. Successful blending was confirmed through Fourier Transform Infrared Spectroscopy (FTIR) analysis, and subsequent Thermogravimetric (TGA) analysis showed improved thermal stability. The rheological evaluation demonstrated improved resistance to permanent deformation at high temperatures. The study's results suggested that 3% R-LLDPE is suitable for most environmental conditions, while 6% is ideal for tropical climates [203]. Previous studies [80], [204] indicated that plastic waste additives could reduce pavement deformation, increase the fatigue resistance, and provide better adhesion between the asphalt and the aggregate in the mix.

Elastomer, plastomer and thermoplastic polymer types have been successfully utilized in asphalt modification[10]. As a result of their success in asphalt binder modification, multi-layer plastic packaging (MPP) is being considered a potential additive for asphalt modification. MPP-modified binders are expected to enhance rheological and physical properties [78]. MPPs consist of multiple layers of plastic films, providing superior strength and durability compared to traditional single-layer plastics. While the use of MPP waste in asphalt mixtures has shown promising results in improving their mechanical properties and moisture resistance, further research is needed to determine the optimal concentration and processing methods of MPP additives in asphalt modification and assess their long-term durability and aging properties. The existing research gap underscores the importance of further investigation into the impacts of MPP additives on the rheological and mechanical properties of asphalt binders and mixtures at high temperatures. The Superpave testing approach recognizes that both asphalt binder and aggregate properties influence the rutting susceptibility of asphalt mixes. However, the Strategic Highway Research Program (SHRP) binder specifications currently use the linear viscoelastic range to measure PG grade, fatigue, and rutting parameters. This approach fails to effectively capture binder performance in asphalt mixes as non-linear behaviour is commonly observed under high stress and strain conditions[205].

The growing demand for sustainable and cost-effective plastic waste management solutions has led to the emergence of MPP additives as a promising alternative for asphalt modification. However, thoroughly understanding their effects on asphalt performance under high-temperature conditions is crucial for ensuring their effectiveness and long-term durability. Thus, performance testing is required to evaluate asphalt mixtures beyond aggregate and asphalt binder properties to address this issue. Therefore, the key objective of this study is to determine how the incorporation of MPP additions affects the modified binder's rheological and mechanical characteristics under high-temperature conditions using both wet and dry processes.

6.2 Materials and Methodology

6.2.1 Materials Properties

6.2.1.1 Asphalt Cement and Aggregate

This study used asphalt cement (AC) PG 58-28 sourced from western crude supplied. This AC had been used in a previous study, and its properties can be found in Table 5-2 [206]. A surface course mix consisting of limestone aggregate called HL-3, following the Ontario Provincial Standards Specifications (OPSS), was used to produce the HMA mixture samples with both conventional and

MPP-modified asphalt binders. Table 6-2 summarizes the properties of the blended aggregates and HMA mix Superpave design properties. The asphalt mixes were prepared using the Superpave mix design and ground limestone to meet the aggregate graduation requirements shown in Figure 6-1.

Table 6-1 Properties of asphalt cement [206]

Property	Values
Ash Content, %	0.03
Viscosity (Pa.s), at 135°C < 3	0.266
Initial boiling point/Boiling range (°C)	228
Flash Point (°C)	243
Specific Gravity (at 21.1°C)	1.03
Solubility in water	None
True Grade	59.4-31.4

Table 6-2 Gradation and volumetric properties of aggregate and HMA mix Superpave design properties.

Sieve (mm)	Composite gradation blend (%)	Superpave Volumetrics		Required	Selected
19	100	N_{des} (% Gmm)		96	96
12.5	95	N_{ini}(% Gmm)		<=89	--
9.5	83	N_{max} (% Gmm)		<=98	97.4
4.75	58	Air Voids (%) @ N_{des}		4	4
2.36	40	VMA (%)	Min	14	14.6
1.18	19	VFA (%)	Min	65	72.6
0.6	12		Max	75	
0.3	8	Dust Proportion	Min	0.6	0.66
0.15	4.5		Max	1.2	
0.075	3	Tensile Strength Ratio, %		80% Minimum	96
Bulk Specific Gravity (G_{sb})	2.661	Asphalt Film Thickness (TF)		N/A	--
Apparent Specific Gravity (G_{sa})	2.765	Traffic Category		D	D

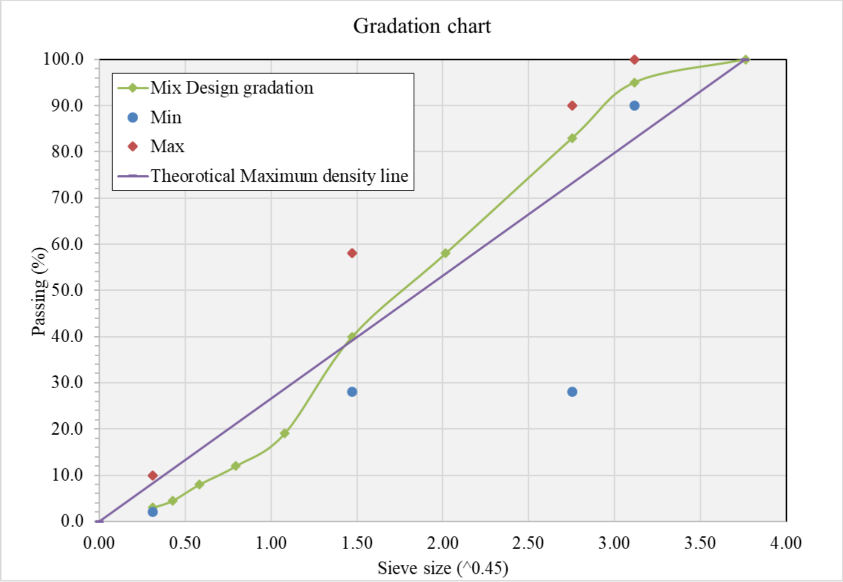


Figure 6-1 Aggregate gradation curve

6.2.1.2 MPP additives and MPP-modified binder

The multi-layer plastic packaging bags used in this project is composed of 89% Polyethylene (PE), 6% Polyester (PET), 2% Nylon (NY), and 3% Metallized Polyester (METPET). The typical physical properties of the film materials used in this study were presented in a previous study [78]. Figure 6-2 shows the systematic approach used to produce the MPP additives and MPP-modified binder.

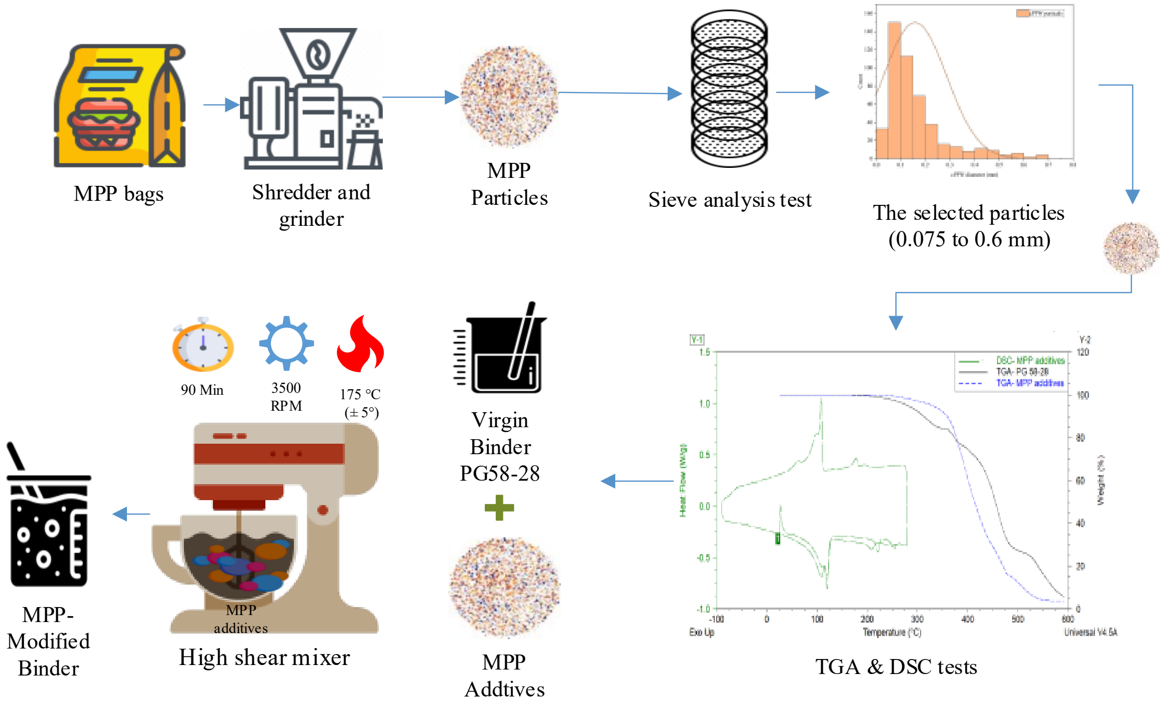


Figure 6-2 Preparation of MPP additives and MPP-modified asphalt

Initially, MPP additives were produced from multi-layer plastic packaging bags mainly containing PE, with less than 15% comprising PET, NY, and METPET. The MPP was shredded into small particles (2-6 mm) using a Micro-Cut electric shredder and then ground into a powder using an Electric Grain Mills Grinder, as shown in Figure 6-3. The MPP powder was then sieved to determine the grain size distribution, with the selected particle size for adding to the asphalt binder ranging from 0.075 to 0.595 mm. Most of these particles melted and integrated into the asphalt binder. In contrast, particles with higher melting points did not melt entirely but were reduced in size to less than 250 µm, which meets the recommendations of AASHTO T 315 and ASTM D7175 standards.

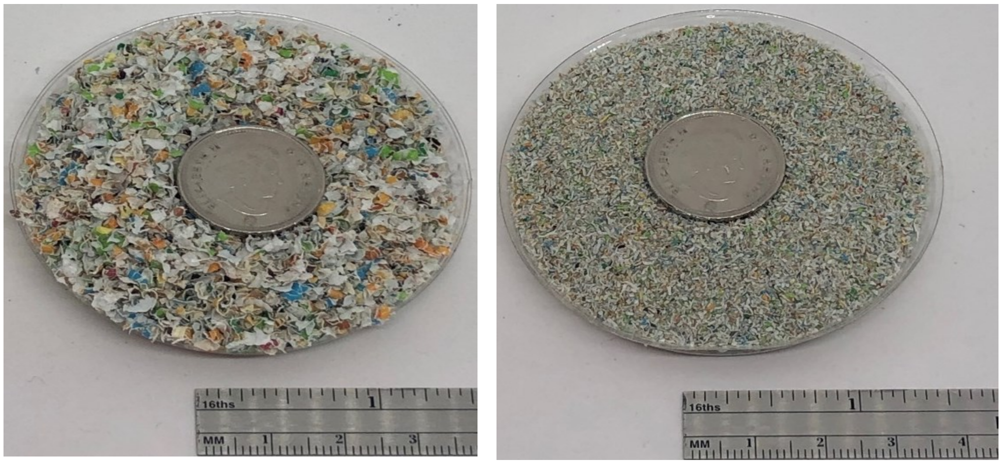


Figure 6-3 MPP in granule form (left) and powdered form (right)

Subsequently, Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) tests were used to analyze the thermal properties and stability of the MPP additives and AC. An endothermic peak, which indicates the melting point, was observed at approximately 120°C for PE and within a range between 248 – 254 °C for NY, PET, and METPET films. The TGA results confirmed no significant changes in the MPP or asphalt cement samples up to 320°C. These results helped to determine the mixing temperature for the MPP additives. Thus, a production temperature of 175°C ± 5°C was used to ensure the PE material entered the melting phase and blended with the liquid asphalt cement. The remaining unmelted components of the MPP were considered to act as fillers due to their high melting points. The ground and sieved MPP were stored and later used to produce HMA via the dry method.

After preparing the MPP-modified asphalt binders, cylindrical glass bottles with a mass of 35 ± 0.5 grams were filled and subjected to short-term aging in a rolling thin-film oven (RTFO), where heat was applied to moving film of semi-solid asphalt material to model the aging process during traditional hot-asphalt mixing. After cooling for approximately 60 minutes, all bottles were placed horizontally in a 15-rpm rotating carousel, and the air was briefly forced into each glass container during each cycle. This 85-minute operation was carried out at 163 °C.

6.2.2 Methodology

To produce MPP-modified binders, 4% and 8% MPP, based on the total asphalt cement weight, were added to the asphalt cement (Blend-4 and Blend-8). Figure 6-4 displays a flowchart of the experiments carried out, and the following sections briefly explain these tests. The physical and rheological properties of the MPP-modified asphalt cement were evaluated using the rotational viscometer (RV) and dynamic shear rheometer (DSR) tests. In addition, a multiple stress creep-recovery test (MSCR) was performed using the DSR at high temperatures after short-term aging using the rolling thin-film oven (RTFO) test. Finally, the complex modulus and Hamburg wheel tracking test (HWTT) were performed to determine the MPP-modified asphalt mixtures' mechanical properties and rutting performance at the mixture level.

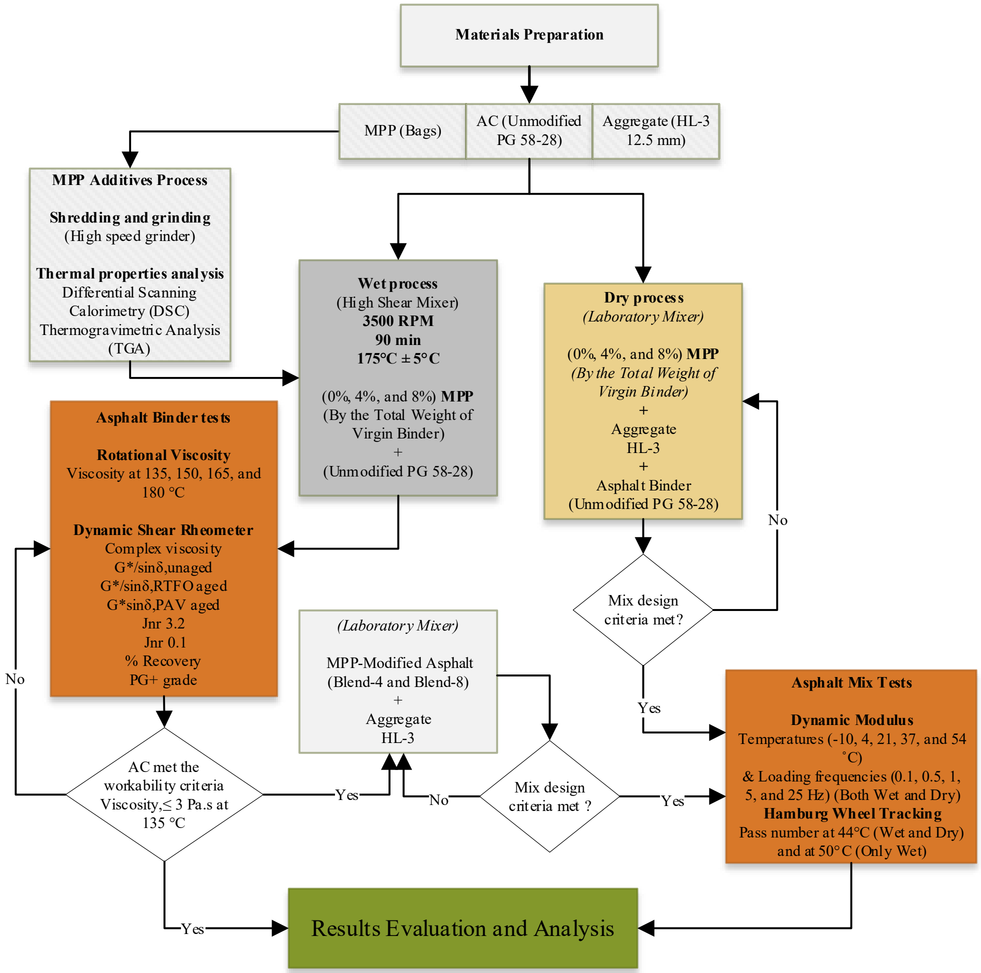


Figure 6-4 Flowchart of MPP-modified asphalt physical, rheological, and mixtures testing

6.2.2.1 Asphalt Binder Procedures

6.2.2.1.1 Rotational Viscometer

The viscosity, frequently referred to as a fluid's "stiffness", measures a substance's resistance to flow under shear loading. Viscosity is a crucial characteristic of asphalt as it impacts the workability and compaction of asphalt mixtures [48]. Viscosity is the ratio between the applied shear stress and the shear rate. The viscosity of MPP-modified binders during the high-temperature range of manufacturing and construction was evaluated via rotational viscometers (RV). The AASHTO T316 [207] test protocol was employed, which involved using an SC4-21 spindle at test temperatures of 135°C, 150°C, and 165°C, and speeds of 20, 50, and 100 rpm, respectively. The values of 0.17 ± 0.02 and 0.28 ± 0.03 Pa. s were used to determine the mixing and compaction viscosity temperatures following AASHTO T316. Duplicate tests were conducted for each asphalt binder sample, and each test result was obtained by averaging three readings for each temperature. To ensure workability, the maximum viscosity of 3 Pa.s at 135 °C, as specified by the Strategic Highway Research Program (SHRP), was not exceeded, as shown in Table 6-3 [48]. Furthermore, the impact of MPP additives on complex viscosity (η^*) was assessed using a dynamic shear rheometer at a constant frequency of 10 rad/s and different temperatures, ranging from 58°C to 82°C.

6.2.2.1.2 Dynamic Shear Rheometer

The Dynamic Shear Rheometer (DSR) was utilized to characterize the viscoelastic behaviour and rheological properties of MPP-modified asphalt binders, following AASHTO 315 standards [48], [126]. The primary outcomes of the DSR test are G^*, representing the sample's total resistance to frequent deformation, and $\delta°$, indicating the delay between the applied shear stress and the resulting shear strain [48]. The performance grades (PG) of neat and MPP-modified asphalt binders at high temperatures were determined by following AASHTO T315. Subsequently, the failure temperatures of RTFO-aged and unaged unmodified and MPP-modified asphalt binders were determined. The effects of frequencies, temperatures, and MPP content on asphalt binders' linear viscoelastic behaviour have been investigated using the frequency sweep (FS) test. The FS test was carried out using a 25 mm diameter plate with a 1-mm gap, and frequencies varied from 0.159 Hz to 15 Hz [0.1 to 100 rad/s]. The temperature sweep (TS) test was applied using a 1.59 Hz [10 rad/s] frequency and different temperatures ranging from 58 °C to 82 °C. Finally, the rheological properties of the MPP-modified asphalt binder, including unaged and short-term aged (RTFO) rutting parameters, as illustrated in Table 6-3, were determined by conducting DSR tests using Anton Paar MCR 302.

Table 6-3 Specification requirements of Superpave binder

Binder Test	Temperature	Test parameter	Aging binder state	Requirement
Dynamic shear rheometer	High PG	$G^*/\sin\delta°$	Original RTFO Residue	$\geq 1.0\ kPa$ @ $10\ rad/s$ $\geq 2.2\ kPa$ @ $10\ rad/s$
Rotational viscometer	135 °C	Viscosity	Original	$\leq 3\ Pa\ s$

6.2.2.1.3 Multiple Stress Creep Recovery

The MSCR test evaluates the resistance to permanent deformation of asphalt binders following AASHTO M332 [143], [205]. This investigation used the MSCR test to determine the asphalt binders' recovery (R) and non-recoverable creep compliance (J_{nr}). AASHTO T 240 guidelines were followed to age all asphalt binder samples using the Rolling Thin Film Oven (RTFO). Then, specimens with a 25 mm diameter were evaluated for creep and recovery under low and high-stress conditions of 0.1 kPa and 3.2 kPa. The mechanism performed include a 1-second loading cycle followed by a 9-second rest interval for ten low-stress cycles (0.01 kPa) and ten high-stress cycles (3.2 kPa). The test results assessed the MPP-modified asphalt binder's permanent deformation using the non-recoverable compliance (J_{nr}) to identify the appropriate traffic range in Equivalent Single Axle Loads (ESALs), as shown in Table 6-4. Equations 1, 2, and 3 were used, respectively, to determine the average percent recovery (R), non-recoverable creep compliance (J_{nr}), and non-recoverable creep compliance difference (J_{nrdiff}).

Equation 6-1

$$\boldsymbol{R = \left(\frac{\epsilon_1 - \epsilon_{10}}{\epsilon_1}\right) \times 100}$$

Equation 6-2

$$\boldsymbol{J_{nr} = \frac{\epsilon_{10}}{\sigma}}$$

Equation 6-3

$$\boldsymbol{J_{nrdiff} = \left(\frac{J_{nr3.2} - J_{nr0.1}}{J_{nr0.1}}\right) \times 100}$$

Where accumulated strain after 1s refer as $\varepsilon 1$., is residual strain after 10s refer as $\varepsilon 10$., σ is applied stress. $J_{nr3.2}$ is non-recoverable creep compliance at a creeping stress of 3.2 kPa, and $J_{nr0.1}$ is non-recoverable creep compliance at a creeping stress of 0.1 kPa.

Table 6-4. MSCR grading according to (AASHTO M332-14)

Jnr(3.2kPa^{-1}) criteria	Designation Traffic Level	ESALs million	Traffic speed	MSCR grading*
Jnr ≤ 0.5	"E" refers to Extremely high-traffic loading	≥30	<20 km/h	PG XX **E**-YY
Jnr ≤ 1.0 and ≥ 0.5	"V" refers to Very high-traffic loading	≤30	<20 km/h	PG XX **V**-YY
Jnr ≤ 2.0 and ≥ 1.0	"H" refers to High traffic loading	10–30	20–70 km/h	PG XX **H**-YY
Jnr ≤ 4.5 and ≥ 2.0	"S" refers to Standard traffic loading	≤10	>70 km/h	PG XX **S**-YY
* XX refers to high-temperature service, and YY refers to low-temperature service				

6.2.2.2 Asphalt Mixtures Procedures

Before testing, all mixes were subjected to a brief aging period in a forced-draft oven. The HMA control mixtures were aged for 4 hours at 135°C per AASHTO R30 and 2 hours at field compaction temperatures. Note: Some graphs display five asphalt mixtures, namely the Control Mixture, Blend-4 W, Blend-4 D, Blend-8 W, and Blend-8 D. The abbreviations "W" and "D" used in the names of some of these mixtures, respectively, stand for the Wet Method and Dry Method.

6.2.2.2.1 Complex (Dynamic) Modulus

The modulus or stiffness of the asphalt mix is an essential design parameter for flexible pavement, influenced by the loading frequency and ambient temperature due to its viscoelastic nature [179]. Due to their viscous nature, asphalt mixtures exhibit a phase lag (δ°) between stress and strain for sinusoidal loading [44]. To determine the stress-strain relationship of asphalt concrete in the laboratory, a non-destructive dynamic modulus method is used. This investigation performed the dynamic modulus test following AASHTO T 342 for dynamic modulus samples produced using the Superpave Gyratory Compactor (SGC) [208]. The gyratory compacted samples were then cored and sliced into 100 mm x

150 mm cylindrical specimens. During the test, the specimen was subjected to sinusoidal axial compressive stress with varying loading frequencies (0.1, 0.5, 1, 5, and 25 Hz) at specific temperatures (-10, 4, 21, 37, and 54 ˚C). The strain response and phase lag were then calculated using three extensometers (positioned 120° apart) connected to the gauge points glued on the specimen surface. The test was performed in a frequency sweep mode, ranging from 25Hz to 0.1Hz, as the temperature was gradually increased from the lowest to the maximum test temperature. The stress of each mix was adjusted according to the standard strain range (50µ to 150µ). A dummy specimen with a thermocouple was constructed to calculate and monitor the specimen temperature. A data-collecting device was used throughout the test to continually measure the applied stress and the specimen's resulting strain response. Rowe et al. [180] developed the Generalized Logistic Sigmoidal (GLS) model expressed in Equation 6-4, an extension of the sigmoidal model used to characterize the stiffness of asphalt mixtures. They recommended using the GSL model to improve master curves for non-symmetric curves, as it performed well for bituminous materials during the study. This investigation utilized the GSL model to develop a master curve for MPP-modified mixtures. The shift factors specified by the Williams, Landel, and Ferry (WLF) Equation 6-5 were used to construct a sigmoid format master curve. The fitting of dynamic modulus and phase angle was simultaneously optimized to complete the construction of the master curve.

Equation 6-4

$$\boldsymbol{log|E^{*}(f,T)| = \delta + \frac{\alpha}{(1+\lambda exp^{\beta+\gamma(log\omega r})^{1/\lambda}}}$$

Where |E*| is the dynamic modulus or the norm of the complex modulus value (MPa), log ωr is the reduced frequencies, δ is the curve's lowest asymptote, α is the deviation between the higher and lower asymptotes' values, and λ is used to account for the curve's non-symmetrical form, and β and γ are shaping coefficients parameters that determine the curve shape between asymptotes and the spot where the inflection point is.

Equation 6-5

$$\boldsymbol{loga_T = \frac{C_1(T-T_{ref})}{C_2+(T-T_{ref})}}$$

Where T is the temperature, T_{ref} is the reference temperature, log a_T is the decadic logarithm of the TTS shift factor, and C_1 and C_2 are constants that are material-specific. The construction of the master curve was facilitated by Microsoft Excel's spreadsheet and solver feature. Table 6-5 presents the coefficients of the shift factor and sigmoidal model equations for various temperatures and additives.

Table 6-5 Summary of sigmoidal model coefficients and shifting factors for Wet and Dry Methods

Mixture ID	Shifting Factors								
	C1	C2	α	β	δ	γ	λ	Tref	R²
Control Mixture	16.7	142.3	2.918	-0.426	1.552	-0.439	1.142	21°C	0.983
Blend-4 W	17.4	145.1	2.816	-0.612	1.675	-0.385	0.714	21°C	0.9835
Blend-4 D	19.5	161.8	2.452	-0.436	1.941	-0.434	0.584	21°C	0.9868
Blend-8 W	20.5	157.3	2.857	-0.947	1.648	-0.301	0.046	21°C	0.986
Blend-8 D	19.9	172.9	2.486	-0.654	2.029	-0.417	0.381	21°C	0.9884

6.2.2.2.2 Hamburg Wheel Tracking Test

Pavement rutting is a type of asphalt road distress that significantly affects road safety and ride comfort, particularly when the depth reaches critical values [57]. The application of loads to the surface of asphalt pavement causes the deformation of asphalt layers. Since the asphalt mix is viscoelastic, a portion of deformation recovers once the load is removed, exhibiting elastic behaviour. However, a portion of the deformation caused by the loads remains, exhibiting plastic behaviour. The amount of deformation is influenced by factors such as the weight of the load, loading frequency, pavement temperature, and type of asphalt mix [54]. The Hamburg Wheel Tracking Test (HWTT) was performed following AASHTO T324 to evaluate the resistance of compacted MPP-modified asphalt mixes, which used 4 and 8% of MPP additives via wet and dry methods to assess rutting and moisture damage. The graph in Figure 6-5 illustrates a typical plot of the HWTT test, which shows three primary stages and traditional parameters such as total rut depth, creep slope, stripping slope, and stripping inflection point (SIP). The graph depicts the pre-consolidation stage, which occurs before linear deformation due to the presence of air voids. The pre-consolidation stage is followed by the linear consolidation stage, primarily influenced by the rutting resistance provided by the binder stiffness and aggregates' interlock (creep stage). Lastly, the asphalt binder separates from the aggregates due to severe moisture damage, which leads to a rapid decrease in resistance to rutting (stripping stage). [142].The stripping inflection point is the intersection of the creep and stripping zones (SIP), which can be calculated from the slopes and intercepts from the creep and stripping stages using Equation 6-6 [142].

Equation 6-6

$$\boldsymbol{SIP = \frac{intercept\ (strip\ stage) - intercept\ (creep\ stage)}{slope\ (creep\ stage) - slope\ (strip\ stage)}}$$

Table 6-6 MTO Thresholds recommendation of HWTT test [209]

PGAC Grade	Recommended Test Temperature (°C)	Minimum wheel (passes)	Rut depth limit (mm)
58-XX and 52-XX	44	20000	12.5
64-XX	50	20000	12.5
70-XX	50	20000	6

This study produced four samples measuring 150 mm in diameter and 63 mm in height with 7% ±0.5 of air space using the Superpave Gyratory Compactor (SGC). The test temperatures of 44 and 50 °C were selected per the Ontario Ministry of Transportation (MTO) Specifications[209], as shown in Table 6-6. All mixtures samples were tested at 44°C to ensure they met the HWTT criteria for the PG 58-XX asphalt binder as per the MTO specification[209], [210]. The test temperature of 50°C was then selected to validate the effectiveness of the MPP additive, as MPP-modified mixes had a higher equivalent binder PG than PG 58. Solid steel wheels were used to test the samples, and Linear Variable Differential Transformers (LVDTs) were used to determine the average rutting depth and permanent deformation. The load on each steel wheel was 705 ± 4.5 N, and the test was set to finish after 20,000 wheel passes or when the rut depth reached 20mm for complete mix performance data. The final rut depth and test variability were calculated by averaging the wheel-tracking side rut depth findings for each combination. To evaluate the rut depth against the wheel passes curve from each side and identify rutting resistance characteristics from moisture susceptibility parameters, the Iowa Department of Transportation (DOT) analysis technique was used. This technique reduced human subjectivity from the AASHTO approach by inserting a sixth-degree polynomial for fitting the loading cycle vs rut-depth curve[211]. The amount and positions of the creep and stripping slopes were determined by fitting the test data using Equation 6-6 and its derivatives. If the creep slope to stripping slope ratio was less than 2.0, the SIP was invalid, and no visible stripping had to be reported. Each mix type was tested with four HWTT samples.

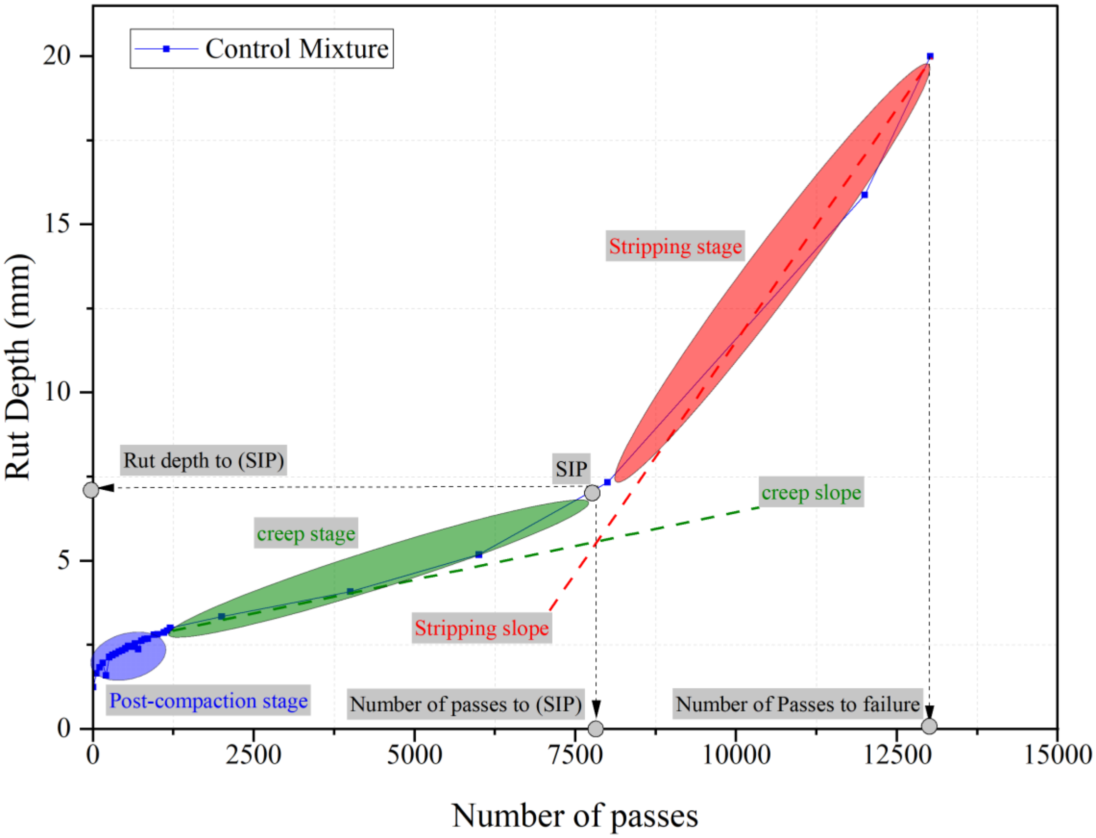


Figure 6-5 HWTT test graph of passes vs rut depth, showing main regions and output parameters

6.3 Results and Discussion

6.3.1 Physical and Rheological Properties

6.3.1.1 Rotational Viscometer

The impact of MPP additives on the rotational and complex viscosity (η*) of asphalt binders was evaluated, as shown in Figure 6-6. The study measured viscosity at different temperatures (135 ◦C, 150 ◦C, 165 ◦C, and 180 ◦C) according to the AASHTO T 316, which determines the mixing and compaction temperatures of asphalt mixtures. The results showed that the MPP-modified asphalt binder had higher viscosities than the unmodified binder but still complied with the Superpave specification maximum threshold of 3 Pa.s at 135 ◦C. This increase in viscosity may be attributed to the formation of chain networks in the asphalt-polymer mixture that results in larger molecules in the fluid [212].

Additionally, Figure 6-6 (b) revealed that the dynamic shear viscosity of all modified asphalt binders increased at different temperatures (58 ◦C, 64 ◦C, 76 ◦C, and 82 ◦C), indicating that the use of MPP additives can significantly impact the rheological properties of asphalt binders. When MPP additives are added to the asphalt binder, it can increase the rotational and complex viscosity of the mixture due to physical and chemical interactions between the plastic particles and the asphalt binder. Physically, adding MPP additives can increase the concentration of solid particles in the asphalt binder, increasing the mixture's viscosity [78]. Polymer particles larger than 10 µm effectively increase the viscosity of asphalt binder [213], [24]. Plastic particles larger than asphalt binder molecules act as a filler, increasing the volume fraction of solids in the mixture [27], [24]. As the concentration of solids in the mixture increases, the viscosity of the mix also increases. This increase in viscosity is caused by the MPP particles restricting the mobility of the asphalt binder molecules, causing them to move more slowly and, therefore, increasing the overall resistance of the mixture to deformation. Chemically, MPP particles can also interact with the asphalt binder on a molecular level, forming new chemical bonds that can further increase the mixture's viscosity [94], [214]. For example, the MPP particles may contain polar functional groups in PET, METPET, and NYLON, such as carboxyl or hydroxyl groups, which can react with the polar functional groups in the asphalt binder through hydrogen bonding or other chemical reactions. These reactions can form a more complex network of cross-linked molecules, increasing the mixture's overall stiffness and viscosity.

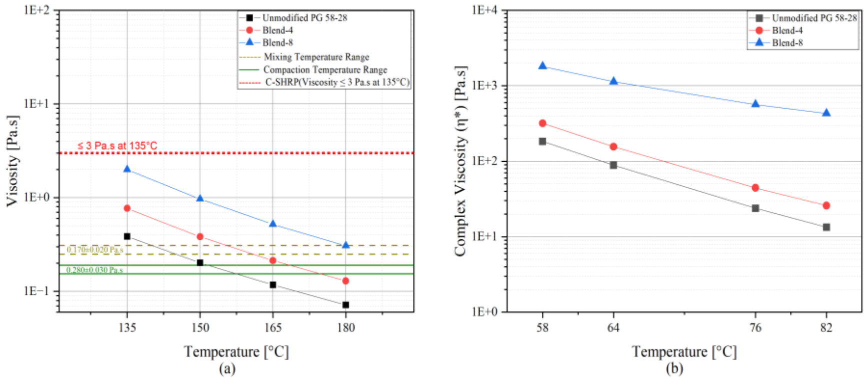


Figure 6-6 Influence of MPP additives on (a) rotational viscosity and (b) complex viscosity

6.3.1.2 Dynamic Shear Rheometer

It has been shown in Figure 6-7 that adding MPP additives to asphalt cement increases G*/sin(δ°) and decreases the phase angle (δ°), which is an indicator of the asphalt's resistance to deformation under shear stress. The results summarized in Table 6-7 show the impact on the MPP-modified asphalt binder rheology's physical and rheological properties by adding different percentages of MPP. The G*/sin(δ°) significantly increased in both unaged and RTFO-aged samples. A noticeable shift at critical high-performance grade temperatures was observed.

Table 6-7 High-temperature asphalt binder properties

MPP (%)	Mixing temperature range °C	Compaction temperature range °C	|G*|/sin(δ) ≥1.0 kPa at 58°C	SD	Unaged grade (°C)	SD	|G*|/sin (δ) ≥ 2.2kPa at 58°C	SD	RTFO grade (°C)	SD
0	153-159	140-146	1.75	0.02	62.70	0.00	4.72	0.27	64.00	0.28
4	167-175	155-160	3.21	0.15	67.90	0.42	9.42	0.79	69.85	0.64
8	190-195	180-185	11.20	1.14	84.90	1.84	49.64	6.66	102.00	10.89

In this study, the rutting factor, G*/sin(δ°), of Blend-4 was found to increase by 74%, 76%, 86%, and 93% at temperatures of 58 ◦C, 64 ◦C, 76 ◦C, and 82 ◦C, respectively, compared to the control binder. Similarly, Blend-8 demonstrated a much larger response to temperature changes, with increases in the rutting factor of 885%, 1184%, 2260%, and 3118% observed at the same temperatures compared to the control binder. Regarding phase angle δ°, the change with Blend-4 compared to the control mix was around a 2% reduction. In comparison, the Blend-8 exhibited a more significant reduction by 37%, 46%, 59%, and 63% at temperatures of 58 ◦C, 64 ◦C, 76 ◦C, and 82 ◦C, respectively, compared to the control binder. This decrease in the phase angle is due to the poorly elastomeric nature of the additives. These findings suggest that the addition of MPP additives to asphalt binder can significantly improve its resistance to rutting at high temperatures. Specifically, the rutting factor of Blend-4 and Blend-8 increased compared to the control binder, with Blend-8 demonstrating a much larger response to temperature changes.

Temperature and frequency are the two main parameters that impact the complex shear modulus of MPP additives in modified asphalt. Understanding how these parameters affect the rheological characteristics of the asphalt is crucial for forecasting how the MPP-modified asphalt would behave in various scenarios. Figure 6-8 shows the effects of temperature and frequency on the complex shear modulus of asphalt binder containing MPP additives. The results indicated that the complex shear modulus increased with increasing temperature and frequency for both Blend-4 and Blend-8 compared to the control, thus, indicating an improvement in the rheological properties of the asphalt. At low frequencies, MPP additives significantly increase the complex modulus of Blend-8, making it stiffer but also more elastic. This increase results from the presence of long-chain polymers that entangle each other and form a network that resists deformation. In general, an increase in additive concentration beyond 4% can shift the angular frequency at which the complex modulus is at its maximum. The results also suggested that adding MPP additives could improve the high-temperature performance of the asphalt.

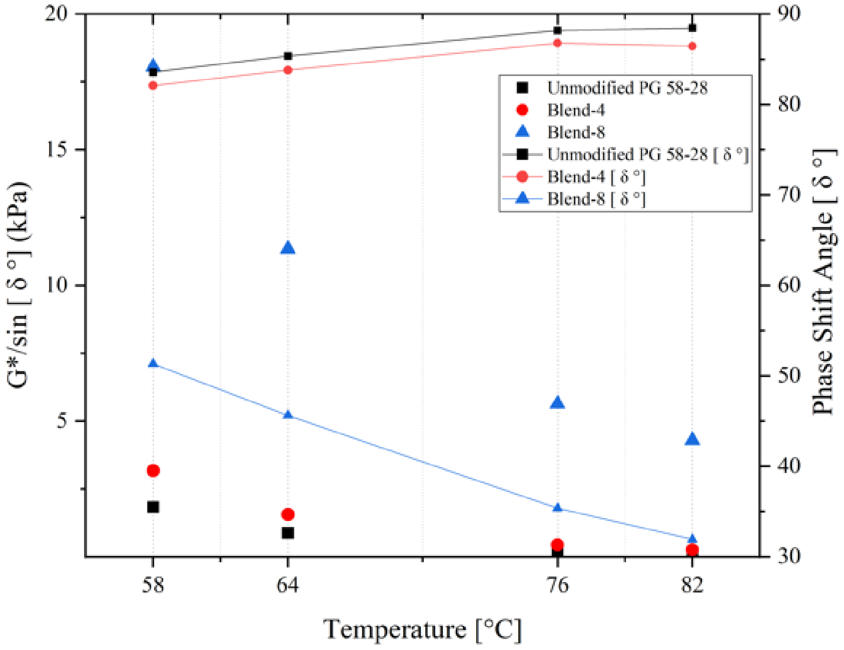


Figure 6-7 Temperature effect on G*/sin(δ°) and phase angle (δ°)

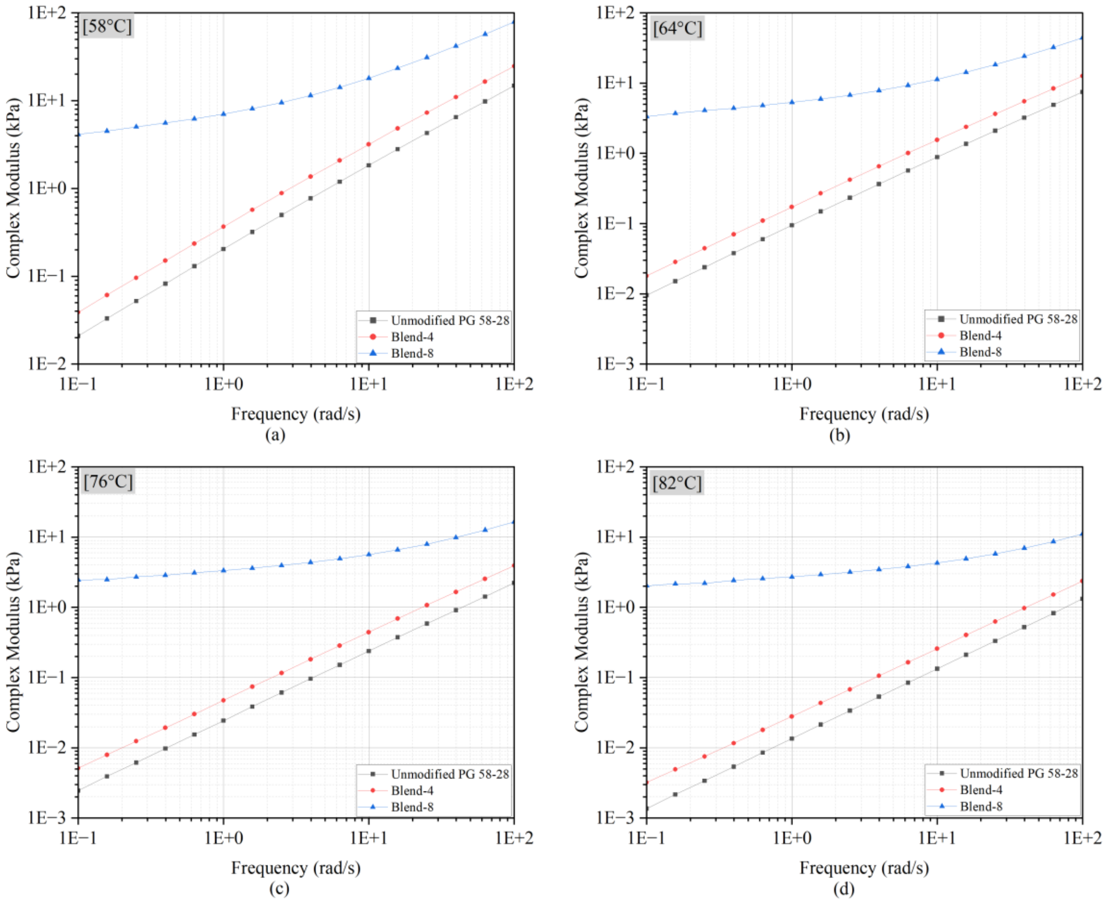


Figure 6-8 Temperature and frequency effects on the complex shear modulus: (a) 58°C, (b) 64°C, (c) 76°C and (d) 82°C

6.3.1.3 Multiple Stress Creep Recovery

The MSCR test is more reliable for evaluating the resistance to rutting compared to the G*/sin δ parameter, as it measures the ability to recover from deformation under different levels of stress and strain, simulating the conditions of traffic loading. The MSCR test provides better data for analyzing rutting resistance in non-recoverable creep compliance J_{nr}, and percent recovery (%R), where J_{nr} is the potential rutting index and %R represents the elasticity of asphalt binders [205], [215]. The results in Table 6-8 were obtained from MSCR at 58°C. The results show that shear stress levels at 0.1 kPa and 3.2 kPa were higher when the MPP additives were added.

Table 6-8 MSCR results of all tested samples at 58°C

MPP (%)	$J_{nr\,3.2}$ (kPa^{-1})	$J_{nr\,0.1}$ (kPa^{-1})	% Recovery	PG+ grading
0	2.06	1.67	2.22	58S
4	0.82	0.68	10.53	58H
8	0.31	0.23	14.68	58E

Note: $J_{nr\,0.1}$*: Non-recoverable creep compliance at 100 kPa., and* $J_{nr3.2}$*: non-recoverable creep compliance at 3200 kPa.*

The percentage recovery and non-recoverable compliance of virgin and multi-phase polymer (MPP) modified binders were evaluated at three different temperatures (52 °C, 58 °C, and 64 °C), as shown in Figure 6-9. The modified binders showed improved performance in traffic grades compared to virgin binders, with an increase in MSCR traffic grades from standard traffic "S" to Heavy "H" and Extremely Heavy traffic "E" upon increasing the MPP modifier content from 4% to 8%. The percentage recovery results for Blend-8 indicated higher percentage recovery, indicating more elastic behaviour, at lower temperatures (i.e., 52 °C). However, none of the MPP mixes met the elastic recovery criteria of AASHTO TP70 (2013), which is unsurprising as not all MPP types typically have poor elongation properties when compared to elastomers or rubber materials. Similarly, HDPE- and PP-modified asphalt binders showed similar recovery results due to their similar non-elastomeric nature. The percentage recovery increased from 13% for the virgin binder to 43% and 59% for Blend-4 and Blend-8, respectively. Blend-8 remained in the "E" designation at all temperatures, while Blend-4 shifted to the "S" grade at 64 °C. These results suggest a higher resistance to permanent deformation of the modified mixtures, indicating the potential of MPP modifiers to enhance the performance of asphalt mixtures under heavy traffic loads.

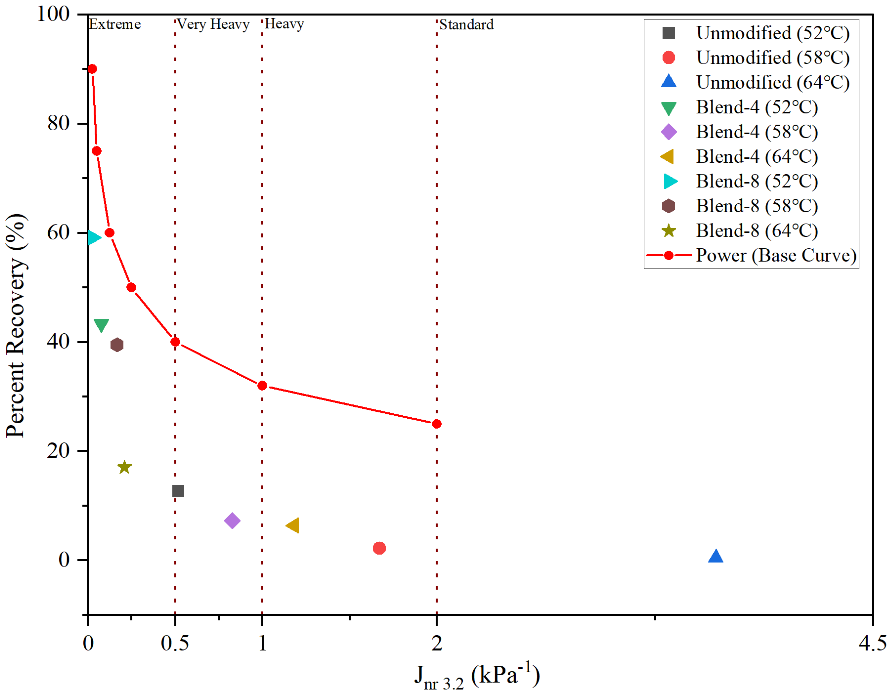
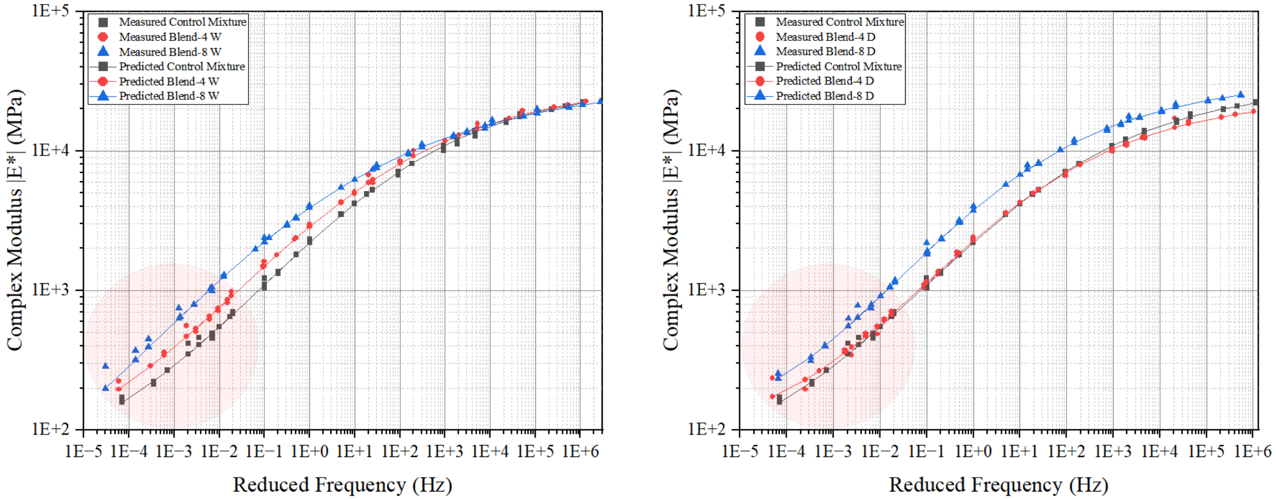


Figure 6-9 Relationship between percent recovery and Jnr3.2 kPa-1 for MPP-modified binders at 52 °C, 58 °C, and 64 °C

6.3.2 Asphalt Mixture Evaluation

6.3.2.1 Complex (Dynamic) Modulus

Figure 6-10 (a) and (b) shows the master curves established for the norm of the complex modulus (|E*|) at the reference temperature (T*ref* = 21 °C) for MPP-modified mixes. The findings indicate a slight increase in the complex modulus at low modified frequencies corresponding to low temperatures and an increase in modulus at high modified frequencies representing high temperatures. The complex modulus for Blend-4 and Blend-8 modified mixes using Wet and Dry Methods increased notably at high temperatures (37 and 54 °C) compared to the virgin mix. The results of the wet method are consistent with earlier findings of this research's binder tests (MSCR and G*/sin δ° tests), which confirmed the high potential of MPP modification in enhancing the permanent deformation resistance.



(a)

(b)

Figure 6-10 Master curve of MPP-modified mixtures using: (a) Wet Method (b) Dry Method at 21°C T_{ref}

The dynamic modulus results of modified asphalt mixtures at higher temperatures, such as 37°C and 54°C, can indicate the mix's resistance to rutting. The effect of MPP additives for each method was evaluated at two high temperatures (37°C and 54°C) and different frequencies (25, 5, and 0.1 Hz) to obtain accurate and comprehensive results. The results demonstrated that the stiffness of Blend-4 and Blend-8 increased compared to the control mix. Specifically, the stiffness of Blend-4D increased by 15%, 28%, and 2% at 37°C and 12%, 4%, and 32% at 54°C, respectively, while Blend-4W exhibited an increase of 50%, 75%, and 60% at 37°C and 50%, 35%, and 72% at 54°C, respectively, at frequencies of 25, 5, and 0.1 Hz. Similarly, Blend-8W showed an increase in stiffness by 87%, 131%, and 114% at 37°C and 84%, 73%, and 119% at 54°C, respectively, while Blend-8D exhibited an increase of 100%, 123%, and 60% at 37°C and 95%, 70%, and 80% at 54°C, respectively, at frequencies of 25, 5, and 0.1 Hz. The results of this comparative study indicate that using MPP additives in the two methods is a promising solution for increasing the stiffness of the mix and potentially improving the resistance to permanent deformation at high temperatures. The study also revealed that the wet method consistently demonstrated a more significant increase in stiffness than the dry method, suggesting the former may be more effective for enhancing the performance of asphalt pavements.

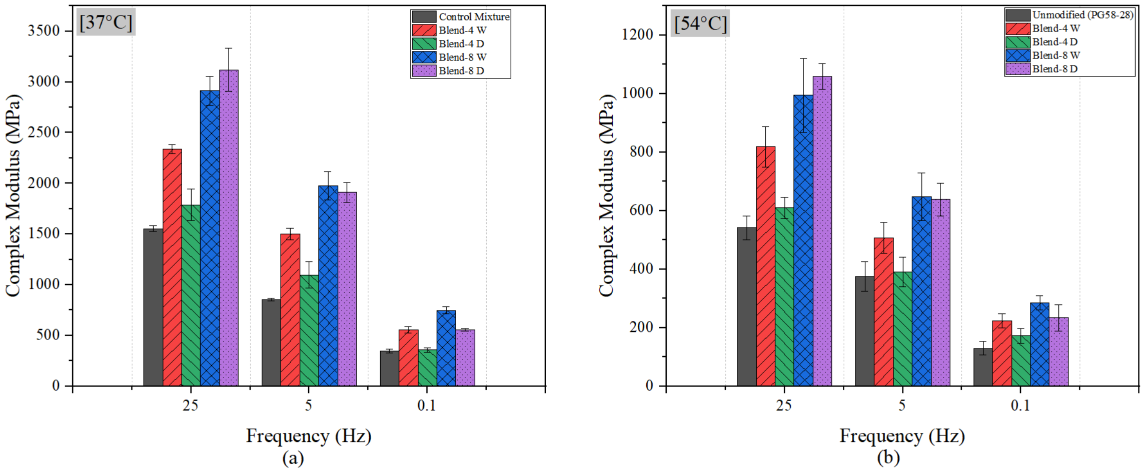


Figure 6-11 Complex modulus of MPP-modified asphalt mixtures at different frequencies: (a) 37 °C and (b) 54 °C

6.3.2.2 Hamburg Wheel Tracking Test

At first, the performance of MPP-modified asphalt mixtures during the HWTT test was evaluated using traditional measures such as maximum wheel passes and rut depth, as illustrated in Figure 6-12. Nevertheless, these measures fell short of providing a comprehensive assessment of the blends' overall performance due to their inability to consider the combined effects of moisture damage and visco-plastic deformation. Consequently, additional analysis was carried out using these outcomes, as demonstrated in Figure 6-13.

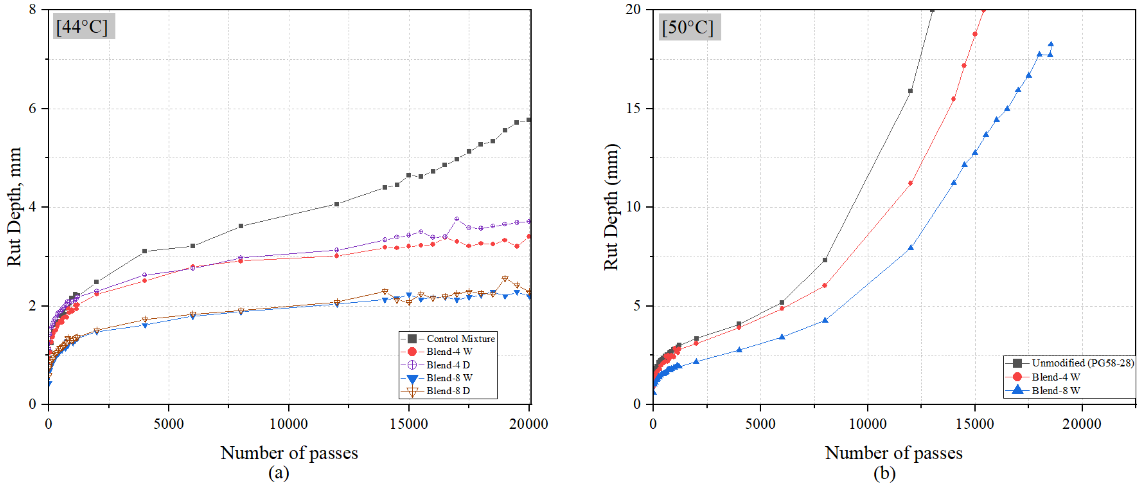


Figure 6-12 Rut depth versus the number of passes of MPP-modified asphalt mixtures at (a) 44 °C and (b) 50 °C

The maximum allowable rut depth was reached by all blends, as demonstrated in Figure 6-13(a). According to Ontario's testing standards (Table 6-6), the failure limit at a test temperature of 44°C is 12.5mm. Compared to the control mix, Blend-4W and Blend-8W showed a slightly superior performance of 5% and 10%, respectively, over Blend-4D and Blend-8D. It's worth noting that the blends prepared using the Wet Method displayed complementary behaviour in all tests, indicating that the Wet Method outperformed the Dry Method. This result is consistent with Haider et al. findings that the Wet mixing method was comparatively better than the Dry mixing method [216].

Asphalt binders modified using 4% and 8% of MPP met the PG 64-XX and PG 70-XX binder grade requirements under the Wet method. Therefore, the test was conducted at 50°C for the Control Mix and Blend-4-8W. Furthermore, Figure 6-13 (b) illustrates the number of passes when the samples reached a rut depth of 12.5mm. The figure indicates that none of the blends reached 20,000-wheel passes as the 12.5mm failure threshold was reached before. However, the numbers of passes to 12.5mm for Blend-4W and Blend-8W were respectively 14% and 35% higher than that of the Control Mix.

Moisture damage weakens the bonds between the asphalt binder and the aggregate, a significant issue for pavement surfaces. This issue can lead to problems such as potholes, ravelling, and stripping, ultimately reducing the pavement's lifespan. The SIP results were determined using the Iowa DOT analysis and AASHTO methods, as shown in Figure 6-13(d), to assess the MPP-modified asphalt mixtures' moisture damage. At 44°C, Blend-4-8W exhibited no SIP, as the slope ratio between the stripping and creep slopes was less than 2%, indicating that no stripping occurred during the test. However, only the Control Mixture showed SIP values of over 14,000 passes using the AASHTO method and over 14,400 passes using the Iowa DOT method at 44°C. The SIP values of Blend-4-8W were determined at 50°C, and compared to the Control Mixture, Blend-4W showed a 40% increase, and Blend-8W showed a 35% increase in SIP, as illustrated in Figure 6-13 (d).

Interestingly, Blend-8W exhibited slightly higher moisture sensitivity than Blend-4W, which may be attributed to the hygroscopic nature of some of the additives, such as PET, METPET, and NY. This type of plastic can increase the overall moisture content of the mixture when exposed to wet conditions [122]. Roja et al. reported that adding polyethylene to asphalt binders can cause separation at high temperatures due to its non-polarity and non-aromaticity. Polyethylene (PE) is the primary component of MPP additives and is incompatible with the polar asphalt component, resulting in reduced adhesion between the asphalt and the aggregate at high temperatures [148]. Using high doses of these additives in asphalt mixtures may have a negative impact on the bond between the asphalt binder and aggregate particles, leading to moisture damage and reduced pavement performance. However, when used at reasonable rates, the negative impact could be minimized [76], [217].

In addition, another parameter, the rutting resistance index (RRI), was used in this study, which was introduced by Wen et al., [218] and defined in Equation 7.

Equation 6-7

$$\boldsymbol{RRI = N_d \times (1 - RD)}$$

Where RRI refers to the rutting resistance index (inch), N_d refers to the number of passes at the completion of the test; and RD refers to the rut depth after the test (inch).

High RRI values suggest better rutting resistance of the mix. RRI accounts for the number of wheel passes and rut depth and enables a comparison of test results terminated at different thresholds, whether the test ended at the end of 20,000 passes or when the maximum allowable rut depth was reached. Although the stripping phase was observed for Blend-4-8D at 44°C, RRI values were similar for both the Dry and Wet Methods. At 50°C, the RRI for Blend-4W and Blend-8W increased by 70% and 169%, respectively, as illustrated in Figure 6-13 (c).

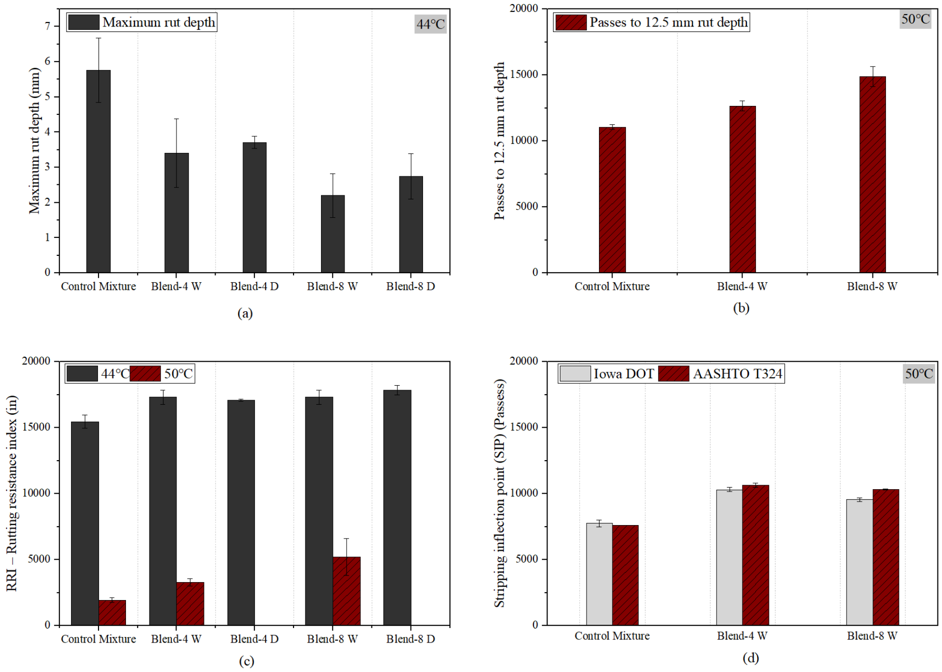


Figure 6-13 HWTT analysis of MPP-modified asphalt mixtures: (a) Maximum rut depth at 44°C (b)Passes to 12.5 mm rut depth at 50°C (c) RRI at 44°C and 50°C (d) SIP at 44°C and 50°C

In addition to their potential as complementary tools in evaluating rutting performance, the MSCR and HWTT tests offer distinct insights into the underlying mechanisms. While the MSCR test provides information about the viscoelastic properties of the asphalt binder, the HWTT test provides an indicator on the mixture's resistance to shear and compressive stresses. This study investigated the correlation between the MSCR and HWTT test results when the MPP additives are incorporated, as depicted in Figure 6-14. The study discovered a positive association between the MSCR parameters $J_{nr\ 3.2}$ (kPa-1) tested at 58°C and 64°C and the HWTT rut depth at 12,000 passes tested at both 44°C and 50°C. Although the correlation tendency exhibits an R^2 value of 0.9 or greater between the HWTT and $J_{nr\ 3.2}$ (kPa^{-1}), additional test samples are needed to validate this finding further. Such correlation has been documented in previous research studies showing that HMA rutting performance correlates strongly with the MSCR [219]–[221]. This study concluded that the MSCR test could serve as a valuable predictor of rutting performance, particularly for MPP-modified binders and can complement the results of the HWTT test.

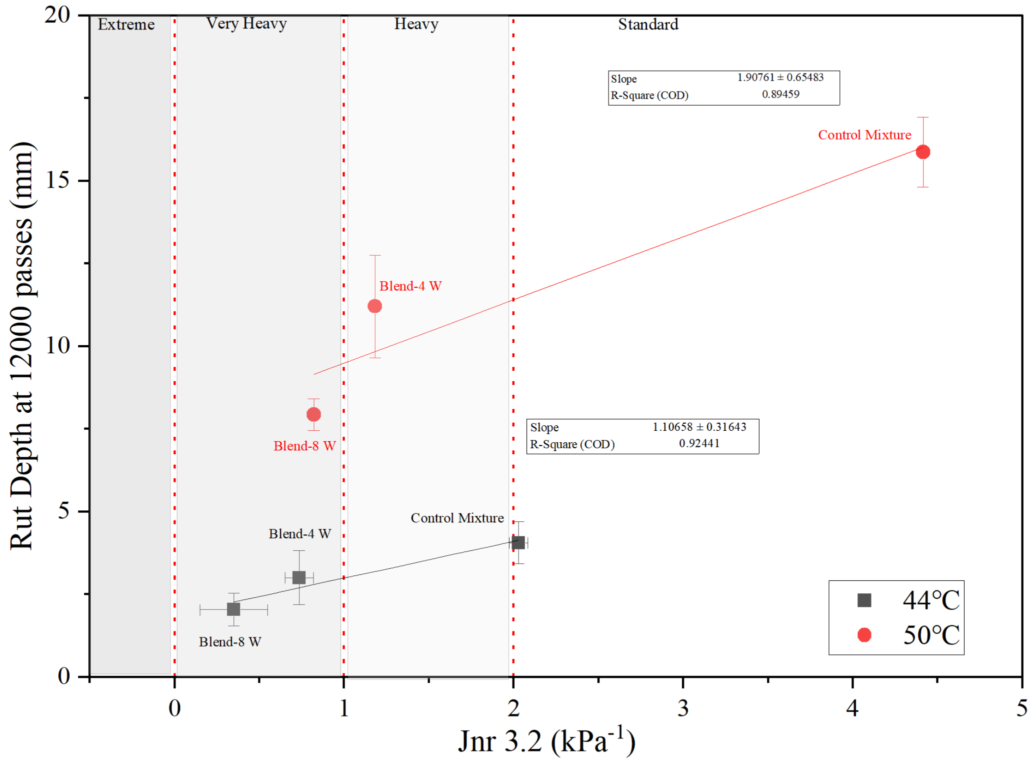


Figure 6-14 The correlation between the MSCR parameters $J_{nr\ 3.2}$ (kPa^{-1}) tested at 58°C and 64°C vs HWTT rut depth at 12000 passes tested at 44°C and 50°C

6.4 Conclusions

In conclusion, this study offers valuable insights into the impact of MPP additives on the physical and rheological properties of asphalt binders and mixtures at elevated temperatures. The key findings are as follows:

- Viscosity and DSR test results show that MPP additives considerably enhance the viscosity and complex viscosity (η*) of asphalt binders. This improvement leads to better physical and rheological properties. According to MSCR results, MPP-modified binders boost the performance of asphalt mixtures under heavy traffic loads. MPP additives increase the stiffness of the binder and enhance its resistance to permanent deformation at high temperatures.

- Dynamic modulus results at higher temperatures (37°C and 54°C) provide insights into the mixtures' rutting resistance. Blend-4 and Blend-8 exhibited increased stiffness compared to the control mix, with the Wet Method demonstrating more pronounced improvements than the dry method.

- Both the Wet and Dry Methods increased the mixture's stiffness and resistance to permanent deformation. However, the Wet Method consistently outperformed the Dry Method. This finding aligns with previous research on other plastic types and highlights the Wet Method's benefits, such as reduced coating loss, rut depth, Marshall stability loss, and increased TSR values. The Wet Method's advantages make it a promising approach for optimizing asphalt pavement performance.

- The study highlighted that MSCR and HWTT tests are complementary tools for evaluating asphalt mixtures' rutting performance, providing distinct insights into rutting mechanisms. The MSCR test focuses on the binder's viscoelastic properties, while the HWTT test measures the mixture's resistance to shear and tensile stresses. Combining test results establishes a strong correlation between MSCR parameters $J_{nr3.2}$ (kPa^{-1}) at 58°C and 64°C and HWTT rut depth at 12,000 passes.

Overall, this study provides a comprehensive understanding of the potential of MPP additives for enhancing the performance and durability of asphalt pavements at high temperatures. The findings could contribute to developing guidelines and recommendations for using MPP additives in asphalt modification, improving the sustainability and durability of asphalt pavements and developing sustainable and cost-effective solutions for plastic waste management. Further research is needed to optimize MPP modifiers to improve asphalt mixtures' elastic recovery and moisture resistance.

7. A Laboratory Study on Enhancing Asphalt Mixture Properties through Dry Mixing with High Dose Multi-Layer Plastic Packaging (MPP) Pellets Additives

This chapter is based on an article prepared for submission to the Cleaner Materials journal. Qabur A, Baaj H, El-Hakim M. " Laboratory Study on Enhancing Asphalt Mixture Properties through Dry Mixing with High Dose Multi-Layer Plastic Packaging (MPP) Pellets Additives" (2023).

Abstract

Flexible pavements are typically vulnerable to the distress caused by fluctuating temperatures and heavy traffic loads, leading to deformations, cracks, and a shorter lifespan. Consequently, this necessitates frequent repairs and replacements. Researchers have explored various methods to improve pavement performance, including using thermoplastic additives. One critical area of investigation is using recycled plastic to modify asphalt, which has yielded promising results. This technical paper investigates the potential of using multi-layer packaging plastics (MPP) additives in asphalt pavement materials. Integrating MPPs into asphalt mixtures can minimize plastic waste, offering a path towards upcycling a valuable waste stream and enhancing pavement performance. By incorporating MPPs into asphalt mixtures, both plastic waste reduction and conservation of virgin aggregate and asphalt cement can be achieved. The MPP stream from the plastic industry can contribute significantly to this endeavour, allowing for a more controlled and superior output than post-consumer plastics. This study analyzed the effects of varying dosages of MPP pellets and asphalt cement (AC) on asphalt mixtures through the dry mixing method. The mixtures included 2%, 3%, and 4% MPP pellets and 5.3%, 5%, 4.7%, and 4.4% AC by the total weight of the mixture. The study utilized various tests to assess the effectiveness of MPP-modified asphalt mixtures, such as the Complex (Dynamic) Modulus Test, Moisture-Induced Damage Test, British Pendulum Skid Resistance Tester, Indirect Tensile Cracking Test, and Hamburg Wheel Rut Test. The findings demonstrate that incorporating MPP additives into asphalt mixtures can significantly improve resistance to softening at higher temperatures, fracture resistance, rutting resistance, load-carrying capacity, and skid resistance while reducing susceptibility to moisture damage. The research offers valuable insights into integrating MPP additives in asphalt modification, enabling the creation of more durable and safer asphalt pavements.

Keywords: Multi-layer Plastic Packaging, Asphalt pavements, Permanent deformation, dry mixing method, Moisture resistance.

7.1 Introduction

Flexible pavements are typically composed of several courses of unbonded granular materials covered with one or more courses of asphalt. As stress is highest at the top layer, the asphalt mixture requires superior strength to withstand heavy vehicle and environmental loading [37], [222], [223]. The asphalt mixture is a heterogeneous material comprising asphalt binder, aggregates, and air voids. Crushed aggregates typically represent about 85% of the mix volume, with asphalt binder at around 10% and air voids comprising the remaining portion [224]. Due to the high cost of maintaining and rehabilitating asphalt pavements, researchers have explored various methods to improve the performance of asphalt materials, including polymers and waste plastic [78], [225], [226].

Polymers can be incorporated into asphalt mixes using wet and dry methods [24], [195]. The wet method involves mixing solid polymer additives directly with unmodified asphalt cement at high temperatures, then blending with aggregates to create modified asphalt mixtures. Previous research has studied the impact of plastic waste as a modifier on the thermal stability and rheological properties of the asphalt binder [27], [28], [79]. While the wet process is currently the most widely used method for modifying asphalt with polymers, owing to its superior thermal behaviour [227], it does have significant limitations [195], [228]. If incompatible polymers are used, the resulting asphalt mixtures may lack cohesion and ductility [229]. Additionally, plastic-modified asphalt prepared via the wet process at high temperatures without a compatibilizer can cause storage stability problems [78], [148]. Therefore, strict blending conditions must be maintained when using the wet process to produce a modified asphalt binder [230].

The dry method involves adding a mixture of solid polymers and aggregates directly to the asphalt cement mix without prior modification. Studies by Awwad et al. have used the dry method with high-density and low-density polyethylene, resulting in improved adhesion between the asphalt binder and aggregate, thus, enhancing pavement deformation and fatigue resistance [8]. Several studies have investigated the effects of incorporating various waste materials, such as Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Rubber End-of-Life Tyres (ELT), Polyester (PF), and

Polyethylene Terephthalate (PET), into asphalt mixtures using different mixing conditions. The inclusion of polymeric wastes, mainly PE, PP, and ELT, led to significant improvements in stiffness and resistance against plastic deformation in Stone Mastic Asphalt (SMA) and Warm Mix Asphalt (WMA) [35]. Polyester fibres obtained from textiles reduced plastic deformation, increased bearing capacity and extended the fatigue life of asphalt mixes [231]. PET particles added using the dry process method improved fatigue performance at dosages as high as 10% PET content [232], [233]. Incorporating PET particles into the asphalt mixture also led to varying levels of rutting behaviour under static and dynamic loadings [234]. Waste polyester fibres improved pavement fatigue resistance [37]. Incorporating High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE) into HMA led to improved pavement deformation and fatigue resistance, as well as better adhesion between the asphalt binder and the aggregate [80].

Similarly, PET bottle-derived additives improved the asphalt mixture's stability and resistance to permanent deformation and fatigue [235]. Studies using the dry process with low and high-density PE have reported improvements in Marshall stability, indirect tensile strength (ITS), and indirect tensile strength ratio (TSR) [236]–[238]. However, the dry process may exhibit considerable variability, particularly when using a high plastic content in the asphalt mixtures [196], [239]. Although several waste materials, such as PE, PP, PS, ELT, PF, and PET, have been explored, further research may be required to optimize preparation and mixing methods to reduce the variability in performance and lower production costs. The observed performance variability in literature may be due to the preparation method, mixing method, and temperature. Therefore, controlling these factors is vital to the performance of the mixture prepared through the dry process.

Multi-layer packaging plastics (MPPs) have emerged as a promising additive for asphalt modification, owing to their superior strength and durability compared to traditional single-layer plastics. In order to ensure the effectiveness and upcycling of MPP additives, it is crucial to understand how they impact asphalt performance under different temperature conditions. The primary objective of this study is to evaluate the feasibility of MPP additives in asphalt mixtures by examining their mechanical, moisture damage, and skid resistance properties. The research will yield valuable insights for MPP integration in asphalt modification, enhancing the durability and longevity of pavements while minimizing plastic waste. The findings can help engineers and researchers develop durable, more resilient asphalt mixtures for pavement design.

7.2 Materials and Methodology

7.2.1 Materials Properties

7.2.1.1 Asphalt Cement and MPP Pellets

A PG 58-28 asphalt cement (AC) was used in this study; it was sourced from western crude and was supplied by Yellowline Asphalt Products Ltd. This AC had previously been used in a separate study, and its properties are detailed in Table 7-1 [206]. In order to incorporate MPP additives into the asphalt mixtures, MPP pellets were utilized derived from multi-layer plastic packaging bags. The packaging bags were mainly composed of 85 to 90% Polyethylene (PE), and the remainder of the layers contained a mix of Polyethylene Terephthalate (PET), Nylon (NY), and Metalized Polyester (METPET). To produce MPP pellets, the bags were first shredded into small pieces that ranged from 4 to 12 mm using an electric shredder. The resulting pieces were then processed into pellets using a pelletizing machine.

Table 7-1 Properties of asphalt cement [206]

Property	Values
Ash Content, %	0.03
Viscosity (Pa.s), at 135°C < 3	0.266
Initial boiling point/Boiling range (°C)	228
Flash Point (°C)	243
Specific Gravity (at 21.1°C)	1.03
Solubility in water	None
True Grade	59.4-31.4

Figure 7-1 presents the results of Differential Scanning Calorimetry (DSC) analysis of the thermal properties of the MPP pellets. Table 7-2 summarizes each polymer's thermal and physical properties in the MPP pellets. Subsequent Thermal Gravimetric Analysis (TGA) data demonstrated that the MPP and the asphalt cement sample showed no significant deterioration up to 320°C. Finally, the MPP pellets were sieved, and a particle size range of 4.75 to 0.595 mm was selected for incorporation into the asphalt mixtures, as shown in Figure 7-2.

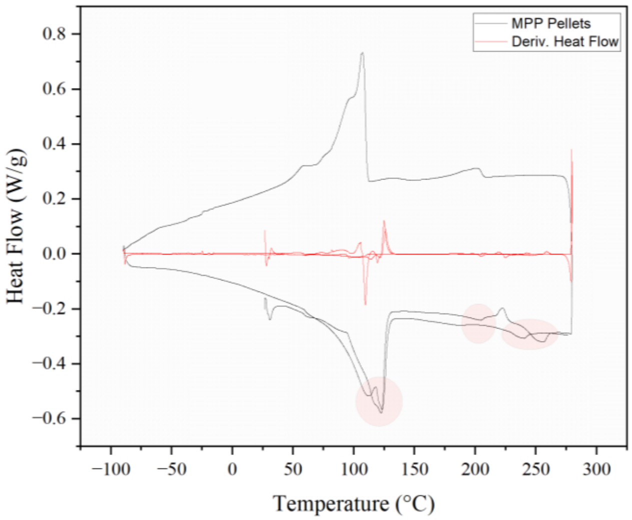


Figure 7-1 Heat flow and Deriv. Heat flow versus temperature for MPP pellets

Table 7-2 The following table provides a summary of the physical and thermal properties of MPP pellets

Property	PET	Nylon	PE	MET PET
Melting Point (°C)	250-260	220-280	120-135	240–255
Density (g/cm³)	1.38	1.225	0.94	1.4
Glass Transition Temperature (°C)	76	47-67	-120 to -80	-

Figure 7-2 A picture showing the MPP pellets used in the asphalt mixture

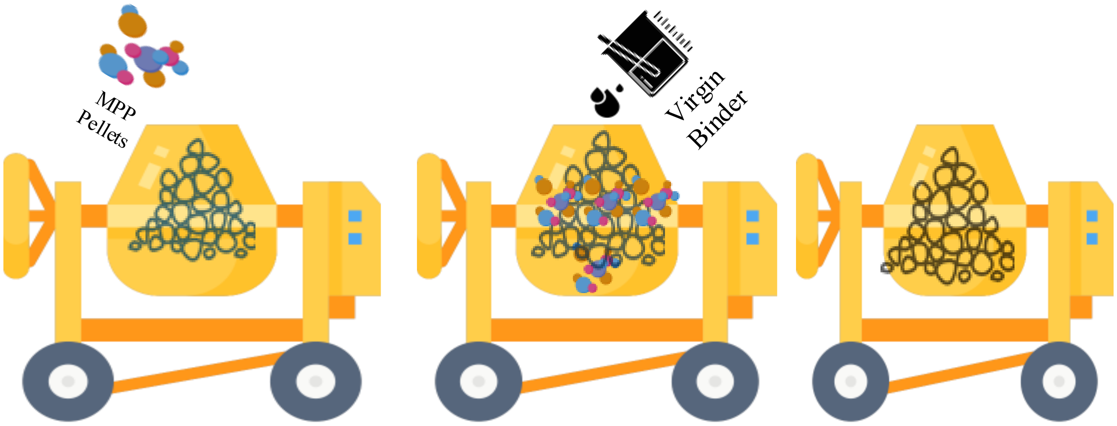
7.2.1.2 MPP-modified Asphalt Mixtures

To produce the HMA mixture samples with both conventional and MPP-modified asphalt binders, a surface course mix made of limestone aggregate called HL-3, following the Ontario Provincial Standards Specifications (OPSS), was utilized. The gradation of the blended aggregates, HMA mix Superpave design, and the relevant control points are provided in Table 7-3.

Table 7-3 Gradation and physical properties of aggregate

Sieve (mm)	Composite gradation blend (%)	Control Points	
		Minimum	Maximum
19	100		
12.5	95		
9.5	83	90	100
4.75	58	28	90
2.36	40		
1.18	19	28	58
0.6	12		
0.3	8		
0.15	4.5		
0.075	3	2	10
Bulk specific gravity (G_{sb})	2.661	Apparent specific gravity (G_{sa})	2.765

The MPP-modified mixtures were produced using a dry method mixing procedure, which involves mixing asphalt and aggregate coated with MPP additives, as illustrated in Figure 7-3. This process is commonly used in hot mix asphalt plants for producing pavement materials. The first step in this process was to heat the aggregate to eliminate any moisture content; this was completed by placing the aggregate in an oven at 110°C overnight. This step is crucial to ensure that the aggregate is dry and moisture-free before it is mixed with the plastic additives and MPP pellets. Once the aggregate was dry, the temperature was raised to 180 ± 5°C for at least 2 hours. The plastic additives were gradually added to the hot aggregate in a mixing drum at a temperature of 180°C and mixed for 60 seconds to ensure a homogeneous blend. The coated aggregate was then mixed with hot asphalt cement (PG58-28) at a temperature of 150°C for another 60 seconds to complete the production of the MPP-modified mixture. This process was applied to all other blends to ensure consistency in the final product.



(a)
Aggregate + MPP Pellets
(60 Sec at 170 °C (± 5°))

(b)
Modified Aggregate
(60 Sec at 150 °C (± 5°))

(c)
MPP Modified
Mixtures

Figure 7-3 Preparation of MPP-modified mixtures using the dry method

The resulting mixtures were conditioned according to the AASHTO R30 guidelines, which define the procedure for preparing and testing asphalt mixtures [240]. The guidelines specify the conditioning procedure, testing procedure, and acceptance criteria for the asphalt mixture. The conditioned mixtures were tested to simulate the environmental conditions the pavement material would experience. Table 7-4 displays the HMA mixture combinations used in the study, including the Control, those with different MPP pellets and AC percentages, and their resulting composition of aggregate, MPP pellets, and AC.

Table 7-4 HMA mixture combinations

Mixture ID	MPP Pellets (%)	AC (%)	Aggregate (%)
Control Mixture	0	5.3	94.7
MPP-2-AC-5.3	2	5.3	92.7
MPP-3-AC-5	3	5	92
MPP-4-AC-4.7	4	4.7	91.3
MPP-4-AC-4-2	4	4.2	91.8

7.2.1.3 HMA volumetric properties

HMA volumetric properties, including air voids (%Va), voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA), maximum relative density (MRD) and bulk relative density (BRD), are measured and evaluated following AASHTO specifications, thus, ensuring that the MPP-Modified mixtures are adequately dense and less permeable to water and air, which can cause damage and deterioration over time [241]–[243]. VMA and VFA play a critical role as it is necessary to determine the required amount of asphalt binder to fill the voids in the aggregate and achieve proper coating. The bulk density reflects the mass of the asphalt mixture per unit volume and may relate to the overall performance and longevity of the pavement. Table 7-5 summarizes the volumetric properties of the Control Mixture and MPP mixtures. VMA and VFA are increased with the MPP mixtures because the addition of MPP pellets and plastic additives increases the volume of the asphalt mixture without adding significant mass.

Moreover, the addition of MPP pellets and plastic additives can enhance the coating of asphalt binder on the aggregate particles. The resultant increase in VFA is essential for good adhesion and overall durability of the asphalt mixture. Therefore, the increase in VMA and VFA observed in the MPP mixtures may lead to better performance and durability of the asphalt pavement. It can help reduce the potential for moisture damage and rutting. According to the Superpave mix design method, the recommended volumetric values for a 12.5 mm nominal maximum aggregate size and traffic level D are 14% min for the VMA and 65%-75% for the VFA [244].

These values are used as targets in the design process to ensure adequate void space for asphalt binder and air voids in the compacted asphalt mixture. However, it is important to note that the actual VMA and VFA values achieved during production may vary due to factors such as aggregate gradation, asphalt binder content, and compaction effort.

Table 7-5 Volumetric properties of the Control Mixture and MPP mixtures

Mixture ID	Av [%]	MRD [g/cm^3]	BRD [g/cm^3]	VMA [%]	VFA [%]
Control Mixture	4.15	2.503	2.403	15.42	74.06
MPP-2-AC-5.3	4.30	2.457	2.352	17.67	77.36
MPP-3-AC-5	4.01	2.430	2.329	18.21	78.03
MPP-4-AC-4.7	4.84	2.394	2.273	19.92	79.92
MPP-4-AC-4-2	4.86	2.444	2.325	17.83	77.56

7.3 Methodology

Figure 6-4 displays a flowchart of the experiments conducted in this study. The experimental plan was selected to evaluate the performance and durability of the MPP-modified asphalt mixtures at intermediate and high service temperatures, including the Complex (Dynamic) Modulus Test (CM), Moisture-Induced Damage Test, British Pendulum (BP) Skid Resistance Tester, Indirect Tensile Cracking Test (IDEAL-CT), and Hamburg Wheel Rut Test (HWRT). Prior to testing, all HMA mixtures experienced a short aging process in a forced-draft oven. According to AASHTO R30 guidelines, the control HMA mixtures were aged for 4 hours at a temperature of 135°C.

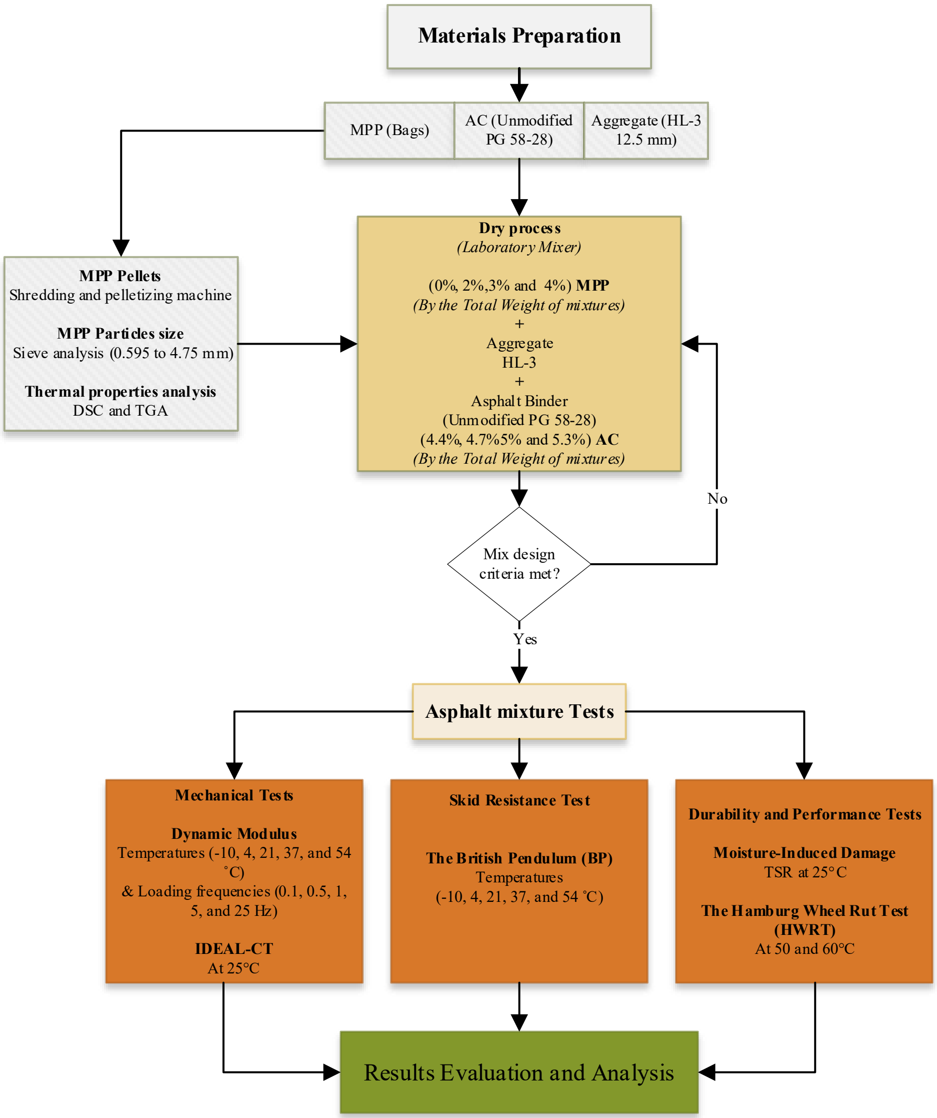


Figure 7-4 Flowchart of the experimental plan

7.3.1 Complex (Dynamic) Modulus

The stiffness of asphalt mixtures is a critical design factor for flexible pavements and can be affected by loading frequency and ambient temperature due to their viscoelastic nature [179]. A non-destructive dynamic modulus test determines the stress-strain relationship of asphalt concrete. This study followed AASHTO T 342 for the dynamic modulus test on samples produced using the Superpave Gyratory Compactor (SGC) [208]. A 100 mm x 150 mm cylindrical specimen was subjected to sinusoidal axial compressive stress with varying loading frequencies (0.1, 0.5, 1, 5, and 25 Hz) at specific temperatures (-10, 4, 21, 37, and 54 ˚C) to measure the strain response and phase lag; the stress was adjusted according to the standard strain range (50µ to 150µ). The Generalized Logistic Sigmoidal (GLS) model, an extension of the sigmoidal model used to characterize the stiffness of asphalt mixtures, was utilized to develop a master curve for MPP-modified mixtures, Equation 7-1[180].

Equation 7-1

$$\boldsymbol{log|E^{*}(f,T)| = \delta + \frac{\alpha}{(1+\lambda exp^{\beta+\gamma(log\omega_r})^{1/\lambda}}}$$

where |E*| represents the absolute value of the dynamic Young's modulus (in MPa), ω_r represents the reduced frequency, δ represents the lowest asymptote of the curve, α represents the deviation between the values of the higher and lower asymptotes, λ is used to account for the curve's non-symmetrical shape, and β and γ are shaping coefficient parameters that determine the shape of the curve between the asymptotes and the location of the inflection point. Making use of the time-temperature superposition (TTS) principle, the shift factors specified by the Williams-Landel-Ferry (WLF) Equation 7-2 was used to construct a sigmoid format master curve:

Equation 7-2

$$\boldsymbol{loga_T = \frac{C_1(T-T_{ref})}{C_2+(T-T_{ref})}}$$

Where T is the temperature, T_{ref} is the reference temperature, log a_T is the decadic logarithm of the TTS shift factor, and C_1 and C_2 are material-specific constants. The master curve was constructed using Microsoft Excel's spreadsheet and solver feature, which allowed for optimizing the fitting of dynamic modulus and phase angle. Table 7-6 presents the coefficients of the shift factor and sigmoidal model equations for various temperatures and additives.

Table 7-6 Summary of sigmoidal model coefficients and shifting factors for Control Mixture and MPP-Modified Mixture

Binder ID	Shift Factors								
	C1	C2	α	β	δ	γ	λ	Tref	R^2
Control Mixture	16.7	142.3	2.918	-0.426	1.552	-0.439	1.142	21°C	0.983
MPP-3-AC-5	30.7	277.6	2.674	-1.247	1.790	-0.305	0.115	21°C	0.995
MPP-4-AC-4.7	18.9	137.7	3.170	-1.683	1.194	-0.227	-0.696	21°C	0.982

7.3.2 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT test is used to determine the intermediate-temperature cracking resistance of asphalt mixtures. It is an important test to evaluate the cracking resistance of asphalt mixtures under traffic and climatic stresses [245]. The test is conducted following ASTM D8225-19 [246]. During the test, a gyratory specimen is subjected to a monotonic load at a constant displacement rate of 50 mm/min at 25°C. The load-displacement curve is recorded during the test, and the work of fracture is determined by analyzing the total area under the curve. Additionally, the slope of the curve at a 25% reduction from the peak load is also determined as it represents the initial stiffness of the material. The cracking tolerance index (CT_{index}) is calculated using Equation 7-3.

Equation 7-3

$$CT_{index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6$$

In the equation, several variables are used to determine the fracture energy of the specimen. The thickness of the specimen is represented by t, while l_{75} represents the displacement at 75% of the peak load. D. represents the diameter of the specimen. The variable G_f represents the fracture energy, which measures the energy required to cause the specimen to fracture. Finally, the slope at 75% of the peak load is represented by the absolute value of "m75".

A higher CT_{index} value indicates a better resistance to cracking. According to the Virginia Transportation Research Council, a minimum CT index of 70 on short-term aged specimens is required to meet the IDEAL-CT criterion [247]. Therefore, in this study, a CT index of 70 on short-term aged specimens is adopted as another validation criterion to assess the MPP pellets' effectiveness.

7.3.3 Hamburg Wheel Tracking Test (HWTT)

Pavement rutting is a common type of distress in asphalt roads that can significantly affect road safety and ride comfort, especially when the depth reaches critical values [57]. The Hamburg Wheel Tracking Test (HWTT), as per the AASHTO T324 standard, was used to evaluate the resistance of MPP-modified mixes to rutting. The test is performed by subjecting the specimen to a cyclic load with a small wheel at a higher temperature; as the wheel tracks over the specimen, rut depth is measured until the specimen fails or the desired number of passes is completed. The results of the HWTT test are denoted by three stages, including pre-consolidation, creep, and stripping; the intersection of the creep and stripping zones determines the stripping inflection point. The AASHTO T324 standard specifies five rut depth curve parameters, including the maximum rut depth, number of wheel passes at the maximum rut depth, creep slope, stripping slope, and stripping inflection point, to assess an asphalt mix's rutting resistance and moisture susceptibility. The stripping inflection point can be calculated from the slopes and intercepts from the creep and stripping stages using Equation 7-4 [142].

Equation 7-4

$$\boldsymbol{SIP = \frac{intercept\ (strip\ stage) - intercept\ (creep\ stage)}{slope\ (creep\ stage) - slope\ (strip\ stage)}}$$

In this study, SGC specimens with a diameter of 150 mm and a height of 63 mm, with air voids of 7% ±0.5, were tested. Test temperatures of 50 and 60°C were chosen to verify the effectiveness of the MPP pellets. The samples were tested using solid steel wheels, and Linear Variable Differential Transformers (LVDTs) were used to measure the average rutting depth after a defined number of passes. Each steel wheel was loaded with 705 ± 4.5 N, and the test was set to end after 20,000-wheel passes or when the rut depth reached 20 mm. The final rut depth and test variability were determined by averaging the wheel-tracking side rut depth findings for each combination.

7.3.4 Moisture-Induced Damage

The Moisture-Induced Damage (MID) test is commonly used to determine the vulnerability of asphalt mixtures to moisture damage, which can lead to a loss of strength and durability and cause damage to asphalt pavements; this vulnerability is particularly important for regions with high precipitation or heavy usage of de-icing salts. To evaluate the susceptibility of the MPP-modified mixture to moisture damage, the Moisture-Induced Damage test (AASHTO T283) was also conducted [248]. The asphalt mixtures were produced with 7 ± 0.5% air voids. Six cylindrical specimens were prepared; three specimens were tested in dry condition, while the remaining three were conditioned for moisture testing. The wet-conditioned samples were vacuumed at an absolute pressure of 30 mmHg for 5 min to reach partial saturation of 70-80% before being cooled to -18 ± 3 °C for 16 hours. Subsequently, the samples were placed in a 24-hour water bath at 60°C, followed by another 2-hour water bath at 20°C before testing. The saturation level was calculated by dividing the volume of water absorbed by the volume of voids and expressed as a percentage, according to AASHTO T283 standards, which specify that the saturation level should be between 55 and 80%. All ITS specimens were then tested at a 50.8 mm/min displacement rate until the maximum load was reached. The ITS test creates tensile stresses along the diametric axis of the test sample, and the maximum load at fracture was measured to determine the ITS (in kPa) using Equation 7-5:

Equation 7-5

$$\boldsymbol{ITS = \frac{2000P}{\pi t D}}$$

Where P represents the peak load (N), and D and t, represent the sample's diameter and height (mm), respectively. The TSR value was calculated using the ratio between the ITS of wet conditioned and unconditioned/ dry sample groups, as shown in Equation 7-6:

Equation 7-6

$$\boldsymbol{TSR = \frac{ITS_{\mathrm{c}}}{ITS_{unc}}}$$

ITS_c is the ITS calculated for conditioned samples (kPa), and ITS_{unc} is calculated for unconditioned samples (kPa). A minimum TSR requirement of 80% in the Moisture-Induced Damage test is typically to demonstrate that the mix is moisture-damage resistant and suitable for paving applications.

7.3.5 The British Pendulum Skid Resistance

The British Pendulum, Skid Resistance Tester, is a widely used tool for assessing surface frictional properties of roadways [249]. While dry pavements generally have a high friction resistance, wet pavements present a challenge, with the number of accidents being twice as high on wet pavements compared to dry pavements[250]. Yan et al. established that a minimum of 42 BNPs is crucial in preventing skidding accidents in traffic [251]. Brassard et al. also found that a BPN range of around 40 to 50, representing the transition from wet to dry conditions, is favourable for runways [252]. Another metric used to assess skid resistance is the minimum skid number (SN), which can be calculated using the BPN value through the Equation 7-7:

Equation 7-7

$$\boldsymbol{SN = 1.32 + BPN - 34.9}$$

Main Rural Highways' recommended minimum SN value is approximately 31, equivalent to 50 BPNs [37]. Thus, in this study, the minimum acceptable friction resistance of MPP-modified mixtures will be considered at 50 BPNs. To evaluate the effect of MPP modification, the test was conducted following AASHTO T278-90 [253]. In the laboratory, specimens are prepared and compacted to a targeted air void content of 7 ± 1 percent using the SGC. A dynamic pendulum impact-type tester swings a rubber slider over a contact path marked on the surface of the specimen. The surface friction is measured by analyzing the energy loss during contact between the slider and the test surface. The drag pointer on the British Pendulum indicates the energy loss as a British Pendulum Number (BPN). Testing is conducted on dry and wet surfaces to capture the effect of MPP additives on friction response. Conditioning is performed at five different temperatures (-10, 4, 21, 37, and 54 °C), and three pendulum swings are made for each dry surface to obtain BPNs. For wet surface testing, approximately 45 mL of distilled water is sprayed across the specimen at the beginning of each set of data collection, and 5 mL of water is sprayed on the specimen surface to replace lost water between swings. The British Pendulum Friction Testing is critical for identifying the effects of MPP pellets on frictional properties, which is essential for ensuring the safety of roadways.

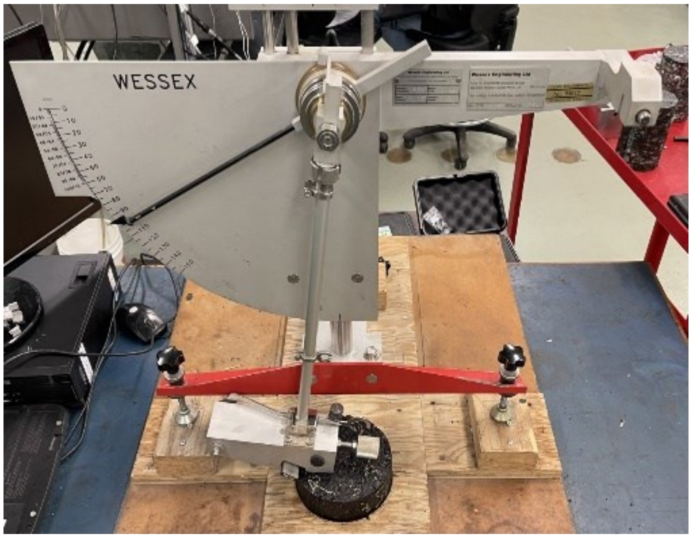


Figure 7-5 British Pendulum Skid Resistance at CPATT Lab

7.4 Results and Discussion

7.4.1 Complex (Dynamic) Modulus

Figure 6-10 shows the master curves established for the norm of the complex modulus (|G*|) at the reference temperature ($T_{ref} = 21$ °C) for MPP-modified mixtures. Based on the results of the master curve fitting process, the MPP-modified mixtures have a lower modulus than the Control Mixture at low temperatures but have a higher resistance to temperature-induced softening than the Control Mixture at higher temperatures. This suggests that the MPP-modified mixtures may provide improved performance in terms of resistance to rutting compared to the Control Mixture.

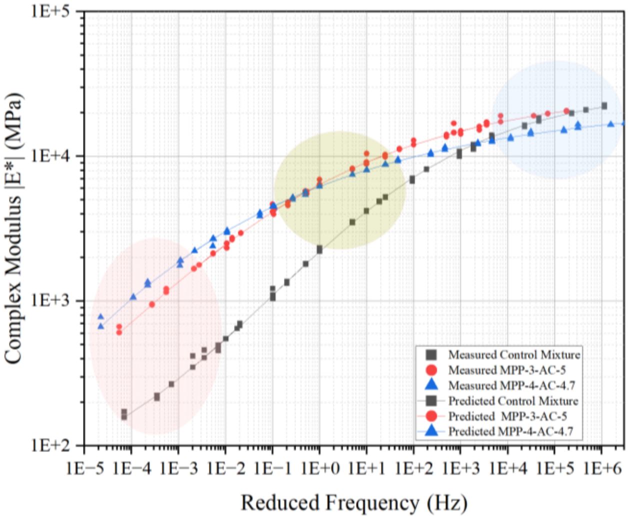
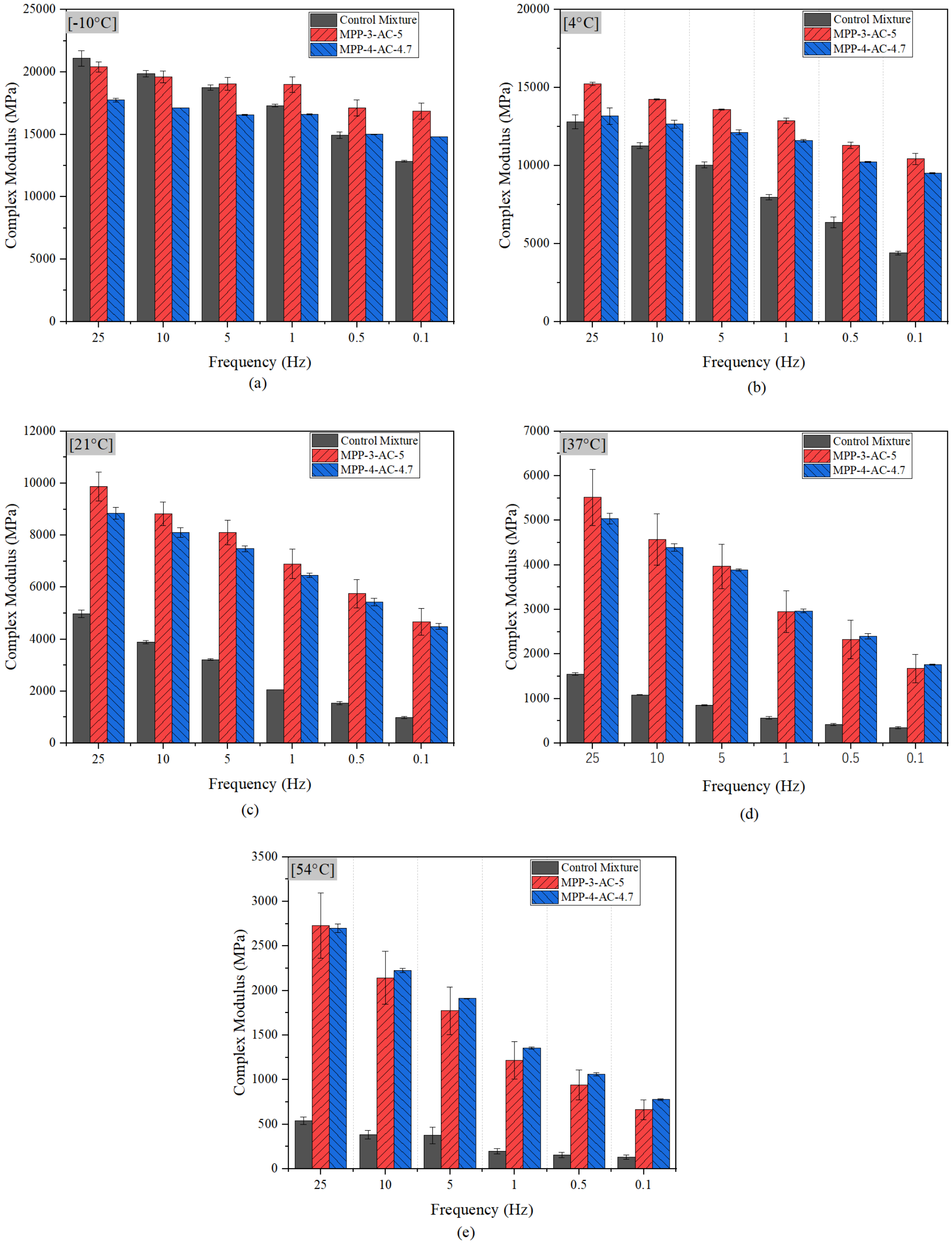


Figure 7-6 Master curve of MPP-modified mixtures using the Dry method at 21 ◦C T_{ref}

Additionally, the results presented in Figure 7-7 show the percentage difference between the Control Mixture and MPP-3-AC-5 or MPP-4-AC-4.7 specimens at different temperatures and frequencies. At low temperatures (-10°C), for example, the difference between the modulus of the Control Mixture and MPP-3-AC-5 materials ranges from -3.25% to 31.13%, and the difference between the modulus of the Control Mixture and MPP-4-AC-4.7 materials ranges from -15.84% to 0.34%. At moderate temperatures (21°C), the difference between the modulus of the Control Mixture and both MPP-3-AC-5 and MPP-4-AC-4.7 materials ranges from 77.72% to 373.81%. At high temperatures (54°C), the stiffness of the MPP-3-AC-5 and MPP-4-AC-4.7 materials ranges from 372.41% to 588.83% higher than the Control Mixture.



(a)

(b)

(c)

(d)

(e)

Figure 7-7 Complex modulus of MPP-modified asphalt mixtures at different frequencies: (a) -10°C (b) 4°C, (c) 21°C, (d) 37 °C and (e) 54 °C

7.4.2 IDEAL-CT

Figure 7-8 displays the three mixtures' IDEAL-CT load versus displacement curves. Although the PG 58-28 control mixture had a lower peak load than the MPP-3-AC-5 and MPP-4-AC-4.7 modified mixtures, their post-peak slopes were similar.

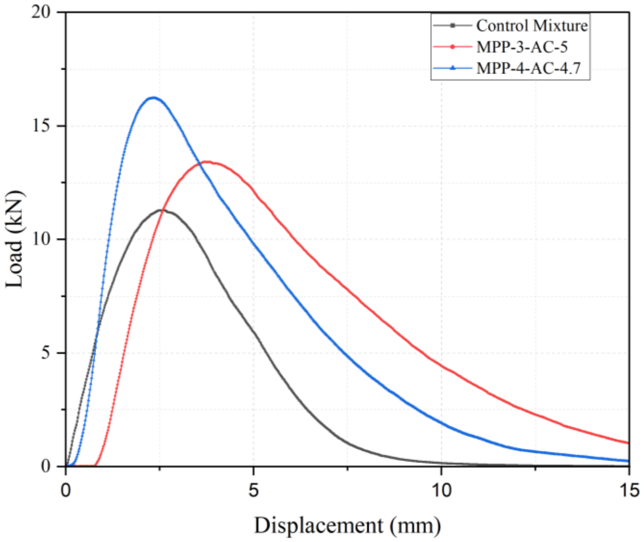


Figure 7-8 Load-Displacement Curves for IDEAL-CT

Figure 7-9 (a) shows the results for fracture energy, which measures the asphalt mixture's resistance to crack propagation. The mean fracture energy for the Control Mixture is 5053, while the mean fracture energy for MPP-4-AC-4.7 and MPP-3-AC-5 are 9535 and 9982, respectively. A simple T-test reveals a significant difference in fracture energy between the Control Mixture and MPP-4-AC-4.7 and MPP-3-AC-5. The MPP-4-AC-4.7 mixture exhibits a higher variance in fracture energy than the other two mixtures, suggesting that it may have a less consistent performance. Figure 7-9 (b) summarizes the calculated CT-index results, indicating that the Control Mixture had the lowest average CT-index value of 64 compared to the two MPP-modified mixtures (MPP-3-AC-5 and MPP-4-AC-4.7), indicating potential lower flexibility and inferior intermediate-temperature cracking resistance. A T-test was also used to compare the CT-index of the Control Mixture with that of the two MPP-modified mixtures. The mean CT_{index} for the Control Mixture was 63.8, while the mean CT_{index} for MPP-4-AC-4.7 and MPP-3-

AC-5 was 100.1 and 236.0, respectively. The T-test results showed that the CT_{index} values for MPP-4-AC-4.7 and MPP-3-AC-5 significantly differed from the Control Mix. When applying the minimum CT_{index} of 70 to short-term aged specimens, the Control Mixture failed to meet the IDEAL-CT criterion. In contrast, the MPP-modified mixture not only met but exceeded the IDEAL-CT criterion, indicating superior performance compared to the Control Mixture. Ultimately, the cracking test results demonstrate the potential benefits of incorporating MPPs in asphalt mixtures to improve fracture resistance and extend service life. Overall, the analysis suggests that adding MPP to asphalt mixtures can significantly improve their CT_{index} and resistance to crack propagation. The MPP-4-AC-4.7 mixture performs more consistently than MPP-3-AC-5, but MPP-modified mixtures outperform the Control Mixture. It is important to note that despite its wide adoption, the IDEAL-CT test remains highly sensitive to various factors, such as RAP content, binder content, binder grade, binder modification, and mix aging. [254], [255]. Therefore, additional fatigue and cracking tests are necessary to validate the effectiveness of MPP additives.

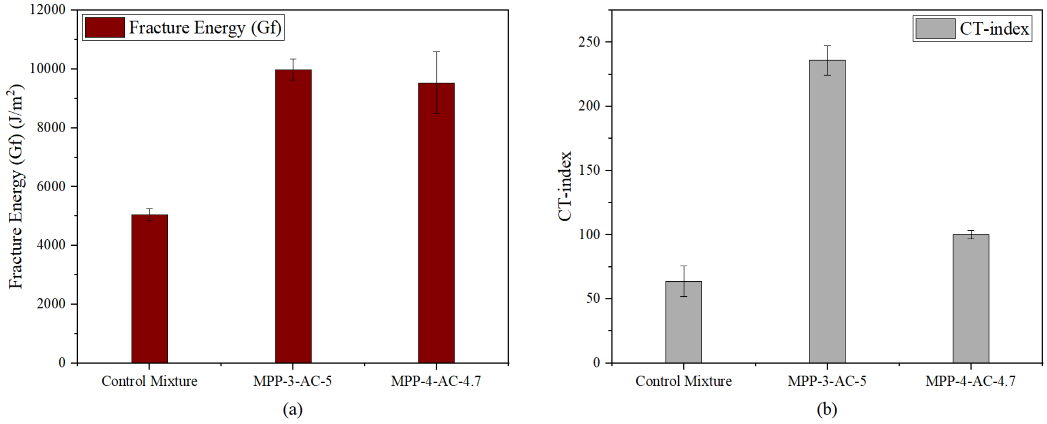
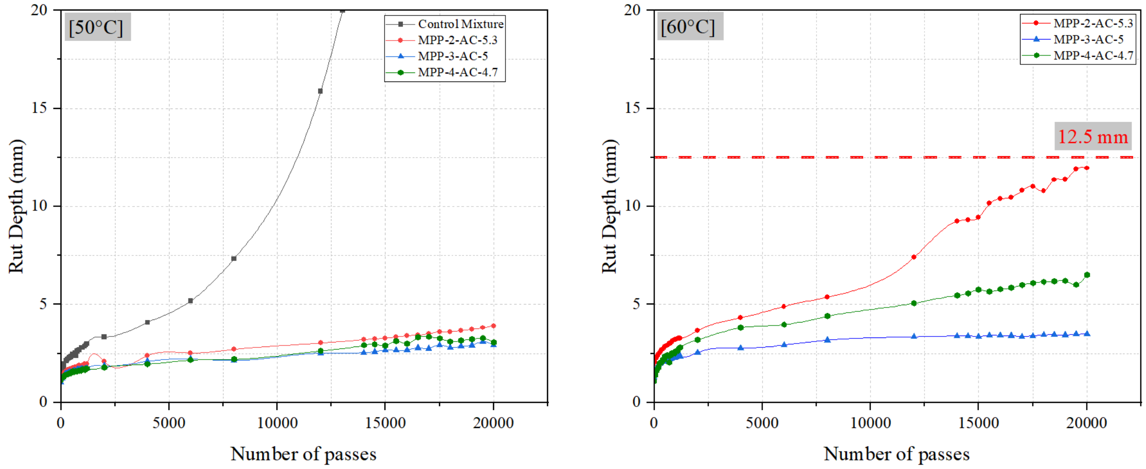


Figure 7-9 IDEAL-CT test parameters: (a) Fracture energy and (b) CT_{index} Results

7.4.3 HWTT

Figure 7-10 shows the MPP-modified asphalt mixtures' performance during the HWTT test using the maximum wheel passes and rut depth. At a testing temperature of 50°C with 12,000 cycles, the Control Mixture exhibited a rut depth of 15.9 mm. However, with the addition of MPP-2-AC-5.3, MPP-3-AC-5, and MPP-4-AC-4.7, the rut depth decreased to 3.0 mm, 2.5 mm and 2.6 mm, respectively. This corresponds to a percentage difference of 80.89%, 84.17%, and 83.43%, respectively, demonstrating the effectiveness of using MPPs to improve the rutting resistance of asphalt mixtures. The beneficial effects of MPPs on the asphalt mixture's thermal viscoelastic-plastic behaviour and their enhancement of adhesive and adhesion properties likely contribute to the observed reduction in rutting deformation under dynamic loads.

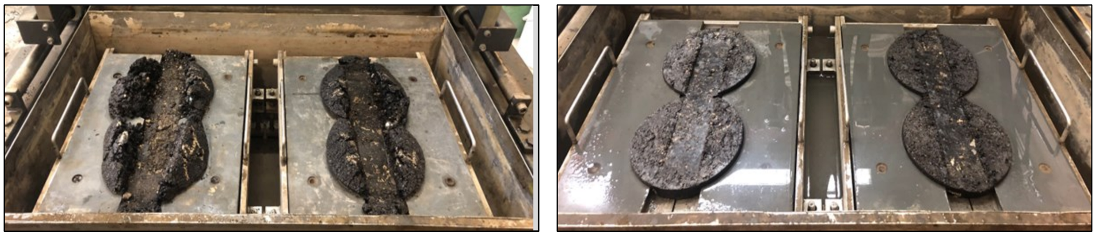


(a)
(b)

Figure 7-10 Rut depth versus the number of passes of MPP-modified asphalt mixtures at (a)50°C and (b) 60°C

Figure 7-11 depicts the appearance of the Control Mixture asphalt mixture and MPP-modified mixtures after being tested by the HWTT at 50°C. To further evaluate the effectiveness of MPP-modified mixtures, a testing temperature of 60°C was selected. Despite all the modified mixtures meeting the 12.5 mm rut depth criterion, the addition of MPPs resulted in a significant reduction in rut depth. The MPP-2-AC-5.3 mixture recorded a rut depth of 12.0 mm. However, the MPP-3-AC-5 and MPP-4-AC-4.7 mixtures recorded rut depths of 3.5 mm and 6.5 mm, significantly improving the Control Mixture. These results suggest incorporating MPPs in asphalt mixtures can enhance their rutting resistance, even at higher temperatures. This finding is crucial as rutting deformation is more prevalent in hot weather conditions, and improved rutting resistance can reduce the need for frequent maintenance.

Moisture damage weakens the bond between the asphalt binder and the aggregate, a significant issue for pavement surfaces. This can lead to problems such as potholes, ravelling, and stripping, ultimately reducing the pavement's lifespan. To assess the MPP-modified asphalt mixtures' moisture damage, the SIP results were determined using AASHTO methods. At 50°C, all MPP-modified mixtures exhibited no SIP, indicating that no stripping occurred during the test (Figure 7-10a). However, only the control mix showed SIP values of 14069 passes. The SIP values of MPP-modified mixtures were determined at 60°C. Only the MPP-2-AC-5.3 mixture showed SIP at 8374 passes, indicating that the MPP-modified mixtures were less susceptible to moisture damage than the Control Mixture.



Control Mixture MPP-3-AC-5

MPP-2-AC-5.3 MPP-4-AC-4.7

Figure 7-11 Appearances of the Control Mixture and MPP-modified mixtures after being tested by the HWTT at 50°C

7.4.4 Moisture-Induced Damage

Figure 7-12 depicts the outcomes of moisture-induced damage tests, including (a) ITS, (b) Max load, (c) TSR%, and (d) the relationship between AC, MPP, and TSR%. The results indicate that all modified asphalt mixtures using MPP demonstrated higher strength values than the Control Mixture before and after conditioning. Specifically, MPP-4-AC-4.7 exhibited the highest strength values, with an ITS value of 1536 kPa before and 1139 kPa after conditioning. In contrast, the Control Mixture showed the lowest strength values, with an ITS value of 489 kPa before conditioning and 468 kPa after conditioning. Additionally, the Maximum Load parameter showed that all modified mixtures had a higher load-carrying capacity than the Control Mixture, with MPP-4-AC-4.7 demonstrating the highest load-carrying capacity.

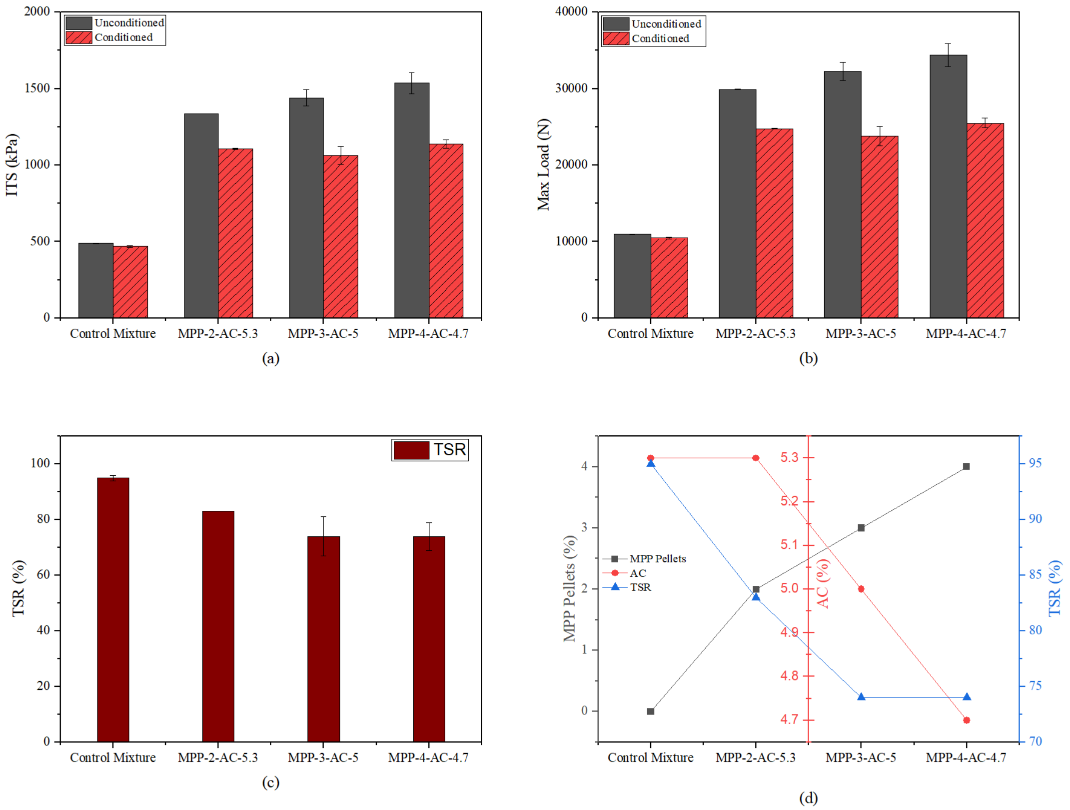
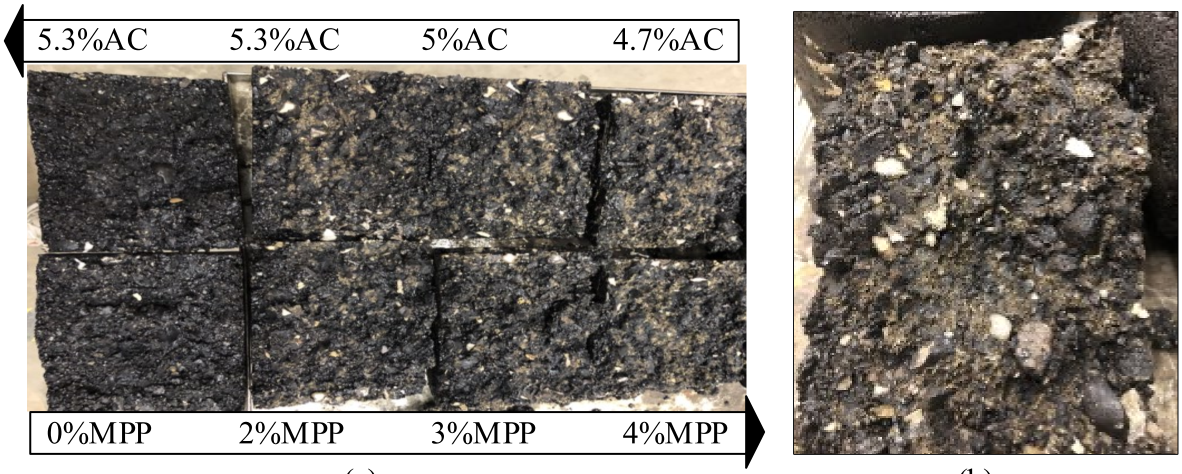


Figure 7-12 The outcomes of moisture-induced damage tests, including (a) ITS, (b) Max load, (c) TSR%, and (d) the relationship between AC, MPP, and TSR

The Tensile Strength Ratio (TSR) value is another crucial parameter for evaluating the moisture resistance of asphalt mixtures. The Asphalt Institute considers a TSR value of 80% or greater acceptable, indicating an asphalt mixture that is not susceptible to moisture damage [44]. However, the TSR% results of this study revealed that all modified asphalt mixtures had lower resistance to moisture than the Control Mixture due to a higher percentage of MPP pellets and a lower percentage of AC. The lower TSR% values in MPP-Modified mixtures may be due to decreased adhesion with aggregate and/or loss of cohesion of the binder, leading to a more brittle and vulnerable mixture. The plastic coating may also hinder proper adhesion of the asphalt binder, resulting in weaker bonding between the aggregate and binder and reduced resistance to cracking. The increased percentage of MPP pellets may occupy more space in the asphalt mixture, potentially reducing adhesion between the asphalt cement and aggregate and weakening the bonding, as shown in Figure 7-13. Despite lower TSR% values observed in this study, a similar study by White (2019) demonstrated that recycled plastic did not significantly affect the moisture damage resistance of the asphalt [256]. To achieve high strength values and resistance to cracking, balancing the percentages of MPP and AC in asphalt mixtures is critical, ensuring that the mixture can withstand moisture damage while maintaining its structural integrity.



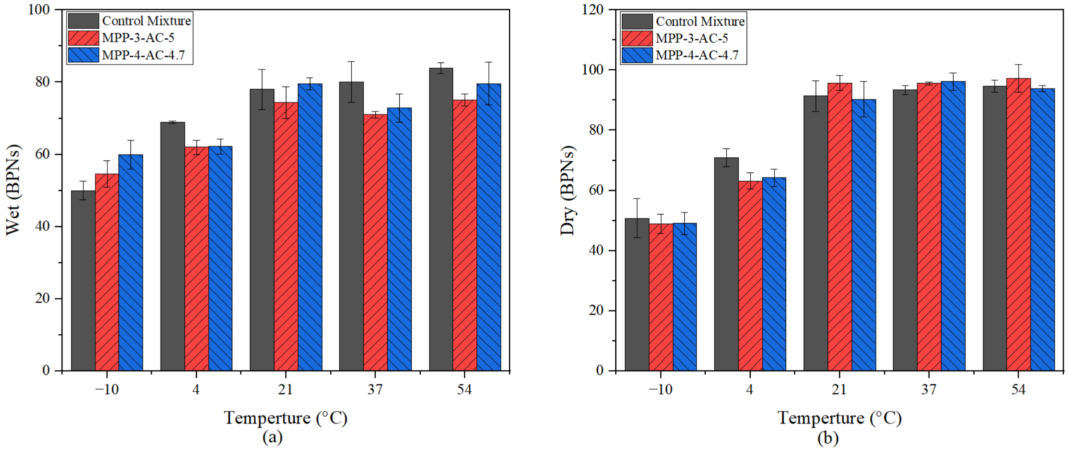
(a) (b)

Figure 7-13 Samples tested for moisture-induced damage, showing (a) variations in AC and MPP percentages, and (b) MPP-4-AC4.7 mixture

7.4.5 The British Pendulum Skid Resistance

Figure 7-14 shows the British Pendulum Numbers (BPNs) for the Control Mixture asphalt mixture and two modified mixtures (MPP-4-AC-4.7 and MPP-3-AC-5) at different temperatures (-10°C, 4°C, 21°C, 37°C, and 54°C) for both dry and wet conditions. The results indicate that the skid resistance of the modified mixtures is generally equal to or greater than 50 BPNs, which is considered acceptable for heavily travelled roads, with a typical minimum value of ≥ 50 BPNs [37], [250]–[252]. When subjected to wet conditions at -10°C, MPP-4-AC-4.7 and MPP-3-AC-5 demonstrated skid resistance levels 9% and 20% higher than the Control Mixture, respectively. However, at temperatures of 4°C, 21°C, 37°C, and 54°C, the MPP-modified mixtures exhibited slightly lower skid resistance levels when compared to the Control Mixture. On the other hand, under dry conditions at 21°C, 37°C, and 54°C, the MPP-modified mixtures consistently outperformed the Control Mixture. At -10°C and 4°C, the Control

Mixture showed higher BPNs. Overall, the study concludes that incorporating MPP pellets in asphalt mixtures does not significantly compromise skid resistance, which is crucial for ensuring the safety of road users.



(a)

(b)

Figure 7-14 Laboratory Results of British Pendulum Number (BPN): (a) Dry condition (b)Wet condition

7.5 Conclusions

This technical paper aimed to evaluate the potential of using multi-layer packaging plastics (MPPs) as an additive in asphalt mixtures. The study employed various tests, such as the Complex (Dynamic) Modulus Test, Moisture-Induced Damage Test, British Pendulum Skid Resistance Tester, Indirect Tensile Cracking Test, and Hamburg Wheel Rut Test, to evaluate the effectiveness of MPP-modified asphalt mixtures. The following conclusions were drawn from the study:

- The Complex (Dynamic) Modulus Test showed that using MPP additives affects the visco-elastic rheological response of the asphalt mixes. The difference between the virgin mix and the two MPP-modified mixes (MPP-3-AC-5 and MPP-4-AC-4.7) appears marginal at low temperatures but becomes significant at intermediate and high temperatures. The use of MPP additives appears to stiffen the asphalt mix at high temperatures, a stronger indicator of the potential improvement of better resistance to permanent deformations.
- The Ideal-CT test has shown that MPP pellets would effectively enhance the resistance of asphalt mixtures to crack propagation at intermediate temperatures. The CT_{index} and fracture energy test results indicate that the control mix would have lower flexibility and inferior

intermediate-temperature cracking resistance compared to the MPP-modified mixtures. The T-test results also indicate that MPP-4-AC-4.7 and MPP-3-AC-5 mixtures outperformed the Control Mixture, with MPP-4-AC-4.7 showing more consistent performance.

- The addition of MPPs to asphalt mixtures significantly reduces rut depth under dynamic loads. Compared to the Control, the rut depths at 12,000 cycles in the HWTT for the experimental mixes, MPP-2-AC-5.3, MPP-3-AC-5, and MPP-4-AC-4.7, were reduced by more than 80%. The observed improvements in rutting deformation are likely due to the beneficial effects of MPPs on the thermal visco-elasto-plastic behaviour and adhesion properties of the asphalt mixture.
- Asphalt mixtures incorporating MPP additives exhibited higher tensile strength values than the Control Mixture before and after moisture conditioning. The MPP-4-AC-4.7 mixture specifically showed the highest strength values. However, the lower TSR% values in MPP-Modified mixtures indicate that the MPP mixture would have a higher moisture sensitivity than the Control Mix. This higher moisture sensitivity would be caused by decreased adhesion or a loss of binder cohesion. These findings suggest that while MPPs can improve the overall tensile strength of asphalt mixtures, they would be more adequate to binder and base courses where they are less prone to moisture damage.
- Based on the British Pendulum test results, using high-concentration MPP pellets in asphalt mixtures does not compromise skid resistance and can be a safe alternative to traditional mixtures. The modified mixtures maintain skid resistance levels ≥ 50 BPNs, which is acceptable for heavily travelled roads.

In conclusion, the findings of this experimental study confirm the potential of using MPP additives in asphalt mixes without compromising the performance of these mixes. The mix with 3% MPP and 5% asphalt cement showed promising performance in terms of fracture resistance, skid resistance, and rutting. However, caution must be taken when adjusting the percentages of MPP pellets and AC to avoid negatively impacting the mixture's resistance to cracking. It is important to note that further research is necessary to optimize the design of MPP-modified mixes and validate their plant production and field performance.

8. Conclusions, Recommendations and Future Work

8.1 General Summary

The use of MPP additives offers a promising solution for improving pavement performance and reducing plastic waste. The findings of the studies presented in this dissertation demonstrate the potential of MPP additives in improving the physical and mechanical properties of asphalt mixtures. The proposed laboratory-scale production method for graded MPP powder offers a cost-effective and reliable means of producing MPP powder, contributing to both sustainable materials and recycling. Developing viable and cost-effective solutions for plastic waste reduction could improve the durability of asphalt pavements, leading to a more sustainable future. Further research and testing are needed to determine MPP additives' long-term durability and effectiveness in asphalt mixtures under various environmental and traffic conditions. The future work includes field trials to monitor the performance of MPP-modified pavements in real-world conditions. Furthermore, it is possible to carry out research to explore the feasibility of utilizing MPP additives in various other applications, including but not limited to aggregate, sand, or other construction materials.

8.2 Conclusions

Road infrastructure quality is crucial in reducing severe and fatal traffic accidents. Researchers have explored using thermoplastic additives, including recycled plastics, such as multi-layer packaging plastics (MPPs), to enhance pavement performance. Incorporating MPPs into asphalt mixtures can minimize plastic waste generation while conserving virgin aggregate and cement, offering a sustainable solution and improving pavement performance. MPPs are composed of polymers such as Polyethylene (PE), Polyester (PET), Nylon (NY), and Metalized Polyester (METPET). The increase in MPP waste has become a growing concern in Canada, leading to significant environmental and economic consequences. Previous studies have successfully used individual components of MPP, such as PE (either as low-density/ “LDPE” or high-density/ “HDPE”) and PET, as asphalt modifiers. A comprehensive study has been conducted to evaluate MPP as a potential asphalt additive. The study takes a comprehensive approach to evaluate the feasibility of using MPP to modify asphalt cement, going beyond simple rheological, mechanical, and performance analysis.

The study started by producing MPP powder at the laboratory scale, which has been successfully demonstrated. The process involved sourcing appropriate post-industrial MPP materials, pre-treating them, grinding them to a fine powder, and ensuring the powder met the required specifications. The laboratory-scale process in this study can provide a cost-effective and reliable means of producing MPP powder, which can have significant benefits and opportunities for research, development, and education.

MPP was evaluated as an asphalt modifier by measuring the physical, morphological, thermal, storage, and rheological properties of MPP-and LDPE-modified binders. The analysis assessed the impact of adding 2%, 4%, and 8% of MPP material and 4% and 8% of LDPE by the total weight of the asphalt cement. Thermogravimetric analysis (TGA) showed that all MPPs tested had multiple melting points ranging from 110 to 254°C. Mass loss for asphalt samples and MPP additives was negligible at elevated temperatures (up to 320°C). This data was used to select the appropriate blending temperature (175°C). Environmental scanning electron microscopy (ESEM) images revealed that the MPP particles became significantly smaller after blending with the virgin asphalt. Most of the MPP additives were well integrated into the asphalt blend. The Brookfield viscosity test results confirmed that all MPP and LDPE additives increased viscosity and reduced flow without exceeding the SHRP allowable limit, thus, resulting in acceptable workability. The rutting factor and Multiple Stress Creep Recovery (MSCR) test results indicated the ability of MPP- and LDPE-modified binders to resist permanent deformation. Blends containing nylon had a higher percentage recovery, reflecting more elasticity than other blends. The temperature-sweep test results showed that all MPP and LDPE-modified binders shifted from predominantly viscous to elastic behaviour, indicating improved rutting resistance. The Linear Amplitude Sweep (LAS) test results showed an increase in the number of cycles to failure for MPP- and LDPE-modified binders compared to the virgin binder, indicating a potential improvement in fatigue cracking resistance. However, MPP- and LDPE-modified binders were shown to have challenges with storage stability.

In addition, the feasibility of using MPP as an asphalt modifier through the Wet Method was investigated. Based on a series of laboratory experiments, MPP-modified binders showed increased stiffness due to the presence of MPP additives. The Superpave Continuous PG and ΔT_c were influenced, but the increase in asphalt stiffness at low temperatures was insignificant at lower MPP modification percentages. Based on the results of this study, it is evident that the chemical composition of MPP can influence the physical and performance properties of the asphalt binder. The Differential Scanning

Calorimetry (DSC) data revealed that saturates' glass transition temperatures (T_g) and MPP's presence did not impact asphaltenes. However, the T_g of aromatics and resins in blends containing 4 and 8% MPP (i.e., Blend-4 and Blend-8) decreased compared to the virgin binder. Only combinations containing 2% MPP passed delta ΔT_c of -2.5°C, whereas all LDPE and MPP modified binders passed when the requirement was increased to a ΔT_c of -5.0°C. Higher concentrations of MPP additives resulted in high binder stiffness at low temperatures. The authors recommended using MPP modification ideally up to 2% and not more than 4% by weight of asphalt binder to maintain low-temperature performance.

At low temperatures, the complex modulus of Blend-4 and Blend-8 mixtures exhibited insignificant changes compared to the virgin mixture. A low dosage of MPP modifier can retain low-temperature cracking performance without a significant effect on low and intermediate-temperature modulus. However, the presence of MPP additive still reduced resistance to thermal cracking. The Temperature Strain Recovery Stress Test (TSRST) experiment results indicated that the MPP-modified materials did not meet the lower PG grade criteria of -28°C for any tested mixtures. Statistical analysis revealed an insignificant impact of MPP on the thermal cracking temperature of the Blend-4 mixture but a significant impact on the Blend-8 mixture. Considering these findings, low dosages of MPP additives are feasible for use in asphalt mixtures when coupled with an appropriate pre-processing procedure. The authors recommend limiting the MPP modification percentage to below 4% of binder weight to avoid significantly decreasing resistance to thermal cracking. The recommended limiting percentage is based on adoption in Southern Ontario, but the MPP modification percentage could be increased for warmer regions after further investigation.

At high temperatures, binder modifications above 4% significantly increase the mixtures' modulus. The dynamic modulus results obtained at 37°C and 54°C provide valuable insights into the resistance of asphalt mixtures to rutting at high temperatures. Blend-4 and Blend-8 showed an increased stiffness compared to the control mixture, indicating an improvement in rutting resistance. The Wet Method resulted in more significant improvements in stiffness than the Dry Method, indicating that the former is more effective in enhancing rutting resistance. Furthermore, both the Wet and Dry Methods increased stiffness and resistance to permanent deformation of the asphalt mixture. However, the Wet Method consistently outperformed the Dry Method in this regard, suggesting that it offers several benefits, including reduced coating loss, rut depth, marshal stability loss, and increased TSR values. Overall, these findings suggest that the Wet Method has great potential for optimizing the performance of asphalt pavements, particularly with regard to their resistance to rutting and permanent deformation at high temperatures.

Lastly, the potential of using high concentrations of MPP pellets as an additive in asphalt mixtures to enhance pavement properties and reduce plastic waste was evaluated. The study employed various tests, such as the Complex (Dynamic) Modulus Test, Moisture-Induced Damage Test, British Pendulum Skid Resistance Tester, Indirect Tensile Cracking Test (Ideal-CT), and Hamburg Wheel Tracking Test (HWTT). In summary, the results presented in the study indicate that adding MPP pellets to asphalt mixtures can significantly enhance the physical and mechanical properties of the pavement, especially at higher temperatures. The Complex Modulus test showed a significant difference in modulus between the Control Mixture and MPP mixtures at various temperatures and frequencies. The Ideal-CT test indicated that adding MPP pellets could effectively enhance the resistance of asphalt mixtures to crack propagation at intermediate temperatures. Furthermore, the addition of MPP to asphalt mixtures has the potential to significantly reduce rut depth at elevated service temperatures. Asphalt mixtures using MPP exhibited higher strength values and load-carrying capacity than the unmodified mixture before and after moisture conditioning. However, the lower TSR% values in MPP-modified mixtures indicate a lower resistance to cracking in the presence of moisture due to decreased adhesion with aggregates or loss of cohesion of the binder. The modified MPP-4-AC-4.7 and MPP-3-AC-5 asphalt mixtures exhibited similar skid resistance to the Control Mixture. While dry pavements generally have high friction resistance, wet pavements at lower temperatures can be challenging, with twice the number of accidents occurring on wet pavements compared to dry ones. However, this study reveals that all MPP-modified mixtures scored at least 50 BNPs, considered acceptable for roads with heavy traffic, with a typical minimum value of ≥ 50 BPNs. Based on the results presented in the study, the MPP-3-AC-5 mixture showed promising performance in terms of fracture, skid, and rutting resistance. However, it is worth noting that caution must be taken when adjusting the percentages of MPP pellets and AC to avoid negatively impacting the mixture's resistance to cracking. Therefore, further research is necessary to optimize the dosages to balance strength, load-carrying capacity, and resistance to cracking.

In conclusion, the findings of these studies demonstrate the potential of using MPP additives as a sustainable solution for enhancing pavement performance and reducing plastic waste generation. The laboratory-scale production of MPP powder can offer a cost-effective and reliable means of producing MPP powder, contributing to sustainable materials and recycling. The studies discussed in this study demonstrate the effectiveness of MPP additives in improving the physical and mechanical properties of asphalt mixtures. However, further research is required to optimize MPP modifiers to improve asphalt mixtures' elastic recovery and moisture resistance and determine the optimal MPP modification for different binder types and grades. Additionally, caution must be taken when adjusting the percentages of MPP pellets and AC to maintain low-temperature performance and avoid negatively impacting the mixture's resistance to cracking. Overall, the findings of these studies have significant implications for developing viable and cost-effective solutions for plastic waste management and improving the sustainability and durability of asphalt pavements.

8.3 Contributions

This dissertation made significant contributions to the research on plastic recycling in asphalt modification. It comprehensively analyzed the consequences of incorporating multi-layer plastic packaging (MPP) additives. The key contributions of the research were:

- Developed a cost-effective and reliable plastic powder production process for laboratory settings to assist researchers in studying plastic additives in asphalt. The process involved collecting, drying, shredding, and grinding MPP waste and testing the powder's quality, thermal properties, and consistency using TGA, DSC, and ESEM.
- Studied the impact of using MPP powder on the modified binders' physical, thermal, rheological, and storage properties using DSR, TGA, DSC, and ESEM.
- Investigated the effects of incorporating MPP additives on the rheological and mechanical characteristics of the modified binder under high-temperature conditions using both wet and dry processes.
- Examined the effect of adding MPP additives on the properties of asphalt binder and mixture, particularly at lower temperatures, and provided guidance on optimal concentration levels for maximum effectiveness.
- Examined the impact of hygroscopic thermoplastic MPP additives on the moisture content of the mixture when subjected to wet conditions.
- Replaced some of the aggregate and asphalt cement with MPP pellets and evaluated the performance of the resulting mixture.

Overall, this dissertation made significant contributions to understanding the role of plastic additives in asphalt and provided insights for future research and practical applications in the field.

8.4 Recommendations and Future Research

8.4.1 Recommendations

Based on the conclusions drawn in this dissertation, the following recommendations are suggested:

- Use both TGA and DSC tests to determine the optimal blending temperature for MPP additives with asphalt to achieve better control over the physical and chemical properties of the resulting mixture.
- Ensure that the particle size distribution of MPP powder added to asphalt binder falls within the range of 0.075 to 0.595 mm and that the MPP powder size does not exceed 250 µm to comply with particle size recommendations set by AASHTO and ASTM.
- Consider the PET, NY, and METPET components of MPP materials, which represent less than 15% of the total MPP weight, as fillers due to their high melting points.
- Limit the percentage of MPP modification to 4% of the binder weight to avoid compromising thermal cracking resistance in colder climates. However, a higher percentage may be employed if low-temperature cracking is not a concern. Using a softer binder (e.g., PG 52-34) as a base binder would also be a possible solution to overcome the low-temperature issues. Nonetheless, additional research is needed to confirm this hypothesis and to provide further insights into the optimal utilization of MPP-modified binders for various asphalt-based applications.
- Use the Wet Method for incorporating MPP additives into asphalt mixtures, as it consistently outperforms the Dry Method in enhancing the mixture's stiffness and resistance to permanent deformation.
- Utilize both MSCR and HWTT tests as complementary tools for evaluating the rutting performance of asphalt mixtures. They can gain a comprehensive insight into rutting mechanisms by analyzing the binder's viscoelastic properties through the MSCR test and measuring the mixture's resistance to shear and tensile stresses with the HWTT test.
- Further research is needed to optimize the dosages of MPP and AC to achieve a balance between strength, load-carrying capacity, and resistance to cracking when using the Dry Method with a higher concentration of MPP pellets. The MPP mixture demonstrates promising performance in terms of fracture resistance, skid resistance, and rutting resistance and can be investigated for developing sustainable pavement materials. Caution

is necessary when modifying dosages of MPP and AC to prevent adverse effects on the mixture's resistance to cracking.

- It is highly recommended to verify the mix gradation after incorporating the MPP pellets. This can be done by extracting the asphalt binder using a solvent and testing the recovered aggregates. The use of an ignition oven is not recommended due to the presence of the plastic in the mix.

8.4.2 Future Research

This research underlined the necessity for continued exploration to refine MPP modifiers and ensure the ideal MPP modification percentage and its influence on various asphalt mixture properties. Moreover, additional investigation is required to examine the following aspects:

- Evaluate MPP additives with various asphalt cement types and mix designs to achieve optimal and consistent distribution within the mixture. A thorough examination of the volumetric properties and mix gradation of asphalt mixtures with significant MPP additive content is essential to make informed decisions about MPP additives' appropriate dosage and mix design.
- Investigate potential solutions to enhance the storage stability of MPP-modified binders through various established compatibilization techniques to promote the practical and economic viability of MPP-modified binders for diverse asphalt-based applications.
- Conducted a detailed investigation of the hygroscopic properties of MPP additives before using them in asphalt modification to better understand their suitability for different applications and develop strategies to mitigate potential adverse effects.
- The Dry Method, which utilizes MPP powder or pellets, has not yet been evaluated using the Temperature Strain Recovery Stress Test (TSST) experiment. Therefore, it is recommended to conduct this evaluation in the future.
- Through field trials and studies, evaluate the long-term performance of MPP-modified asphalt mixtures, including their resistance to aging, cracking, and deformation over time. Evaluating the possibility of re-recycling of asphalt with plastic should also be part of future research.
- To understand their environmental footprint, investigate the environmental impact of MPP modifiers, such as their potential leaching into the environment and effects on soil and water quality.

- Evaluate the influence of MPP modifiers on road noise and their ability to reduce noise pollution, focusing on optimizing them, their long-term performance, environmental effects, cost-efficiency, and noise reduction potential.
- Conduct a comprehensive study on the Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) of MPP-modified mixtures to assess their economic and environmental effects throughout their life cycle, enabling informed decision-making.

8.4.3 Gaps and limitation

A significant limitation of this study is the lack of research on the long-term durability of MPP-modified asphalt mixtures. Although the studies presented demonstrate that MPP can enhance the physical and mechanical properties of asphalt mixtures in laboratory settings, long-term durability testing is required to assess MPP's efficacy as an additive throughout the pavement's lifespan, including its resistance to aging, fatigue, and environmental factors. The impact of MPP on the workability of asphalt mixtures has not been extensively researched. While the studies suggest MPP can improve crack propagation resistance and decrease rut depth under dynamic loads, further investigation is needed to evaluate its effect on workability to ensure it does not negatively impact this property. The studies have only assessed MPP's effectiveness as an asphalt modifier using the wet and dry method, leaving alternative incorporation methods unexplored.

Further research should evaluate other potential methods and investigate MPP's efficacy as an additive in various types of asphalt mixtures, such as porous asphalt, warm mix asphalt, stone mastic asphalt, and open-graded friction course, as well as with different binder grades and types. A primary challenge is the production of MPP powder. Laboratory-scale production has been achieved after numerous trials, but the process requires improvement to facilitate upscaling to larger quantities necessary for field trials and asphalt production. Lastly, the environmental impact of using MPP as an asphalt modifier should be investigated, as it might reduce plastic waste generation but may have other associated environmental impacts. In conclusion, while the studies show promising evidence for MPP's potential as an asphalt modifier, future research must address existing gaps and limitations, including long-term durability testing, examining MPP's impact on workability, exploring alternative incorporation methods, assessing MPP's effectiveness in various asphalt mixtures, and evaluating its environmental implications.

Bibliography

[1] World Health Organization, *Global status report on road safety 2018*. Geneva: World Health Organization, 2018. Accessed: Feb. 28, 2023. [Online]. Available: https://apps.who.int/iris/handle/10665/276462

[2] CIRC, "Canada Infrastructure Report Card 2019," 2019. [Online]. Available: http://canadianinfrastructure.ca/en/about.html

[3] "Canada's Core Public Infrastructure Survey: Roads, bridges and tunnels, 2020," no. 11, 2022, [Online]. Available: https://www150.statcan.gc.ca/n1/en/daily-quotidien/220524/dq220524a-eng.pdf?st=to2twErh

[4] S. K. Ghosh, *Circular Economy: Global Perspective*. 2020. doi: 10.1007/978-981-15-1052-6.

[5] C. Weetman, *A circular economy handbook for business and supply chains: Repair, remake, redesign, rethink*. Kogan Page Publishers, 2016.

[6] "Economic study of the Canadian plastic industry, markets and waste : summary report to Environment and Climate Change Canada.," Environment and Climate Change Canada, Gatineau, QC, Canada, Monograph, 2019.

[7] Y. Becker, M. P. Mendez, and Y. Rodriguez, "Polymer modified asphalt." 2001.

[8] W. H. Daly, *Relationship Between Chemical Makeup of Binders and Engineering Performance*, no. Project 20-015 (Topic 47-13). 2017.

[9] A. Behnood and J. Olek, "Rheological properties of asphalt binders modified with styrene-butadiene-styrene (SBS), ground tire rubber (GTR), or polyphosphoric acid (PPA)," *Construction and Building Materials*, vol. 151, pp. 464–478, 2017.

[10] X. Lu and U. Isacsson, "Modification of road bitumens with thermoplastic polymers," *Polymer testing*, vol. 20, no. 1, pp. 77–86, 2000.

[11] Q. Zhang, S. W. Goh, and Z. P. You, "Study on dynamic modulus of waste plastic modified asphalt mixture using waste plastic bag chips," in *Advanced Materials Research*, Trans Tech Publ, 2011, pp. 824–828.

[12] Y. Yildirim, "Polymer modified asphalt binders," *Construction and Building Materials*, vol. 21, no. 1, pp. 66–72, 2007.

[13] Z. N. Kalantar, M. R. Karim, and A. Mahrez, "A review of using waste and virgin polymer in pavement," *Construction and Building Materials*, vol. 33, pp. 55–62, 2012.

[14] M. Porto, P. Caputo, V. Loise, S. Eskandarsefat, B. Teltayev, and C. Oliviero Rossi, "Bitumen and bitumen modification: A review on latest advances," *Applied Sciences*, vol. 9, no. 4, p. 742, 2019.

[15] X. Lu and U. Isacsson, "Artificial aging of polymer modified bitumens," *J. Appl. Polym. Sci.*, vol. 76, no. 12, pp. 1811–1824, Jun. 2000, doi: 10.1002/(SICI)1097-4628(20000620)76:12<1811::AID-APP12>3.0.CO;2-1.

[16] Y. Peng, R. Ruibo, W. Lizhi, and Z. Xiaoning, "Characteristic Behavior of Asphalt with SBS and PE," in *Sustainable Construction Materials 2012*, Wuhan, China: American Society of Civil Engineers, Dec. 2012, pp. 421–429. doi: 10.1061/9780784412671.0035.

[17] L. Sun, Y. Wang, and Y. Zhang, "Aging mechanism and effective recycling ratio of SBS modified asphalt," *Construction and Building Materials*, vol. 70, pp. 26–35, Nov. 2014, doi: 10.1016/j.conbuildmat.2014.07.064.

[18] D. Kaya, A. Topal, J. Gupta, and T. McNally, “Aging effects on the composition and thermal properties of styrene-butadiene-styrene (SBS) modified bitumen,” *Construction and Building Materials*, vol. 235, p. 117450, Feb. 2020, doi: 10.1016/j.conbuildmat.2019.117450.

[19] CIRC, “Canada Infrastructure Report Card 2019,” p. 56, 2019.

[20] Transport Canada, “Transportation in Canada 2011,” pp. 1–155, 2011, doi: T1-23A/2011E-PDF.

[21] Minister of Transport, “Transportation In Canada 2016 Comprehensive Report,” 2016. doi: 15357 E.

[22] M. A. Dalhat, K. Al-Adham, and A. Y. Adesina, “High-Temperature Performance of Recycled Low-Density Polyethylene-Modified Asphalt Binder Reinforced with Thermally Treated Polyacrylonitrile Fiber,” *Arabian Journal for Science and Engineering*, 2020, doi: 10.1007/s13369-020-04431-8.

[23] H. A. Saleh, A. Musbah, and A. Allam, “Evaluation of the Mechanical Properties of Asphalt Mixture Modified with RPET,” vol. 7, no. 2, pp. 27–31, 2019, doi: 10.13189/ujes.2019.070201.

[24] A. Behnood and M. M. Gharehveran, “Morphology, rheology, and physical properties of polymer-modified asphalt binders,” *European Polymer Journal*, vol. 112, pp. 766–791, 2019.

[25] N. S. Mashaan, A. Rezagholilou, and H. Nikraz, “Waste Plastic as Additive in Asphalt Pavement Reinforcement: A review,” in *AAPA International Flexible Pavements Conference, 18th, 2019, Sydney, New South Wales, Australia*, 2019.

[26] M. R. M. Hasan, J.-W. Chew, A. Jamshidi, X. Yang, and M. O. Hamzah, “Review of sustainability, pretreatment, and engineering considerations of asphalt modifiers from the industrial solid wastes,” *Journal of Traffic and Transportation Engineering (English Edition)*, 2019.

[27] M. Garcia-Morales, P. Partal, F. J. Navarro, and C. Gallegos, “Effect of waste polymer addition on the rheology of modified bitumen,” *Fuel*, vol. 85, no. 7–8, pp. 936–943, 2006.

[28] M. Naskar, T. K. Chaki, and K. S. Reddy, “Effect of waste plastic as modifier on thermal stability and degradation kinetics of bitumen/waste plastics blend,” *Thermochimica Acta*, vol. 509, no. 1–2, pp. 128–134, 2010.

[29] Yotam Ottolenghi, “BrainyQuote,” 2013. https://www.brainyquote.com/quotes/yotam_ottolenghi_606729

[30] G. White and G. Reid, “Recycled waste plastic for extending and modifying asphalt binders,” *Symposium on Pavement Surface Characteristics (SURF)*, no. May, pp. 1–13, 2018.

[31] A. F. Ahmad, A. R. Razali, and I. S. M. Razelan, “Utilization of polyethylene terephthalate (PET) in asphalt pavement: A review,” *IOP Conference Series: Materials Science and Engineering*, vol. 203, no. 1, 2017, doi: 10.1088/1757-899X/203/1/012004.

[32] J. de A. A. e. Silva, J. K. G. Rodrigues, M. W. de Carvalho, L. C. de F. L. Lucena, and E. H. Cavalcante, “Mechanical performance of asphalt mixtures using polymer-micronized PET-modified binder,” *Road Materials and Pavement Design*, vol. 19, no. 4, pp. 1001–1009, 2018, doi: 10.1080/14680629.2017.1283353.

[33] M. A. Dalhat and H. I. Al-Abdul Wahhab, “Performance of recycled plastic waste modified asphalt binder in Saudi Arabia,” *International Journal of Pavement Engineering*, vol. 18, no. 4, pp. 349–357, 2017.

[34] J. Zhu, B. Birgisson, and N. Kringos, “Polymer modification of bitumen: Advances and challenges,” *European Polymer Journal*, vol. 54, pp. 18–38, 2014.

[35] P. Lastra-González, M. A. Calzada-Pérez, D. Castro-Fresno, Á. Vega-Zamanillo, and I. Indacoechea-Vega, “Comparative analysis of the performance of asphalt concretes modified by

dry way with polymeric waste," *Construction and Building Materials*, vol. 112, pp. 1133–1140, 2016.

[36] D. Ge, K. Yan, Z. You, and H. Xu, "Modification mechanism of asphalt binder with waste tire rubber and recycled polyethylene," *Construction and Building Materials*, vol. 126, pp. 66–76, 2016.

[37] Y. H. Huang, *Pavement analysis and design*. Pearson Prentice Hall Upper Saddle River, NJ, 2004.

[38] J. Read, D. Whiteoak, and R. N. Hunter, *The shell bitumen handbook*. Thomas Telford, 2003.

[39] S. E. D. TIGHE, "Pavement asset design and management guide," 2013.

[40] S. Mangiafico, "Linear viscoelastic properties and fatigue of bituminous mixtures produced with Reclaimed Asphalt Pavement and corresponding binder blends," *ENTPE, Lyon*, 2014.

[41] H. Di Benedetto, "Modélisation: écart entre état des connaissances et applications," *Journée LAVOC, École Polytechnique fédérale de Lausanne, Lausanne, Suisse*, 1998.

[42] E. A. P. Association, "The use of Warm-Mix Asphalt: EAPA–Position Paper," *Brussels, Belgium, available on www. eapa. org/userfiles/2/Asphalt-WMA/EAPA Position Paper-WMA–version October*, 2014.

[43] C. W. Jenks, C. F. Jencks, E. T. Harrigan, M. Adcock, E. P. Delaney, and H. Freer, "NCHRP Report 673: A manual for design of hot mix asphalt with commentary," *Transportation Research Board, Washington, DC*, 2011.

[44] A. Institute., *The Asphalt handbook.* Lexington, Ky.: Asphalt Institute, 2007.

[45] J. Murali Krishnan and and K. R. Rajagopal, "Review of the uses and modeling of bitumen from ancient to modern times," *Appl. Mech. Rev.*, vol. 56, no. 2, pp. 149–214, 2003.

[46] Y. Huang, R. N. Bird, and O. Heidrich, "A review of the use of recycled solid waste materials in asphalt pavements," *Resources, conservation and recycling*, vol. 52, no. 1, pp. 58–73, 2007.

[47] N. Kulo g ˇ lu, "Effect of astragalus on characteristics of asphalt concrete," *Journal of materials in civil engineering*, vol. 11, no. 4, pp. 283–286, 1999.

[48] *Superpave mix design (SP-2)*. Lexington, KY, USA: Asphalt Institute, 1996.

[49] A. Qabur, "Fatigue Characterization of Asphalt Mixes with Polymer Modified Asphalt Cement," University of Waterloo, Waterloo, Ontario, Canada, 2018.

[50] M. J. Khattak and V. Kyatham, "Viscoelastic behavior of hydrated lime-modified asphalt matrix and hot-mix asphalt under moisture damage conditions," *Transportation Research Record*, vol. 2057, no. 1, pp. 64–74, 2008.

[51] R. B. McGennis, R. M. Anderson, T. W. Kennedy, and M. Solaimanian, "Background of SUPERPAVE asphalt mixture design and analysis," United States. Federal Highway Administration. Office of Technology Applications, 1995.

[52] M. Soltani, T. B. Moghaddam, M. R. Karim, and H. Baaj, "Analysis of fatigue properties of unmodified and polyethylene terephthalate modified asphalt mixtures using response surface methodology," *Engineering Failure Analysis*, vol. 58, pp. 238–248, 2015.

[53] A. Khodaii and A. Mehrara, "Evaluation of permanent deformation of unmodified and SBS modified asphalt mixtures using dynamic creep test," *Construction and Building Materials*, vol. 23, no. 7, pp. 2586–2592, 2009.

[54] T. B. Moghaddam, M. Soltani, and M. R. Karim, "Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test," *Materials & Design*, vol. 53, pp. 317–324, 2014.

[55] R. Muniandy and B. B. K. Huat, “Laboratory diameteral fatigue performance of stone matrix asphalt with cellulose oil palm fiber,” *American Journal of Applied Sciences*, vol. 3, no. 9, pp. 2005–2010, 2006.

[56] L. P. T. L. Fontes, G. Trichês, J. C. Pais, and P. A. A. Pereira, “Evaluating permanent deformation in asphalt rubber mixtures,” *Construction and Building Materials*, vol. 24, no. 7, pp. 1193–1200, 2010.

[57] S. Tayfur, H. Ozen, and A. Aksoy, “Investigation of rutting performance of asphalt mixtures containing polymer modifiers,” *Construction and Building Materials*, vol. 21, no. 2, pp. 328–337, 2007.

[58] M. des T. du Québec, “Guide de mesure des dégradations des chaussées souples,” *Direction des communications, MTQ, É diteur*, 2007.

[59] F. L. Roberts, P. S. Kandhal, E. R. Brown, D.-Y. Lee, and T. W. Kennedy, “Hot mix asphalt materials, mixture design and construction,” 1991.

[60] H. Wen, “Fatigue performance evaluation of WesTrack asphalt mixtures based on viscoelastic analysis of indirect tensile test,” 2001.

[61] N. R. Council, *Fatigue response of asphalt-aggregate mixes*. 1994.

[62] M. W. Witczak and M. M. El-Basyouny, “Calibration of fatigue cracking models for flexible pavements En: Guide for Mechanistic-Empirical Design,” *Appendix IT-1. Washington, DC: National Cooperative Highway Research Program*, 2004.

[63] R. Y. Liang and J. Zhou, “Prediction of fatigue life of asphalt concrete beams,” *International journal of fatigue*, vol. 19, no. 2, pp. 117–124, 1997.

[64] W. Zeiada, *Endurance limit for HMA based on healing phenomenon using viscoelastic continuum damage analysis*. Arizona State University, 2012.

[65] P. K. Das, D. Jelagin, and B. Birgisson, “Evaluation of the low temperature cracking performance of asphalt mixtures utilizing HMA fracture mechanics,” *Construction and Building Materials*, vol. 47, pp. 594–600, 2013.

[66] H. K. Kanerva, T. S. Vinson, and H. Zeng, *Low-temperature cracking: Field validation of the thermal stress restrained specimen test*, no. SHRP-A-401. 1994.

[67] B. Behnia, W. G. Buttlar, and H. Reis, “Nondestructive low-temperature cracking characterization of asphalt materials,” *Journal of Materials in Civil Engineering*, vol. 29, no. 5, p. 4016294, 2017.

[68] D. A. Anderson and T. W. Kennedy, “Development of SHRP binder specification (with discussion),” *Journal of the Association of Asphalt Paving Technologists*, vol. 62, 1993.

[69] D. A. Anderson *et al.*, “Binder characterization and evaluation, volume 3: Physical characterization,” *Strategic Highway Research Program, National Research Council, Report No. SHRP-A-369*, 1994.

[70] and et all Alan Carter, Hugh Donovan, Keith Maclnnis, Todd Strynadka, *Hot Mix Asphalt*. West Kelowna, BC, Canada: Canadian Technical Asphalt Association, 2018.

[71] G. D. Airey, “Rheological properties of styrene butadiene styrene polymer modified road bitumens☆,” *Fuel*, vol. 82, no. 14, pp. 1709–1719, 2003.

[72] S. Hınıslıoğlu and E. Ağar, “Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix,” *Materials letters*, vol. 58, no. 3–4, pp. 267–271, 2004.

[73] A. I. Al-Hadidy and T. Yi-Qiu, “Mechanistic approach for polypropylene-modified flexible pavements,” *Materials & Design*, vol. 30, no. 4, pp. 1133–1140, 2009.

[74] J.-S. Chen, M.-C. Liao, and M.-S. Shiah, “Asphalt modified by styrene-butadiene-styrene triblock copolymer: Morphology and model,” *Journal of materials in civil engineering*, vol. 14, no. 3, pp. 224–229, 2002.
[75] D. Lesueur, J.-F. Gérard, P. Claudy, J.-M. Létoffé, D. Martin, and J.-P. Planche, “Polymer modified asphalts as viscoelastic emulsions,” *Journal of Rheology*, vol. 42, no. 5, pp. 1059–1074, 1998.
[76] F. Giustozzi and S. Nizamuddin, “Plastic Waste for Sustainable Asphalt Roads”, [Online]. Available: https://app.knovel.com/hotlink/toc/id:kpPWSAR001/plastic-waste-sustainable/plastic-waste-sustainable
[77] P. Pay, “Effect of polymer modified bitumen on deformation characteristics of low-traffic asphalt pavements.” NTNU, 2017.
[78] A. Qabur, H. Baaj, and M. El-Hakim, “Incorporation of the Multi-Layer Plastic Packaging in the Asphalt Binders: Physical, Thermal, Rheological, and Storage Properties Evaluation,” *Polymers*, vol. 14, no. 24, p. 5396, Dec. 2022, doi: 10.3390/polym14245396.
[79] U. Isacsson and H. Zeng, “Relationships between bitumen chemistry and low temperature behaviour of asphalt,” *Construction and Building Materials*, vol. 11, no. 2, pp. 83–91, 1997.
[80] M. T. Awwad and L. Shbeeb, “The use of polyethylene in hot asphalt mixtures,” *American Journal of Applied Sciences*, vol. 4, no. 6, pp. 390–396, 2007.
[81] F. S. Rostler and R. M. White, “Influence of chemical composition of asphalts on performance, particularly durability,” in *Symposium on Road and Paving Materials—1959*, ASTM International, 1960.
[82] R. L. Griffin, W. C. Simpson, and T. K. Miles, “Influence of Composition of Paving Asphalt on Viscosity, Viscosity-Temperature Susceptibility, and Durability.,” *Journal of Chemical and Engineering Data*, vol. 4, no. 4, pp. 349–354, 1959.
[83] J. C. Petersen, “Chemical composition of asphalt as related to asphalt durability,” *Developments in petroleum science*, vol. 40, pp. 363–395, 2000.
[84] D. Lesueur, “The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification,” *Advances in colloid and interface science*, vol. 145, no. 1–2, pp. 42–82, 2009.
[85] M. L. Williams, R. F. Landel, and J. D. Ferry, “The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-forming Liquids,” *Journal of the American Chemical Society*, vol. 77, no. 14, pp. 3701–3707, 1955, doi: 10.1021/ja01619a008.
[86] P. Kriz, J. Stastna, and L. Zanzotto, “Glass transition and phase stability in asphalt binders,” *Road Materials and Pavement Design*, vol. 9, no. sup1, pp. 37–65, 2008.
[87] J. F. Masson, P. Collins, G. Robertson, J. R. Woods, and J. Margeson, “Thermodynamics, phase diagrams, and stability of bitumen− polymer blends,” *Energy & Fuels*, vol. 17, no. 3, pp. 714–724, 2003.
[88] A. Fawcett and T. McNally, “Polystyrene and asphaltene micelles within blends with a bitumen of an SBS block copolymer and styrene and butadiene homopolymers,” *Colloid and Polymer Science*, vol. 281, no. 3, pp. 203–213, 2003.
[89] J. J. Breen and J. E. Stephens, *The Glass Transition Temperature and the Mechanical Properties of Asphalt*. University of Connecticut, School of Engineering, Civil Engineering Department, 1967.
[90] A. Behnood and J. Olek, “Rheological properties of asphalt binders modified with styrene-butadiene-styrene (SBS), ground tire rubber (GTR), or polyphosphoric acid (PPA),” *Construction and Building Materials*, vol. 151, pp. 464–478, 2017.

[91] J. Ponniah and G. Kennepohl, “Polymer-modified asphalt pavements in Ontario: Performance and cost-effectiveness,” *Transportation research record*, vol. 1545, no. 1, pp. 151–160, 1996.

[92] J. F. Masson, G. M. Polomark, and P. Collins, “Time-dependent microstructure of bitumen and its fractions by modulated differential scanning calorimetry,” *Energy & Fuels*, vol. 16, no. 2, pp. 470–476, 2002.

[93] J. Brandrup, E. H. Immergut, and E. A. Grulke, “Polymer Handbook, John & Wiley Sons,” *Inc., New York*, pp. 171–186, 1999.

[94] N. Z. Habib, I. Kamaruddin, and M. Napiah, “Compatibility of Plastomeric Modified Bituminous Blends: Its Effect on the Performance Behavior of Modified Bituminous Mixture,” in *InCIEC 2014*, R. Hassan, M. Yusoff, A. Alisibramulisi, N. Mohd Amin, and Z. Ismail, Eds., Singapore: Springer Singapore, 2015, pp. 915–925.

[95] B. Singh, L. Kumar, M. Gupta, and G. S. Chauhan, “Polymer-modified bitumen of recycled LDPE and maleated bitumen,” *Journal of applied polymer science*, vol. 127, no. 1, pp. 67–78, 2013.

[96] N. Ali, S. Zahran, J. Trogdon, and A. Bergan, “A mechanistic evaluation of modified asphalt paving mixtures,” *Canadian Journal of Civil Engineering*, vol. 21, no. 6, pp. 954–965, 1994.

[97] C. Fang *et al.*, “Preparation, characterization and hot storage stability of asphalt modified by waste polyethylene packaging,” *Journal of Materials Science & Technology*, vol. 29, no. 5, pp. 434–438, 2013.

[98] A. Pérez-Lepe, F. J. Martınez-Boza, C. Gallegos, O. González, M. E. Munoz, and A. Santamarıa, “Influence of the processing conditions on the rheological behaviour of polymer-modified bitumen☆,” *Fuel*, vol. 82, no. 11, pp. 1339–1348, 2003.

[99] F. J. Navarro, P. Partal, F. J. Martínez-Boza, and C. Gallegos, “Influence of processing conditions on the rheological behavior of crumb tire rubber-modified bitumen,” *Journal of applied polymer science*, vol. 104, no. 3, pp. 1683–1691, 2007.

[100] Z. You *et al.*, “Nanoclay-modified asphalt materials: Preparation and characterization,” *Construction and Building Materials*, vol. 25, no. 2, pp. 1072–1078, 2011.

[101] E. A. P. Association, “The use of Warm-Mix Asphalt: EAPA–Position Paper,” *Brussels, Belgium, available on www. eapa. org/userfiles/2/Asphalt-WMA/EAPA Position Paper-WMA–version October*, 2014.

[102] T. Baghaee Moghaddam and H. Baaj, “The use of rejuvenating agents in production of recycled hot mix asphalt: A systematic review,” *Construction and Building Materials*, vol. 114, pp. 805–816, Jul. 2016, doi: 10.1016/j.conbuildmat.2016.04.015.

[103] O. González *et al.*, “Rheological Techniques as a Tool To Analyze Polymer− Bitumen Interactions: Bitumen Modified with Polyethylene and Polyethylene-Based Blends,” *Energy & fuels*, vol. 16, no. 5, pp. 1256–1263, 2002.

[104] S. Satapathy, A. Nag, and G. B. Nando, “Thermoplastic elastomers from waste polyethylene and reclaim rubber blends and their composites with fly ash,” *Process Safety and Environmental Protection*, vol. 88, no. 2, pp. 131–141, 2010.

[105] Y. Becker, M. P. Mendez, and Y. Rodriguez, “Polymer modified asphalt,” in *Vision tecnologica*, Citeseer, 2001.

[106] D. Casey, C. McNally, A. Gibney, and M. D. Gilchrist, “Development of a recycled polymer modified binder for use in stone mastic asphalt,” *Resources, Conservation and Recycling*, vol. 52, no. 10, pp. 1167–1174, 2008.

[107] C. Fang, R. Yu, Y. Zhang, J. Hu, M. Zhang, and X. Mi, “Combined modification of asphalt with polyethylene packaging waste and organophilic montmorillonite,” *Polymer Testing*, vol. 31, no. 2, pp. 276–281, 2012.

[108] C. Maharaj, R. Maharaj, and J. Maynard, “The effect of polyethylene terephthalate particle size and concentration on the properties of asphalt and bitumen as an additive,” *Progress in Rubber Plastics and Recycling Technology*, vol. 31, no. 1, pp. 1–23, 2015.

[109] S. Wang, C. Yuan, and D. Jiaxi, “Crumb tire rubber and polyethylene mutually stabilized in asphalt by screw extrusion,” *Journal of Applied Polymer Science*, vol. 131, no. 23, 2014.

[110] K. Yan, H. Xu, and L. You, “Rheological properties of asphalts modified by waste tire rubber and reclaimed low density polyethylene,” *Construction and Building Materials*, vol. 83, pp. 143–149, 2015.

[111] Y. Kim and T.-S. Park, “Reinforcement of recycled foamed asphalt using short polypropylene fibers,” *Advances in Materials Science and Engineering*, vol. 2013, 2013.

[112] M. A. Dalhat, H. I. Al-Abdul Wahhab, and K. Al-Adham, “Recycled Plastic Waste Asphalt Concrete via Mineral Aggregate Substitution and Binder Modification,” *J. Mater. Civ. Eng.*, vol. 31, no. 8, p. 04019134, Aug. 2019, doi: 10.1061/(ASCE)MT.1943-5533.0002744.

[113] I. A. El-Naga and M. Ragab, “Benefits of utilization the recycle polyethylene terephthalate waste plastic materials as a modifier to asphalt mixtures,” *Construction and Building Materials*, vol. 219, pp. 81–90, Sep. 2019, doi: 10.1016/j.conbuildmat.2019.05.172.

[114] S. Ho, R. Church, K. Klassen, B. Law, D. MacLeod, and L. Zanzotto, “Study of recycled polyethylene materials as asphalt modifiers,” *Canadian Journal of Civil Engineering*, vol. 33, no. 8, pp. 968–981, 2006, doi: 10.1139/L06-044.

[115] D. Jubinville, E. Esmizadeh, S. Saikrishnan, C. Tzoganakis, and T. Mekonnen, “A comprehensive review of global production and recycling methods of polyolefin (PO) based products and their post-recycling applications,” *Sustainable Materials and Technologies*, vol. 25, p. e00188, Sep. 2020, doi: 10.1016/j.susmat.2020.e00188.

[116] D. X. Lu, M. Enfrin, Y. J. Boom, and F. Giustozzi, “Future recyclability of hot mix asphalt containing recycled plastics,” *Construction and Building Materials*, vol. 368, p. 130396, Mar. 2023, doi: 10.1016/j.conbuildmat.2023.130396.

[117] R. Vasudevan, A. Ramalinga Chandra Sekar, B. Sundarakannan, and R. Velkennedy, “A technique to dispose waste plastics in an ecofriendly way - Application in construction of flexible pavements,” *Construction and Building Materials*, vol. 28, no. 1, pp. 311–320, 2012, doi: 10.1016/j.conbuildmat.2011.08.031.

[118] Paul Ridden, “The streets of Vancouver are paved with ... recycled plasticNo Title,” *New Atlas*, 2012. https://newatlas.com/vancouver-recycled-plastic-warm-mix-asphalt/25254/

[119] G. White and G. Reid, “Recycled waste plastic for extending and modifying asphalt binders,” in *8th Symposium on Pavement Surface Characteristics (SURF)*, Brisbane, Queensland, Australia: ARRB Group Ltd, 2018, pp. 1–13.

[120] C. Chin and P. Damen, *Viability of using recycled plastics in asphalt and sprayed sealing applications*, no. AP-T351-19. 2019.

[121] L. W. McKeen, “Introduction to Plastics and Polymers,” in *Film Properties of Plastics and Elastomers*, 4th ed.The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, United Kingdom: Elsevier, 2017, pp. 1–24.

[122] J. Jeffery, “Manufacturing Methods and The Impact of Moisture on Plastic Resins”.

[123] M. Aurilio, A. Qabur, P. Mikhailenko, and H. Baaj, “Comparing the Fatigue Performance of HMA Samples with PMA to their Multiple Stress Creep Recovery and Double Notched Tension

Test Properties," in *Proceedings of the Sixth-Third Annual Conference of the Canadian Technical Asphalt Association (CTAA)*, Regina, Saskatchewan, Canada: Canadian Technical Asphalt Association 2018, Nov. 2018, p. 26.

[124] D20 Committee, "Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry," ASTM International. doi: 10.1520/D3418-21.

[125] P. Mikhailenko, H. Kadhim, H. Baaj, and S. Tighe, "Observation of asphalt binder microstructure with ESEM," *Journal of Microscopy*, vol. 267, no. 3, pp. 347–355, 2017, doi: 10.1111/jmi.12574.

[126] AASHTO, "T315 Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)," *American Association of State Highway and Transportation Officials*, 2012.

[127] D04 Committee, "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer," ASTM International, 2008. doi: 10.1520/D7175-08.

[128] Y. Yildirim, "Polymer modified asphalt binders," *Construction and Building Materials*, vol. 21, no. 1, pp. 66–72, 2007.

[129] Y. Zheng, Z. Shen, C. Cai, S. Ma, and Y. Xing, "The reuse of nonmetals recycled from waste printed circuit boards as reinforcing fillers in the polypropylene composites," *Journal of Hazardous Materials*, vol. 163, no. 2–3, pp. 600–606, 2009.

[130] X. Xu *et al.*, "Sustainable Practice in Pavement Engineering through Value-Added Collective Recycling of Waste Plastic and Waste Tyre Rubber," *Engineering*, vol. 7, no. 6, pp. 857–867, Jun. 2021, doi: 10.1016/j.eng.2020.08.020.

[131] S. Wang, C. Yuan, and D. Jiaxi, "Crumb tire rubber and polyethylene mutually stabilized in asphalt by screw extrusion," *J. Appl. Polym. Sci.*, vol. 131, no. 23, p. 7, Dec. 2014, doi: 10.1002/app.41189.

[132] C. Fang *et al.*, "Preparation, Characterization and Hot Storage Stability of Asphalt Modified by Waste Polyethylene Packaging," *Journal of Materials Science and Technology*, vol. 29, no. 5, pp. 434–438, 2013, doi: 10.1016/j.jmst.2013.02.016.

[133] M. R. M. Hasan, B. Colbert, Z. You, A. Jamshidi, P. A. Heiden, and M. O. Hamzah, "A simple treatment of electronic-waste plastics to produce asphalt binder additives with improved properties," *Construction and Building Materials*, vol. 110, pp. 79–88, 2016.

[134] C. Fang, M. Zhang, R. Yu, and X. Liu, "Effect of preparation temperature on the aging properties of waste polyethylene modified asphalt," *Journal of Materials Science & Technology*, vol. 31, no. 3, pp. 320–324, 2015.

[135] R. Yu, C. Fang, P. Liu, X. Liu, and Y. Li, "Storage stability and rheological properties of asphalt modified with waste packaging polyethylene and organic montmorillonite," *Applied Clay Science*, vol. 104, pp. 1–7, 2015, doi: 10.1016/j.clay.2014.11.033.

[136] M. Arabani and M. Pedram, "Laboratory investigation of rutting and fatigue in glassphalt containing waste plastic bottles," *Construction and Building Materials*, vol. 116, pp. 378–383, 2016, doi: 10.1016/j.conbuildmat.2016.04.105.

[137] B. Yu, L. Jiao, F. Ni, and J. Yang, "Evaluation of plastic-rubber asphalt: Engineering property and environmental concern," *Construction and Building Materials*, vol. 71, pp. 416–424, 2014, doi: 10.1016/j.conbuildmat.2014.08.075.

[138] A. Behl, G. Sharma, and G. Kumar, "A sustainable approach: Utilization of waste PVC in asphalting of roads," *Construction and Building Materials*, vol. 54, pp. 113–117, 2014, doi: 10.1016/j.conbuildmat.2013.12.050.

[139] E. S. Okhotnikova, Y. M. Ganeeva, I. N. Frolov, T. N. Yusupova, and A. A. Firsin, “Plastic properties and structure of bitumen modified by recycled polyethylene,” *Petroleum Science and Technology*, vol. 36, no. 5, pp. 356–360, 2018.

[140] P. Mikhailenko, H. Kadhim, H. Baaj, and S. Tighe, “Observation of asphalt binder microstructure with ESEM,” *Journal of Microscopy*, vol. 267, no. 3, pp. 347–355, 2017, doi: 10.1111/jmi.12574.

[141] AASHTO, “T 316 Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer,” American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, USA, 2013.

[142] AASHTO, “T324 Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures,” American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, USA, 2014.

[143] AASHTO, “M 332 Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test,” American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, USA, 2018.

[144] C. Hintz, R. Velasquez, C. Johnson, and H. Bahia, “Modification and validation of linear amplitude sweep test for binder fatigue specification,” *Transportation Research Record*, no. 2207, pp. 99–106, 2011, doi: 10.3141/2207-13.

[145] C. Hintz and H. Bahia, “Simplification of linear amplitude sweep test and specification parameter,” *Transportation research record*, vol. 2370, no. 1, pp. 10–16, 2013.

[146] N. I. Nur, D. Mounier, G. Marc-Stéphane, M. Rosli Hainin, G. D. Airey, and H. Di Benedetto, “Modelling the rheological properties of bituminous binders using the 2S2P1D Model,” *Construction and Building Materials*, vol. 38, pp. 395–406, 2013, doi: 10.1016/j.conbuildmat.2012.08.038.

[147] ASTM, “D7173 Standard Practice for Determining the Separation Tendency of Polymer from Polymer Modified Asphalt,” ASTM International, West Conshohocken, PA, USA, ASTM Standards D7173, May 2020. doi: 10.1520/D7173-20.

[148] K. L. Roja, A. Rehman, M. Ouederni, S. K. Krishnamoorthy, A. Abdala, and E. Masad, “Influence of polymer structure and amount on microstructure and properties of polyethylene-modified asphalt binders,” *Materials and Structures/Materiaux et Constructions*, vol. 54, no. 2, pp. 1–17, 2021, doi: 10.1617/s11527-021-01683-0.

[149] J. Youtcheff, N. Wijayatilleke, and A. Shenoy, “Evaluation of the Laboratory Asphalt Stability Test (NCHRP) 9-10,” Federal Highway Administration, 6300 Georgetown Pike McLean, VA, USA, Tech FHWA-HRT-04-111, 2005.

[150] A. Behnood and M. M. Gharehveran, “Morphology, rheology, and physical properties of polymer-modified asphalt binders,” *European Polymer Journal*, vol. 112, pp. 766–791, 2019.

[151] J. A. Deacon, J. T. Harvey, A. Tayebali, and C. L. Monismith, “Influence of Binder Loss Modulus on the Fatigue Performance of Asphalt Concrete Pavements,” in *Asphalt Paving Technology 1997*, Salt Lake City, Utah, USA: Association of Asphalt Paving Technologists (AAPT), Mar. 1997, pp. 633–685. [Online]. Available: https://www.asphalttechnology.org/site_page.cfm?pk_association_webpage_menu=9169&pk_association_webpage=19109

[152] J.-S. Chen and C.-J. Tsai, “How Good Are Linear Viscoelastic Properties of Asphalt Binder to Predict Rutting and Fatigue Cracking?,” *Journal of Materials Engineering and Performance*, vol. 8, no. 4, pp. 443–449, Aug. 1999, doi: 10.1361/105994999770346747.

[153] H. Di Benedetto, F. Olard, C. Sauzéat, and B. Delaporte, "Linear viscoelastic behaviour of bituminous materials: From binders to mixes," *Road Materials and Pavement Design*, vol. 5, no. sup1, pp. 163–202, 2004.

[154] F. Zhou, W. Mogawer, H. Li, A. Andriescu, and A. Copeland, "Evaluation of Fatigue Tests for Characterizing Asphalt Binders," *J. Mater. Civ. Eng.*, vol. 25, no. 5, pp. 610–617, May 2013, doi: 10.1061/(ASCE)MT.1943-5533.0000625.

[155] A. Subhy, "Advanced analytical techniques in fatigue and rutting related characterisations of modified bitumen: Literature review," *Construction and Building Materials*, vol. 156, pp. 28–45, Dec. 2017, doi: 10.1016/j.conbuildmat.2017.08.147.

[156] OPSS, "MUNI 1150 Municipal Material Specifications, Hot Mix Asphalt," ONTARIO PROVINCIAL STANDARD SPECIFICATION, 57 Mill Street N., Suite 308 Brampton ON L6X 1S9, Canada, Nov. 2018. Accessed: Jan. 01, 2022. [Online]. Available: https://www.roadauthority.com/Standards/

[157] M. Sabouri, D. Mirzaeian, and A. Moniri, "Effectiveness of Linear Amplitude Sweep (LAS) asphalt binder test in predicting asphalt mixtures fatigue performance," *Construction and Building Materials*, vol. 171, pp. 281–290, 2018, doi: 10.1016/j.conbuildmat.2018.03.146.

[158] J. D. Ferry, *Viscoelastic properties of polymers*. Hoboken, NJ, USA: John Wiley & Sons, 1980.

[159] A. M. Rodríguez-Alloza, J. Gallego, and F. Giuliani, "Complex shear modulus and phase angle of crumb rubber modified binders containing organic warm mix asphalt additives," *Mater Struct*, vol. 50, no. 1, p. 77, Feb. 2017, doi: 10.1617/s11527-016-0950-1.

[160] M. R. Kakar, P. Mikhailenko, Z. Piao, M. Bueno, and L. Poulikakos, "Analysis of waste polyethylene (PE) and its by-products in asphalt binder," *Construction and Building Materials*, vol. 280, p. 122492, Apr. 2021, doi: 10.1016/j.conbuildmat.2021.122492.

[161] A. A. Yousefi, "Polyethylene Dispersions in Bitumen: The Effects of the Polymer Structural Parameters," *Journal of Applied Polymer Science*, vol. 90, no. 12, pp. 3183–3190, 2003, doi: 10.1002/app.12942.

[162] A. Shalaby, "Analytical and experimental investigation of thermal cracking in asphalt pavements.," Doctor of Philosophy, Carleton University, Ottawa, Ontario, 1997. doi: 10.22215/etd/1997-03582.

[163] L. Xiang, J. Cheng, and S. Kang, "Thermal oxidative aging mechanism of crumb rubber/SBS composite modified asphalt," *Construction and Building Materials*, vol. 75, pp. 169–175, Jan. 2015, doi: 10.1016/j.conbuildmat.2014.08.035.

[164] A. Hamid, H. Alfaidi, H. Baaj, and M. El-Hakim, "Evaluating Fly Ash-Based Geopolymers as a Modifier for Asphalt Binders," *Advances in Materials Science and Engineering*, vol. 2020, pp. 1–11, Feb. 2020, doi: 10.1155/2020/2398693.

[165] D. Zhang *et al.*, "Chemical characteristics analyze of SBS-modified bitumen containing composite nanomaterials after aging by FTIR and GPC," *Construction and Building Materials*, vol. 324, p. 126522, Mar. 2022, doi: 10.1016/j.conbuildmat.2022.126522.

[166] A. A. Yousefi, "Rubber-polyethylene Modified Bitumens," *Iranian Polymer Journal (English Edition)*, vol. 13, no. 2, pp. 101–112, 2004.

[167] A. I. Al-Hadidy and T. Yi-qiu, "Effect of polyethylene on life of flexible pavements," *Construction and Building Materials*, vol. 23, no. 3, pp. 1456–1464, 2009, doi: 10.1016/j.conbuildmat.2008.07.004.

[168] M. Attaelmanan, C. P. Feng, and A. I. Al-Hadidy, "Laboratory evaluation of HMA with high density polyethylene as a modifier," *Construction and Building Materials*, vol. 25, no. 5, pp. 2764–2770, 2011.

[169] C. Fang *et al.*, “Pavement Properties of Asphalt Modified With Packaging-Waste Polyethylene,” 2014, doi: 10.1002/vnl.

[170] F. Yin, R. Moraes, M. Fortunatus, N. Tran, and M. Elwardany, “Performance evaluation and chemical characterization of asphalt binders and mixtures containing recycled polyethylene,” p. 45, 2020.

[171] C. Valkering and D. Jongeneel, “Acoustic emission for evaluating the relative performance of asphalt mixes under thermal loading conditions (with discussion),” *Journal of the Association of Asphalt Paving Technologists*, vol. 60, 1991.

[172] L. Wuennenberg and C. M. Tan, “Plastic Waste in Canada :,” vol. 3, no. July, pp. 2019–2022, 2019.

[173] M. Gürü, M. K. Çubuk, D. Arslan, S. A. Farzanian, and I. Bilici, “An approach to the usage of polyethylene terephthalate (PET) waste as roadway pavement material,” *Journal of Hazardous Materials*, vol. 279, pp. 302–310, 2014, doi: 10.1016/j.jhazmat.2014.07.018.

[174] S. Amirkhanian, “Investigations of Rheological Properties of Asphalt Binders Modified with Scrap Polyethylenes Report Prepared for: Ms. Kim Holmes Vice President, Sustainability Plastics Industry Association,” no. November, 2018.

[175] AASHTO, “M 320 Standard Specification for Performance-Graded Asphalt Binder,” American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, USA, 2019.

[176] S. Liu, W. Cao, S. Shang, H. Qi, and J. Fang, “Analysis and application of relationships between low-temperature rheological performance parameters of asphalt binders,” *Construction and Building Materials*, vol. 24, no. 4, pp. 471–478, 2010.

[177] P. Blankenship, R. M. Anderson, G. N. King, and D. I. Hanson, “AIRFIELD ASPHALT PAVEMENT TECHNOLOGY PROGRAM (AAPTP),” 2010.

[178] FHWA-HIF-21-042, “Delta Tc Binder Specification Parameter.” Federal Highway Administration (FHWA), 2021.

[179] T. Pellinen and S. Xiao, “Stiffness of Hot-Mix Asphalt,” Purdue University, West Lafayette, IN, FHWA/IN/JTRP-2005/20, 2644, 2006. doi: 10.5703/1288284313390.

[180] G. Rowe, G. Baumgardner, and M. Sharrock, “Functional forms for master curve analysis of bituminous materials,” in *Advanced Testing and Characterization of Bituminous Materials*, A. Loizos, M. Partl, T. Scarpas, and I. Al-Qadi, Eds., CRC Press, 2009. doi: 10.1201/9780203092989.ch9.

[181] T. K. Pellinen, M. W. Witczak, and R. F. Bonaquist, “Asphalt Mix Master Curve Construction Using Sigmoidal Fitting Function with Non-Linear Least Squares Optimization,” in *Recent Advances in Materials Characterization and Modeling of Pavement Systems*, Columbia University, New York, United States: American Society of Civil Engineers, Dec. 2003, pp. 83–101. doi: 10.1061/40709(257)6.

[182] N. I. Md. Yusoff, M. T. Shaw, and G. D. Airey, “Modelling the linear viscoelastic rheological properties of bituminous binders,” *Construction and Building Materials*, vol. 25, no. 5, pp. 2171–2189, May 2011, doi: 10.1016/j.conbuildmat.2010.11.086.

[183] M. L. Williams, R. F. Landel, and J. D. Ferry, “The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-forming Liquids,” *Journal of the American Chemical Society*, vol. 77, no. 14, pp. 3701–3707, 1955, doi: 10.1021/ja01619a008.

[184] A. A. Butt, *Low temperature performance of wax modified mastic asphalt*. 2009.

[185] K. L. Roja, A. Rehman, M. Ouederni, S. K. Krishnamoorthy, A. Abdala, and E. Masad, “Influence of polymer structure and amount on microstructure and properties of polyethylene-

modified asphalt binders," *Materials and Structures/Materiaux et Constructions*, vol. 54, no. 2, pp. 1–17, 2021, doi: 10.1617/s11527-021-01683-0.

[186] L. W. McKeen, "1-Introduction to plastics, polymers, and their properties,"," *The Effect of Temperature and other Factors on Plastics and Elastomers*, pp. 1–45, 2014.

[187] X. Lu and U. Isacsson, "Effect of Binder Rheology on the Low-Temperature Cracking of Asphalt Mixtures," *Road Materials and Pavement Design*, vol. 2, no. 1, pp. 29–47, Jan. 2001, doi: 10.1080/14680629.2001.9689893.

[188] Technical Activities Division, Transportation Research Board, and National Academies of Sciences, Engineering, and Medicine, *Development in Asphalt Binder Specifications*. Washington, D.C.: Transportation Research Board, 2010, p. 22903. doi: 10.17226/22903.

[189] D. J. Mensching, G. M. Rowe, J. S. Daniel, and T. Bennert, "Exploring low-temperature performance in Black Space," *Road Materials and Pavement Design*, vol. 16, no. sup2, pp. 230–253, Aug. 2015, doi: 10.1080/14680629.2015.1077015.

[190] P. Romero, "Using the bending beam rheometer for low temperature testing of asphalt mixtures : final report.," no. UT-16.09, Jul. 2016, [Online]. Available: https://rosap.ntl.bts.gov/view/dot/31113

[191] A. Abed, N. Thom, D. Lo Presti, and G. Airey, "Thermo-rheological analysis of WMA-additive modified binders," *Mater Struct*, vol. 53, no. 3, p. 52, Jun. 2020, doi: 10.1617/s11527-020-01480-1.

[192] H. K. Kanerva, T. S. Vinson, and H. Zeng, *Low-temperature cracking: Field validation of the thermal stress restrained specimen test*. 1994.

[193] T. B. Moghaddam and H. Baaj, "Rheological characterization of high-modulus asphalt mix with modified asphalt binders," *Construction and Building Materials*, vol. 193, pp. 142–152, Dec. 2018, doi: 10.1016/j.conbuildmat.2018.10.194.

[194] H. Baaj, P. Mikhailenko, H. Almutairi, and H. Di Benedetto, "Recovery of asphalt mixture stiffness during fatigue loading rest periods," *Construction and Building Materials*, vol. 158, pp. 591–600, Jan. 2018, doi: 10.1016/j.conbuildmat.2017.10.016.

[195] S. Angelone, F. Martinez, and M. Cauhape Casaux, "A Comparative Study of Bituminous Mixtures with Recycled Polyethylene Added by Dry and Wet Processes," in *8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials*, F. Canestrari and M. N. Partl, Eds., in RILEM Bookseries, vol. 11. Dordrecht: Springer Netherlands, 2016, pp. 583–594. doi: 10.1007/978-94-017-7342-3_47.

[196] B. Mishra and M. K. Gupta, "Use of plastic waste in bituminous mixes by wet and dry methods," presented at the Proceedings of the Institution of Civil Engineers-Municipal Engineer, Thomas Telford Ltd, 2020, pp. 87–97.

[197] Y. Ma *et al.*, "The utilization of waste plastics in asphalt pavements: A review," *Cleaner Materials*, vol. 2, p. 100031, Dec. 2021, doi: 10.1016/j.clema.2021.100031.

[198] A. Kumar, R. Choudhary, and A. Kumar, "Characterization of thermal storage stability of waste plastic pyrolytic char modified asphalt binders with sulfur," *PLoS ONE*, vol. 16, no. 3, p. e0248465, Mar. 2021, doi: 10.1371/journal.pone.0248465.

[199] F. J. Navarro, P. Partal, F. Martínez-Boza, C. Valencia, and C. Gallegos, "Rheological characteristics of ground tire rubber-modified bitumens," *Chemical Engineering Journal*, vol. 89, no. 1–3, pp. 53–61, Oct. 2002, doi: 10.1016/S1385-8947(02)00023-2.

[200] M. Garcia-Morales, P. Partal, F. J. Navarro, and C. Gallegos, "Effect of waste polymer addition on the rheology of modified bitumen," *Fuel*, vol. 85, no. 7–8, pp. 936–943, 2006.

[201] N. M. Reddy and M. C. Venkatasubbaiah, “Effects of high density polyethylene and crumb rubber powder on properties of asphalt mix,” vol. 04, no. 06, 2017.

[202] H. A. A. Gibreil and C. P. Feng, “Effects of high-density polyethylene and crumb rubber powder as modifiers on properties of hot mix asphalt,” *Construction and Building Materials*, vol. 142, pp. 101–108, Jul. 2017, doi: 10.1016/j.conbuildmat.2017.03.062.

[203] S. Nizamuddin, M. Jamal, R. Gravina, and F. Giustozzi, “Recycled plastic as bitumen modifier: The role of recycled linear low-density polyethylene in the modification of physical, chemical and rheological properties of bitumen,” *Journal of Cleaner Production*, vol. 266, p. 121988, Sep. 2020, doi: 10.1016/j.jclepro.2020.121988.

[204] C. Fang, M. Zhang, R. Yu, and X. Liu, “Effect of Preparation Temperature on the Aging Properties of Waste Polyethylene Modified Asphalt,” *Journal of Materials Science and Technology*, vol. 31, no. 3, pp. 320–324, 2015, doi: 10.1016/j.jmst.2014.04.019.

[205] J. A. D’Angelo, “The Relationship of the MSCR Test to Rutting,” *Road Materials and Pavement Design*, vol. 10, no. sup1, pp. 61–80, Jan. 2009, doi: 10.1080/14680629.2009.9690236.

[206] M. Aurilio, P. Mikhailenko, and H. BAAJ, “Predicting HMA Fatigue Using the Double Edge Notched Tension Test and Multiple Stress Creep Recovery Test,” in *Proceedings of the Sixth-Second Annual Conference of the Canadian Technical Asphalt Association (CTAA): Halifax, Nova Scotia*, 2017.

[207] A. T. 316-13, “Standard method of test for viscosity determination of asphalt binder using rotational viscometer.” American Association of State and Highway Transportation Officials …, 2013.

[208] AASHTO, “T342 Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixture,” American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, USA, 2011.

[209] G. Vasiliu, S. Tabib, and I. Bashir, “MTO Perspectives on Performance Testing,” presented at the 2020 OAPC Asphalt Technical Symposium Webinar, Jun. 16, 2020. [Online]. Available: https://orba.org/wp-content/uploads/2020/07/2020-ATS_Gelu-V.-Seyed-T.-Imran-.B._MTO-Perspectives-on-Performance-Testing.pdf

[210] S. S. Ashani, “Development of Performance-Related Specifications for Asphalt Mixtures in Ontario”.

[211] Iowa Department of Transportation, “MOISTURE SENSITIVITY TESTING OF ASPHALT MIXTURES,” 2013. https://www.iowadot.gov/erl/current/im/content/319.htm

[212] T. G. Mezger, *Applied rheology: with Joe flow on rheology road*. Anton Paar, 2015.

[213] M. Stroup-Gardiner and D. Newcomb, “POLYMER LITERATURE REVIEW. INTERIM REPORT,” 1995.

[214] M. Naskar, T. K. Chaki, and K. S. Reddy, “Effect of waste plastic as modifier on thermal stability and degradation kinetics of bitumen/waste plastics blend,” *Thermochimica Acta*, vol. 509, no. 1–2, pp. 128–134, 2010.

[215] X. Yang and Z. You, “High temperature performance evaluation of bio-oil modified asphalt binders using the DSR and MSCR tests,” *Construction and Building Materials*, vol. 76, pp. 380–387, 2015, doi: 10.1016/j.conbuildmat.2014.11.063.

[216] S. Haider, I. Hafeez, Jamal, and R. Ullah, “Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures,” *Construction and Building Materials*, vol. 235, p. 117496, Feb. 2020, doi: 10.1016/j.conbuildmat.2019.117496.

[217] M. Fonseca, S. Capitão, A. Almeida, and L. Picado-Santos, “Influence of Plastic Waste on the Workability and Mechanical Behaviour of Asphalt Concrete,” *Applied Sciences*, vol. 12, no. 4, p. 2146, Feb. 2022, doi: 10.3390/app12042146.

[218] H. Wen, S. Wu, L. N. Mohammad, W. Zhang, S. Shen, and A. Faheem, “Long-Term Field Rutting and Moisture Susceptibility Performance of Warm-Mix Asphalt Pavement,” *Transportation Research Record*, vol. 2575, no. 1, pp. 103–112, Jan. 2016, doi: 10.3141/2575-11.

[219] J. A. D’Angelo, “The Relationship of the MSCR Test to Rutting,” *Road Materials and Pavement Design*, vol. 10, no. sup1, pp. 61–80, Jan. 2009, doi: 10.1080/14680629.2009.9690236.

[220] T. L. J. Wasage, J. Stastna, and L. Zanzotto, “Rheological analysis of multi-stress creep recovery (MSCR) test,” *International Journal of Pavement Engineering*, vol. 12, no. 6, pp. 561–568, Dec. 2011, doi: 10.1080/10298436.2011.573557.

[221] J. Zhang, L. F. Walubita, A. N. M. Faruk, P. Karki, and G. S. Simate, “Use of the MSCR test to characterize the asphalt binder properties relative to HMA rutting performance – A laboratory study,” *Construction and Building Materials*, vol. 94, pp. 218–227, Sep. 2015, doi: 10.1016/j.conbuildmat.2015.06.044.

[222] P. K. Gautam, P. Kalla, A. S. Jethoo, R. Agrawal, and H. Singh, “Sustainable use of waste in flexible pavement: A review,” *Construction and Building Materials*, vol. 180, pp. 239–253, Aug. 2018, doi: 10.1016/j.conbuildmat.2018.04.067.

[223] I. M. Khan, S. Kabir, M. A. Alhussain, and F. F. Almansoor, “Asphalt Design Using Recycled Plastic and Crumb-rubber Waste for Sustainable Pavement Construction,” *Procedia Engineering*, vol. 145, pp. 1557–1564, 2016, doi: 10.1016/j.proeng.2016.04.196.

[224] and et all A. C. Strynadka Hugh Donovan, Keith Maclnnis, Todd, *Hot Mix Asphalt*. West Kelowna, BC, Canada: Canadian Technical Asphalt Association, 2018. [Online]. Available: https://www.ctaa.ca

[225] M. Arabani and M. Pedram, “Laboratory investigation of rutting and fatigue in glassphalt containing waste plastic bottles,” *Construction and Building Materials*, vol. 116, pp. 378–383, 2016, doi: 10.1016/j.conbuildmat.2016.04.105.

[226] A. Behl, G. Sharma, and G. Kumar, “A sustainable approach: Utilization of waste PVC in asphalting of roads,” *Construction and Building Materials*, vol. 54, pp. 113–117, 2014, doi: 10.1016/j.conbuildmat.2013.12.050.

[227] L. N. Mohammad, S. B. Cooper, and M. A. Elseifi, “Characterization of HMA Mixtures Containing High Reclaimed Asphalt Pavement Content with Crumb Rubber Additives,” *J. Mater. Civ. Eng.*, vol. 23, no. 11, pp. 1560–1568, Nov. 2011, doi: 10.1061/(ASCE)MT.1943-5533.0000359.

[228] R. Yu, C. Fang, P. Liu, X. Liu, and Y. Li, “Storage stability and rheological properties of asphalt modified with waste packaging polyethylene and organic montmorillonite,” *Applied Clay Science*, vol. 104, pp. 1–7, 2015, doi: 10.1016/j.clay.2014.11.033.

[229] G. Polacco, S. Berlincioni, D. Biondi, J. Stastna, and L. Zanzotto, “Asphalt modification with different polyethylene-based polymers,” *European polymer journal*, vol. 41, no. 12, pp. 2831–2844, 2005.

[230] D. Lo Presti, “Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review,” *Construction and Building Materials*, vol. 49, pp. 863–881, Dec. 2013, doi: 10.1016/j.conbuildmat.2013.09.007.

[231] T. R. Herráiz, J. I. R. Herráiz, L. M. Domingo, and F. C. Domingo, “Posidonia oceanica used as a new natural fibre to enhance the performance of asphalt mixtures,” *Construction and Building Materials*, vol. 102, pp. 601–612, 2016, doi: 10.1016/j.conbuildmat.2015.10.193.

[232] A. Modarres and H. Hamedi, “Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes,” *Materials and Design*, vol. 61, pp. 8–15, 2014, doi: 10.1016/j.matdes.2014.04.046.

[233] A. Modarres and H. Hamedi, “Developing laboratory fatigue and resilient modulus models for modified asphalt mixes with waste plastic bottles (PET),” *Construction and Building Materials*, vol. 68, pp. 259–267, 2014, doi: 10.1016/j.conbuildmat.2014.06.054.

[234] T. Baghaee Moghaddam, M. Soltani, and M. R. Karim, “Experimental characterization of rutting performance of Polyethylene Terephthalate modified asphalt mixtures under static and dynamic loads,” *Construction and Building Materials*, vol. 65, pp. 487–494, 2014, doi: 10.1016/j.conbuildmat.2014.05.006.

[235] D. Movilla-Quesada, A. C. Raposeiras, and J. Olavarría, “Effects of Recycled Polyethylene Terephthalate (PET) on Stiffness of Hot Asphalt Mixtures,” *Advances in Civil Engineering*, vol. 2019, 2019.

[236] E. Ahmadinia, M. Zargar, M. R. Karim, M. Abdelaziz, and P. Shafigh, “Using waste plastic bottles as additive for stone mastic asphalt,” *Materials and Design*, vol. 32, no. 10, pp. 4844–4849, 2011, doi: 10.1016/j.matdes.2011.06.016.

[237] S. E. Zoorob and L. B. Suparma, “Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt),” *Cement and Concrete Composites*, vol. 22, no. 4, pp. 233–242, 2000, doi: 10.1016/S0958-9465(00)00026-3.

[238] M. T. Awwad and L. Shbeeb, “The use of polyethylene in hot asphalt mixtures,” *American Journal of Applied Sciences*, vol. 4, no. 6, pp. 390–396, 2007.

[239] P. Lastra-González, M. A. Calzada-Pérez, D. Castro-Fresno, Á. Vega-Zamanillo, and I. Indacoechea-Vega, “Comparative analysis of the performance of asphalt concretes modified by dry way with polymeric waste,” *Construction and Building Materials*, vol. 112, pp. 1133–1140, 2016, doi: 10.1016/j.conbuildmat.2016.02.156.

[240] AASHTO, “R 30 Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA),” *American Association of State Highway and Transportation Officials*, p. 5, 2002.

[241] AASHTO, “T 269 Percent Air Voids in Compacted Dense and Open Asphalt Mixtures,” *American Association of State Highway and Transportation Officials*, p. 5, 2015.

[242] AASHTO, “T 209 Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt (HMA),” *American Association of State Highway and Transportation Officials*, p. 17, 2016.

[243] AASHTO, “T 166 Bulk Specific Gravity (Gmb) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens,” *American Association of State Highway and Transportation Officials*, p. 7, 2016.

[244] *MS-2 Asphalt Mix Design Methods*, Seventh. USA: Asphalt Institute, 2015.

[245] F. Zhou, “Development of an IDEAL cracking test for asphalt mix design, quality control and quality assurance,” *NCHRP-IDEA Program Project Final Report*, no. 195, 2019.

[246] D04 Committee, “Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature,” ASTM International. doi: 10.1520/D8225-19.

[247] J. Habbouche, I. Boz, S. D. Diefenderfer, and Y. K. Bilgic, “Round Robin Testing Program for the indirect tensile cracking test at intermediate temperature: Phase I,” Virginia Transportation Research Council (VTRC), 2021.

[248] AASHTO, “T283 Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage,” *American Association of State Highway and Transportation Officials*, p. 9, 2014.

[249] B. Mataei, H. Zakeri, M. Zahedi, and F. M. Nejad, “Pavement Friction and Skid Resistance Measurement Methods: A Literature Review,” *OJCE*, vol. 06, no. 04, pp. 537–565, 2016, doi: 10.4236/ojce.2016.64046.

[250] W. Meyer and J. Reichert, Eds., *Surface Characteristics of Roadways: International Research and Technologies*. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International, 1990. doi: 10.1520/STP1031-EB.

[251] Yan, Mao, Zhong, Zhang, and Zhang, “Experimental Study on Wet Skid Resistance of Asphalt Pavements in Icy Conditions,” *Materials*, vol. 12, no. 8, p. 1201, Apr. 2019, doi: 10.3390/ma12081201.

[252] J.-D. Brassard, A. Beaulieu, M. M. Tremblay, and G. Momen, “Assessment of Runway Surface Conditions by British Pendulum Testing under the Global Reporting Format Winter Conditions,” *Applied Sciences*, vol. 12, no. 19, p. 9646, Sep. 2022, doi: 10.3390/app12199646.

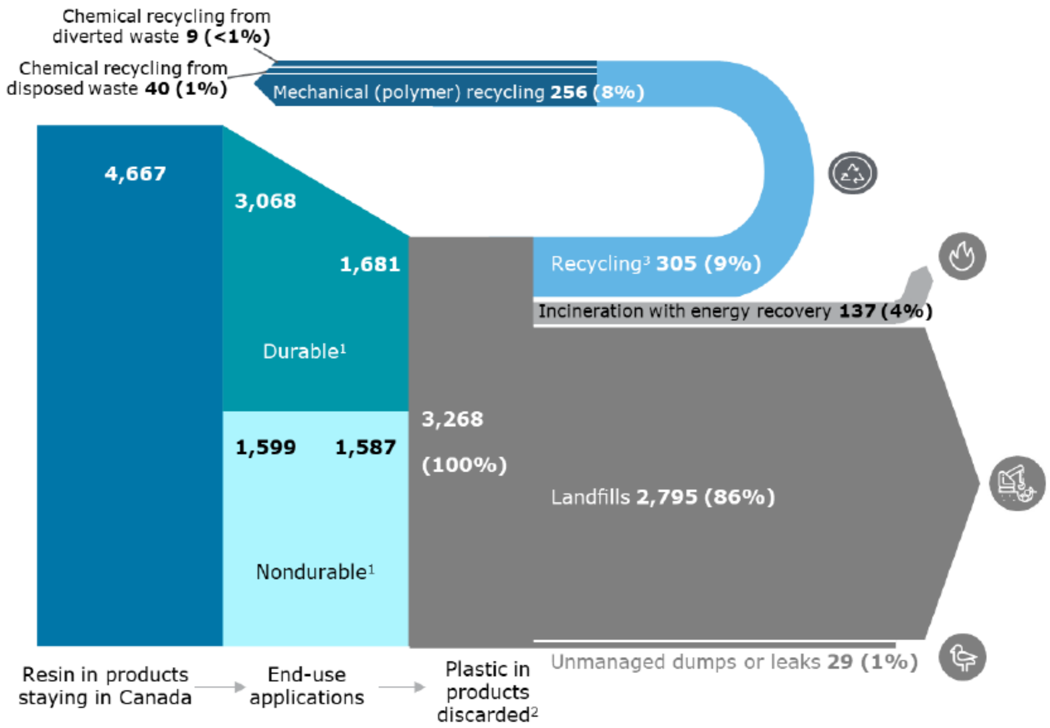
[253] AASHTO, “T278 Standard Method of Test for Surface Frictional Properties Using the British Pendulum Tester,” *American Association of State Highway and Transportation Officials*, p. 9, 1990.

[254] D. Zhao, M. Aurilio, P. Tavassoti, and H. Baaj, “Evaluating IDEAL-CT for Elastomer Modified Asphalt Concrete,” in *Proceedings of the 67th Annual Conference of the Canadian Technical Asphalt Association (CTAA)*, Kelowna BC: Canadian Technical Asphalt Association, 2022.

[255] P. Romero-Zambrana, “Variability of the IDEAL-CT Test for Pavement Cracking to Achieve a Balanced Asphalt Mix Design,” Mountain-Plains Consortium, 2023.

[256] G. White, “EVALUATING RECYCLED WASTE PLASTIC MODIFICATION AND EXTENSION OF BITUMINOUS BINDER FOR ASPHALT,” 2019.

Appendix A: The Canadian Plastics Economy

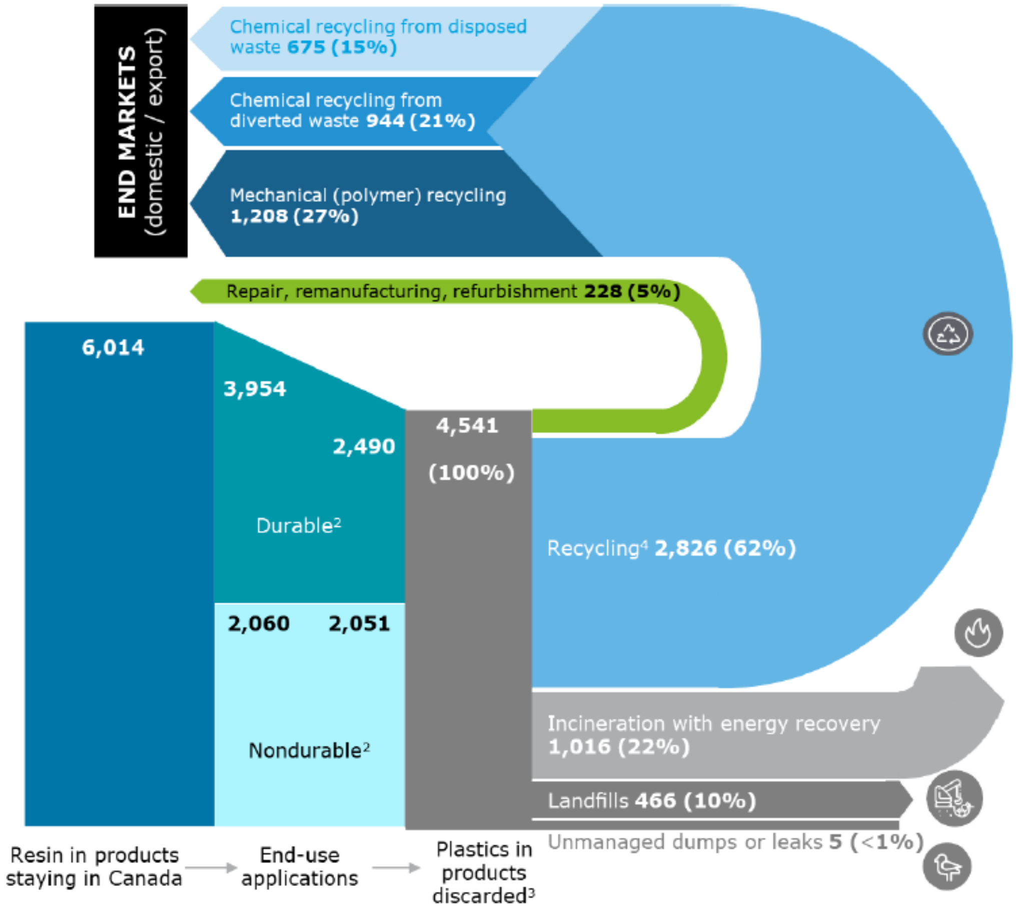


[1] Durable applications with an average lifetime >1 year will end up as waste only in later years; given market growth and increase share of plastics in durable applications (e.g., construction, cars) plastics waste generated today is less than what is being put in the market that same year. On the contrary nondurable applications go almost straight to waste.

[2] 1,587 thousand metric tons of mixed plastic waste from nondurable applications plus 1,681 thousand metric tons of mixed plastic waste from production in previous years.

[3] Output recycling rate, after taking into account process losses.

Canada's annual resin output is measured in thousands of tonnes in 2016 [6]



[1] Scenario based on a multi-stakeholder push to boost recycling, including investment in new facilities, regulatory measures to encourage recycling, significant progress on technologies and favorable end-markets demand.

[2] Durable applications with an average lifetime >1 year will end up as waste only in later years; given market growth and increase share of plastics in durable applications (e.g., construction, cars) plastics waste generated today is less than what is being put in the market that same year. On the contrary nondurable applications go almost straight to waste.

[3] 2,051 thousand metric tons of mixed plastic waste from nondurable applications plus 2,490 thousand metric tons of mixed plastic waste from production in previous years.

[4] Output recycling rate, after taking into account process losses

Scenario for 2030 resin production in Canada in thousands of tonnes [6]

The following table provides a summary of the typical properties of MPP materials [78], [121], [122]

Property	PET	Nylon	PE	MET PET	LDPE
Chemical Resistance	Good resistance to acids and bases, resistant to alcohol, oils, and greases.	Resistant to many solvents, chemicals, and oils. Affected by acids and bases.	Good resistance to acids and bases. Not resistant to organic solvents.	Resistant to many chemicals, solvents, and oils.	Good resistance to acids and bases. Not resistant to organic solvents.
Thermal Conductivity (W/m·K)	0.15-0.24	0.25-0.35	0.4-0.5	0.15-0.25	0.33–0.38
Specific Heat Capacity (J/g·K)	1.3-1.4	1.3-1.5	2.2-2.5	1.2-1.5	1.9–2.5
Flammability	Melts and drips when exposed to flame, self-extinguishing after flame removal.	Melts and burns when exposed to flame, self-extinguishing after flame removal.	Melts and burns when exposed to flame, does not self-extinguish.	Melts and shrinks when exposed to flame, self-extinguishing after flame removal.	Melts and burns when exposed to flame, does not self-extinguish.
Water Absorption (%)	(Less than 0.8)	(Up to 10)	(Less than 0.1)	(Less than 0.5)	(Less than 0.1)
Applications	Beverage bottles, food packaging, polyester fibers, film, and tapes.	Clothing, carpeting, seat belts, and ropes.	Packaging films, shopping bags, and pipes.	Food packaging, industrial films, capacitors, and insulation.	Packaging films, shopping bags, and pipes.

Appendix B: Bituminous Mix Design Report

CTA LAB
Construction Testing Asphalt Lab Ltd.

BITUMINOUS MIX DESIGN REPORT

CONTRACT No.		**HOT MIX TYPE/USE**	**HL3 OPSS**	ITEM No.	
HIGHWAY		**LOCATION**			
PREPARED FOR	**Halton Asphalt Supply Ltd.**	**JOB MIX FORMULA No.** **Issued by Quality Assurance**			
LAB MIX No.	MD21-034	**DATE SAMPLES REC'D**	February 26, 2021		
		DATE COMPLETED	March 23, 2021		
TEST DATA CERTIFIED BY:	**Peter Lung, C.E.T.**	**REVIEWED BY:**	**Ivana Lung, M.Sc., P.Eng.**		

JOB MIX FORMULA - GRADATION PERCENT PASSING

% AC			26.5 mm	19.0 mm	16.0 mm	13.2 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 µm	300 µm	150 µm	75 µm
5.00					100.0	99.5	84.0	54.8	47.5	39.9	34.8	24.0	8.3	3.4

MARSHALL	REQUIREMENTS	SELECTED	% CA#1	47.5	% RAP	
% VOID (min-min)	3.5 - 4.5	4.4	% CA#2		% AC. RAP	
FLOW (min)	8.0	13.0	% FA#1	27.5	% DUST	1.0
STABILTY, N (min)	8,900	11,560	% FA#2	25.0	BRIQ, BRD	2.403
% VMA (min)	15.0	15.6	% FA#3		MRD	2.515
			Gb	2.705	MRD (SD)	

ASPHALT CEMENT		ADDITIVE		
SUPPLIER	PENETRATION	SUPPLIER	TYPE	AS % OF AC
McAsphalt	PG 58 - 28J			

AGGREGATE TYPE	SOURCE / INVENTORY No.	AGGREGATE TYPE	SOURCE / INVENTORY No.
COARSE AGG. # 1	**HL3 Stone, Lincoln, Nelson Aggregate Co.**	FINE AGG. # 2	**TC Sand, Stueher, Waynco**
COARSE AGG. # 2		FINE AGG. # 3	
FINE AGG. # 1	**Asphalt Sand, Stuehler, Waynco**	RAP AGG. # 2	

AGG. TYPE	BULK DENSITY	ABSOR.	AGGREGATE GRADATION - PERCENT PASSING											
			26.5	19.0	16.0	13.2	9.5	4.75	2.36	1.18	600	300	150	75
CA #1	2.691	1.135			100	99.0	66.0	5.0	2.0	1.9	1.8	1.7	1.6	1.5
CA #2														
FA #1	2.735	0.827					100	97.8	76.7	50.5	33.8	19.8	8.0	4.3
FA #2	2.700	1.396						100	99.4	98.0	95.7	68.0	17.5	2.3
FA #3														
RAP														
Plant Dust										100	100	100	100	100

REMARKS:

1) Fines returned to mix. = 1.0 %
2) The briquettes were compacted with a manual hammer 75 blows each face @ 135.0 °C
3) No air voids (SSD) correction is required.
4) Gradations from samples (Checked against process control).
5) MTO, LS and AI MS-2 Procedures followed.
6) This Mix Design is subject to Marshall Compliance Check that may require JMF adjustment.
7) The recommended recompaction temperature = 135.0 °C
8) Typical Briquette weight to achieve 63.5 mm +/- 1.5 = 1235.0 g.
9) The Lab Mixing temperature is = 145.0 °C

MARSHALL MIX DESIGN WORKSHEET

PROJECT No.	
CLIENT	Halton Asphalt Supply Ltd.

DATE:	March 23, 2021
LAB No.	MD21-034

MIX TYPE:	HL3 OPSS
% Passing 4.75 mm:	54.8
% A.C.:	
Gb(Agg.)	2.705
MANUAL 75 BLOWS @	135 °C

BLEND		
47.5	%C.A. # 1	HL3 Stone, Lincoln, Nelson Aggregate Co.
	%C.A. # 2	
27.5	%F.A. # 1	Asphalt Sand, Stuehler, Waynco
25.0	%F.A. # 2	TC Sand, Stueher, Waynco
	%F.A. # 3	
	% RAP	
1.0	% DUST	Plant Dust

				Gmm (MRD) Calculation From Average Gse		
		1	2	3	4	5
Pb	% A.C. Pb	5.0	5.5	4.0	4.5	6.0
Gb(A.C.)	Specific Gravity of A.C. Gb	1.020	1.020	1.020	1.020	1.020
Gmm	Theoretical Max Specific Gravity (MRD)	2.515	2.496	2.554	2.535	2.477
Gse	Effective Specific Gravity -- Calculated	2.725	2.725			
	Average Effective Specific Gravity	2.725		2.725	2.725	2.725

SUMMARY OF MARSHALL TEST RESULTS

% A.C	4.0	4.5	5.0	5.5	6.0
STABILITY @ 60 °C	8993	10965	11560	11934	11509
FLOW (2.5 mm)	12.2	12.4	13.0	13.6	13.8
BULK RELATIVE DENSITY (BRD)	2.361	2.387	2.403	2.412	2.419
MAXIMUM RELATIVE DENSITY (MRD)	2.554	2.535	2.515	2.496	2.477
% AIR VOIDS	7.6	5.8	4.4	3.4	2.3
% V.M.A	16.2	15.7	15.6	15.7	15.9
Gb	2.705				

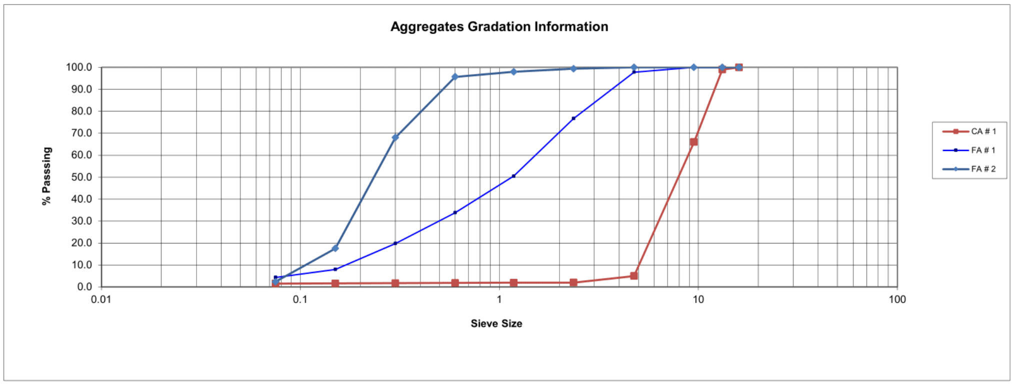
JOB AGGREGATES AND JMF GRADATION CHART

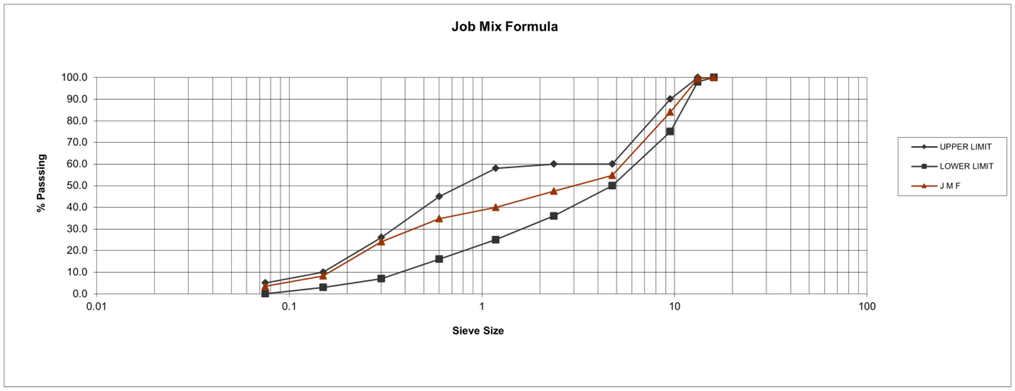
PROJECT No.	
CLIENT	Halton Asphalt Supply Ltd.

DATE:	March 23, 2021
LAB No.	MD21-034

MIX TYPE : HL3 OPSS

AGGERAGATE TYPE	AGGREGATE GRADATION - PERCENT PASSING										
	26.5 mm	19 mm	16.0 mm	13.2 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 µm	300 µm	150 µm	75 µm
CA # 1			100.0	99.0	66.0	5.0	2.0	1.9	1.8	1.7	1.6	1.5
CA # 2												
FA # 1					100.0	97.8	76.7	50.5	33.8	19.8	8.0	4.3
FA # 2						100.0	99.4	98.0	95.7	68.0	17.5	2.3
FA # 3												
RAP												
J M F			**100.0**	**99.5**	**84.0**	**54.8**	**47.5**	**39.9**	**34.8**	**24.0**	**8.3**	**3.4**



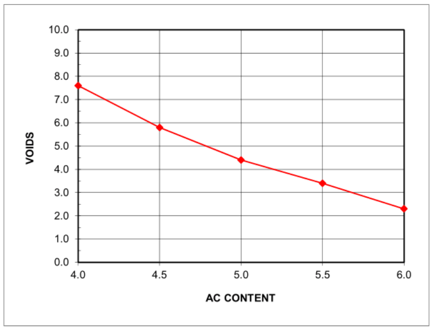


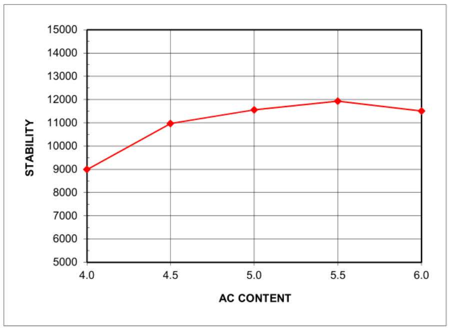
Marshall Test Property Curves

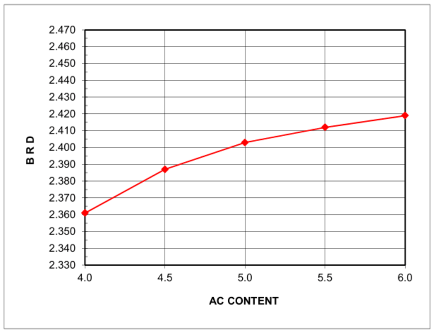
PROJECT No.
CLIENT Halton Asphalt Supply Ltd.

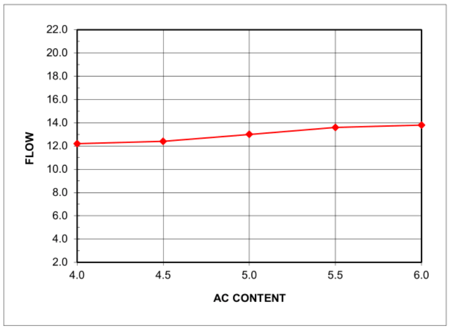
DATE: March 23, 2021
LAB No. MD21-034

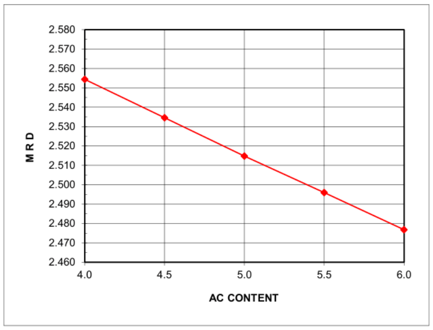
MIX TYPE : HL3 OPSS

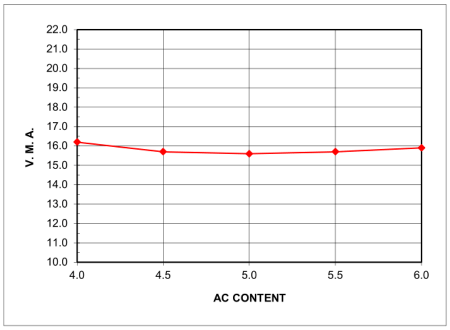












MARSHALL MIX DESIGN WORKSHEET

PROJECT No.	
CLIENT	Halton Asphalt Supply Ltd.

DATE:	March 23, 2021
LAB No.	MD21-034

MIX TYPE:	HL3 OPSS
% Passing 4.75 mm:	54.8
% A.C.:	4.0
Gb(Agg.)	2.705
MANUAL 75 BLOWS @	135 °C

BLEND		
47.5	%C.A. # 1	HL3 Stone, Lincoln, Nelson Aggregate Co.
	%C.A. # 2	
27.5	%F.A. # 1	Asphalt Sand, Stuehler, Waynco
25.0	%F.A. # 2	TC Sand, Stueher, Waynco
	%F.A. # 3	
	% RAP	
1.0	% DUST	Plant Dust

		BRIQUETTE No.			
		1	2	3	AVE.
A	MASS OF COMPACTED SPECIMEN IN AIR	1220.2	1220.7	1219.7	
B	SURFACE DRY MASS OF SPECIMEN	1222.8	1223.2	1222.3	
C	MASS OF COMPACTED SPECIMEN IN WATER	705.7	706.8	705.3	
D	VOLUME [B-C]	517.1	516.4	517.0	
E	BULK RELATIVE DENSITY (BRD) [A/D]	**2.360**	**2.364**	**2.359**	**2.361**
F	MASS OF FLASK AND MIXTURE IN AIR				
G	MASS OF FLASK IN AIR				
H	MASS OF MIXTURE IN AIR [F-G]				
I	SURFACE DRY MASS OF MIXTURE IN AIR				
J	MASS OF FLASK AND MIXTURE IN WATER				
K	MASS OF FLASK IN WATER				
L	MASS OF MIXTURE IN WATER [J-K]				
M	VOLUME [H-L]				
N	*S.D. VOLUME [I-L]				
O	MAXIMUM RELATIVE DENSITY (MRD) [H/M]				2.554
P	S.D. MAXIUMUM RELATIVE DENSITY (S.D. MRD) [H/N]				
Q	% VOIDS IN MIXTURE [(O-E)/O*100]				7.6
R	*S.D. %VOIDS IN MIXTURE [(P-E)/P*100]				
S	% V. M. A				16.2

MARSHALL TEST VALUES				
BRIQ. No.	1	2	3	AVE.
STABITLITY, N	8874	9180	8925	
VOL. CORR.	1.00	1.00	1.00	
CORR. STAB. N	8874	9180	8925	8993
FLOW 0.25 mm	12.1	12.2	12.1	12.2

VISUAL OBSERVATIONS	
MIX APPEARANCE	MEDIUM TO DRY
BRIQ. APPEARANCE	MEDIUM TO DRY
COATING C. AGG	GOOD
COATING F. AGG	GOOD TO FAIR
STRIPPING	NIL
C. AGG FRACTURE	SLIGHT

MARSHALL MIX DESIGN WORKSHEET

PROJECT No.	
CLIENT	Halton Asphalt Supply Ltd.

DATE:	March 23, 2021
LAB No.	MD21-034

MIX TYPE:	HL3 OPSS
% Passing 4.75 mm:	54.8
% A.C.:	4.5
Gb(Agg.)	2.705
MANUAL 75 BLOWS @	135 °C

BLEND		
47.5	%C.A. # 1	HL3 Stone, Lincoln, Nelson Aggregate Co.
	%C.A. # 2	
27.5	%F.A. # 1	Asphalt Sand, Stuehler, Waynco
25.0	%F.A. # 2	TC Sand, Stueher, Waynco
	%F.A. # 3	
	% RAP	
1.0	% DUST	Plant Dust

		BRIQUETTE No.			
		4	5	6	AVE.
A	MASS OF COMPACTED SPECIMEN IN AIR	1226.5	1226.1	1225.6	
B	SURFACE DRY MASS OF SPECIMEN	1228.5	1228.2	1227.6	
C	MASS OF COMPACTED SPECIMEN IN WATER	714.9	714.1	714.5	
D	VOLUME [B-C]	**513.6**	**514.1**	**513.1**	
E	BULK RELATIVE DENSITY (BRD) [A/D]	**2.388**	**2.385**	**2.389**	**2.387**
F	MASS OF FLASK AND MIXTURE IN AIR				
G	MASS OF FLASK IN AIR				
H	MASS OF MIXTURE IN AIR [F-G]				
I	SURFACE DRY MASS OF MIXTURE IN AIR				
J	MASS OF FLASK AND MIXTURE IN WATER				
K	MASS OF FLASK IN WATER				
L	MASS OF MIXTURE IN WATER [J-K]				
M	VOLUME [H-L]				
N	*S.D. VOLUME [I-L]				
O	MAXIMUM RELATIVE DENSITY (MRD) [H/M]				2.535
P	S.D. MAXIUMUM RELATIVE DENSITY (S.D. MRD) [H/N]				
Q	% VOIDS IN MIXTURE [(O-E)/O*100]				5.8
R	*S.D. %VOIDS IN MIXTURE [(P-E)/P*100]				
S	% V. M. A				15.7

MARSHALL TEST VALUES				
BRIQ. No.	4	5	6	AVE.
STABTILITY, N	11016	10761	11118	
VOL. CORR.	1.00	1.00	1.00	
CORR. STAB. N	11016	10761	11118	10965
FLOW 0.25 mm	12.4	12.3	12.5	12.4

VISUAL OBSERVATIONS	
MIX APPEARANCE	MEDIUM
BRIQ. APPEARANCE	MEDIUM
COATING C. AGG	GOOD
COATING F. AGG	GOOD
STRIPPING	NIL
C. AGG FRACTURE	SLIGHT

MARSHALL MIX DESIGN WORKSHEET

PROJECT No.	
CLIENT	Halton Asphalt Supply Ltd.

DATE:	March 23, 2021
LAB No.	MD21-034

MIX TYPE:	HL3 OPSS
% Passing 4.75 mm:	54.8
% A.C.:	5.0
Gb(Agg.)	2.705
MANUAL 75 BLOWS @	135 °C

BLEND		
47.5	%C.A. # 1	HL3 Stone, Lincoln, Nelson Aggregate Co.
	%C.A. # 2	
27.5	%F.A. # 1	Asphalt Sand, Stuehler, Waynco
25.0	%F.A. # 2	TC Sand, Stueher, Waynco
	%F.A. # 3	
	% RAP	
1.0	% DUST	Plant Dust

		BRIQUETTE No.			
		7	8	9	AVE.
A	MASS OF COMPACTED SPECIMEN IN AIR	1233.8	1234.3	1233.4	
B	SURFACE DRY MASS OF SPECIMEN	1235.3	1235.9	1234.8	
C	MASS OF COMPACTED SPECIMEN IN WATER	721.6	722.1	722.1	
D	VOLUME [B-C]	513.7	513.8	512.7	
E	BULK RELATIVE DENSITY (BRD) [A/D]	**2.402**	**2.402**	**2.406**	**2.403**
F	MASS OF FLASK AND MIXTURE IN AIR	2170.9	2159.8		
G	MASS OF FLASK IN AIR	666.0	655.5		
H	MASS OF MIXTURE IN AIR [F-G]	1504.9	1504.3		
I	SURFACE DRY MASS OF MIXTURE IN AIR				
J	MASS OF FLASK AND MIXTURE IN WATER	1488.1	1478.7		
K	MASS OF FLASK IN WATER	581.8	572.4		
L	MASS OF MIXTURE IN WATER [J-K]	906.3	906.3		
M	VOLUME [H-L]	598.6	598.0		
N	*S.D. VOLUME [I-L]				
O	MAXIMUM RELATIVE DENSITY (MRD) [H/M]	2.514	2.516		2.515
P	S.D. MAXIUMUM RELATIVE DENSITY (S.D. MRD) [H/N]				
Q	% VOIDS IN MIXTURE [(O-E)/O*100]				4.4
R	*S.D. %VOIDS IN MIXTURE [(P-E)/P*100]				
S	% V. M. A				15.6

MARSHALL TEST VALUES				
BRIQ. No.	7	8	9	AVE.
STABITLITY, N	11526	11322	11832	
VOL. CORR.	1.00	1.00	1.00	
CORR. STAB. N	11526	11322	11832	11560
FLOW 0.25 mm	13.0	12.9	13.1	13.0

VISUAL OBSERVATIONS	
MIX APPEARANCE	MEDIUM TO RICH
BRIQ. APPEARANCE	MEDIUM TO RICH
COATING C. AGG	VERY GOOD
COATING F. AGG	GOOD
STRIPPING	NIL
C. AGG FRACTURE	SLIGHT

MARSHALL MIX DESIGN WORKSHEET

PROJECT No.	
CLIENT	Halton Asphalt Supply Ltd.

DATE:	March 23, 2021
LAB No.	MD21-034

MIX TYPE:	HL3 OPSS
% Passing 4.75 mm:	54.8
% A.C.:	5.5
Gb(Agg.)	2.705
MANUAL 75 BLOWS @	135 °C

BLEND		
47.5	%C.A. # 1	HL3 Stone, Lincoln, Nelson Aggregate Co.
	%C.A. # 2	
27.5	%F.A. # 1	Asphalt Sand, Stuehler, Waynco
25.0	%F.A. # 2	TC Sand, Stueher, Waynco
	%F.A. # 3	
	% RAP	
1.0	% DUST	Plant Dust

		BRIQUETTE No.			
		10	11	12	AVE.
A	MASS OF COMPACTED SPECIMEN IN AIR	1240.6	1240.1	1239.8	
B	SURFACE DRY MASS OF SPECIMEN	1241.5	1241.1	1240.7	
C	MASS OF COMPACTED SPECIMEN IN WATER	726.9	726.8	726.8	
D	VOLUME [B-C]	514.6	514.3	513.9	
E	BULK RELATIVE DENSITY (BRD) [A/D]	**2.411**	**2.411**	**2.413**	**2.412**
F	MASS OF FLASK AND MIXTURE IN AIR	2113.5	2187.3		
G	MASS OF FLASK IN AIR	601.8	675.7		
H	MASS OF MIXTURE IN AIR [F-G]	1511.7	1511.6		
I	SURFACE DRY MASS OF MIXTURE IN AIR				
J	MASS OF FLASK AND MIXTURE IN WATER	1431.4	1495.7		
K	MASS OF FLASK IN WATER	525.2	589.9		
L	MASS OF MIXTURE IN WATER [J-K]	906.2	905.8		
M	VOLUME [H-L]	605.5	605.8		
N	*S.D. VOLUME [I-L]				
O	MAXIMUM RELATIVE DENSITY (MRD) [H/M]	2.497	2.495		2.496
P	S.D. MAXIUMUM RELATIVE DENSITY (S.D. MRD) [H/N]				
Q	% VOIDS IN MIXTURE [(O-E)/O*100]				3.4
R	*S.D. %VOIDS IN MIXTURE [(P-E)/P*100]				
S	% V. M. A				15.7

MARSHALL TEST VALUES				
BRIQ. No.	10	11	12	AVE.
STABITLITY, N	11985	11730	12087	
VOL. CORR.	1.00	1.00	1.00	
CORR. STAB. N	11985	11730	12087	11934
FLOW 0.25 mm	13.5	13.7	13.5	13.6

VISUAL OBSERVATIONS	
MIX APPEARANCE	MEDIUM TO RICH
BRIQ. APPEARANCE	MEDIUM TO RICH
COATING C. AGG	VERY GOOD
COATING F. AGG	GOOD
STRIPPING	NIL
C. AGG FRACTURE	SLIGHT

MARSHALL MIX DESIGN WORKSHEET

PROJECT No.	
CLIENT	Halton Asphalt Supply Ltd.

DATE:	March 23, 2021
LAB No.	MD21-034

MIX TYPE:	HL3 OPSS
% Passing 4.75 mm:	54.8
% A.C.:	6.0
Gb(Agg.)	2.705
MANUAL 75 BLOWS @	135 °C

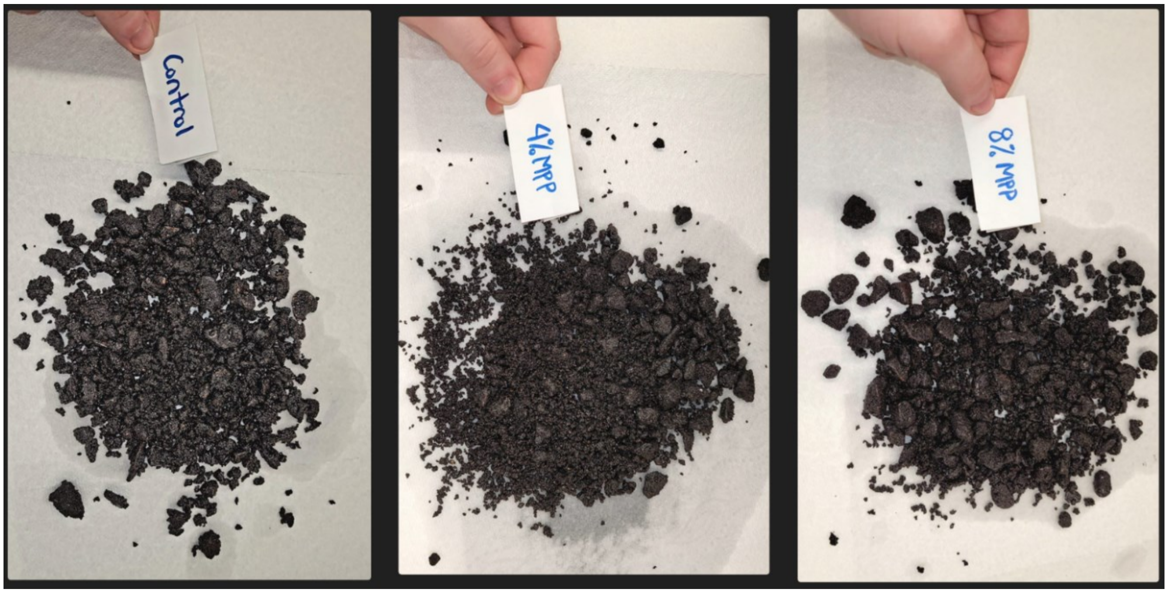
BLEND		
47.5	%C.A. # 1	HL3 Stone, Lincoln, Nelson Aggregate Co.
	%C.A. # 2	
27.5	%F.A. # 1	Asphalt Sand, Stuehler, Waynco
25.0	%F.A. # 2	TC Sand, Stueher, Waynco
	%F.A. # 3	
	% RAP	
1.0	% DUST	Plant Dust

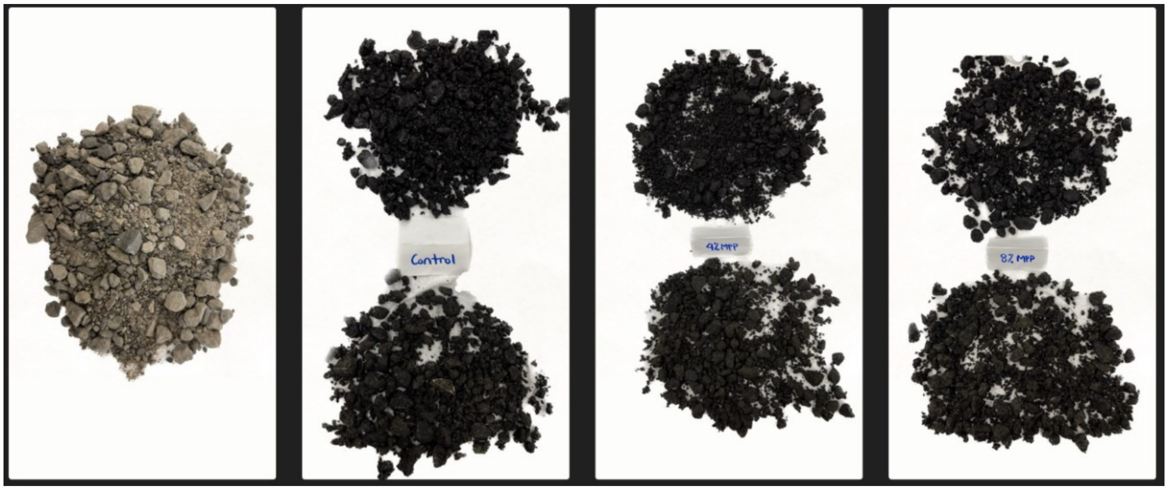
		BRIQUETTE No.			
		13	14	15	AVE.
A	MASS OF COMPACTED SPECIMEN IN AIR	1249.1	1248.8	1248.2	
B	SURFACE DRY MASS OF SPECIMEN	1249.6	1249.2	1248.6	
C	MASS OF COMPACTED SPECIMEN IN WATER	733.1	733.1	732.6	
D	VOLUME [B-C]	516.5	516.1	516.0	
E	BULK RELATIVE DENSITY (BRD) [A/D]	**2.418**	**2.420**	**2.419**	**2.419**
F	MASS OF FLASK AND MIXTURE IN AIR				
G	MASS OF FLASK IN AIR				
H	MASS OF MIXTURE IN AIR [F-G]				
I	SURFACE DRY MASS OF MIXTURE IN AIR				
J	MASS OF FLASK AND MIXTURE IN WATER				
K	MASS OF FLASK IN WATER				
L	MASS OF MIXTURE IN WATER [J-K]				
M	VOLUME [H-L]				
N	*S.D. VOLUME [I-L]				
O	MAXIMUM RELATIVE DENSITY (MRD) [H/M]				2.477
P	S.D. MAXIUMUM RELATIVE DENSITY (S.D. MRD) [H/N]				
Q	% VOIDS IN MIXTURE [(O-E)/O*100]				2.3
R	*S.D. %VOIDS IN MIXTURE [(P-E)/P*100]				
S	% V. M. A				15.9

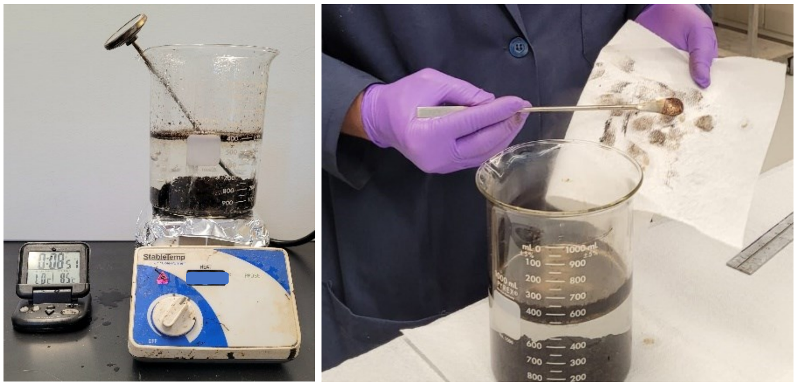
MARSHALL TEST VALUES				
BRIQ. No.	13	14	15	AVE.
STABITLITY, N	11322	11679	11526	
VOL. CORR.	1.00	1.00	1.00	
CORR. STAB. N	11322	11679	11526	11509
FLOW 0.25 mm	13.7	13.8	13.8	13.8

VISUAL OBSERVATIONS	
MIX APPEARANCE	MEDIUM TO RICH
BRIQ. APPEARANCE	MEDIUM TO RICH
COATING C. AGG	VERY GOOD
COATING F. AGG	GOOD
STRIPPING	NIL
C. AGG FRACTURE	SLIGHT

Appendix C: Effect of Water on Asphalt-Coated Aggregate Using Boiling Water







Control Mixture unboiled

Control Mixture After boiling

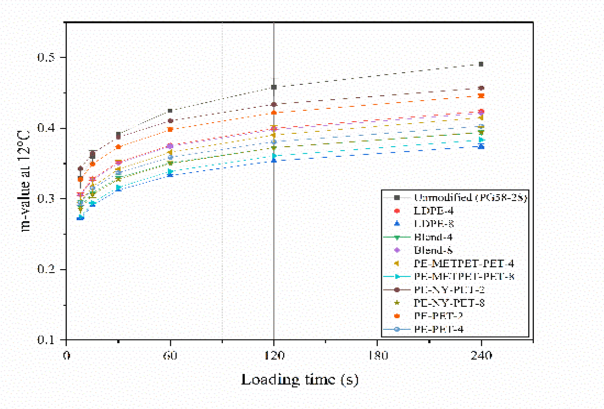
Blend-4 W unboiled

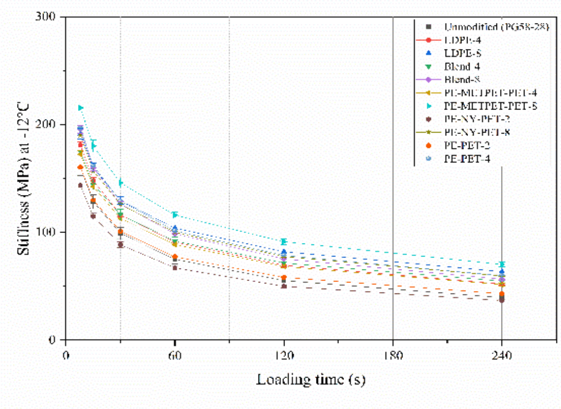
Blend-4 W After boiling

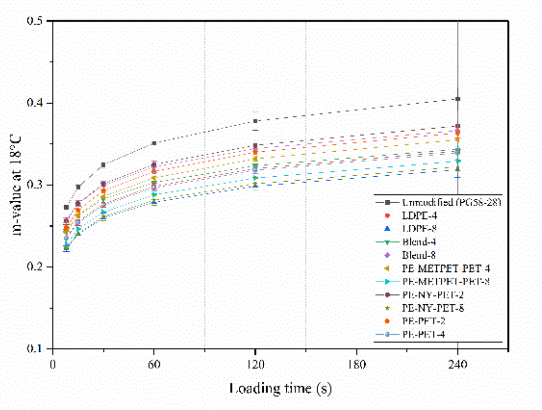
Blend-8 W unboiled

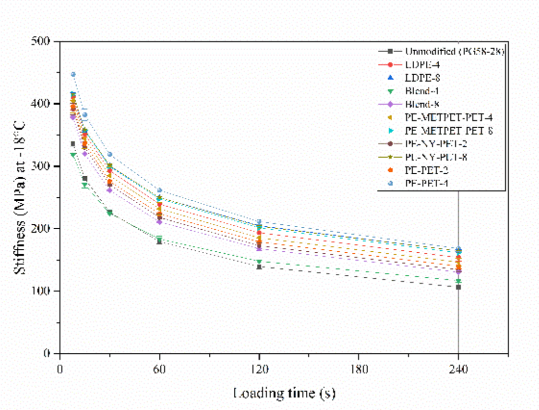
Blend-8 W After boiling

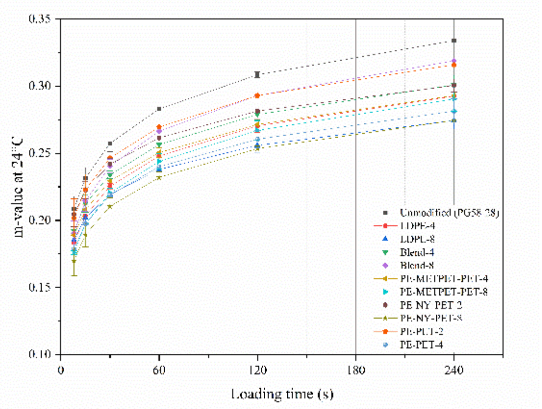
Appendix D: BBR Results of MPP-modified Asphalt Binders

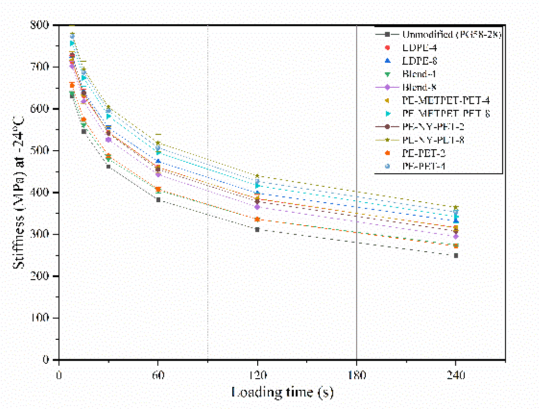


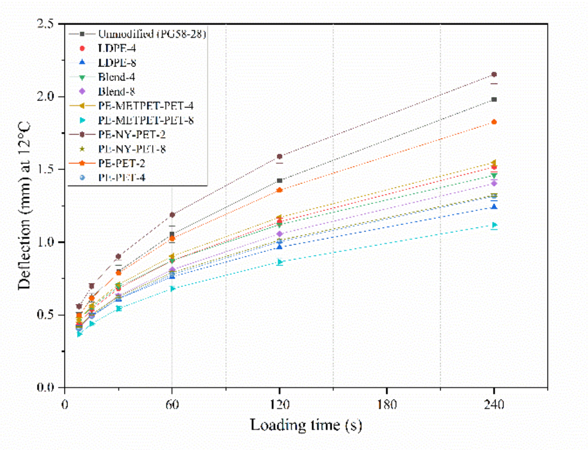


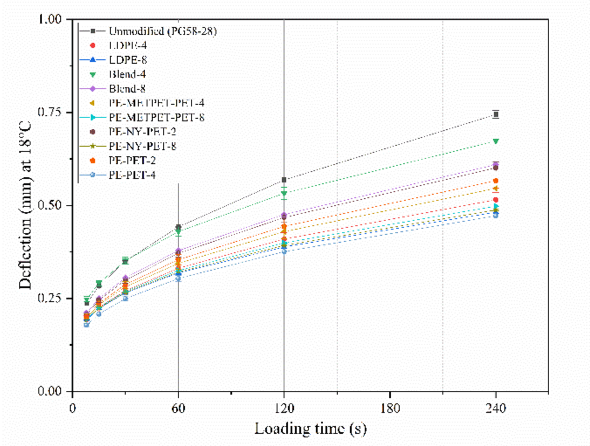


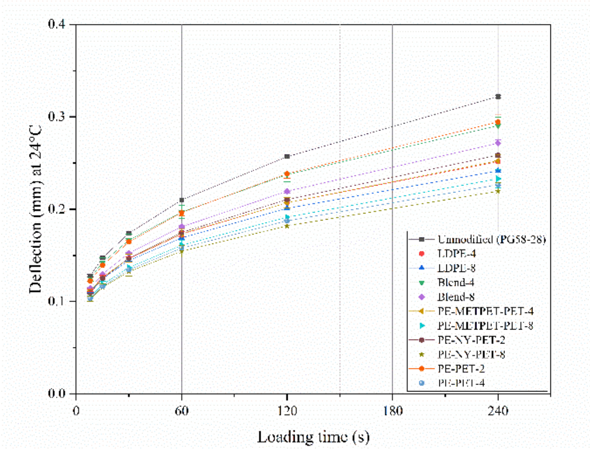







Deflection (mm) at 12°C
Loading time (s)
0.0
0.5
1.0
1.5
2.0
2.5
0
60
120
180
240
Unmodified (PG58-28)
LDPE-4
LDPE-8
Blend-4
Blend-8
PE-METPET-PET-4
PE-METPET-PET-8
PE-NY-PET-2
PE-NY-PET-8
PE-PET-2
PE-PET-4


Deflection (mm) at 18°C
Loading time (s)
0.00
0.25
0.50
0.75
1.00
0
60
120
180
240
Unmodified (PG58-28)
LDPE-4
LDPE-8
Blend-4
Blend-8
PE-METPET-PET-4
PE-METPET-PET-8
PE-NY-PET-2
PE-NY-PET-8
PE-PET-2
PE-PET-4


Deflection (mm) at 24°C
Loading time (s)
0.0
0.1
0.2
0.3
0.4
0
60
120
180
240
Unmodified (PG58-28)
LDPE-4
LDPE-8
Blend-4
Blend-8
PE-METPET-PET-4
PE-METPET-PET-8
PE-NY-PET-2
PE-NY-PET-8
PE-PET-2
PE-PET-4

Appendix E: DSC Results of MPP-modified Asphalt Binders